Blended Visible, Passive Microwave and Scatterometer Global Snow Products

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ABSTRACT

This paper presents findings of the current status of our joint U.S. Air Force – NASA work in developing a blended snow product to map global snow cover extent 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. On the two maps presented here (February 5 and February 25), more than 1/3 of the northern portions of North America and Eurasia were obscured by clouds. The AMSR-E product is especially useful in detecting snow through clouds. However, passive microwave data misses snow in those regions where the snow cover is rather thin, along the margins of the continental snow line and on the lee side of the Rocky Mountains, for instance. In these regions, MODIS can easily map shallow snow cover. Because the confidence for mapping snow cover extent is greater with the visible product than with the microwave product, when cloud free MODIS observations are available, they will be used as "truth." The microwave-derived snow cover will be used as "truth" only in those areas where MODIS is not usable due to the presence of clouds and darkness. AMSR-E data at 19 GHz (horizontal channel) will be used in association with the difference between ascending and descending satellite passes (Diurnal Amplitude Variations, DAV) to detect the onset of melt, and QuikSCAT data (14 GHz) will be used to map areas of snow that are actively melting.

INTRODUCTION

The Air Force Weather Agency's (AFWA) snow depth analysis model (SNODEP) is responsible for generating daily global snow depth and snow age analyses and is crucial for use by numerous other AFWA programs and external customers. The operational SNODEP model uses snow depth reports from synoptic observations combined with Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSMI) Passive Microwave (PM) data and climatology to generate a global analysis of snow depth and snow age. The sparse synoptic snow depth observations presents a unique challenge to accurately represent snow information in foreign locations where regular meteorological observations are lacking due to conflict, sparse

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populations, or lack of technology. Recent advances in the area of remote sensing have lead to further algorithm development to more accurately measure snow depths from space using the Advanced Microwave Scanning Radiometer for NASA's Earth Observing System (AMSR-E) sensor. Additionally, algorithms operating on a combination of visible, near infrared and infrared radiances from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor, on board the NASA Aqua and Terra satellites produce a spectral snow mask useful in detecting the existence of snow at resolutions of 500 m and finer. The algorithms developed to operate on AMSR-E and MODIS data are potentially applicable to other current operational satellite missions, including current NOAA polar orbiting satellites, MeteoSat 8/9 satellites, and the planned NPOESS Visible Infrared Imager/Radiometer Suite (VIIRS) and Microwave Imager/Sounder (MIS) sensors. NASA is presently working with AFWA to improve the SNODEP model to take advantage of the new spectral techniques to measure snow cover using remotely sensed measurements blended from both AMSR-E and MODIS sensors.

Currently, there is no single product that provides the suite of global-snow measurements that we discuss herein. Our blended-snow product will be fully automated and thus amenable to the production of climate-data records (CDRs) or Earth Science Data Records (ESDRs), following necessary re-processing. Specifically, this comprehensive blended-snow product includes SWE from the current Advanced Microwave Scanning Radiometer for EOS – (AMSR-E) product, snow extent with fractional snow cover from existing MODIS products, and, melt onset from AMSR-E and the SeaWinds scatterometer on the QuikSCAT satellite. The QuikSCAT and AMSR-E will be also used together to map snow-covered area in those areas where it is not possible for MODIS to map snow because of clouds and nighttime darkness. The intent is to generate a blended-snow product, with error bars, daily and weekly at a 25-km resolution.

Though snow-cover extent and snow albedo are currently available from various sensors including the MODIS (see Hall et al., 2007), and SWE is available from AMSR-E (see Kelly et al., 2003; Foster et al., 2005), snowpack ripening is currently unavailable as a product. Nonetheless, there is a significant body of literature showing that QuikSCAT scatterometer data 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: 46º for H and 54º for V channel, SSM/I/AMSR-E: ~53º); 3) both sensors have a wide swath (QuikSCAT 1800 km, e.g. SSM/I 1400 km) and sun-synchronous polar orbits allowing excellent global coverage and frequent polar coverage.

It is difficult for the snow community to utilize all of the above separate products together because some are not global, the file types are not consistent, the footprint sizes of the various sensors are not the same, and they use different geographic grids. Temporal frequency varies as well. The blended product that we are developing will provide all of the necessary snow inputs in one user-friendly product. It will also provide error bars that are needed for scientific use of the product, including for data assimilation and forecast initialization. It is expected that the accuracy of the product will increase over time as a result of proposed validation efforts.

