The Retrievals of Snow Cover Extent and Snow Water Equivalent from a Blended Passive Microwave–Interactive Multi-Sensor Snow Product

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ABSTRACT

The retrieval of Snow Water Equivalent (SWE) from remote sensing satellites continues to be a very challenging problem. In this paper, we evaluate a new SWE product derived from the blending of a passive microwave Snow Water Equivalent product based on the Advanced Microwave Sounding Unit (AMSU) with the Interactive Multi-sensor Snow and Ice Mapping System (IMS). The microwave measurements have the ability to penetrate the snow pack, and thus the retrieval of SWE is best accomplished using the AMSU measurements. On the other hand, the IMS maps snow cover more reliably due to the use of multiple satellite and ground observations. The evolution of global snow cover extent from the blended, the AMSU and the IMS products was examined during the 2006 snow season. Despite the overall good inter-product agreement, it was shown that the retrievals of snow cover extent are improved using IMS, with implications for improved microwave retrievals of SWE. In a separate investigation, the microwave retrievals of SWE were examined globally and in Central Europe. Qualitative evaluation of global SWE patterns showed dependence on land surface temperature: the lower the temperature, the higher the SWE retrieved. This temperature bias was attributed in part to temperature effects on those snow properties that impact microwave response. Therefore, algorithm modifications are needed with more dynamical adjustments for changing snow cover. Quantitative evaluation over Slovakia for a limited period in 2006 showed reasonably good performance for SWE less than 100 mm. Sensitivity to deeper snow decreased significantly.

Keywords: Snow cover, Snow Water Equivalent, Advanced Microwave Sounding Unit (AMSU), Interactive Multisensor Snow and Ice Mapping Unit (IMS)

INTRODUCTION

The retrievals of Snow Water Equivalent (SWE) from satellites continue to be a very difficult and challenging problem. While mapping of global snow cover has been accomplished using visible or passive microwave measurements, the mapping of SWE from space has long been an exclusive domain of passive microwave sensors. Visible measurements are typically more sensitive to snow cover surfaces than passive microwave measurements due to the high visible

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reflectance of snow cover as compared to other surface features, and therefore, they typically provide more accurate mapping of snow cover than the microwave imagery. On the other hand, passive microwaves at specific window frequencies penetrate much deeper into the snow pack due to longer wavelengths, and have shown to provide information on the snow cover properties including SWE. Another advantage of passive microwaves is their ability to penetrate cloudy atmospheres at specific window frequencies and thus to provide retrievals of land surface parameters in near all-weather conditions. Despite the near all-weather capability, the current microwave sensors provide measurements and thus retrievals at much coarser resolution (25 km) than the visible satellite sensors (1 km). Another disadvantage of passive microwave imagery is its limited capability to penetrate wet snow cover.

The need for continuous regional and global snow cover mapping for climate, hydrological and weather applications has led, especially in recent years, to the development of snow cover mapping products based on multi-sensor data sources. For example, the National Oceanic and Atmospheric Administration (NOAA), the National Environmental Satellite Data and Information Systems (NESDIS) uses the Interactive Multi-sensor Snow and Ice Mapping System (IMS) operationally to provide Northern Hemispheric (NH) snow and ice mapping as input to environmental prediction models. The IMS system utilizes in an interactive fashion, through the interpretation of an analyst, visible and microwave satellite imagery as well as ground observations. Over the years, as more satellite sensors have become available, the IMS has incorporated more satellite data sources and has evolved into a more efficient snow mapping system (Ramsay, 1997, Helfrich et al., this issue). Another multi-sensor snow and ice mapping product is the NOAA's AUTOSNOW product (Romanov et al., 2000). It utilizes visible, infrared and microwave satellite data to automatically generate high-resolution and continuous NH snow and ice mapping.

Main research objective of this study is to evaluate the accuracy of a new SWE product derived from the blending of a passive microwave SWE product based on the Advanced Microwave Sounding Unit (AMSU) with the IMS snow cover extent product. The blended SWE product is needed (in addition to snow cover extent) as input to environmental prediction models. Besides being delivered in compatible format with the IMS snow cover extent, the blended product would be value-added in that SWE would be improved due to more reliable IMS snow mapping. Similar approaches have been reported in literature, e.g., the blending of a microwave SWE product based on the Special Sensor Microwave Imager (SSM/I) or the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) with the snow cover extent product derived from the Moderate Resolution Imaging Spectrometer (MODIS) (Armstrong et al. (2003). Compared to SSM/I and AMSR-E, the AMSU has some unique characteristics: Despite its coarse resolution, it has a wider spatial coverage than AMSR-E and SSM/I, and has additional microwave channels at frequencies in the window, oxygen and water vapor absorption regions. These additional features could potentially be utilized for the development of more robust SWE retrievals.

In this paper, we evaluate the blended SWE product for its accuracy in mapping snow cover and SWE. In terms of snow cover mapping, we inter-compare the AMSU snow cover extent product with that of IMS. Inter-comparability of snow cover extent retrieved from the AMSU and from IMS is important to investigate as it has implications for the accuracy of the blended SWE product. Next, the microwave-derived SWE estimates are also evaluated globally and regionally over Central Europe (Slovakia).

METHODS

The IMS Product

The IMS was designed to allow mapping of snow cover interactively on a daily basis using a variety of data sources within a common geographic system. Such data sources include NOAA Polar Orbiting Environmental Satellites (POES) and Geostationary Environmental Satellites (GOES) data, Japanese Geostationary Meteorological Satellites (GMS), European geostationary meteorological satellites (METEOSAT) and US Department of Defense (DOD) polar orbiters (DMSP). Since its inception in 1997, the IMS system has evolved significantly in terms of input data sources, production technology and output format. For more detailed description of evolution and capabilities of the IMS system, the reader is referred to Helfrich et al., (this issue) and Ramsay (1998; 2000). The IMS snow and ice mapping is currently accomplished once daily over the Northern Hemisphere. The product is generated at 4 km and 24 km resolution in Polar Stereographic (PS) Projection.

The AMSU Instrument

The AMSU instrument contains two modules: AMSU-A and AMSU-B. The A module has 15 channels in the 23-89 GHz frequency range (1-15, Table 1). The B module has five channels in the 89-183 GHz frequency range (16–20, Table 1). The AMSU-A has an instantaneous field of view (FOV) of 48 km at nadir for all frequency channels, and scans $\pm 48^0$ from nadir with a total of 30 measurements across the scan. For AMSU-B, 90 measurements are made across the scan with a nadir resolution of 16 km for all channels. The nadir resolution degrades at larger scan angles. The swath width of both AMSU-A and –B is 2343 km.

