12.1 A NEW BLENDED GLOBAL SNOW PRODUCT USING VISIBLE, MICROWAVE AND SCATTEROMETER SATELLITE DATA

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ABSTRACT

This purpose of this paper is to show our results in developing a joint U.S. Air Force/NASA blended, global snow 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. The initial blended-snow product is an example of data fusion with minimal modeling in order to more expeditiously yield improved snow products, which include snow cover extent, fractional snow cover, onset of snowmelt, and areas of snow cover that are actively melting. Snow products will be of medium resolution (currently 25 km), initially validated 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. 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 under cloud-free conditions. 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 are used as "truth." The microwave-derived snow cover are 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) are 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) is used to map areas of snow that are actively melting..

1. INTRODUCTION

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 over 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 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.

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 used extensively by other AFWA programs and external customers. The operational

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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 paucity of synoptic snow depth observations presents a unique challenge to accurately represent snow information in locations where regular meteorological observations are lacking due to political reasons, sparse populations, or lack of technology. Recent advances in the area of remote sensing have lead to further algorithm development to more accurately observe 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 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. The algorithms developed for 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, QuikSCAT and MODIS sensors.

Our blended-snow product will be fully automated and thus amenable to the production of future 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/or nighttime darkness.

Though snow-cover extent and snow albedo (as a beta product) are currently available from various sensors including the MODIS (see Hall and Riggs, 2007 and Hall et al., in press), 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 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 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, they use different geographic grids, and the temporal frequency varies as well. The blended product that we are developing will provide all of the necessary snow inputs (snow extent, SWE, fractional snow cover, snowpack ripening, and onset of snowmelt), globally, in a single user-friendly product.

This 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. It is an all-weather product with snow mapped by both visible and near-IR (MODIS) and microwave (AMSR-E and QuikSCAT) data for clear-sky conditions, and by AMSR-E and QuikSCAT data when clouds obscure the surface. Note that QuikSCAT data are available from June 1999 to present. 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 actively-melting snow.

2. DATA SETS

2.1 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, fractional-snow cover (FSC) and snow albedo (Hall and Riggs, 2007; Riggs et al., 2005a and b). Validation activities for snow extent and FSC have been conducted by the data-product developers and also by other investigators (Hall et al., 2004; Salomonson and Appel, 2004).

2.2 AMSR-E Data Set

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 (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).

2.3 Scatterometer (QuikSCAT) 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).

3.SNOW EXTENT FROM THE BLENDED PRODUCT

The current operational AFWA SNODEP model lacks a capability to accurately measure global snow depths and snow water equivalent due to the sparse nature of synoptic observations combined with a lack of remotely sensed observations used within the model infrastructure. Failure to address these deficiencies will result in continued poor representation of snow depth analysis, which is used by the AFWA Land Information System (LIS) to accurately represent the surface water and energy budgets, and by the Weather Research and Forecasting (WRF) models to predict the surface water and energy budget. The SNODEP model also supports current operational customers in the National Intelligence Community (NIC) and U.S. Army. Improvements to the SNODEP model are also required to improve the AFWA Cloud Depiction and Forecast System version II (CDFSII) global cloud analysis. Finally, inability to improve SNODEP will also affect AFWA NPOESS preparation, with AFWA unable to accurately use NPOESS VIIRS or replacement Microware Imager/Sounder datasets within its land surface modeling capability.

We have developed a satellite-based snow algorithm to derive various snow parameters using data blended from visible, near infrared and microwave observations. This is referred to as the Air Force Weather Agency/NASA Snow Algorithm (ANSA). Because the confidence for mapping snow cover extent has been demonstrated to be greater with visible products than with the microwave products, 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.

Figures 1-3 show Northern Hemisphere ANSA maps of the blended visible and passive microwave images for January, February and April 2007, respectively. Twenty one separate categories are shown, 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 -- especially evident near the border of the continental snowline, where snow depths are typically shallow (Figure 3). 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. The bottom half of each figure shows only the blended snow cover extent.

Notice the amount of cloud cover from MODIS (black) over both North America and Eurasia -- more than 1/3 of the northern portions of both continents are obscured by clouds during many winter months. As mentioned previously, the passive microwave product is especially useful in detecting snow through clouds. However, with passive microwave approaches, there is difficulty observing snow in those regions where the snow cover is rather thin (<5 cm), along the margins of the continental snow line and on the lee side of the Rocky Mountains, for instance. In these areas MODIS can easily map shallow snow cover (>2cm).