OBJECTIVES

The primary goal of this paper is develop a global, daily, 25-km resolution, blended-snow product that includes snow extent, fractional snow cover (FSC), snowpack ripening, and melting snow.

The product will eventually be available for use to a wider community in a near-real-time basis through a sophisticated production system, which will include user-friendly tools. The blended-snow product will begin with the first combined MODIS/AMSR-E data from the Aqua satellite (June of 2002) and continue through the present. QuikSCAT data are available from June 1999 to present.

The blended-snow product is an all-weather product with snow mapped by both visible and near-IR (MODIS) and microwave data (AMSR-E and QuikSCAT) for clear sky conditions. Only

AMSR-E and QuikSCAT will be employed when clouds obscure the surface (as determined using daily MODIS data). By fusing products we will complement their capabilities and aid in reducing the limitations and errors inherent in each separate product.

Melt onset at global scale will be derived by using QuikSCAT and AMSR-E data. AMSR-E data will be used to estimate the brightness temperatures when QuikSCAT detects melting snow.

DATA SETS

AMSR-E Data

A validated global daily SWE product is currently unavailable, however, passive microwave-derived methods to estimate regional to global snow depth or SWE have been developed that use frequent and wide-swath-coverage observations from satellite passive-microwave instruments. There is a heritage of more than 25 years of global-daily observations from such instruments (Chang et al., 1987; Walker and Goodison, 2000). For the foreseeable future, similar passive-microwave sensors will be part of the U.S. operational satellite capability (e.g., CMIS on NPOESS).

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 -- future sensors may improve on this.

There is a large body of literature describing 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).

MODIS Data

MODIS data have been used since early 2000 to produce validated daily, global snow maps in an automated environment. These maps, available at a variety of spatial resolutions – 500 m, 0.05 deg. and 0.25 deg. – provide snow extent and FSC as well as snow albedo (Hall et al., 2007; Klein and Stroeve, 2002). Validation activities for snow extent and FSC have been conducted by the data-product developers and also by other investigators (see, for example, Hall et al. 2004 and 2007; Maurer et al., 2003; Klein and Barnett, 2003; Salomonson and Appel, 2004).

The MODIS snow algorithms used to create the maps were developed from heritage algorithms and include numerous additional features that are unique to this product (Riggs and Hall 2004; Riggs et al., 2005 & 2006). Inputs to the products include the MODIS cloud mask (Ackerman et al., 1998), land/water mask, geolocation product (Wolfe et al., 2002), radiance products and surface-reflectance product (for snow albedo) and land cover. The MODIS snow products are archived and distributed through the National Snow and Ice Data Center.

Scatterometer (QuikSCAT) Data

The sensitivity of space-borne scatterometer data to snow parameters data has been studied (e.g. Nghiem and Tsai 2001; Kimball et al. 2001, Hillard et al 2003, 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 (Nghiem et al., 2005).

RESULTS AND DISCUSSION

This preliminary blended-snow product is an example of data fusion with minimal modeling in order to more expeditiously yield improved snow products. Figure 1 shows a map of the blended visible and passive microwave images for February 5, 2003, and Figure 2 shows a map showing the blended snow extent based on both the visible and passive microwave data. Figure 3 is similar to Figure 1 but shows snow extent as mapped on February 25, 2003 – Figure 4 is the resulting blended snow map for this date.

Twenty one separate categories are shown on Figures 1 and 3, fifteen of which show snow from either or both the MODIS and AMSR-E products. The deeper blue color shows snow cover from both products, red portrays areas where MODIS detects snow and AMSR-E misses, and on this rendition, the yellow color represents snow that AMSR-E has observed but MODIS does not. Gray areas are snow free according to both products, and black shows lands that are snow covered on AMSR-E but cloud covered on this day from MODIS.

Notice the amount of cloud cover from MODIS (black) over both North America and Eurasia. On both February 5 and February 25 as well, more than 1/3 of the northern portions of both continents was obscured by clouds. The passive microwave product is especially useful in detecting snow through clouds.

The AMSR-E product has difficulty observing snow in those regions where snow is rather thin, along the margins of the continental snow line and on the lee side of the Rocky Mountains, for instance. However, MODIS can more easily map shallow snow cover. Again, the red color on Figures 1 and 3 are areas where MODIS observes snow but AMSR-E shows bare land.

