P1.6 SNOW MICROWAVE PRODUCTS FROM THE NOAA's ADVANCED MICROWAVE SOOUNDING UNIT

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1. INTRODUCTION

The retrievals of cold land atmospheric and surface parameters from space continue to be one of the more challenging and increasingly important areas of satellite research. Of particular interest to hydrologists, atmospheric scientists and climatologists are the regional and global retrievals of snow cover parameters (extent, water equivalent and depth) and cold season precipitation rates (frozen rain and snowfall). Snow cover affects both the global water and energy budgets at regional and global scales. Snowfall, on the other hand, represents a substantial portion of global precipitation in many parts of the world and is coupled to snow cover. On a regional scale, snowfall retrievals are particularly important for winter weather forecasting and water resource management.

The retrievals of winter precipitation from satellites (visible, infrared and microwave) have proven to be extremely difficult primarily due to the unique characteristics associated with such precipitation. Unlike summer rainfall which is often the result of strong atmospheric convection, cold precipitation systems are mostly stratiform, and thus difficult to discriminate against non-precipitating winter clouds. In addition, snowfall is often associated with snow cover on the ground, which can be another source of confusion for the observing satellite.

Most recent research and development at NOAA/NESDIS using measurements from the Advanced Microwave Sounding Unit (AMSU) has shown that similar to rainfall, winter precipitation- and snow cover-sized particles scatter microwave radiation at specific microwave frequencies. The discrimination between snowfall, rain and snow cover signatures can be made successfully utilizing the unique combination of the AMSU frequency channels in the atmospheric window (23, 31, 89, 150 GHz), opaque water vapor (183±1, ±3, ±7 GHz) and oxygen absorption (50-60 GHz) bands. This unique combination of channels has led to important extensions of the existing retrieval base: the extension of the NOAA's rain rate operational product (Weng et al., 2003**)** to include snowfall detection (Ferraro et al., 2004; Kongoli et al., 2003), and the extension of the snow cover extent product to include snow water equivalent (SWE) retrievals (Kongoli and Ferraro, 2004; Kongoli et al., in press).

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These snow products are generated, along with other atmospheric and land surface products, within an operational framework called the Microwave Surface and Precipitation Products System (MSPPS), which is administered by NOAA/NESDIS (National Environmental Satellite, Data and Information Service/Office of Satellite Data Processing and Distribution) (Weng et al., 2003; Ferraro et al., 2002).

The objective of this paper is to describe these AMSU-based snow products and most recent work in more detail. Specifically, the paper describes each algorithm and discusses its main retrieval concepts, techniques and future challenges. Validation examples and case studies results are also presented. The layout of this paper is as follows: Section 2 provides a brief description of the AMSU instrument. Section 3 describes the identification of snow cover. Section 4 describes the retrievals of SWE. Section 5 describes the identification of snowfall. Section 6 describes the retrievals of precipitation type (rain or snow), and finally the "conclusions" section summarizes the paper and outlines future work.

2. DESCRIPTION OF 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 ±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 is flown on board the NOAA 15, NOAA 16, and NOAA 17 satellites. This three-satellite suite offers a global sampling nearly every 4 hours. The products within the MSPPS are generated operationally for the three satellites on an orbit-by-orbit basis (Ferraro et al., 2002). The suite of operational MSPPS products includes rain rate, total precipitable water, cloud liquid water, ice water path, snow cover, sea ice concentration and land surface temperature. The variety of surface and atmospheric products is due to 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.

Table 1. AMSU channel frequency specifications

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

3. THE IDENTIFICATION OF SNOW COVER

3.1 The retrieval concept

The microwave radiation emitted from most natural materials depends primarily on the absorption properties of water. Since the absorption due to water increases with frequency, the emitted radiation also increases with frequency for surfaces such as soil, vegetation and melting snow. Other materials such as dry snow-cover, desert sand and precipitating clouds are composed of particles which scatter microwave radiation at specific window frequencies. In contrast to absorbing surfaces, the emitted radiation decreases with increasing frequency for scattering surfaces such as dry snow and precipitation (Grody, 1991). Figure 1 exhibits the spectral signatures of snow cover and non-scattering surfaces such as soil and vegetation. As shown, for snow cover surface emissivity decreases (due to scattering by ice crystals) with increasing frequency. Hence, the brightness temperature (TB) observed by the satellite at specific microwave window frequencies also decreases