The extensive turquoise area on the January image (Figure 1) over northern Siberia, Alaska and the Canadian Archipelago results from the darkness of polar winter. In mid January, the Sun is not yet above the horizon in far northern latitudes. MODIS cannot see the non-illuminated surface, however, since the microwave portion of the spectrum is indifferent to daylight or darkness, these areas can be mapped with the blended product. Of course, this far north at this time of year, these latitudes are always snow covered.

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 because the atmosphere is so dry. The AMSR-E product overestimates snow extent here because the passive microwave 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 4 shows a MODIS and AMSR-E map for January 27, 2007. Here, the AMSR-E swath gaps visible on Figure 1-3 have been filled. Current day AMSR-E swath gaps are filled with SWE data from previous day. The SWE gap filling is done prior to application of the ANSA sensor blending rules. Swath gap discontinuities are eliminated and snow cover is mapped using both sensors.

4. ASSESSING SNOWMELT

3.1 Snowmelt *from Scatterometer Data*

Ku band scatterometer (QuikSCAT) data are 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.

c. Developing a QuikSCAT algorithm to derive snow depth.

Figure 5 shows QuikSCAT maps (14 GHz data) from the winter of 2003. 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.
With the wide swath (1,800 km) 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. 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.

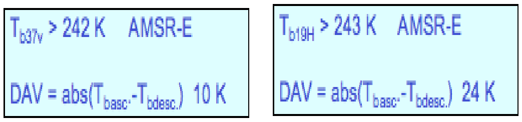
To determine where snowmelt occurs, we use a diurnal difference algorithm, a relative quantity between morning and afternoon measurements in half a day. We co-locate the data from the early morning (t_a) in an ascending orbit pass and late afternoon (t_p) in a descending pass for each day. The diurnal 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. We then adapt this algorithm for snowmelt detection over land.

This 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 QSCAT and future satellite scatterometers; it is independent of absolute backscatter from different snow classes and snow conditions; both snow melt and refreezing is 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, we present snowmelt results over the Northern Hemisphere in Figure 4 -- a series of snowmelt maps during the month of April (2001). The series of continental snowmelt patterns shows nicely 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 in lower row 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.

3.2 Snowmelt from AMSR-E data (Snowmelt Onset)

Passive microwave radiometry is 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.



$T_{b37v} > 242$ K AMSR-E

$DAV = abs(T_{basc.} - T_{bdesc.})$ 10 K

$T_{b19H} > 243$ K AMSR-E

$DAV = abs(T_{basc.} - T_{bdesc.})$ 24 K

Threshold values used within the DAV algorithm for different frequencies

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.

From Figure 6, only those areas classified as snow by MODIS are used to produce the snow onset maps. We see that the cumulative number of melting days between February and April 2003 ranges from 2 to 16 days. The area showing the highest number of melting days is located in north-west Canada. It is also possible to see that, as expected, the number of days when melting occurs is increasing from northern to southern locations. 2 (c) shows that some melting occurred during February 2003 in Alaska, Russia, the Great Lakes region, and in the Mid Atlantic region of the U.S. Upwards of 50 cm of snow accumulated during a storm near mid February. Following this storm, the melt in this region was substantial -- due to high values of both sensible and latent heat. In fact, wide spread flooding (in some cases record flooding) ensued.

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 (AMSR-E, 19 GHz horizontal channel), and areas where snow is actively melting (QuikSCAT, 14 GHz).

4.0 EVALUATION OF THE BLENDED SNOW PRODUCT

The ANSA product for snow cover and snow-water equivalent products has been evaluated for the Lower Great Lakes region during the winter of 2002-03 (Hall et al., in press). This study area is challenging for mapping snow cover using passive microwave sensors due to varied land cover and the frequency of lake-effect snows (deep and wet snowfalls). National Weather Service Co-Operative Observing Network stations and student-acquired snow data were used as ground truth. An interpolation scheme was used to map snow cover on the ground from the station measurements for each day of the study period. It is concluded that this technique does not represent the actual ground conditions adequately to permit evaluation of the new snow product in an absolute sense. However, use of the new product was found to improve the mapping of snow cover as compared to using either the MODIS or AMSR-E product, alone (Hall et al., in press). Further evaluation is underway, for example, see Hall et al. (2008 – this volume) for a description of the validation activities in North America for the 2002-03 snow season.