Those areas in yellow that AMSR-E appears to map but MODIS does not are primarily located on very high and dry plateaus, such as the Tibet Plateau in western China. This massive plateau, though almost always below freezing during the winter months, is generally snow free since the atmosphere is so dry. The AMSR-E product overestimates snow extent here because the algorithm is detecting a very cold surface (low brightness temperatures), and therefore this region is mapped as being snow covered when in fact, the surface is free of snow.

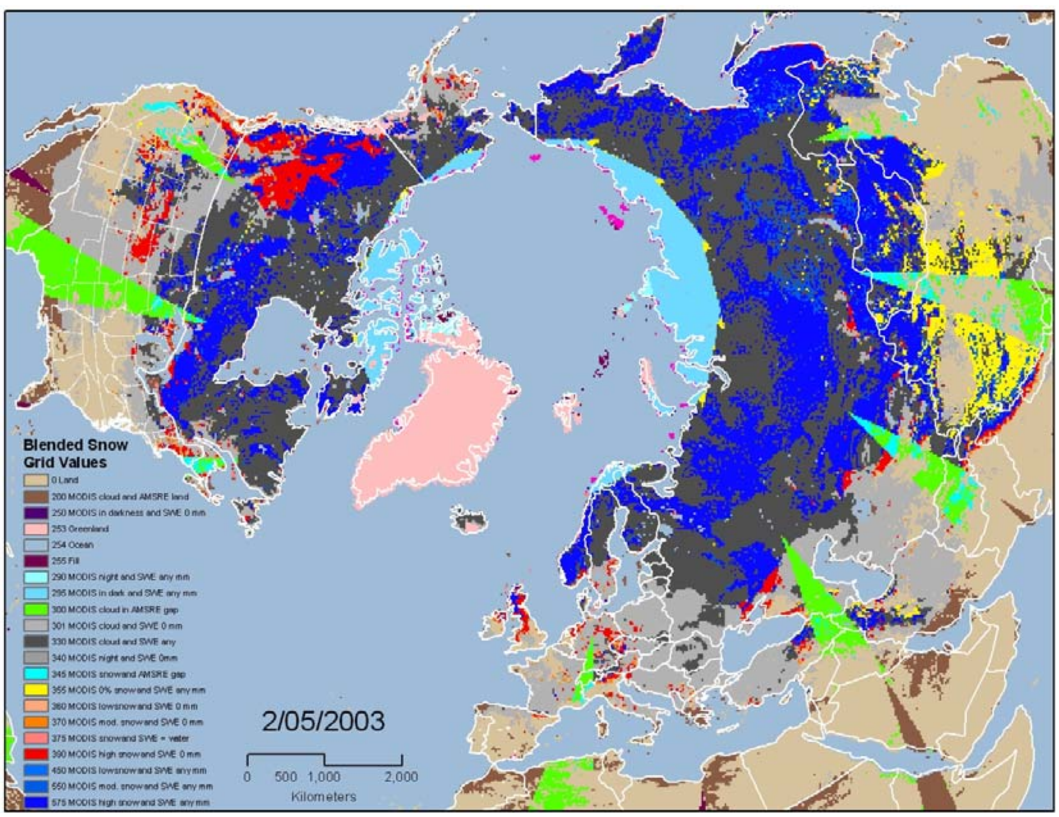

Figure 1. Map showing blended product for February 5, 2003.