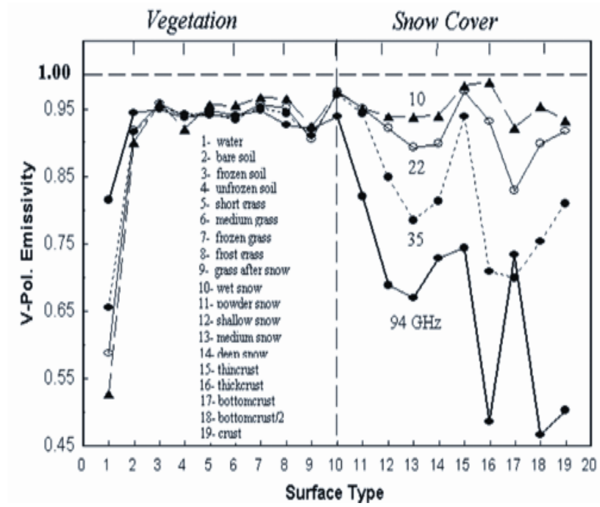

Figure 1. Spectral signatures of snow cover surfaces (Matzler, 1994).

in a similar manner. This snow-scattering spectral signature, i.e., a positive difference in the TB measurement at two window frequencies, TBv1-TBv2, where v indicates frequency and v2 > v1, is the first of several steps used to identify snow cover (Grody, 1991; Grody and Basist, 1996).

3.2 Algorithm description

In AMSU, the pair of microwave window channels used to separate snow-cover over land from non-scattering surfaces is 23 and 89 GHz (Table 1, channels 1 and 15, 16), which are used to compute the scattering index at 89 GHz (SI89):

$$SI89 = TB23 – TB89 \quad (1)$$

Snow cover is associated with positive SI89 values. Over land, the AMSU-B 89 GHz channel (Table 1, channel 16) is currently used due to its finer spatial resolution than its AMSU-A counterpart, whereas over coastlines the AMSU-A 89 GHz channel (Table 1, channel 15) is used to minimize aliasing effects due to disparate resolutions at AMSU-A 23 GHz and AMSU-B 89 GHz.

Equation 1 is necessary but not sufficient to identify snow cover. Other atmospheric and land surface scatterers such as rain and deserts exhibit scattering at 89 GHz relative to 23 GHz, and hence, can be associated with positive SI89 values. To remove confusions from these sources several filters have been developed. Rain signatures are removed from snow cover using the following filters:

$$TB23 < 262 \quad (2)$$
$$TB23 < 168.0 + 0.49*TB89 \quad (3)$$

Condition (2) uses TB23 as a measure of land surface temperature in K. Assuming a land surface emissivity of 0.97, the 262 K threshold would be TB23 that would correspond to a land surface temperature of 273 K or 0^0 C. Condition (3) removes scattering signatures due to convective rain, which is often associated with strong scattering at 89 GHz relative to scattering at 23 GHz. To remove cold desert surfaces from snow cover, the following empirical condition is used, which combines the TB at 23 GHz (TB23) and at 50 GHz (TB50):

$$10.2+0.036*TB23-0.074*TB50 > 0.4 \quad (4)$$

3.3 Validation examples

The AMSU-based snow cover extent product is operational, and along with other operational products within MSPPS is generated 6 times a day at approximately 4-hourly intervals using measurements from NOAA-15, -16, and -17 satellites.

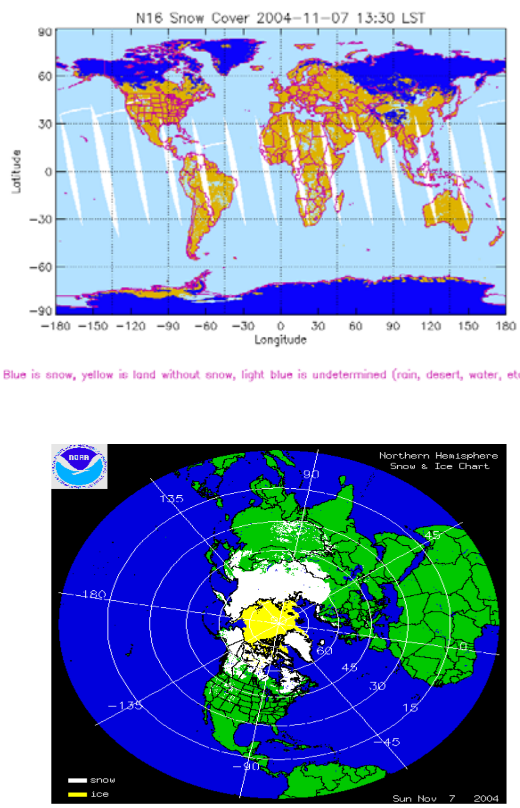

Figure 2. Example of global snow cover retrievals from AMSU (top panel) and over the Northern Hemisphere from the interactive multisensor snow and ice mapping product (bottom panel) on November 7, 2004.

