

A GLOBAL SNOWMELT PRODUCT USING VISIBLE, PASSIVE MICROWAVE AND SCATTEROMETER SATELLITE DATA

James Foster¹, Son Nghiem², Marco Tedesco³, George Riggs⁴, Dorothy Hall¹, and John Eylander⁵

¹ NASA/GSFC, Hydrospheric and Biospheric Sciences Laboratory, Greenbelt, MD, USA

² California Institute of Technology/JPL, 4800 Oak Grove Drive, Pasadena, CA, USA

³ City University of New York, NY

⁴ Science Systems and Applications, Greenbelt, MD, USA

⁵ HQ AF Weather Agency, 106 Peacekeeper Dr. Suite 2N3, Offutt AFB, NE, USA

Commission VIII, WG VIII/8

KEY WORDS: Microwave, Scatterometer, Snow, Snowmelt, Global, AMSR-E, QuikSCAT,

ABSTRACT:

Seasonal snow cover is a key component of the Earth's energy balance and a key storage mechanism for water. In many areas of the world, people rely on snowmelt runoff for their water resources. For example, melting snow contributes upwards of 70% of the total annual water supply in the western U.S., and in India, Pakistan, Afghanistan, and Nepal snow and ice melt from the Hindu Kush and Himalayan ranges is a vital resource for nearly 1 billion people. The ability to characterize snow storage more accurately at the drainage basin scale is crucial for improved water resource management. Snow-water equivalent (SWE), snow cover, and melt onset are critically-needed parameters for climate modeling and the initialization of forecasts at weather and seasonal-time scales. Snowmelt data are also needed in hydrological models to improve flood control and irrigation. In addition, knowledge of snowpack ripening is essential for natural-hazards applications such as flood prediction. This purpose of this paper is to show results of a blended, global snowmelt product utilizing Moderate Resolution Imaging Spectrometer (MODIS), Advanced Microwave Scanning Radiometer for NASA's Earth Observing System (AMSR-E) passive microwave data and QuikSCAT scatterometer data. These data are being blended into a single, global, daily, user-friendly product. Though snow-cover extent is currently a product available from various sensors, including MODIS, and snow water equivalent (SWE) is an available product from AMSR-E, snowpack ripening and snowmelt are currently unavailable as satellite-derived products. Nonetheless, there is a significant body of literature showing that AMSR-E radiometric data and QuikSCAT scatterometer data are highly suited to these tasks. AMSR-E data will be used to estimate the onset of snowmelt by looking at increases in brightness temperatures. QuikSCAT will be used to detect melting snow at 14 GHz - Ku-band (13.4 GHz) backscatter is sensitive to snow wetness properties. The detection of wet snow from space-borne microwave data is possible because a strong and sudden increase of the imaginary part of snow permittivity (and as a consequence of brightness temperature) occurs when liquid water particles appear within the snowpack, even in small amount. If snow is dry during the night (either frozen or refrozen) and it becomes wet during the day, then daytime brightness temperature will be higher than those acquired during nighttime. Also, if melting persists during the night, then the brightness temperature will remain high. At the wavelength of 2.2 cm (Ku-band, 13.4 GHz), QSCAT backscatter is highly sensitive to snow wetness. In wet snow, liquid water (no salinity) has an imaginary part of about 19,000 times larger than that of dry ice. Thus, a small amount of wetness can significantly change the imaginary part of the snow effective permittivity, and consequently decrease the backscatter. The initial blended-snowmelt product will be 25 km resolution and validated (to begin with) using data from the lower Great Lakes region of the U.S. and from data gathered in Colorado at Cold Lands Project Experiment (CLPX) sites in 2002 and 2003.

1. INTRODUCTION

Melting snow is a vital fresh water resource in India, Pakistan, Afghanistan, and Nepal. When snow and ice melts in the Hindu Kush and Himalayan ranges during the spring and summer months, water is supplied to between 0.5-1 billion people (Foster et al., 2007). The ability to characterize snow storage more accurately at the drainage basin scale is crucial for improved management of our precious water resources. Snowmelt data are needed in hydrological models to improve flood control and irrigation, and in addition snow-water equivalent (SWE), snow cover, and melt onset are critically needed parameters for climate modeling and the initialization of forecasts at weather and seasonal time scales.