We also explored the evaluation of the blended products using field observations from the NASA's Cold Land Processes Experiment-1 (CLPX-1). Specifically, we used observations from Feb 2003 Intensive Observing Period (IOP-3) in Colorado, USA. CLPX-1 was a large-scale snow remote sensing field campaign in support of future NASA snow satellite missions. It included airborne and ground measurements for three 25 x 25 km meso-cell study areas. Of particular interest in the present context is the North Fork cell area, where distributed ground truth was collected within a 25 x 25 km area on Feb. 22, 2003.

These in situ measurements were kriged with 500 m resolution to form a "true SWE" distribution. The mean SWE for the whole MSA was 18.9 mm with a standard deviation of 11.6 mm (because the snow cover was patchy). While Feb. 22 coincided with an AMSR-E swath, we can see that the "true SWE" of 18.9 mm for that date (Feb. 22, 2003) was only 14% larger than the AMSR-E derived mean SWE for Feb. 21, and Feb. 23. While it is very difficult to draw definitive conclusion from such temporally sparse data, this is at least encouraging for this rare case of directly measured wide-area SWE. To expand validation of the ANSA product in space and time, future comparisons will necessarily involve airborne and interpolated station measurements of the "true SWE."

Additional validation efforts are underway. We have been comparing AFWA SNODEP maps with the preliminary ANSA product for the 2007-08 snow season. And, for the 2002-03 snow season, we have monitored the areas of active snowmelt using the ANSA algorithm along with the QuikSCAT algorithm derived from the work of Nghiem and Tsai (2001).

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

This preliminary blended-snow product is an example of data fusion with minimal modeling in order to expeditiously yield improved snow products, which here include snow-cover extent, SWE, FSC, onset of snowmelt, and areas of snow cover that are actively melting. These maps will be in a user-friendly format, at a medium resolution (currently 25 km) and have been validated thus far using data from the lower Great Lakes region and from the CLPX site in Colorado.

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).

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 5 km. We will also incorporate an 89-GHz global snow detection and SWE algorithm into the blended product software. Finally, we will further 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.

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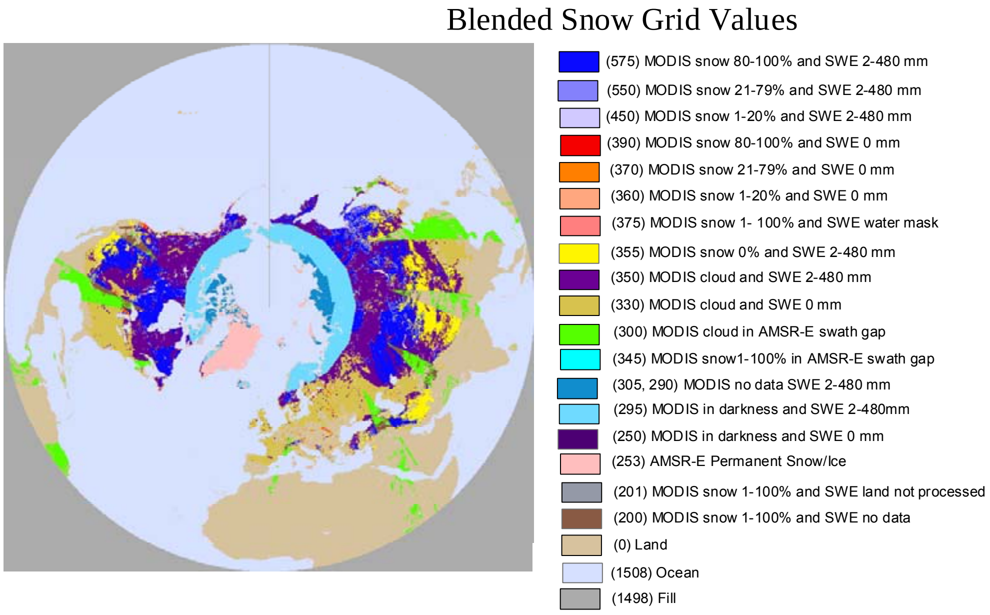
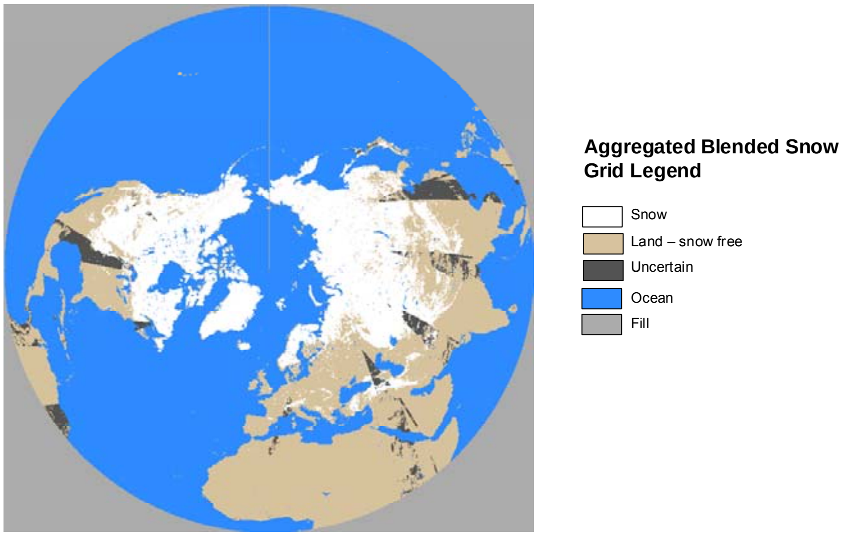