The AMSU-A and -B is flown on board the NOAA 15, NOAA 16, and NOAA 17 POES. This three-satellite suite offers a near-real time global sampling nearly every 4 hours. The unique combination of channels in the microwave window (23, 31, 89, 150 GHz), opaque water vapor (183±1, ±3, ±7 GHz) and oxygen absorption (50-60 GHz) regions has led to the development of a variety of surface and atmospheric products, generated in near-real time within a system called the Microwave Surface and Precipitation Product System (MSPPS). The suite of operational MSPPS products (Ferraro et al., 2002) includes rain rate, total precipitable water, cloud liquid water, ice water path, snow cover, sea ice concentration and land surface temperature and emissivities at 23, 31 and 50 GHz. Recent additions include a snowfall detection (Ferraro et al., 2004), and the extension of the snow cover extent product to include snow water equivalent (SWE) retrievals (Kongoli and Ferraro, 2004). In May 2005, a new POES satellite, NOAA 18, was launched and was also incorporated into MSPPS. This new satellite contains a new instrument, the Microwave Humidity Sensor (MHS) which replaced the AMSU-B. Similar to AMSU-B, the MHS is a five-channel radiometer. However, it differs from AMSU-B in that channel 2 and channel 5 (channels 17 and 20 in Table 1) are 157 GHz and 190 GHz. Calibration and validation of the new MHS instrument within MSPPS has been completed and is described in Meng et al. (2006). As a result, similar products that are generated from the three satellites are now also generated from NOAA-18.

Table 1. AMSU-A and –B channel characteristics. Channels 1-15 are AMSU-A channels and channels 16-20 are AMSU-B channels

Channel number	Center frequency (GHz)	Number of pass bands	Band width (MHz)	Center frequency stability (MHz)	FOV at Nadir (km)
1	23.80	1	251	10	48
2	31.40	1	161	10	48
3	50.30	1	161	10	48
4	52.80	1	380	5	48
5	53.59±0.115	2	168	5	48
6	54.40	1	380	5	48
7	54.94	1	380	10	48
8	55.50	1	310	0.5	48
9	57.29 = fo	1	310	0.5	48
10	fo±0.217	2	76	0.5	48
11	fo±0.322±0.048	4	34	0.5	48
12	fo±0.322±0.022	4	15	0.5	48
13	fo±0.322±0.010	4	8	0.5	48
14	fo±0.322±0.004	4	3	0.5	48
15	89.00	1	2000	50	48
16	89.00	1	5000	50	16
17	150	1	4000	50	16
18	183±1	1	1000	50	16
19	183±3	2	2000	50	16
20	183±7	2	4000	50	16

The AMSU Snow Cover Extent Product

The identification of snow cover over land is based on the algorithm of Grody (1991) and Grody and Basist (1996). Snow is identified in a series of steps that discriminate snow from non-scattering surfaces such as wet land and vegetation (Figure 1) and from other scatterers such as deserts and rain. This is accomplished using a number of scattering indices that utilize a combination of the AMSU window frequency channels at 23, 31, 50 and 89 GHz (Table 1, AMSU-A channels 1, 2, 3 and AMSU-B channel 16, respectively). As shown in Figure 1, snow exhibits a unique spectral signature in the 10–100 GHz microwave frequency region: The brightness temperature, and hence, the surface emissivity decreases with increasing frequency. In contrast, other surfaces such as wet land and vegetation exhibit a rather flat or reverse response. More recently, additional filters have been incorporated that utilize a combination of AMSU channels at 150 GHz (Table 1, channel 17) at 53.6 GHz (Table 1, channel 5) and at 183 ± 3 GHz (Table 1, channel 19) for improved snow–rain discrimination (Kongoli et al. 2005).

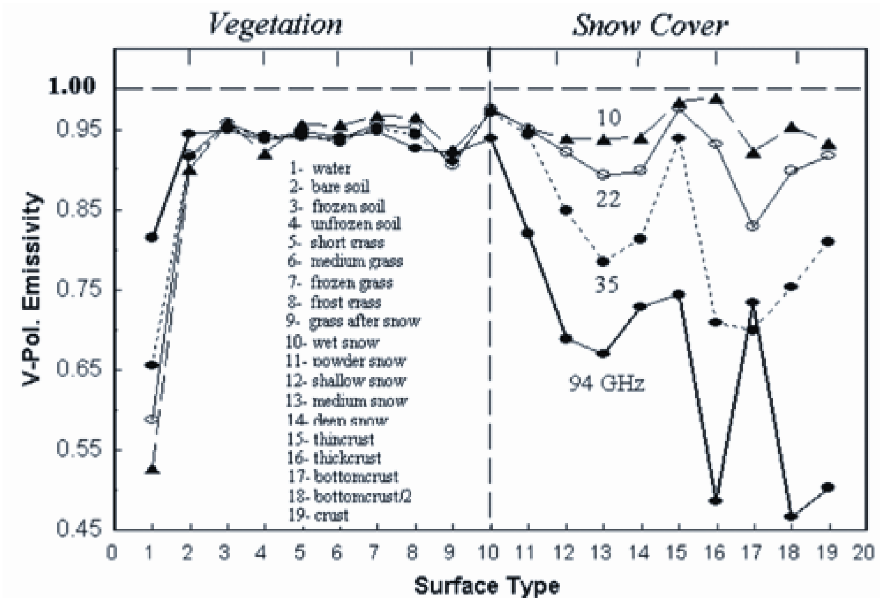

Figure 1. Microwave spectral characteristics of vegetation and snow cover (Matzler, 1994).