Recent advances in the area of remote sensing have led to more accurate observations of snow parameters from space using, for example, the Advanced Microwave Scanning Radiometer (AMSR-E) for NASA's Earth Observing System and QuikSCAT. NASA scientists are presently working with the Air Force Weather Agency (AFWA) to improve their SNOBEP model by taking advantage of new spectral techniques for mapping and monitoring melting snow. In essence, remotely sensed measurements are being blended together using input from the MODIS, AMSR-E, and QuikSCAT satellite sensors. This blended-snow product will be a fully automated and thus consistent dataset.

Though snow-cover extent is currently available from various sensors, including MODIS (see Hall and Riggs, 2007), and

SWE is available from AMSR-E (Kelly et al., 2003; Foster et al., 2005), snowpack ripening is currently unavailable as a product. Nonetheless, QuikSCAT scatterometer data and AMSR-E (19 GHz channels are highly suited to this task (Nghiem and Tsai, 2001). There are several advantages in using active and passive microwave observations together for snow monitoring: 1. The resolution is similar (~20-25km); 2. the incidence angle is constant (QuikSCAT: 46° for H and 54° for V channel, SSM/I/AMSR-E: ~53°); 3. both sensors have a wide swath (QuikSCAT 1,800 km, SSM/I 1400 km) and sun-synchronous polar orbits allowing excellent global coverage and frequent polar coverage.

2. SNOWMELT FROM SCATTEROMETER DATA

The sensitivity of space-borne scatterometer data to snow parameters has been gaining more attention in recent years (e.g. Nghiem and Tsai 2001; Kimball et al. 2001; Hallikainen et al., 2004). In Nghiem and Tsai (2001), the authors show the potential of the NASA scatterometer (NSCAT) data for applications to remote sensing of snow at the global scale showing that Ku-band (14 GHz) backscatter is sensitive to snow properties and that onset of snowmelt can be detected using NSCAT data. Preliminary results show that the detection of snow cover can be improved when both active and passive data are used together, rather than each used alone (e.g. Nghiem et al., 2005; Tedesco and Miller 2006a & b).

Ku band scatterometer data (QuikSCAT) is used to obtain snowmelt area. This entails: a. Obtaining daily snowmelt area from QuikSCAT data over cold land regions. b. Obtaining daily snow cover area from QuikSCAT data to supplement MODIS product over cloud-obscured areas (Hall and Riggs, 2007), and c. Developing a QuikSCAT algorithm to derive snow depth.

Figure 1 shows a QuikSCAT map (14 GHz data) from March of 2003. Note the extensive snow covered areas that are observed to be melting (in red) across southern Canada, eastern Europe and central and eastern Asia. With the wide swath of the QuikSCAT sensor, there is coverage two times per day over most cold land regions -- once in the morning and once in the afternoon. Since the orbit of QuikSCAT is Sun synchronous, due to diurnal cycling of air temperature, this means we can obtain a morning “cold” and an evening “warm” snow image that allows us to use the amount of backscatter cycling to help identify the stage of the snowmelt transition.

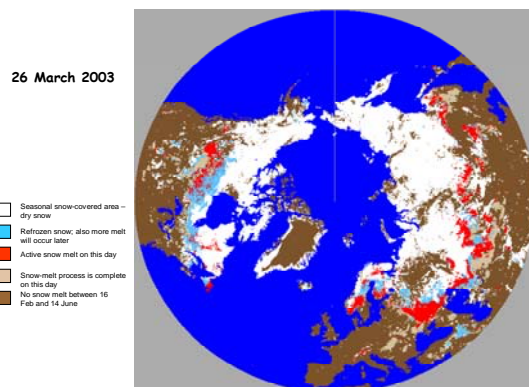


Figure 1: Snowmelt map for March 26, 2003.