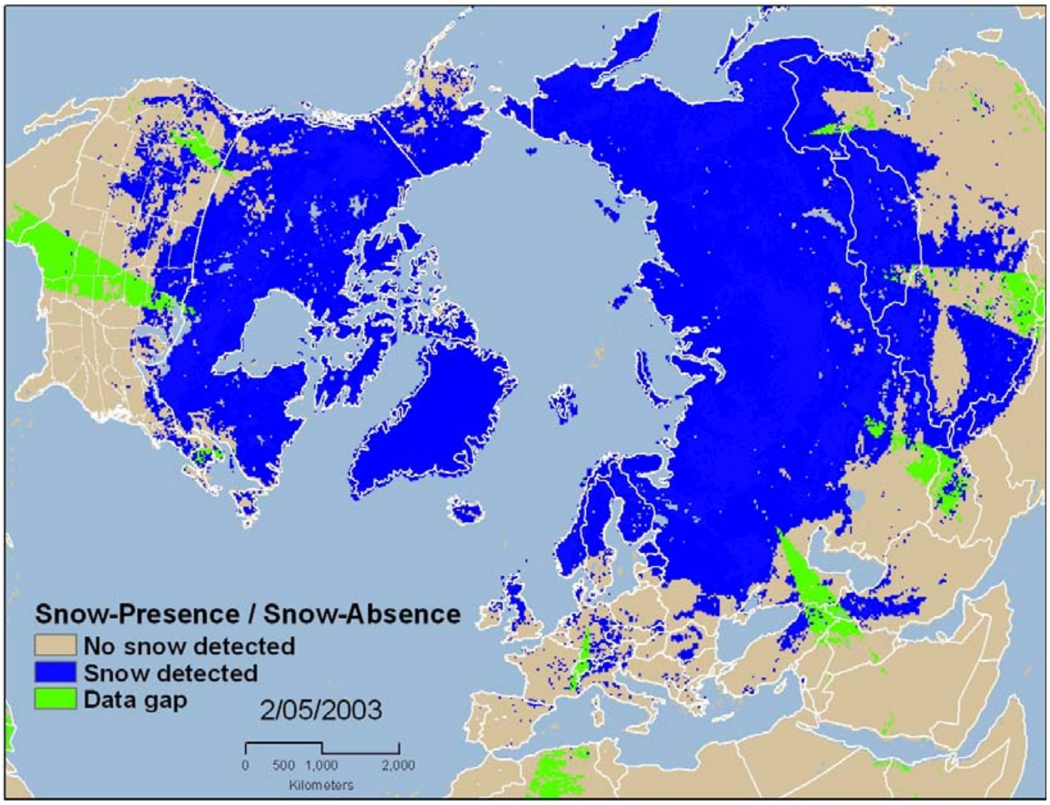

Figure 2. Blended snow cover extent for February 5, 2003.

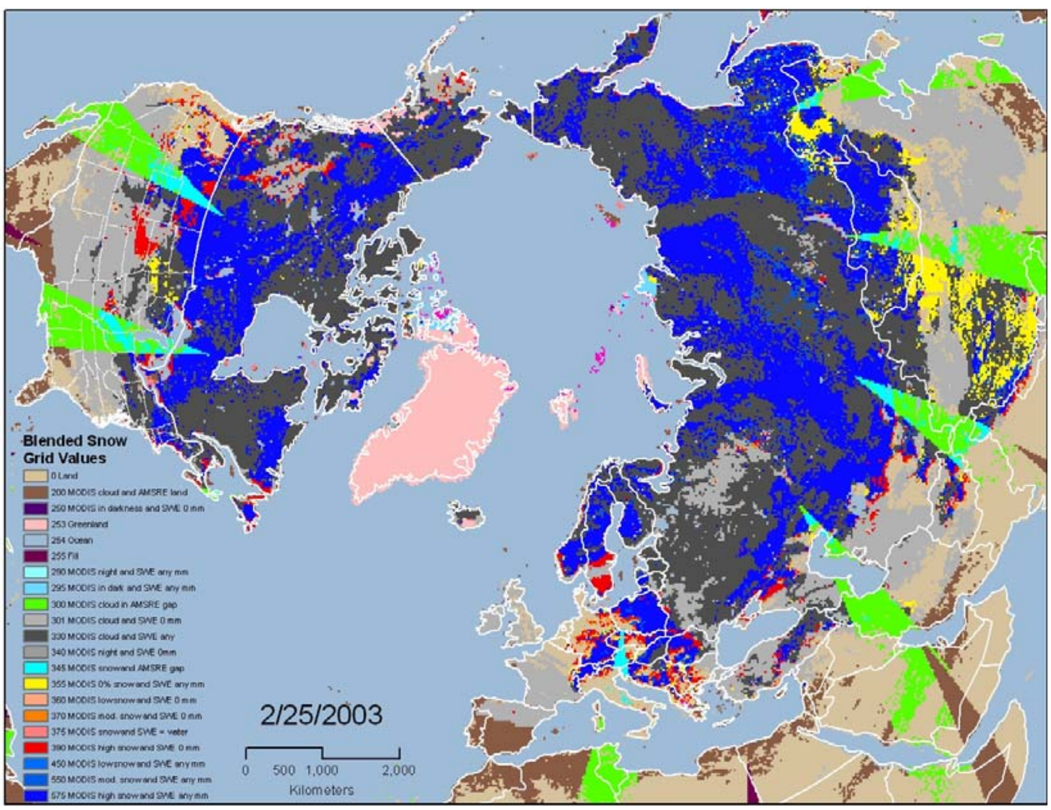

Figure 3. Map showing MODIS blended product for February 25, 2003.