Figure 2 shows a recent retrieval of global snow cover extent from the AMSU (top panel) and from the interactive multisensor snow and ice mapping product over the Northern Hemisphere (bottom panel, Ramsay, 1998) on November 7, 2004 at near-coincident times (NOAA-16 ascending pass, around 13:30 local standard time). Dark blue (top panel) and white (bottom panel) depict snow cover. As shown, there is generally good agreement between the AMSU-based and the interactive snow cover product, except for north-eastern Canada, where the AMSU-based snow product underestimates snow cover extent. It is important to note that during daytime, when near-surface air temperatures rise to above-freezing levels, surface melting of snow can depress scattering signals, leading to omission of snow-cover with AMSU or other microwave sensors. However, the scattering signal often recovers during night-time, when near-surface air temperatures drop below freezing levels. Therefore, night-time passes are generally preferred for snow-cover extent retrievals from microwave sensors.

4. SNOW WATER EQUIVALENT

4.1 The retrieval concept

Similar to snow cover identification, most of the existing microwave algorithms for the retrievals of SWE utilize the dual-frequency approach. The physical basis for these retrievals is the (ideally distinct) relationship between the volume of snow crystals present in the snow pack and the degree of scattering, measured by the drop in TB at a specific window frequency, or by the increase in SI when a dual channel approach is used. So, the deeper the snow pack, the more scatterers are present, thus the larger the drop in TB at a single channel or the larger the SI. Current SWE and snow depth retrieval algorithms typically use the index approach limited to frequencies in the 20-40 GHz range (Chang et al., 1987; Goodison and Walker, 1994).

Recent studies with the AMSU instrument have shown promise that the performance of the static SWE algorithms can be improved if in addition to frequencies lower than 40 GHz, specific higher window frequencies (e.g., 89 and 150 GHz) are utilized (Kongoli et al., in press). A wider frequency range in AMSU has shown to capture a wider variety of naturally-occurring snow covers, e.g., finer-grained, newly fallen snow. Figure 3 shows examples of AMSU measurements at 23, 31, 89 and 150 GHz window frequency channels during a recent snowfall event. Note that microwave sensitivity to snow cover shifts from higher (89-150 GHz) to lower (20-30 GHz) frequency regions as the snow ages. For freshly-fallen snow (6 hr old), the steepest TB 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

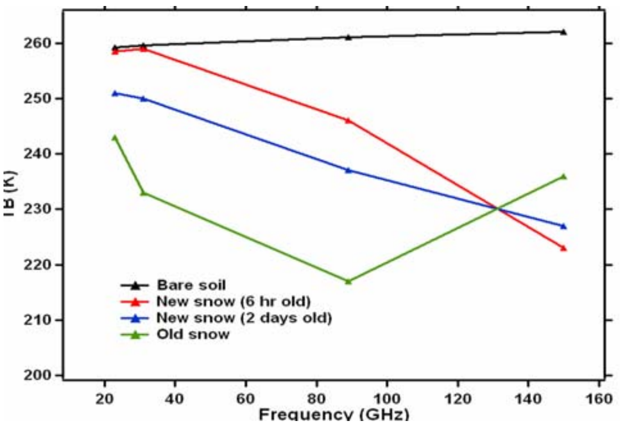

Figure 3. Examples of AMSU measurements over snow cover surfaces and bare soil.

grain size increases, sensitivity shifts to the 30-90 GHz region which attains the steepest TB gradient. Only for coarse-grained, metamorphosed snow cover, referred to in Figure 3 as "old snow" does the microwave sensitivity increase significantly at 23 and 31 GHz. Note also that for "old snow", the spectral gradient in the 89-150 GHz reverses. This reversal is explained by grain size effects. For large grain sizes, the geometric optics limit is reached at 150 GHz, after which TB150 stays fairly constant, whereas TB31 and TB89 decrease due to scattering at 31 and 90 GHz. Figure 3 also shows that over all, the most sensitive microwave region for snow-cover detection is 30-90 GHz due to scattering at 89 GHz by a broad range of snow ice grains.