The AMSU SWE Product

The retrieval of SWE is based on the AMSU brightness temperature measurements at 23 (TB23), 31 (TB31) and 89 (TB89) GHz. Based on these channel measurements, two scattering indices are computed:

$$SI31 = TB23 - TB89 \quad (1)$$
$$SI89 = TB23 - TB31 \quad (2)$$

The SWE is computed for the snow-covered pixels by the following empirical relationships:

$$SWE = K1 + K2 * SI89 \quad (3)$$
$$SWE = K3 + K4 * SI31 \quad (4)$$

where K1, K2, K3, and K4 are empirically derived coefficients. SWE is computed only over snow-covered land retrieved by the AMSU snow cover extent algorithm. The SWE algorithm implicitly differentiates between two snow-cover types: finer-grained fresh snow (Eq. 3) and coarser-grained older (Eq. 4) snow-cover via the estimation of a switch (mean grain size) parameter, which is also estimated from a linear relationship with TB23, TB31 and TB89. The coefficient values for K1, K2, K3 and K4 and the switch parameter are fixed. They were derived from regional studies in the U.S Great Plains areas (Kongoli et al., 2004). It is also important to note that atmospheric or land surface vegetation effects are not accounted for in the current version. The concept behind the algorithm using the scattering indices (1) and (2) and Equations (3) and (4), respectively, is illustrated in Figure 2, which depicts examples of AMSU measurements at 23, 31, 89 and 150 GHz window frequency channels. Note that microwave sensitivity to snow cover shifts from lower (20–30 GHz) to higher (89–150 GHz) frequency regions as the snow ages. For freshly fallen snow (6 hr old), the steepest microwave gradient occurs in the 89–150 GHz region (about 25 K), due to strong scattering at 150 GHz by finer-grained snow cover. Note the flat response in the 20–30 GHz region, suggesting low microwave sensitivity in this lower frequency range. As the snow becomes older and the grain size increases, sensitivity shifts to the 30–90 GHz region which attains the steepest gradient. Only for coarse-grained, metamorphosed snow cover, referred to in Figure 2 as "old snow" does the microwave sensitivity increase significantly at 23 and 31 GHz. In the current algorithm, 150 GHz is not utilized for the retrievals of SWE. It is important to note, however, that this dual snow type discrimination is a crude approximation and representation of the much greater snow cover type and hence grain size and (micro)structure variability, e.g., as illustrated in Figure 1.

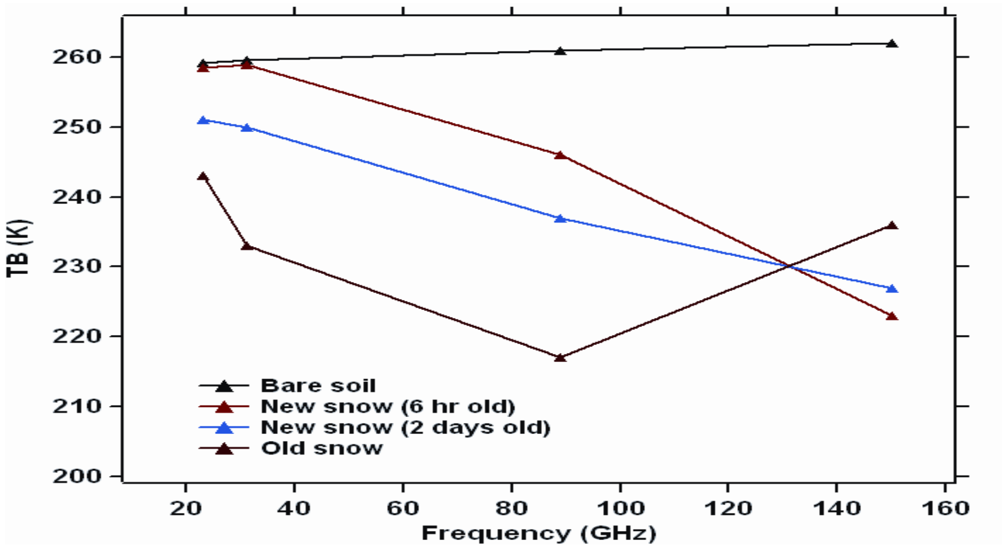

Figure 2. Example of AMSU measurements over snow covered land

Blending Procedure

Primary satellite data are not used in the blended product. Instead, the data inputs include AMSU SWE product files and IMS snow cover product files. The SWE data are obtained from the MSPPS Level 2 swath geographical products available in the Hierarchical Data Format-Earth Observing System (HDF-EOS) at NOAA/NESDIS. These swath files are generated on an orbital basis from NOAA-15, 16, 17 and more recently the NOAA-18 satellites. Spatial resolution of the AMSU SWE swath data is that of AMSU-B: 16 km at nadir viewing angle. Resolution degrades as viewing angle increases. The IMS snow cover data are obtained daily as ASCII files in $1/16^{th}$ mesh PS Projection, or approximately 24 km in resolution. The data flow and rules for generating merged product are as follows:

- Obtain daily IMS snow cover product file,
- Obtain the AMSU SWE swath product files. The NOAA-18 instrument was selected as the most recent instrument, and the descending (night-time) was selected to minimize SWE retrieval errors due to surface melting during day-time,
- Convert the AMSU swath SWE data into gridded data compatible with the IMS snow cover product file.
- Inter-compare the AMSU SWE and IMS snow cover values on a grid cell-by-cell basis. If SWE value is missing or zero over snow cover as identified by IMS, retrieve previous day SWE value (two-day compositing). If previous-day SWE value is positive assign that SWE value to grid cell. Otherwise, flag as “indeterminate” the grid cell that corresponds to missing or zero AMSU SWE and IMS snow-covered land. Also, label as “indeterminate” instances of positive AMSU SWE value that correspond to IMS snow-free land. At this point, no revision of SWE values over these “indeterminate” grid cells is made. This is reserved for future development,
- Generate blended SWE output file, a statistics file with grid cell confusion data, and image input and blended output grid files for product visualization and monitoring

Ground SWE measurements over Slovakia

The SWE retrievals were quantitatively evaluated against SWE measurements over Slovakia during February–March 2006. The SWE data and maps were provided by the Slovak National Hydro-meteorological Institute which maintains a dense network of ground stations that record snow depth and SWE on a weekly basis (Figure 3). Dotted green points denote station locations, whereas in red are depicted grid points spaced 0.25 by 0.25 degrees Latitude and Longitude. The areas depicted in brown in Central and North Slovakia denotes higher elevation terrain. To statistically evaluate SWE retrievals, station SWE data were matched up with the AMSU observations and retrieved SWE. Station SWE data were averaged over a cell of 0.5 X 0.5 degree in latitude and longitude centered at the centroid of AMSU FOV. This size represents the average resolution of the AMSU instrument. Along with the average SWE, average values of snow depth and elevation, the number of stations per cell, as well as standard deviations of SWE, depth and elevation were computed. Only cells with over 5 stations were included in the analysis. Due to the higher density of stations, cells with over five stations were predominant.