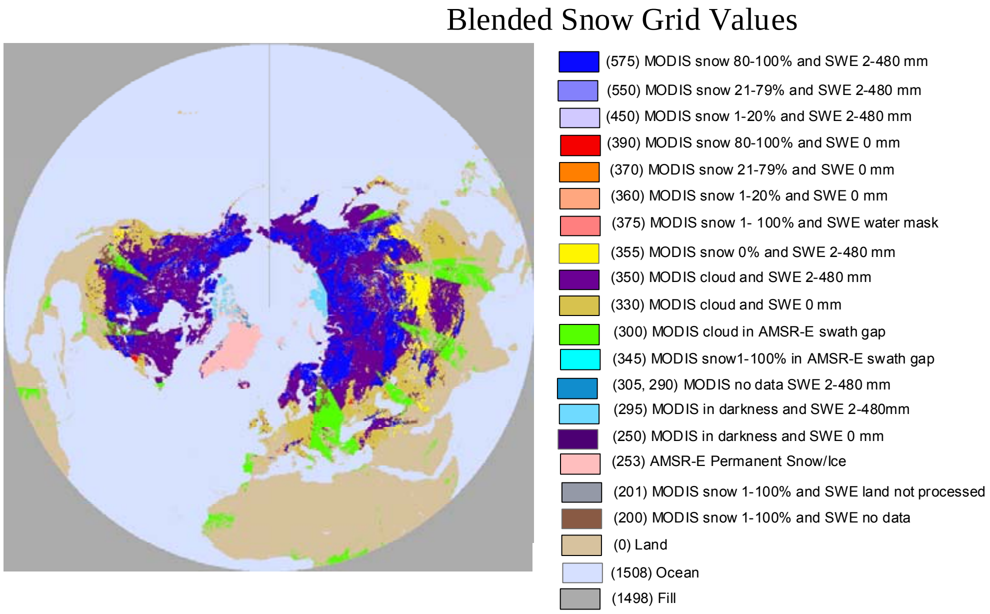
ANSA snow map 15 January 2007



ANSA snow map 15 January 2007

Figure 1
January 2007 ANSA Snow Map

ANSA snow map 15 February 2007



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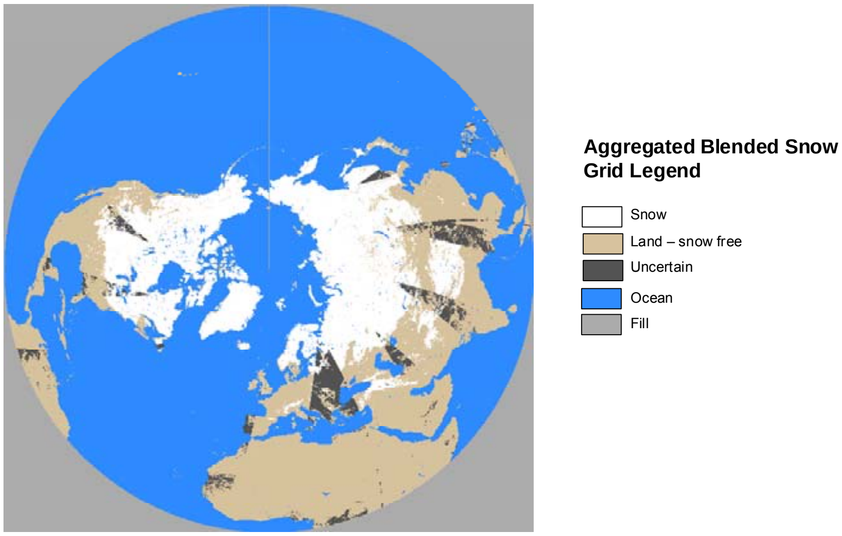
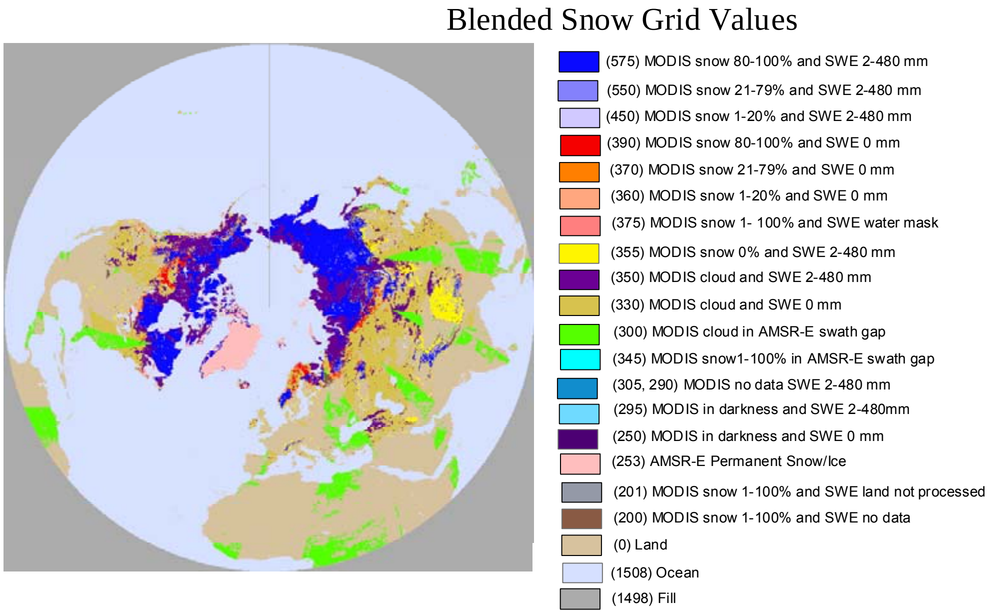