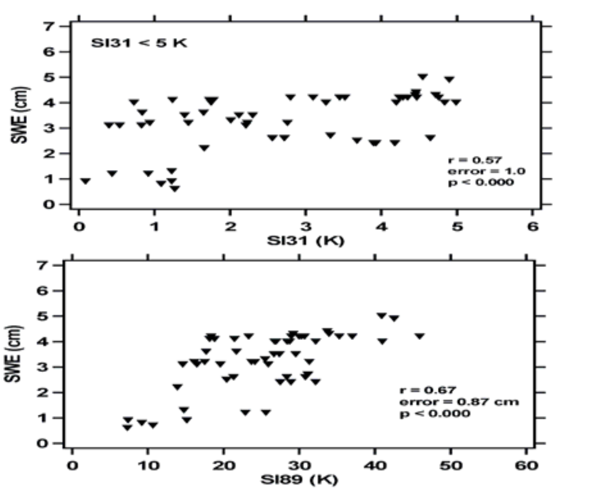

Figure 4. Scatter plot of SWE versus SI31 and SI89 for SI31 < 5 K.

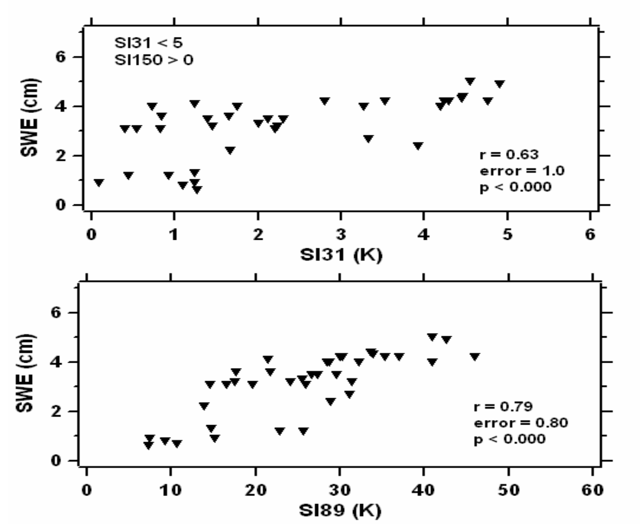

Figure 5. Scatter plot of SWE versus SI31 and SI89 for SI 31 < 5 K and SI150 > 0 K.

Figures 4 and 5 depict scatter plots of SWE and the AMSU scattering indices SI31 and SI89 (Kongoli et al., in press). As shown, correlation (r) improves at higher frequencies (SI89) for low microwave sensitivity in the 20-30 GHz range (SI31 = TB23 – TB31 < 5 K). Correlation improves further (Figure 5) for fresh snow-covers associated with high microwave sensitivity in the 89-150 GHz range (SI150 = TB89 – TB150 > 0 K).

4.2 Algorithm description

The new AMSU-based SWE algorithm is more dynamic in nature than the existing retrieval algorithms It also extends the utility of microwave measurements to higher frequencies. The current formulation implicitly "discriminates" between two snow cover types: fresh, finer grained and older, coarser-grained snow. The algorithm in its present form utilizes three AMSU channels: 23, 31 and 89 GHz. From TB measurements at these frequencies, two scattering indices, SI31 and SI89 are computed. For new snow cover surfaces, SI89 is used to estimate SWE based on the following empirically-derived relationship:

$$SWE = 0.08 * SI89 + 1.15 \quad (5)$$

Where SWE is in cm. For older snow-cover, SI31 is used instead:

$$SWE = 0.60*SI31 + 1.71 \quad (6)$$

The switch from SI89 (Eq. 5) to SI31 (Eq. 6) occurs when the ratio between SI89 and SI31 is less than an established threshold, corresponding to low SI31 values (less than 5 K). Larger ratios indicated stronger scattering and sensitivity to SWE in the 30-90 GHz region than in the 20-30 GHz frequency range, a characteristic of new snow-cover (see also Figure 2).

Lower ratios indicated a larger sensitivity to SWE in the 20-30 GHz region, which is indicative of older snow-cover.

4.3. Validation examples

The new AMSU-based SWE algorithm is being implemented at NOAA/NESDIS within the MSPPS system in experimental mode. Figure 6 shows a recent example of SWE retrievals over US (top), North America (middle) and over the globe (bottom) on November 4, 2004 using NOAA-16 measurements, descending pass. It should be noted that the SWE algorithm is applied over snow-covered land, retrieved from the AMSU-based snow cover extent product.