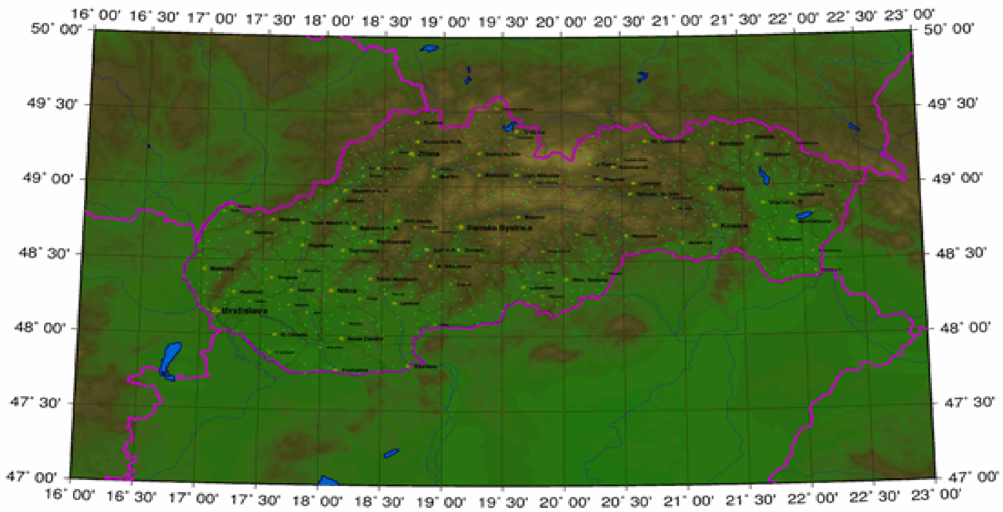

Figure 3. Map of Slovakia and locations of ground SWE stations

RESULTS AND DISCUSSION

Inter-comparison of blended snow cover with that retrieved from the AMSU and IMS products

The blended product system has been automated and running experimentally on a UNIX machine since November 2005. Examples of blended SWE product are shown in Figure 4. Figure 4 displays merged SWE (left) and inter-comparison of AMSU and IMS snow cover extent (right) on November 7, 2005 (top panels) and on February 15, 2006 (bottom panels). The inter-comparison map depicts the blended SWE area in blue, the underestimated microwave SWE area in green (AMSU-SWE values are zero but IMS snow cover is positive), and the overestimated microwave SWE area in brown (AMSU-SWE is positive but IMS snow cover is zero). The red color depicts areas when AMSU-SWE is labeled as "undetermined" due to confusion with rain, and is displayed for diagnostic purposes. Note the green-coded area over Eastern Canada on November 7, 2005 (top right), denoting underestimation of snow cover and hence SWE by the AMSU snow cover extent product. In the blended SWE product, these undetermined SWE areas are denoted as "white". Examination of ground observations from several Canadian meteorological stations indicated continuous snowfall occurrences prior to November 7. The deposited new snow was not captured by the AMSU snow cover extent product, but was identified by the IMS snow cover product. Interestingly, these snowfall occurrences were retrieved by the AMSU snowfall product. An example of the AMSU snowfall product retrievals on November 2, 2005 is given in Figure 5. The AMSU snowfall algorithm utilizes frequencies at 89 GHz and above (AMSU-B channels 16-20 in Table 1) to identify precipitation in the form of snowfall

(Kongoli et al., 2003). Examination of the AMSU measurements on November 7, 2005 indicated that the 89 GHz frequency channel was not sufficiently sensitive to this newly deposited snow. However, the 150 GHz window frequency channel exhibited scattering response, e.g., depressed brightness temperatures relative to that of 89 GHz (see also Figure 2). Note that frequency channels above 89 GHz are not available for the SSM/I or AMSR-E sensors. This unique capability of the AMSU instrument to retrieve snowfall and to detect newly deposited snow cover could be potentially incorporated and utilized for improved SWE retrievals for new snow. On the other hand, in the blended SWE product, SWE over part of Mongolia as determined by the AMSU product but labeled as "snow-free" land by the IMS is correctly left out. This overestimation of snow cover over Mongolia by the AMSU persisted during much of the winter season of 2006, and is also shown on February 15, 2006 (bottom panels). It is shown that overall, there is better agreement between the microwave-derived SWE and the IMS snow cover, e.g., over Eastern Canada, than in early winter. Exception is areas over Mongolia where overestimation of the AMSU-SWE persists throughout the winter. Examination of MODIS snow cover maps indicated that indeed these areas did not have snow cover, and therefore, they represent "false" snow areas by the AMSU SWE product. Examination of the AMSU measurements over Mongolia indicated relatively small values of the scattering index at 89 GHz (SI89), which is used in the AMSU snow cover extent product to identify snow cover and in the AMSU-SWE product to compute fresh snow SWE (Eq. 2 and 4). This low scattering signal at 89 GHz was present during night-time (low temperatures) and day-time (above freezing temperatures). The presence of scattering in a wide range of atmospheric conditions over Mongolia would be indicative of ground rather than atmospheric effects, e.g., soil grain scattering (Basist et al., 1996). Figure 6 is a plot of the percentage of the retrieved AMSU-SWE area relative to the IMS snow coverage from December 1, 2005 through April 15, 2006 (left-hand vertical axis) and of the overestimated AMSU-SWE area as a percentage of the IMS snow coverage (right-hand vertical axis). It is shown that the net SWE area mapped by the AMSU is at about 75% as compared to that of IMS, which is relatively high for a microwave instrument. The overestimation of snow cover by the AMSU is about 6 % relative to IMS snow coverage.