To determine where snowmelt occurs we use the diurnal difference, a relative quantity between morning and afternoon measurements in half a day. We co-locate the data from the early morning (t_a) in an ascending orbit pass and late afternoon (t_p) in a descending pass for each day. The diurnal backscatter change is defined as the backscatter difference in the decibel (dB) domain as $\Delta\sigma_{VV} = \sigma_{VV}(t_p) - \sigma_{VV}(t_a)$, where σ_{VV} is the vertical-polarization backscatter and all quantities are in dB (Nghiem et al., 2005). We adapt this algorithm for snowmelt detection on land. This algorithm is independent of the absolute calibration since it is based on the relative diurnal backscatter difference.

This diurnal snowmelt detection algorithm has several advantages such as: it is independent of the scatterometer long-term gain drift, it is independent of the cross-calibration between QuikSCAT and future satellite scatterometers; it is independent of absolute backscatter from different snow classes and snow conditions; both snow melt and refreezing are detected; and there is daily coverage over most cold land regions. In addition, it is independent of the absolute calibration since it is based on the relative diurnal backscatter difference.

To illustrate the capability of QuikSCAT to monitor daily snowmelt on a hemispheric scale, in Figure 2 we present snowmelt results over the Northern Hemisphere -- snowmelt maps during the month of April (2001). Continental snowmelt patterns shows the expected northward migration of the melting process. An interesting observation is that the snowmelt regime may appear as a coherent extensive longitudinal band as seen, for example, by the red band across the North American continent on 18 April 2001 (center panel of Figure 4). Note that the northern extent of this snowmelt band approximately occurs along the Canadian Shield from the west of Hudson Bay to the east of Yukon Territory. The temporal evolution of large-scale snowmelt is not abrupt and exhibits periods of melting and refreezing as the snowmelt advances northward.

At the wavelength of 2.2 cm (Ku-band 14 GHz), QSCAT backscatter is highly sensitive to snow wetness. In wet snow, liquid water (with zero salinity) has an imaginary part of about 19,000 times larger than that of non-melting ice. Thus, a small amount of wetness can significantly change the imaginary part of the snow effective permittivity, and consequently decrease the backscatter.

This algorithm has several advantages; it is: a. Independent of the scatterometer long-term gain drift, b. Independent of the cross-calibration between QSCAT and future satellite scatterometers, Independent of absolute backscatter from different snow classes and snow conditions, c. Detection of both snow melt and refreezing, and D. Daily coverage over most cold land regions.

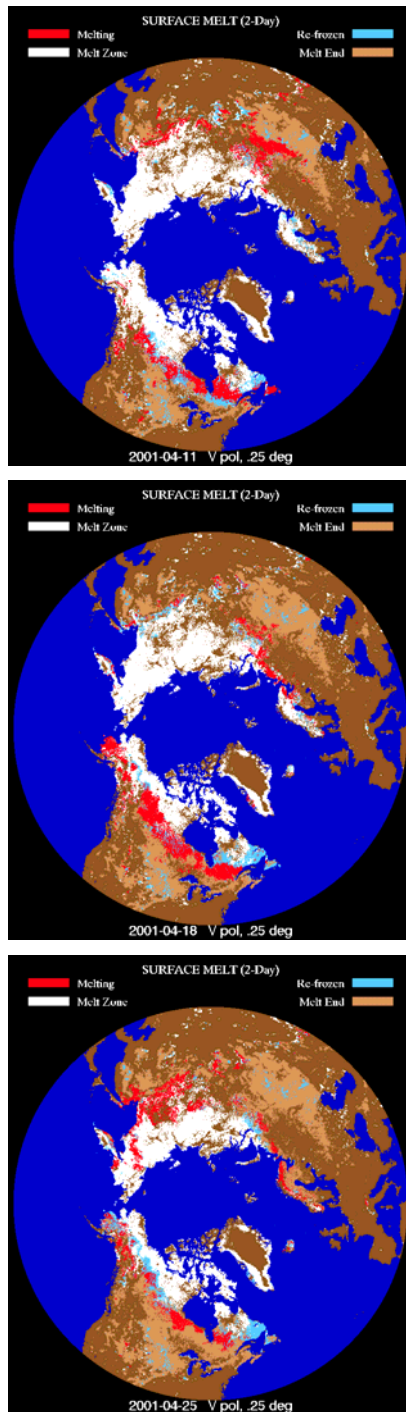


Figure 2: Snowmelt maps derived from global QuikSCAT backscatter data from 4/11/2001 to 4/25/2001. White is frozen snow, red is currently melting snow, light blue is re-frozen snow after previously melting conditions, light brown is completed snowmelt (snow-free of bare ground), and dark brown is undetectable snow.