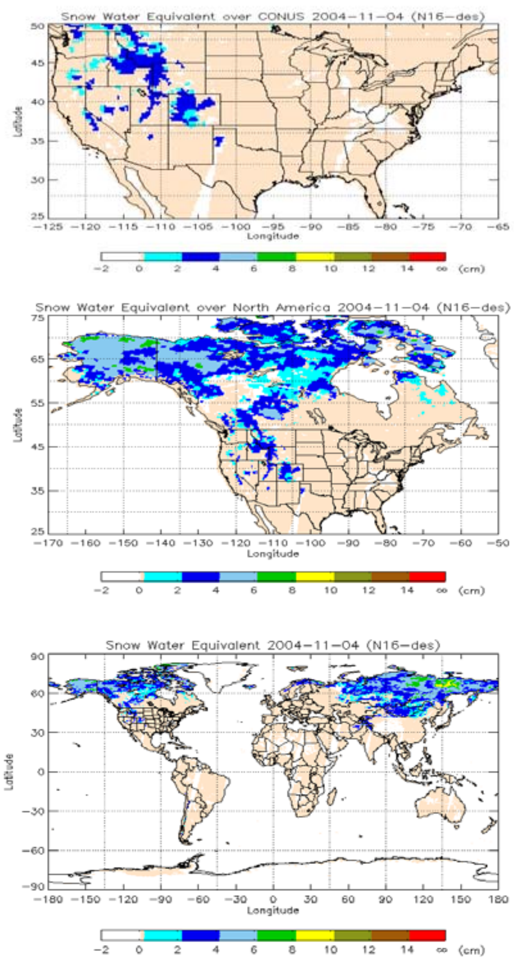

Figure 6. Example of AMSU-based SWE retrievals over US (top), North America (middle) and over the Globe (bottom).

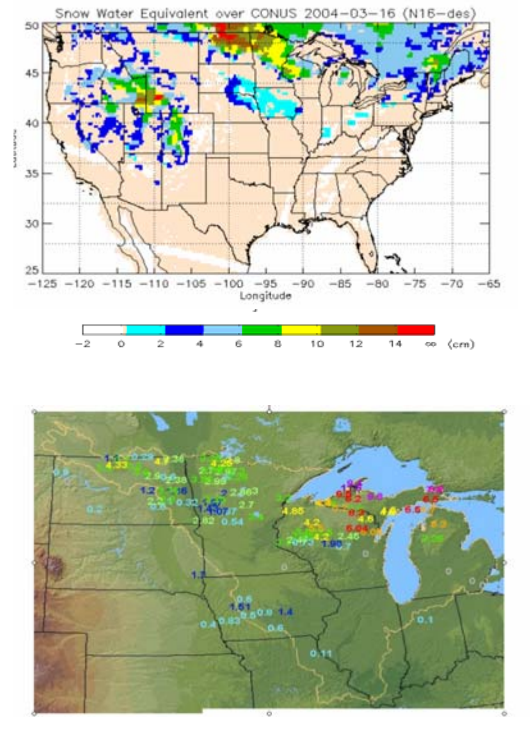

Figure 7. AMSU-based retrievals of SWE over the US (top) and SWE measurements over a region of the US Great Plains (bottom) on March 16, 2004.

Figure 7 shows an example of SWE retrievals over US and SWE measurements over a region of the US Great Plains on March 16, 2004. The low SWE values over Iowa resulted from recently fallen snow, whereas larger SWE in North Dakota resulted from previous accumulations over the winter season. The robustness of the new algorithm to capture this large range in SWE is due to the discriminate use of 89 GHz for new snow and 31 GHz for older snow retrievals.

5. IDENTIFICATION OF SNOWFALL OVER LAND

5.1 The retrieval concept

The greatest challenge in the identification of snowfall over land is the discrimination between this type of atmospheric precipitation and snow on the ground. Similar to rain, cold precipitation-sized ice particles scatter microwave radiation at window frequency channels, e.g., at 89 and 150 GHz. However, identification of snowfall using these window channels is extremely difficult due to similar scattering signatures from fresh, finer-grained snow on the ground under non-precipitating atmospheres (Kongoli et al., 2003; Kongoli et al., in press; Grody, 2004). As Figure 3 above shows, fresh snow can exhibit large scattering at 150 GHz.