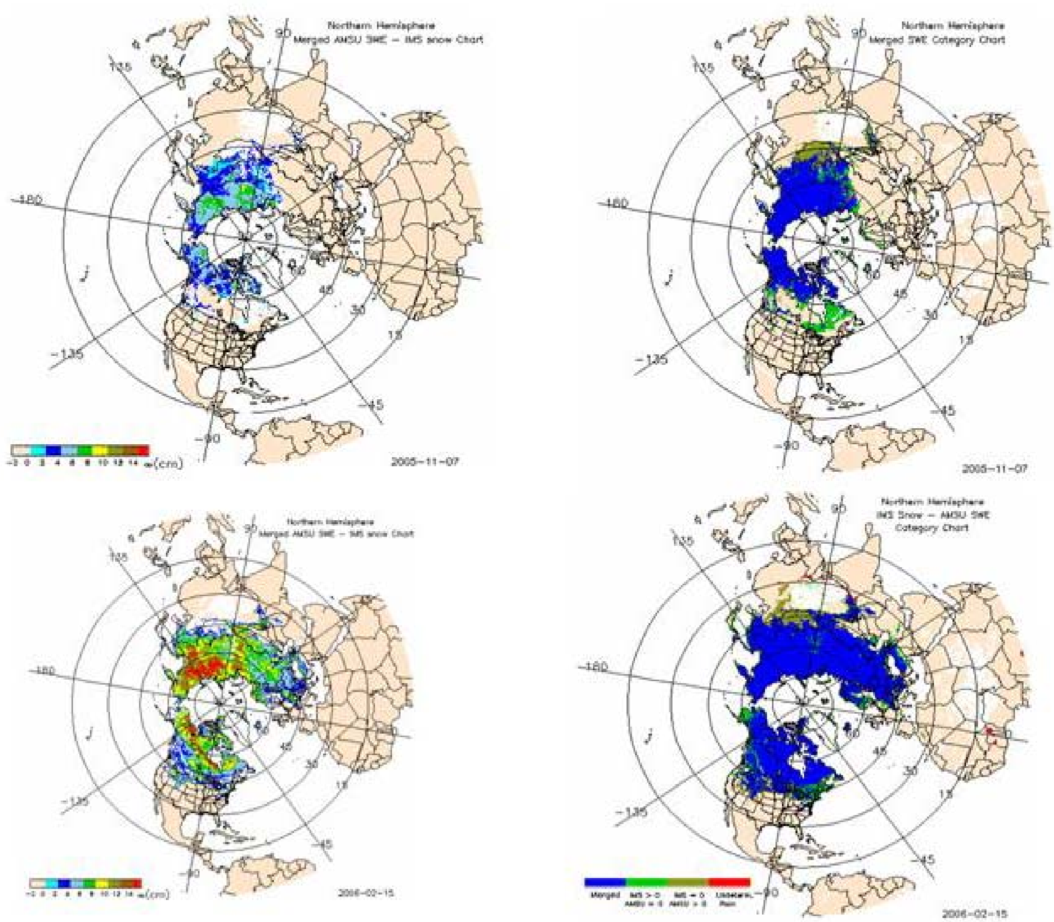

Figure 4. Example of blended SWE product retrievals over Northern Hemisphere on November 7, 2005 and February 15, 2006. Left-hand images depict the blended SWE and the right-hand images depict blended and unblended areas.

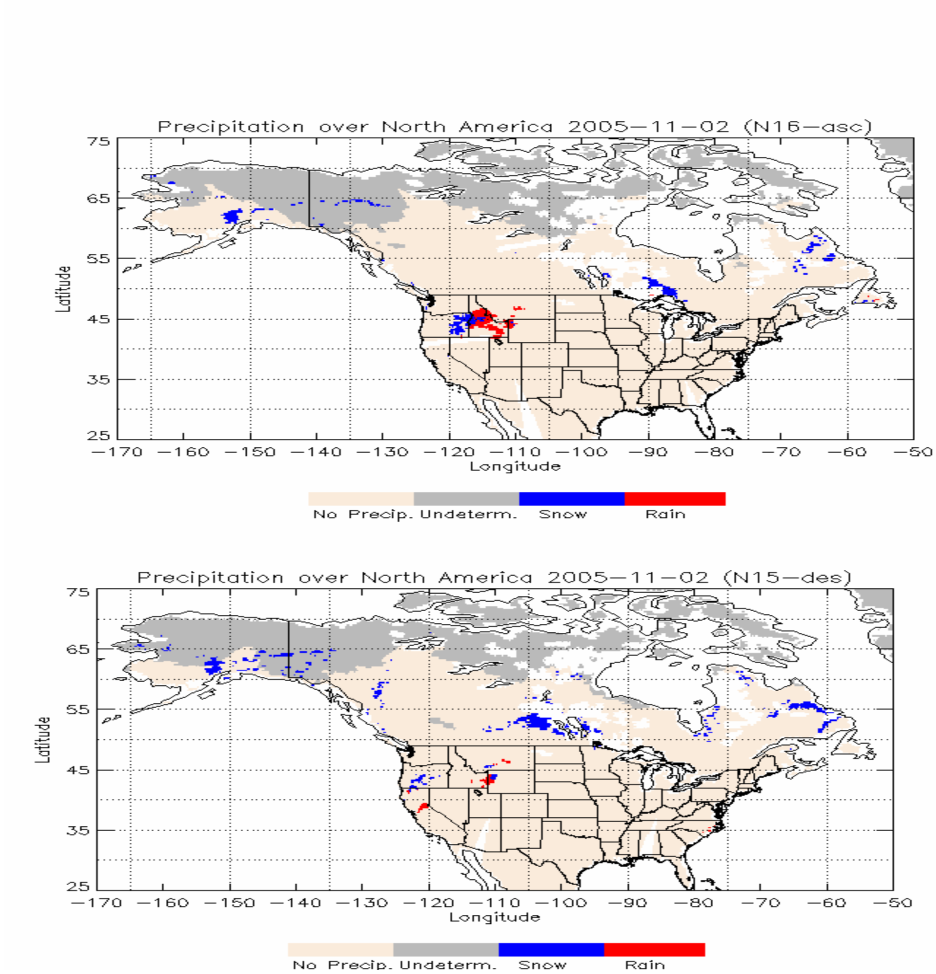

Figure 5. The AMSU snowfall retrievals over North American on November 2, 2005.