Ku-band backscatter is also sensitive to snow accumulation. Change in backscatter as a function of snow depth at Ivotuk (68.5°N, 155.8°W) in Alaska is shown in Figure 3 for snow seasons in 1999, 2000, and 2001. Regression analysis shows that the slope of the snow depth change versus backscatter change is similar in different years. The bias in absolute backscatter in each year is probably dependent on the condition of the landscape in different seasons (different number of

bushes, different characteristics in the initial snow cover layer at the beginning of the snow season, etc.). This result indicates that snow depth at Ivotuk can be retrieved consistently- based on the backscatter change from the initial backscatter level, which is determined by the minimum background backscatter at the beginning of the snow season. The root-mean-squared errors for snow depth retrieval can be between 4 to 6.6 cm, or 1.3 to 2.2 cm in SWE.

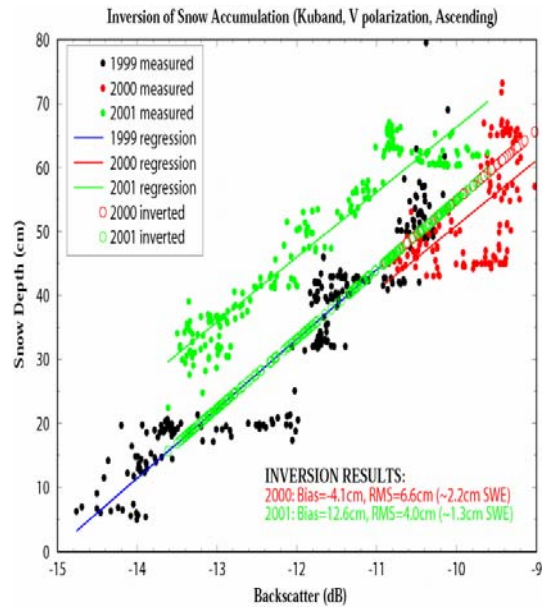


Figure 3: Results for backscatter versus snow depth at Ivotuk, Alaska. Note the similarity in the slope of the curves for different years.

3. SNOWMELT FROM PASSIVE MICROWAVE DATA

A heritage of nearly 30 years of global-daily passive microwave observations exists (Chang et al., 1987; Walker and Goodison, 2000). The AMSR-E sensor, on board Aqua, is the most recent addition to the passive microwave suite of instruments. The AMSR-E snow products (Kelly et al., 2003) are archived and distributed through the National Snow and Ice Data Center. Passive-microwave satellite footprints are currently ~25 km (at 37 GHz) -- future sensors should improve this resolution. An extensive body of literature describes the ability of passive-microwave instruments to estimate snow extent, SWE and melt onset (see Chang et al., 1987, for example). There is also a growing body of literature describing systematic errors and uncertainties in SWE retrievals using passive-microwave data (Kelly et al., 2003; Foster et al., 2005).

In addition to detection of SWE and snow depth, passive microwave radiometry can be utilized to assess the onset of snowmelt. Melt onset is detected when the AMSR-E brightness temperature at 19.35 GHz (horizontal polarization) and the difference between ascending and descending passes (Diurnal Amplitude Variations, DAV) exceed fixed thresholds. In order to account for melting that eventually might persist during the night, we use the rule that snow is melting when both ascending and descending brightness temperatures are greater than the threshold value. The main hypothesis is that histograms of brightness temperatures measured during both dry and wet snow conditions can be modeled by means of a bimodal distribution, with the left-normal distribution (LND) being representative of

dry snow conditions and the right-normal distribution (RND) representative of wet snow conditions. Thus, wet snow can be detected according to the condition that measured brightness temperature belongs to the RND and that the difference between nighttime and daytime measurements is greater than a threshold value. This last condition assures us that the change in brightness temperatures is related to the appearance of liquid water (because of the abrupt and sudden change in brightness temperature) instead of other factors.