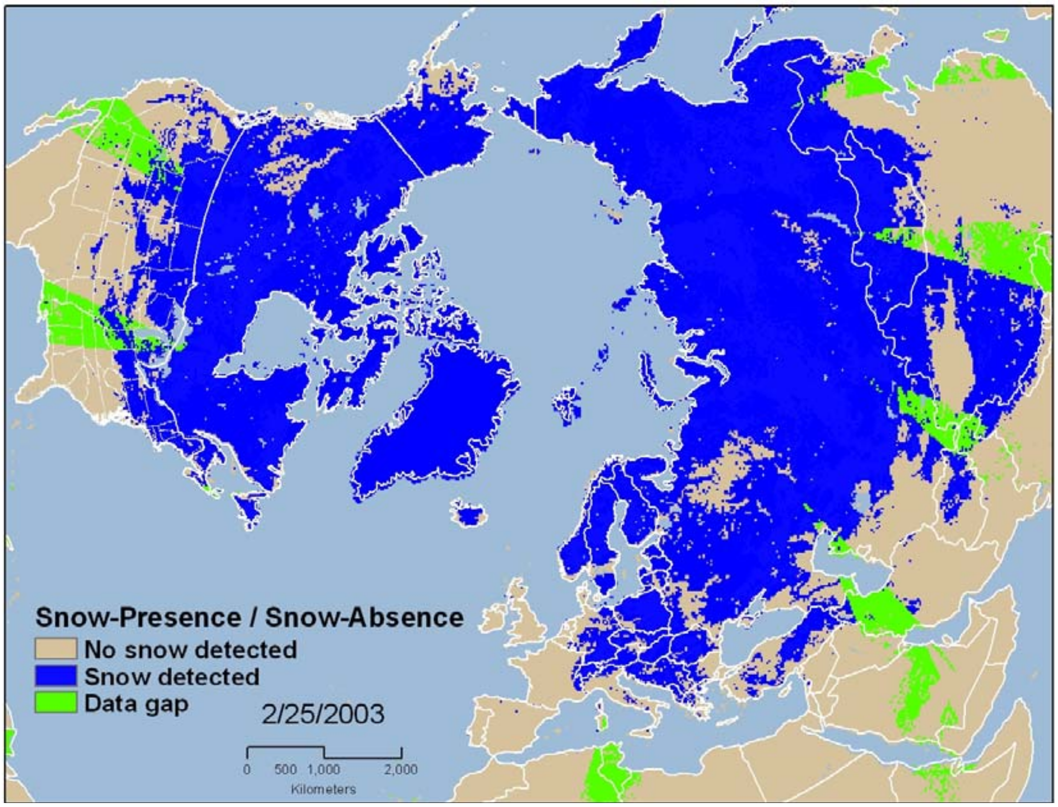

Figure 4. Blended snow cover map for February 25, 2003.

Comparing the maps for February 5 and 25, the most obvious difference is the extensive turquoise area on February 5 over northern Siberia, Alaska and the Canadian Archipelago. On February 25, only a small area of turquoise exists in extreme north central Siberia. These differences are due to the northward migration of the Sun. As it approaches the Equator is late February, almost all of the Northern Hemisphere's land surface is exposed to sunlight during a MODIS overpass. Earlier in February and indeed for most of the period from November through February, areas north of about 66 degrees latitude are dark when MODIS passes over. However, since the microwave portion of the spectrum can be used irrespective of daylight or darkness, these areas can be mapped with the blended product. Of course, this far north, during mid winter, this region is always snow covered.

Some reduction of the AMSR-E overestimation of snow (yellow) between February 5 and 25 can be seen on the Tibet Plateau. Much more noticeable is the increase in shallow snow missed by AMSR-E (red) over western North America. Snow areas to the lee of the Canadian Rocky Mountains and the Coast Mountains of western Canada are thinner now than earlier in the month and are also undergoing melt.