One approach to remove the confusion in the interpretation of snowfall signatures from newly fallen snow is to utilize additional channels less susceptible to land surface emissivity, e.g., the AMSU channels around the 183 GHz water vapor absorption region (Table 1, channels 18-20) (Kongoli et al., 2003; Chen and Staelin, 2003). The presence of water vapor obscures land surface emissivity effects around 183 GHz. At the same time, these channels respond to atmospheric scattering due to precipitation-sized ice crystals. For colder, drier atmospheres, however, surface emissivity effects can also be observed at channels around 183 GHz due to smaller amounts of atmospheric water vapor. Therefore, additional information on atmospheric moisture is needed to limit the retrievals to moister atmospheres. Knowledge about atmospheric moisture can be obtained using the AMSU's temperature sounding channels in the oxygen absorption band, e.g., at 53.6 GHz.

5.2 Algorithm description

The new snowfall identification scheme is an important extension to the NOAA's operational rain rate product. The following is only a brief description of main algorithm steps. More detailed accounts of this algorithm are provided in the work of Kongoli et al. (2003) and Ferraro et al. (2004).

The decision tree of the new snowfall detection scheme is as follows:

- Apply the AMSU rain rate algorithm, which imbeds surface temperature estimate from forecast models, to identify rain,

- When rain is not present, limit the retrievals to snowfall events associated with TB at 53.6 GHz (hereafter referred to as TB54) above the 245 K threshold,

- When TB54 is above 245 K, identify potential snowfall when SI150, computed as the difference between TB89 and TB150, is positive and above an established threshold.

- Identify snowfall (from fresh snow on the ground) when TB at 183±1, ±3, ±7 GHz channels (hereafter referred to as TB182, TB180 and TB176, respectively) drop below empirically established thresholds.

At present, areas associated with TB54 less than 245 K are labeled as "indeterminate" in the operational product. Testing of an experimental snowfall product is under way that extends the retrievals to colder atmospheres associated with TB54 below the 245 K threshold.

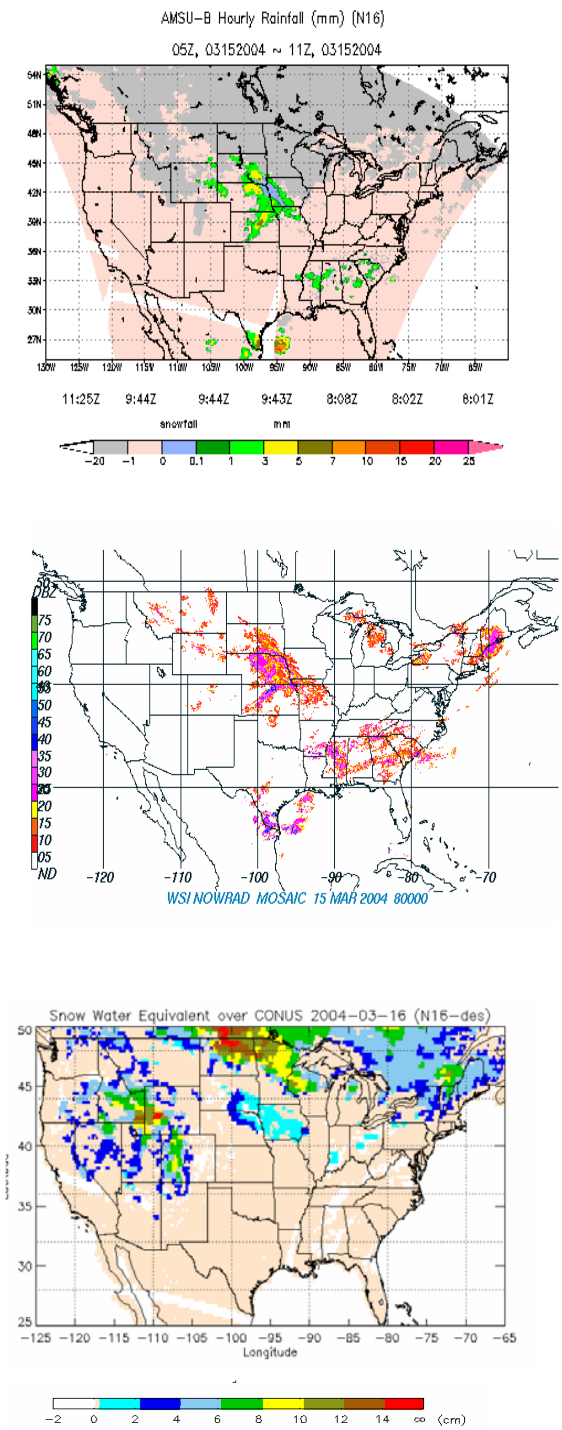

Figure 8. Precipitation retrievals from AMSU (top), and NEXRAD (middle) on March 15, 2004, and SWE retrievals from AMSU (bottom) on March 16, 2004.