Figure 2
February 2007 ANSA Snow Map

ANSA snow map 15 April 2007



ANSA snow map 15 April 2007

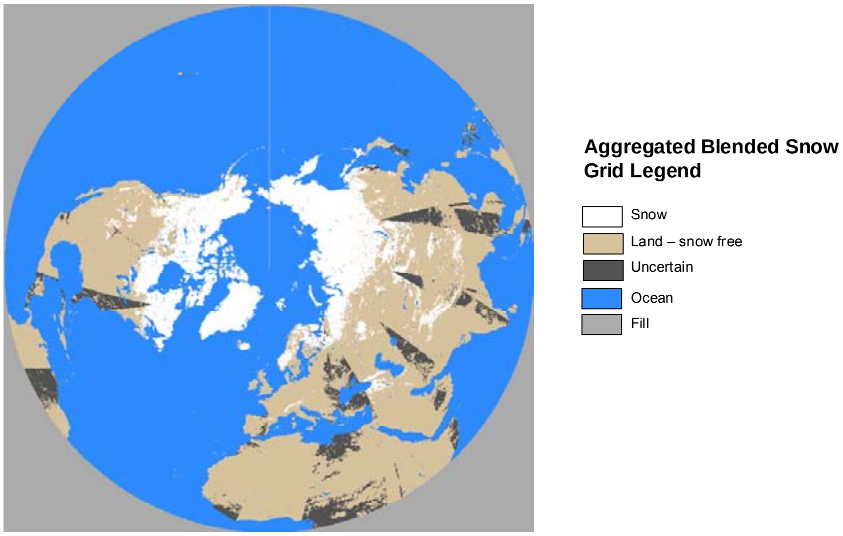