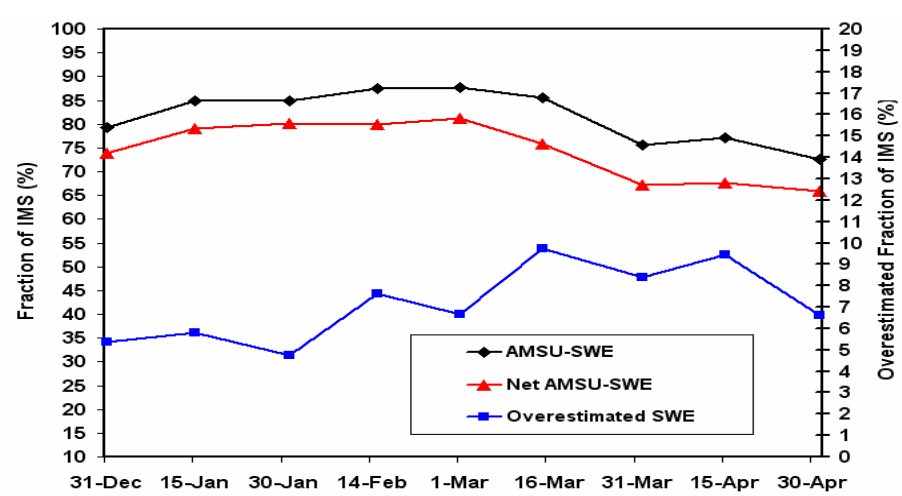

Figure 6. Inter-comparison of global SWE and IMS snow cover extent

Evaluation of the global distribution of retrieved SWE

Figure 7 depicts example of retrievals of AMSU SWE (left) and Land Surface Temperature (LST) (right) in March 2002 and 2003. Note the predominance of high SWE values (depicted in red) over North-central and Eastern Siberia, over Northern Canada and Alaska. Interestingly, these patterns are similar to the ones retrieved in 2006 (Figure 4). Although global SWE data are not available to quantitatively evaluate retrieved SWE, some general observations can be made. For example, the increase in SWE from Western to Eastern Siberia may be unrealistic given the dry, low-temperature climate predominant in Eastern Siberia. These trends appear to be strikingly similar in 2002, 2003 and 2006. Despite large-scale similarity, a closer visual inspection revealed some inter-annual differences over specific regions. For instance, retrieved SWE over some Western US regions, e.g., Colorado, Wyoming and Idaho, and over Canada, e.g, Alberta, were higher in 2002 than in 2003. Another observed difference was the larger extent of high SWE over Siberia in 2003 than in 2002. This inter-annual variability in SWE appears to follow that of LST: The lower the LST the higher the retrieved SWE. For instance, lower LST in 2002 than in 2003 over Western US was associated with retrieved SWE higher in 2002 than in 2003. LST also appears to influence to a large extent the global distribution of retrieved SWE. A possible explanation of this temperature bias could be the influence of temperature on the evolution of snow cover properties that impact the microwave response. As explained earlier, the AMSU SWE algorithm coefficients are static. Foster et al., 2005 report a new dynamical approach where algorithm coefficients are adjusted based on a geo-referenced snow classification system (Sturm et al., 1995). The authors report improved performance compared to static retrievals.

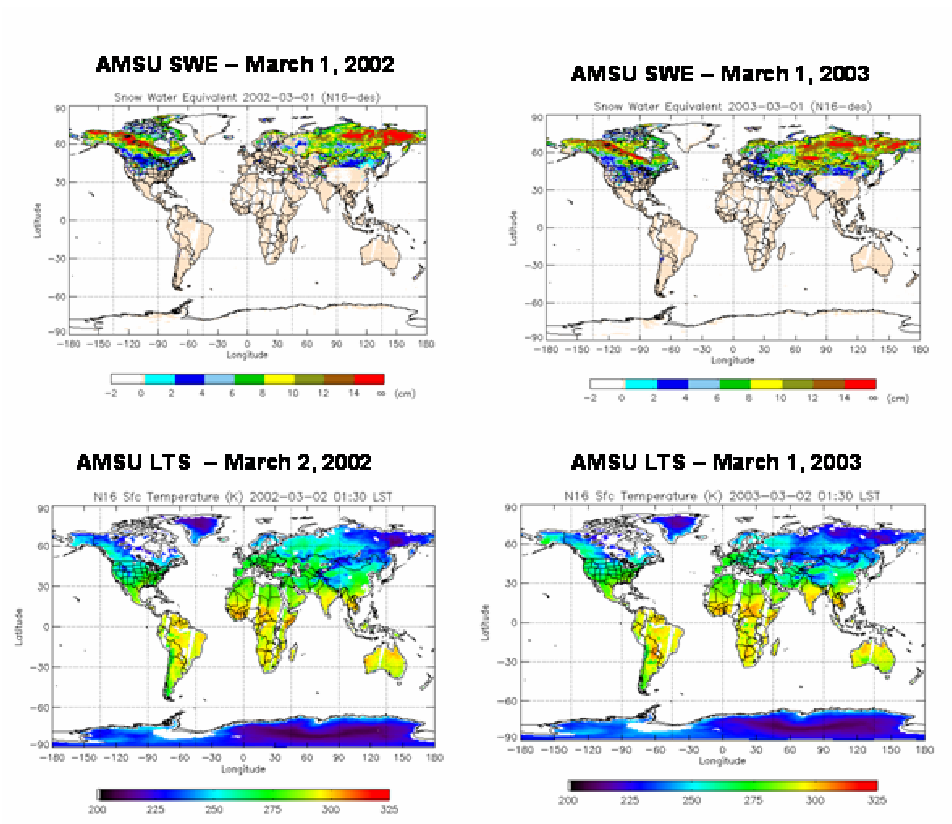

Figure 7. AMSU retrieval of SWE (top) and Land Surface Temperature (bottom) in March 2002 and 2003.

Evaluation of SWE retrievals over Slovakia

Figure 8 plots the histogram of station averaged SWE over Slovakia (top panel) and the average and standard deviation of SWE matched up with the AMSU measurements as a function of average elevation (bottom panel). As shown, SWE is most frequent around 50 mm. There is, however, a good distribution of SWE in the 50- to 150-mm range. Note also that the standard deviation of SWE increases with elevation and the SWE amount. Figure 9 displays plots of retrieved SWE versus measured SWE for elevations less than 400 m (top panel left) and for all elevation ranges (bottom panel left). As shown, there is good agreement of retrieved SWE versus measured SWE for elevations less than 400 m. Elevations less than 400 mm had an average SWE of 40 mm and maximum SWE and snow depth of 100 mm and 30 cm, respectively. For higher elevations, retrieved SWE is significantly underestimated. The right hand panels in Figure 9 depict plots of the bias (retrieved SWE–measured SWE) as a function of elevation (top) and as a function of measured SWE (bottom). As shown, the bias exhibits stronger dependence on SWE amounts than on elevation. Microwave signal saturation at SWE values above 100 mm is also reported in literature (Dong et al., 2005). However, given the high standard deviation of measured SWE within the AMSU FOV, a more rigorous examination of the possible error sources would have required additional information on snow cover and ground station distribution. Figure 10 displays AMSU SWE retrievals over Central Europe including Slovakia (left panel) and the map of station derived SWE over Slovakia (right panel) on February 27, 2006. As shown, the highest AMSU SWE retrieved over Slovakia is in the 100- to 120-mm range in Northeastern Slovakia, compared to station derived SWE over 180 mm. Note, however, the highly variable station-derived SWE over Northeastern Slovakia. Large-scale SWE patterns are retrieved reasonably well, e.g., the increase in SWE towards the Northeast. Small-scale patterns, however, are not well captured due to the coarse AMSU resolution.