5.3 Validation example

Figure 8 shows an example of precipitation retrievals over the US from the NOAA's operational rain rate product (top panel), the NEXRAD product (middle panel) and SWE retrievals from the experimental AMSU-based SWE product. Note the retrievals of snow cover extent (light blue) in Eastern Nebraska and Iowa by the rain rate product (top panel) and the precipitation retrievals from NEXRAD (middle panel) on March 15, 2004. Note that NEXRAD cannot discriminate precipitation as snow or rain. However, the AMSU-based SWE product (bottom panel) shows snow-cover in Eastern Iowa and Nebraska on March 16, 2004, associated with small SWE values. This new snow was the result of snowfall that fall on March 15, 2004.

6. AMSU-BASED DISCRIMINATION BETWEEN RAIN AND SNOWFALL

6.1 AMSU-based versus forecast-based retrievals

The NOAA's operational rain rate product identifies precipitation type as rain or snow based on surface temperature estimates from forecast models for snow-free areas. For snow-covered areas, precipitation that falls is implicitly classified as snowfall (Ferraro et al., 2004). This classification scheme has been shown to work generally well especially for major snowfall events. However, it may misclassify precipitation type especially during transition periods, e.g., in early spring, when land surface temperatures rise close to 0^{0}C. At such temperatures, even small forecast errors may lead to misclassification errors in precipitation type. Additionally, rain-on-snow events may not be correctly classified as rain under the current scheme.

To improve current classification, a new precipitation type algorithm has been developed at NOAA/NESDIS that discriminates between rain and snow based solely on AMSU measurements. The algorithm incorporates scattering and upper atmospheric and surface temperature information derived from AMSU measurements in the window (23, 31, 89 and 150 GHz), oxygen absorption (50, 52.8 and 53.6 GHz) and water vapor (183±3,±7 GHz) microwave regions. As such, it has the potential to be more accurate than surface forecast models especially in capturing precipitation events during transition times. Theoretically, it is difficult to discriminate between surface rain and snow based solely on the scattering signatures, since what is being detected through scattering are precipitation-sized ice crystals in the atmosphere. However, rain systems are often convective in nature and therefore exhibit stronger scattering as compared with snow events which are often stratiform. Therefore, the degree of scattering, e.g, at 150 GHz and at 183±3 and ±7 GHz, is one characteristic used to classify rain and snow. Other important characteristics are upper-air temperature information, derived from TB54, and surface temperature information, derived from a combination of TB23 and TB50.

6.2 Validation example

The new AMSU-based precipitation type algorithm is being implemented within MSPPS in experimental mode. The algorithm has undergone extensive validation, which has shown very promising results. Below we provide a validation example of a significant snow event.

The snow storm that hit South and North Carolina on February 26, 2004 was reported to have deposited about 17 inches of snow on the ground. Figure 9 shows the rain rate and snow cover extent retrievals from the NOAA's operational rain rate product (top panel), and the precipitation type retrievals from the experimental precipitation type product. (bottom panel). Note that the experimental product (bottom panel) retrieves precipitation type based solely on AMSU measurements, whereas the NOAA's operational rain rate product (top panel) determines precipitation type based on surface temperature derived from forecast models.