Figure 3
April 2007 ANSA Snow Map

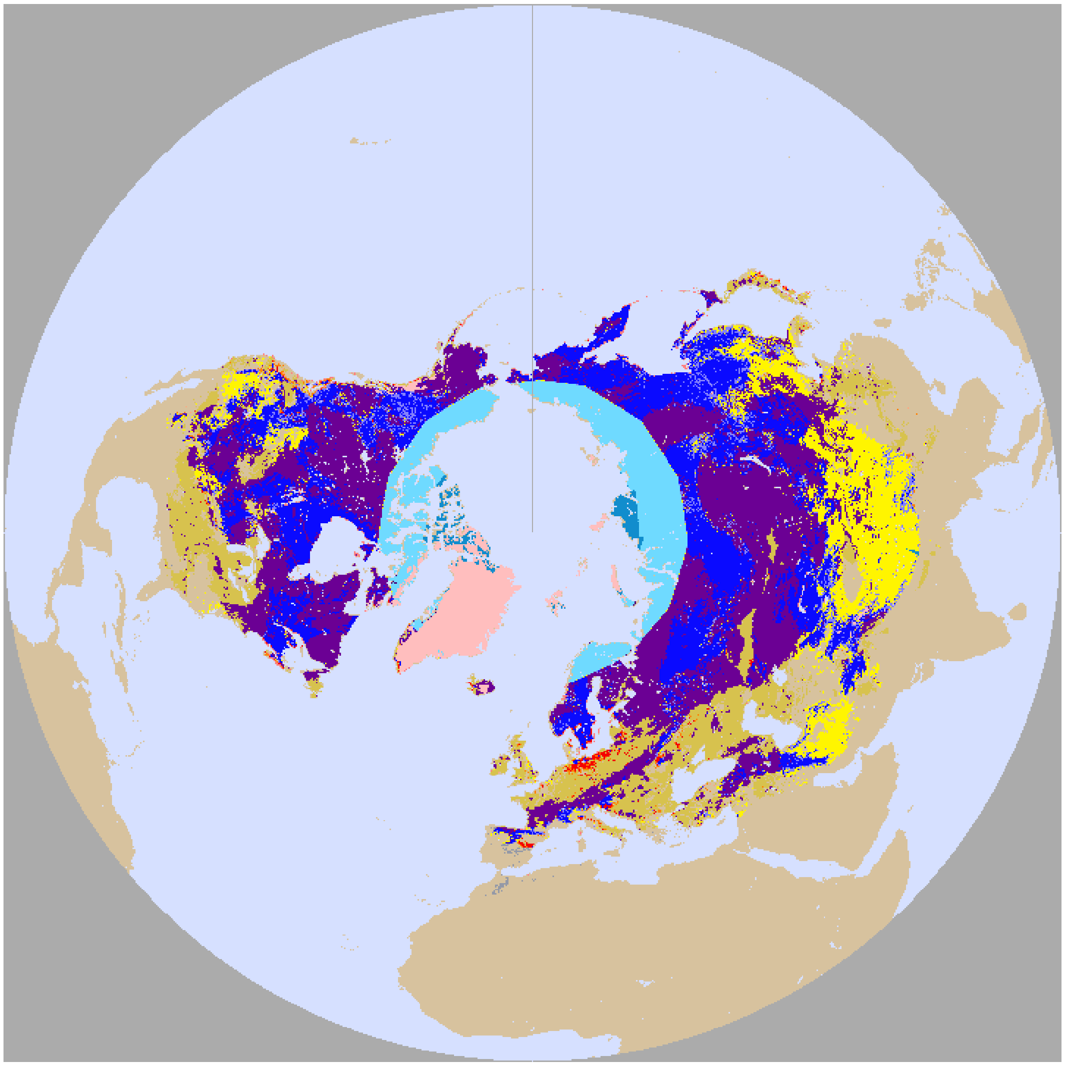
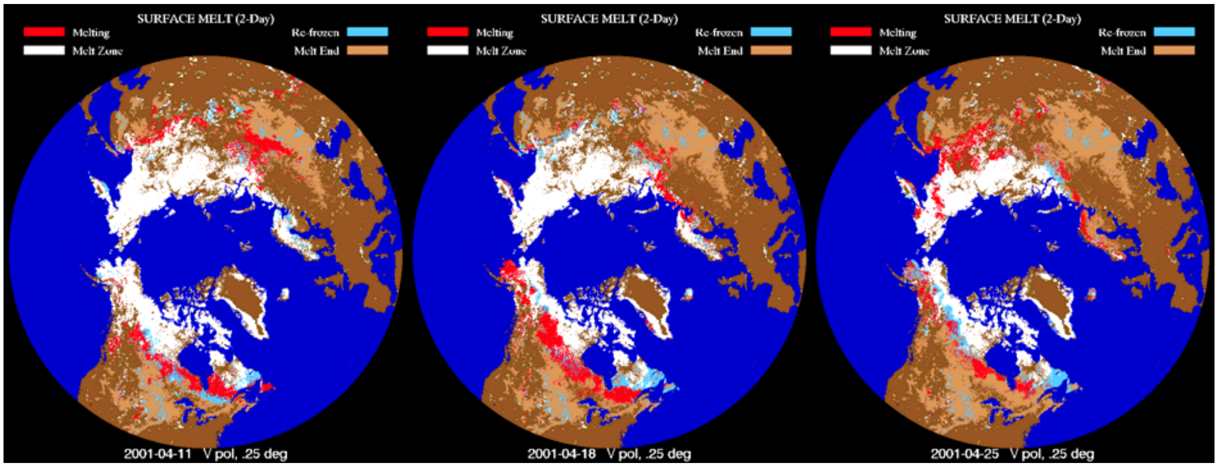