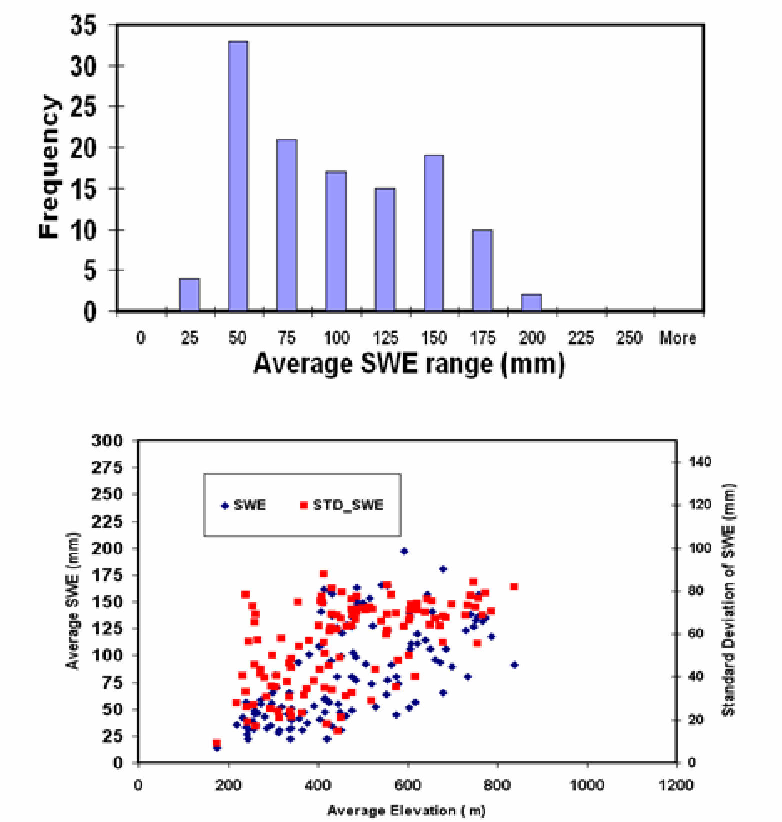

Figure 8. Average measured SWE distribution matched up with AMSU data

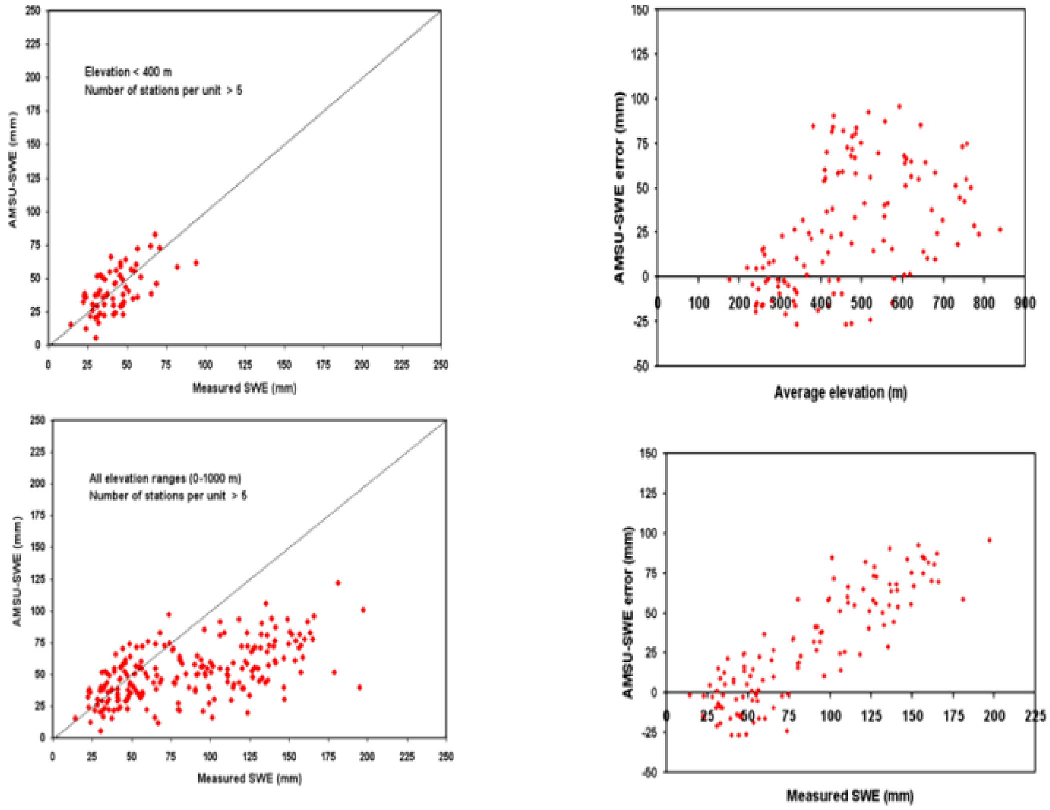

Figure 9. Inter-comparison plots of AMSU versus measured SWE (left panels) and of the bias of retrieved SWE as a function of elevation and measured SWE (right panels)

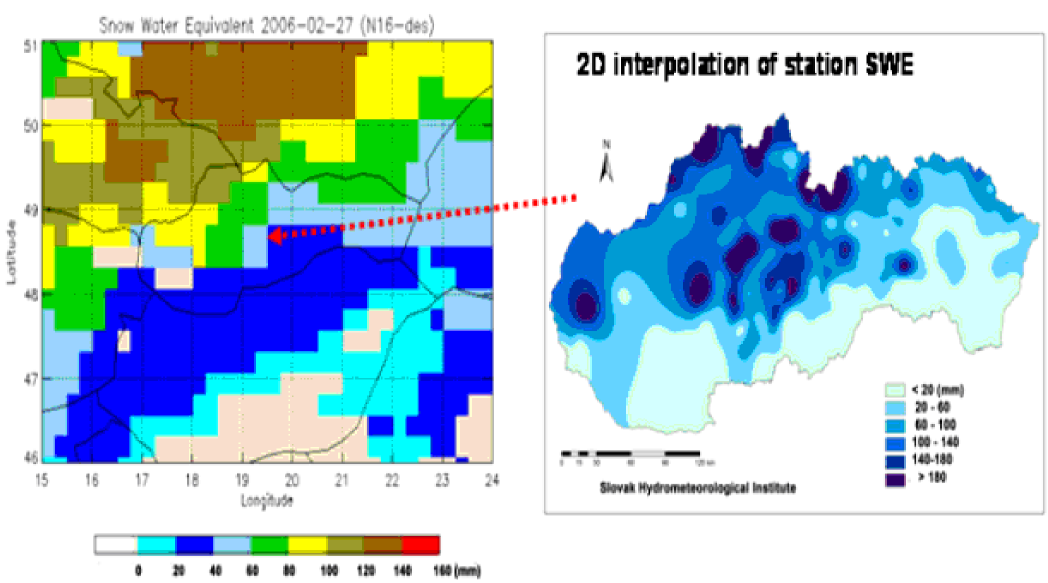

Figure 10. AMSU retrieved SWE over central Europe (left) and station SWE over Slovakia on February 27, 2006.