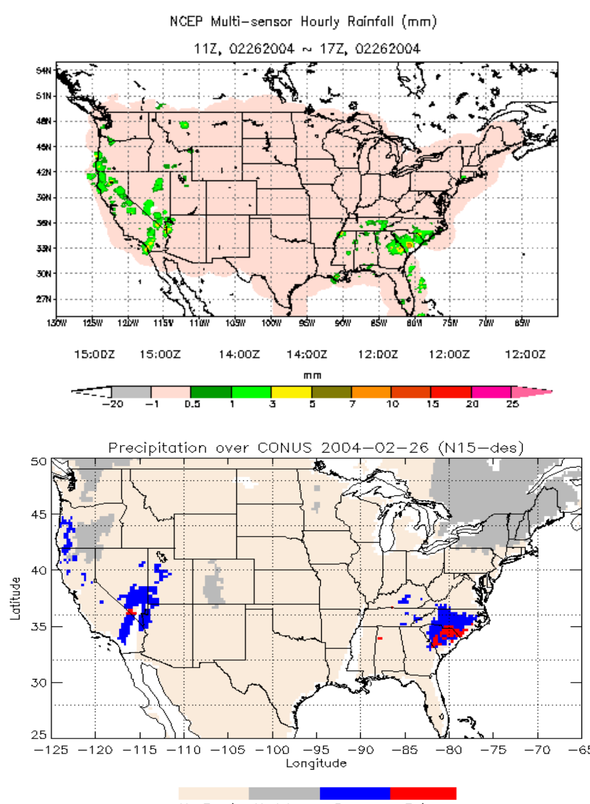

Figure 9. Rain rate and snow cover extent retrievals from the NOAA's operatioinal rain rate product (top) and rain and snow cover extent retrievals from the AMSU-based experimental precipitation type retrieval algorithm (bottom) on February 26, 2004.

In Figure 9, light blue (top panel) and dark blue (bottom panel) is snow cover. The color scheme other than light blue depicts rain rates (top panel) and the red color (bottom panel) depicts rain. As shown, the operational rain product that relies on weather forecast estimates of surface temperature (top panel) missed the snowfall in South and North Carolina that was otherwise captured by the AMSU-based precipitation type algorithm.

7. CONCLUSIONS AND FUTURE WORK

The retrievals of winter precipitation from satellites (visible, infrared and microwave) have proven to be extremely difficult primarily due to the unique characteristics associated with such precipitation. Most recent research and development at NOAA/NESDIS using measurements from the Advanced Microwave Sounding Unit (AMSU) has shown that winter precipitation- and snow cover-sized particles scatter microwave radiation at specific microwave frequencies. The discrimination between snowfall, rain and snow cover signatures can be made successfully utilizing the unique combination of the AMSU frequency channels in the atmospheric window (23, 31, 89, 150 GHz), opaque water vapor (183±1, ±3, ±7 GHz) and oxygen absorption (50-60 GHz) bands. The objective of this paper was to describe the NOAA's AMSU-based product algorithms in more detail. Specifically, the paper described main retrieval concepts, algorithm steps and validation examples for the identification of snow cover, the retrievals of SWE, the identification of snowfall and discrimination of precipitation type (rain versus snowfall). Of particular importance was the description of the retrievals of SWE based on a more dynamic scheme that utilizes higher window frequency channels in addition to lower frequency ones. Another important description in the paper was the AMSU-based identification of snowfall utilizing channels in the oxygen and water vapor absorption regions. Work is under way to further improve these important snow products. In particular, the identification of snow cover associated with above-freezing near surface air temperatures is not possible under the current scheme. Testing is underway for improved snow cover extent retrievals under such weather conditions that utilize microwave frequencies higher than 89 GHz. In addition, work is under way to improve the retrievals of SWE using other AMSU frequency channels, e.g., 150 GHz.

The views, opinions, and findings contained in this report are those of the author(s) and should not be construed as an official National Oceanic and Atmospheric Administration or U.S. Government position, policy, or decision.

8. REFERENCES

Chang, A.T.C., J.L. Foster, and D.K Hall, 1987: Nimbus-7 derived global snow cover parameters, *Ann. Glaciol., 9*, 39-44.

Chen, F.W., and D.H. Staelin, 2003: AIRS/AMSU/HSB precipitation estimates, *IEEE Trans. Geosci. Remote Sens.*, 41(2), 410-4127.

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.

Goodison, B.E., and A. Walker, 1994: Canadian development and use of snow cover information from passive microwave satellite data, in *Passive Microwave Remote Sensing of Land-Atmosphere Interactions*, edited by B. Choudhury, Y. Kerr, E. Njoku, and P. Pampaloni, pp. 245-262, VSP BV, Utrecht, The Netherlands.

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.

Grody, N.C., 2004: Relationship between passive microwave measurements and snow parameters, 8th Specialist Meeting on Microwave Radiometry and Remote Sensing Applications, 24-27 February, Rome, Italy.

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., 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. Lett.*, *30(14)*, 1756-1759.

Kongoli, C., N.C. Grody, and R. Ferraro: Interpretation of AMSU measurements for the retrievals of snow water equivalent and snow depth (In Press), *Journal of Geophysical Research-Atmospheres.*

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

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

Weng, F.W., L. Zhao, R. Ferraro, G. Poe, X. Li and N.C. Grody, 2003: Advanced Microwave Sounding Unit (AMSU) cloud and precipitation algorithms, *Radio Science*, *38(4)*, 8068-8083.