Current Methodology

$T_{b37v} > 245 \text{ K}$ SSM/I DAV = $\text{abs}(T_{\text{basic}} - T_{\text{obsc}}) > 10 \text{ K}$	$T_{b19H} > 242 \text{ K}$ SSM/I DAV = $\text{abs}(T_{\text{basic}} - T_{\text{obsc}}) > 25 \text{ K}$
$T_{b37v} > 242 \text{ K}$ AMSR-E DAV = $\text{abs}(T_{\text{basic}} - T_{\text{obsc}}) > 10 \text{ K}$	$T_{b19H} > 243 \text{ K}$ AMSR-E DAV = $\text{abs}(T_{\text{basic}} - T_{\text{obsc}}) > 24 \text{ K}$

Figure 4: Threshold used within the DAV algorithm for different frequencies.

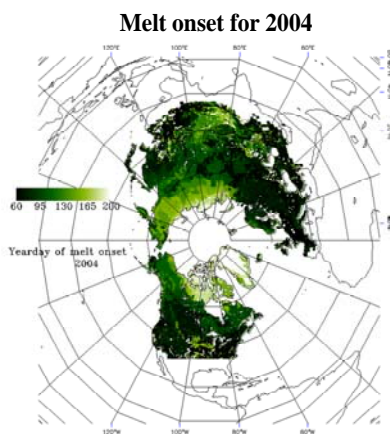


Figure 5: Onset of snowmelt from AMSR-E for 2004

With the DAV algorithm, we are able to assess the onset of snowmelt regionally as well as globally (Figure 5). Only those areas classified as snow by the MODIS sensor (visible data) are used to produce the snow onset maps.

4. CONCLUSIONS

Using AMSR-E and QuikSCAT data we have the capability of showing areas of dry snow (AMSR-E, 37 GHz), areas where melt is in the incipient stages using AMSR-E (19 GHz horizontal channel), and areas where snow is actively melting using QuikSCAT (14 GHz). Preliminary results show that the

detection of snow cover can be improved when both active and passive data are used together, rather than when each is used alone.

REFERENCES

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

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

Foster, J., D. Hall, J. Eyelander, E. Kim, G. Riggs, M. Tedesco, S. Nghiem, R. Kelly, B. Choudhury, and R. Reichle: Proceedings of the 64th Meeting of the Eastern Snow Conference, St. Johns Newfoundland, May 2007.

Hall D K and Riggs G A, 2007: Accuracy assessment of the MODIS snow-cover products, *Hydrological Processes* 21:1534-1547.

Hallikainen M., P. Halme, P. Lahtinen and J. Pulliainen, 2004: Retrieval of snow characteristics from spaceborne scatterometer data, Proc. Of IEEE Geoscience and Remote Sensing Symposium, IGARSS 2004, Anchorage, Alaska, USA, Conference CD

Kelly R.E., A.T. Chang, L. Tsang, and J.L. Foster, 2003: A prototype AMSR-E global snow area and snow depth algorithm, *IEEE Trans. Geosci. Remote Sens.*, EO-1 Special Issue, 41 (2):230-242.

Kimball J.S., K.C. McDonald, A.R. Keyser, S. Froking and S. W. Runing, Application of NASA Scatterometer (NSCAT) for determining the daily frozen and nonfrozen landscape of Alaska, 2001: *Remote Sensing of Environment*, 75:113-126.

Nghiem, S.V., and W.Y. Tsai, 2001: Global snow cover monitoring with spaceborne Ku-band scatterometer. *IEEE Transactions on Geoscience and Remote Sensing*, 39, 2118-2134.

Nghiem S.V., K. Steffen, G. Neumann and R. Huff, 2005: Mapping ice layer extent and snow accumulation in the percolation zone of the Greenland ice sheet, *Journal of Geophysical Research*, 110.

Tedesco M. and Miller J., 2006a: Investigation on the correlation of QuikSCAT data to snow depth and SSM/I brightness temperatures: preliminary results, submitted to *Geophysical Research Letters*.

Tedesco M. and Miller J., 2006b: Combining space-borne active and passive microwave data for remote sensing of snow at global scale, IGARSS 2006, Denver, Colorado.