SUMMARY

Main research objective of this study was to evaluate the accuracy of a new SWE product derived from the blending of a passive microwave SWE product based on AMSU instrument with the IMS snow cover extent product. The blended SWE product is needed (in addition to snow cover extent) as input to environmental prediction models. The paper described data and evaluation methodology. The blending procedure between the AMSU SWE and IMS snow cover extent products was also described. Next, snow cover extent retrievals by the AMSU, IMS and the blended product were evaluated for the 2005–2006 snow season. Despite good inter-product agreement, it was shown that the IMS had better skills than the AMSU snow cover extent product in retrieving new snow cover in early winter and in correctly identifying snow-free land, e.g., over Mongolia, that was otherwise reported as "snow" by the AMSU product. These problem areas were also evaluated using other observation sources, e.g., the MODIS snow cover product and the AMSU snowfall product. In a separate investigation, the paper also described the evaluation of the microwave SWE product globally and over central Europe (Slovakia). Qualitative evaluation of the large-scale, global SWE patterns showed dependence of AMSU retrieved SWE on land surface temperature: the lower the land surface temperature, the higher the SWE retrieved. This temperature bias was attributed in part to temperature effects on snow properties that impact microwave response. Therefore, AMSU SWE algorithm modifications are needed, e.g., adjustment of algorithm coefficients for changing snow properties. Quantitative evaluation over Slovakia for a limited period in 2006 showed reasonably good agreement for SWE less than 100 mm and snow depth less than 30 cm, associated with low elevation terrain (less than 400 m). Sensitivity to snow deeper than 100 mm in SWE decreased significantly.

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REFERENCES

Armstrong, R., M.J. Brodzik, and M. Savoie, 2003: Multisensor approach to mapping snow cover using data from NASA's Terra and Aqua Spacecraft (AMSR-E and MODIS), *Eos Trans. AGU,* **84**(46).

Basist, A., D. Garrett, R. Ferraro, N. Grody and K. Mitchell, 1996: A comparison between snow cover products derived from visible and microwave observations, *J. Appl. Meteorol.,* **35**:163–177.

Dong, J., J.P. Walker, and P. R. Houser, 2005: Factors affecting remotely sensed snow water equivalent uncertainty, *Remote Sensing of Environment* **97**: 68–82.

Ferraro, R., C. Kongoli, and P. Pellegrino, 2004: An Evaluation of a New AMSU-Derived Falling Snow Retrieval Algorithm (Preprint), 13th Conference on Satellite Meteorology and Oceanography, *American Meteorological Society*, 20–23 September, 2004, Norfolk, VA.

Ferraro, R. R., F. Weng, N.C. Grody, I. Guch, C. Dean, C. Kongoli, H. Meng, P. Pellegrino, and L. Zhao, 2002: NOAA satellite-derived hydrological products prove their worth, *Eos Trans. AGU,* **83**: 429–437.

Foster J.L., C. Sun, J.P. Walker, R. Kelly, A. Chang, J. Dong, and H. Powell, 2005: Quantifying the uncertainty in passive microwave snow water equivalent observations, *Remote Sensing of Environment* **94**: 187–203.

Grody, N.C., 1991: Classification of snow cover and precipitation using the special sensor microwave imager, *J. Geophys. Res.,* **96***(D4)*: 7423–7435.

Grody, N.C., and A.N. Basist, 1996: Global identification of snow cover using SSM/I Measurements, *IEEE Trans. Geosci. Remote Sens.* **34**(1): 237–249.

Helfrich, S.R., D. McNamara, B.H.Ramsay, T. Baldwin, and T. Kasheta (2006), Enhancements and forthcoming developments to the Interactive Multisensor Snow and Ice Mapping System (IMS), *Hydrological Processes (this issue).*

Kongoli, C., N.C. Grody, and R. Ferraro, 2004: Interpretation of AMSU measurementsfor the retrievals of snow water equivalent and snow depth, *J. Geophys. Res,* **109***: do:10.1029/2004JD004836.*

Kongoli, C., and R. Ferraro, 2004: Development and evaluation of the AMSU-based SWE product (Preprint), 13th Conference on Satellite Meteorology and Oceanography, *American Meteorological Society*, 20–23 September, 2004, Norfolk, VA.

Kongoli, C., R. Ferraro, P. Pellegrino, and H. Meng, 2005 (Preprint): *Sn*ow Microwave Products from the NOAA's Advanced Microwave Sounding Unit*,* 19*th* Conference on Hydrology, *American Meteorological Society*, 8–14 January, 2005, San Diego, CA.

Kongoli, C., P. Pellegrino, R.R. Ferraro, C. Grody, and H. Meng, 2003: A new snowfall detection algorithm over land using measurements from the Advanced Microwave Sounding Unit (AMSU), *Geophys. Res. Let.* **30**(14): 1756–1759.

Matzler, C., 1994: Passive microwave signatures of landscapes in winter, *Meteorol. Atmos. Phys*. **54**: 241–260.

Meng H., L. Zhao, R. Ferraro, F. Weng, Q. Liu, 2006 (Preprint): Calibration andvalidation of N-18 AMSU-A and MHS, 14th Conference on Satellite Meteorology and Oceanography, *American Meteorological Society*, 28 January–2 February, 2006, Atlanta, GA.

Ramsay, B.H., 1998: The interactive multisensor snow and ice mapping system, *Hydrological Processes,* **12:**1537–1546.

Ramsay, B.H., 2000: Prospects for the Interactive Multisensor Snow and Ice Mapping System (IMS), Proceedings of the 57th Eastern Snow Conference, 18–19 May 2000, Syracuse,NY, 161–170.

Romanov, P. G. Goodman and I. Csiszar, 2000: Automated monitoring of snow cover over North America with multispectral satellite data, *J. Appl. Meteorol.,* **39**: 1866–1880.

Sturm, M., J. Holmgren, and G.E. Liston, 1995: A seasonal snow cover classification system for local to global applications*, Journal of Climate***, 8**(5): 1261–1283.