Because the confidence for mapping snow cover extent has been demonstrated to be greater with the visible product than with the microwave product, when cloud free MODIS observations are available, they will be used as "truth." The microwave-derived snow cover will be used as "truth" only in those areas where MODIS is rendered less useful due to the presence of by clouds and darkness.

Figure 5 shows a QuikSCAT snow map on March 20, 2003. This is scatterometer data at 14 GHz (Ku band), which as mentioned earlier has been demonstrated to accurately depict areas of snow that are actively melting. Note the extensive snow covered areas that are observed to be melting (in red) across southern Canada and in portions of the Rocky Mountains of Colorado and Wyoming.

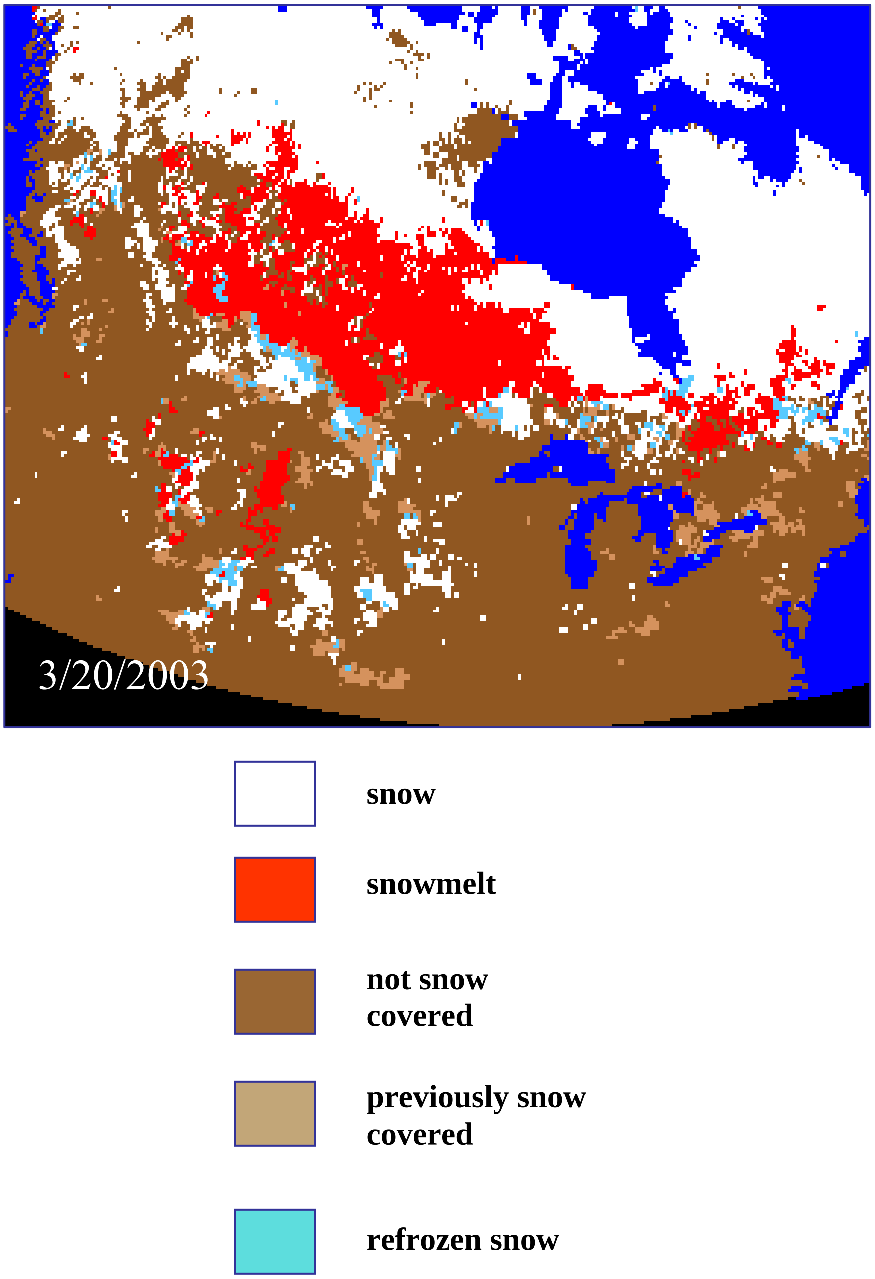

Figure 5. Map showing areas of actively melting snow on March 20, 2003
as determined using QuikSCAT data.