Figure 4
ANSA snow map for 27 January 2007 with AMSR-E swath gap fill filled with SWE data from previous day.



. **Figure 5**

Snowmelt maps derived from global QuikSCAT backscatter data from 3/21/2001 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.

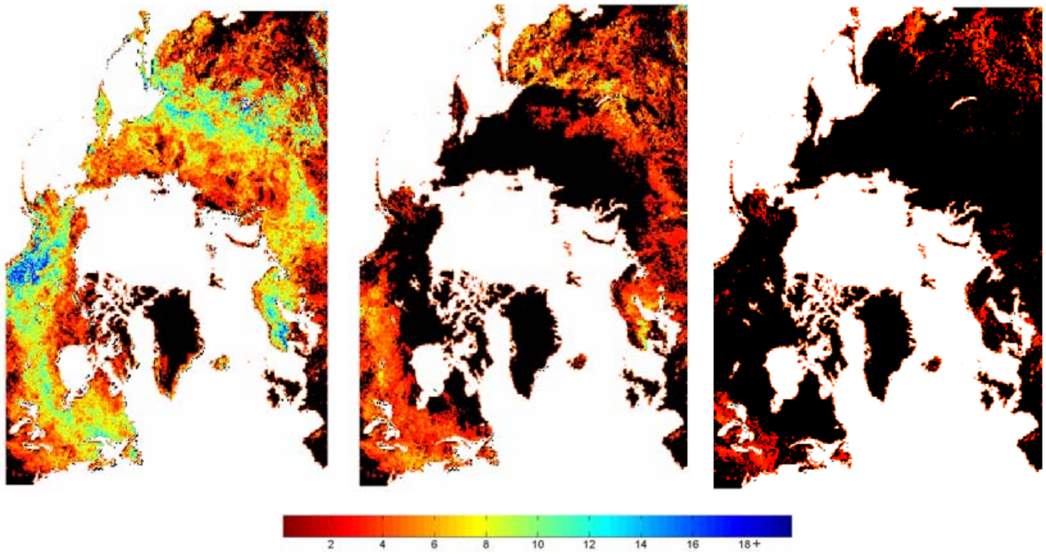


Figure 6

Number of melting days observed in 2003 for the period (a) February – April, (b) March and (c) February.