For mapping the onset of snowmelt using passive microwave radiometry, the approach used in this study is that wet snow is detected when the AMSR-E brightness temperature at 19.35 GHz (horizontal polarization) exceeds 245 K, and the difference between ascending and descending AMSR-E passes (Diurnal Amplitude Variations, DAV) exceeds 25 K fixed threshold. See Ramage and Isaacs (2003) for more on the DAV technique. In order to account for melting that persists during the night, snow is considered to be melting when both ascending and descending brightness temperatures are greater than 245 K (Tedesco, 2007).

Our blended snow product will have the capability of showing areas of dry snow (AMSR-E, 37 GHz) where melt is in the incipient stages (AMSR-E, 19 GHz horizontal channel), and areas where snow is actively melting (QuikSCAT, 14 GHz).

VALIDATION

Validation Datasets

Validation of our blended product will be accomplished by utilizing ground measurements to the extent possible from National Weather Service co-op station data and Air Force surface observations of the lower Great Lakes region, and SNOTEL sites, and measurements collected during the CLPX-1 2002-03 field experiment in Colorado and from Environment Canada. Currently, validation is underway for the lower Great Lakes area. A validation of the preliminary blended-snow product has been accomplished over the Lower Great Lakes region by Hall et al. (this issue). Results show that the blended product provides more accurate determination of snow-covered area than is possible to obtain using either MODIS or AMSR-E alone. Validation of the SWE will be undertaken in the near future.

Data acquired during the CLPX experiment focused on a) active- and passive-microwave remote sensing observations from ground, aircraft, and satellite platforms, b) intensive in situ observations of snow and soil characteristics, and c) in-situ meteorological observations (Tedesco et al., 2005). Airborne and ground-based Ku-band scatterometer data were collected in conjunction with brightness temperatures at 19 and 37 GHz to support the development of a retrieval algorithm for SWE.

The MODIS and AMSR-E data products are in HDF-EOS format but are generated at different spatial (500 m to 25 km) and temporal (multiple swaths or daily). The QuikSCAT data are produced with a 22.5 km resolution with multiple or daily swaths. In an effort to convey the accuracy or error associated with the blended snow product, error estimates will be included in the product. The accuracy of these products is affected by many factors including land cover type and viewing geometry. An accuracy index is being developed for the lower Great Lakes data set. The MODIS land cover product will be utilized to analyze errors in the blended product related to land cover type.

CONCLUSIONS AND FUTURE DIRECTIONS

This initial blended-snow product is an example of data fusion with minimal modeling in order to more expeditiously yield improved snow products, which here include snow cover extent, fractional snow cover, onset of snowmelt, and areas of snow cover that are actively melting. These products will be of medium resolution (currently 25 km), validated using data from the lower Great Lakes region and from CLPX, and will be available in a user-friendly format.

The next step is to include snow water equivalent (SWE) into our blended product. Initially, we will be using the version 5 algorithm of the AMSR-E product in order to derive SWE. We will soon begin work on enhancing the resolution (currently 25 km) of the global daily snow cover and SWE products. It is envisioned that we can improve the resolution, in some wavelengths, to perhaps 5 km. An optimal goal is to provide a global snow depth analysis at 5 km. We will also incorporate an 89-GHz global snow detection and SWE algorithm into the blended-product software. Additionally, we will compare MODIS snow cover extent retrievals from the EOS Terra and Aqua satellites to determine if snow retrievals from Aqua, using slightly different spectral channels, provide similar values to those obtained from Terra. Finally, we will validate our snow products to the extent possible by using data from well maintained and reliable meteorological stations such as in Finland, Canada and selected World Meteorological Organization sites. A key component of this blending effort is to produce and provide error bars, globally, that vary with land-cover type. Including information on uncertainties will be critical for use in data-assimilation models. Further into the future (within 5-7 years), it is planned that data assimilation techniques will be utilized to provide snow products to users in a near real time basis. See for instance Reichle and Koster (2004) and Sun et al. (2004).

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