DRAFT: For student review only. Article has been accepted with minor revision for publication in Geography Compass. Final version to be submitted December 2008.

A New Generation of Satellite Snow Observations

for Large Scale Earth System Studies

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Abstract

Snow cover variations over Northern Hemisphere lands result in dramatic changes in the earth's hydrology and surface energy balance over a range of time scales. These variations play a role in the complex web of feedbacks that control the earth's climate; and these feedbacks are likely to modulate any climate change that occurs during this century. The ongoing need for reliably observed indicators of climate change, and for refined climate models, to facilitate the detection and attribution of climate change; and the declining global meteorological observation network; underscore the increasing importance of accurate remotely-sensed information. A new generation of remotely sensed products in the last decade provides information at unprecedented temporal, spatial, and spectral resolutions. This article reviews the characteristics and theoretical underpinnings of these snow products; shows examples of their application in climatological analyses; and discusses current and future directions in their application and development.

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1. Introduction

We live in an era of extraordinary changes in the earth's cryosphere (Serreze et al. 2000; ACIA 2004; Serreze and Francis 2006; Serreze et al. 2007; Stroeve, Holland et al. 2007; Stroeve, Serreze et al. 2007; Hanna et al. 2008). Indeed, our understanding of how the first signs of global climate change should theoretically be driven by cryospheric feedbacks in the Arctic region have evolved within the last decade from an *expectation* of seeing the first changes in the Arctic to a *realization* that Arctic changes are occurring more rapidly than expected (Sheperd and Wingham 2007; Stroeve et al. 2007). What about that component of the cryosphere whose spatial extent varies most from season to season: snow cover?

In the earth's recent climatic regime, snow is found over significant portions of Northern Hemisphere lands during winter, while during the warm season snow is restricted to higher elevations, Greenland and other ice sheets, and sea ice, making it one of the most dramatic seasonal environmental changes (Gutzler and Rosen 1992; Robinson et al. 1993; Robinson and Frei 2000). In the Southern Hemisphere, outside of Antarctica and its surrounding ice sheets, snow is generally limited to smaller regions such as Patagonia and high elevations. On decadal time scales, snow variations over Northern Hemisphere lands have also been significant (Barry et al. 1995; Brown and Braaten 1998; Ye et al. 1998; Frei et al. 1999; Brown 2000; Derksen et al. 2004; Mote et al. 2005; Mote 2006), with declines in spring associated with air temperature depressions (Leathers and Robinson 1993; Groisman et al. 1994; IPCC 2007) and the expectation of changes that are even more dramatic (Ye and Mather 1997; Frei and Gong 2005; Raisanen

2007) and spatially and temporally complex (Nolin and Daly 2006; Brown and Mote 2008) during this century.

While large scale changes in snow cover are useful as indicators of general climatic shifts, snow also affects other components of the earth system. By virtue of its radiative and thermal properties which modulate transfers of energy and mass at the surface-atmosphere interface (Zhang 2005), snow affects the overlying atmosphere (Walsh 1984; Cohen 1994; Ellis and Leathers 1999; Barry 2002; Barry et al. 2007; Mote 2008) and thereby plays an important role in the complex web of feedbacks that control the earth's climate (see discussion section). Snow also modulates the hydrologic cycle (Leathers et al. 1998; Todhunter 2001; Graybeal and Leathers 2006; Dyer 2008); influences ecosystem functioning (Jones et al. 2001); is a significant resource for populations whose water is derived from mountainous and northerly cold regions (Barry et al. 2007); and snow observations are critical for the calibration and validation of climate models (Foster et al. 1996; Roesch et al. 1999; Frei et al. 2003; Frei et al. 2005; MacKay et al. 2006). Thus, accurate snow cover information for applications in earth system studies is of growing importance.

There exists considerable contrast between surface, or *in situ*, and remote snow observations with regards to the snow pack properties that can be measured, their spatial and temporal resolutions and domains, and the methods employed to make measurements (Goodison and McKay 1981; Brown and Armstrong 2008). In general, the number of *in situ* meteorological observation sites worldwide increased during most of the twentieth century but has decreased in recent years due to budgetary concerns in many countries, exacerbating the need for accurate satellite observations.

The purpose of this article is to present to the geographic community the new generation of satellite-based snow observations that has become available during the first decade of the twenty first century. Theoretical considerations for the remote sensing of snow are reviewed in section 2. Some of the digital products are discussed (section 3), followed by examples from two state-of-the-art, widely used products (section 4), finishing with a discussion of important issues for future researchers (section 5). In this article, the focus is on snow cover over land surfaces of the Northern Hemisphere; on studies over large (i.e. regional to continental) spatial scales; and on recent literature. This article is complementary and introductory to classic (Gray and Male 1981) and recent (Armstrong and Brun 2008) edited volumes, to which the reader is referred for more detailed treatments of some of the topics presented here.

2. Theoretical Considerations

Remote snow observations are possible because of the manner in which snow on the ground interacts with electromagnetic radiation (Matzler 1994; Rango et al. 2000; Schmugge et al. 2002; Scherer et al. 2005). The two types of instruments that have been most widely used for monitoring large scale snow variations measure electromagnetic radiation in either visible or microwave bands. Both instruments are passive, meaning that they measure only natural emissions, as opposed to emitting radiation themselves and then measuring a return signal.

While both visible (VIS) and passive microwave (PMW) methods work well in theory, in practice they are to some extent limited by factors that tend to confound the remotely-sensed signal. For example, interpretation of both types of observations can be difficult in mountainous terrain, where complex terrain cause considerable spatial variation within each remotely-sensed footprint of snow depth, surface characteristics, and satellite viewing angles. Nevertheless, products based on these observations have been vital for monitoring snow, and for our understanding of the role of snow in the earth system. Although a number of other techniques (e.g. gamma and active microwave sensing techniques) are used for the remote sensing of snow extent, amount, melt, or snow pack properties at finer spatial scales (see discussion section), here the focus is on regional to continental scale studies.

2.1 Visible band observations (VIS)

Snow extent (i.e. presence or absence of snow, regardless of snow amount) is, in many circumstances, relatively straightforward to observe using VIS observations because of the high albedo (reflectivity in the visible part of the spectrum) of snow relative to most surfaces. The primary limitations are related to four factors, the first of which is associated with clouds, which impede the VIS signal in two ways. All but the thinnest clouds reflect a significant portion of visible radiation, preventing any VIS radiative information about the surface from reaching the satellite. And, because the albedos of clouds and snow are similar, the discrimination of cloud-covered from snow-covered surfaces can be difficult.

The second factor is the presence of surface vegetation. Forest canopies protrude above the snow pack, lowering the surface albedo (Robinson and Kukla 1985) and partially or completely obscuring the underlying surface, making it difficult to determine snow extent or amount (Chang et al. 1996; Klein et al. 1998; Goita et al. 2003; Nolin 2004). For example, in figure 1 one can see that the surface brightness perceived from a remote viewpoint depends on the characteristics of the overlying vegetation as well as on the viewing and solar insolation angles. In fact, the impact of even low vegetation on the snow-albedo feedback (Sturm et al. 2005) remains a significant uncertainty in climate modeling.

The third factor is related to the earth's daily and seasonal orbital cycles. VIS imagery works only for the portion of the surface illuminated by sunlight, precluding information from VIS at night, during the polar winter, and often at low insolation angles. The fourth, and least studied, is the presence of numerous frozen lakes in Arctic regions, which may contribute to the overestimation of snow covered area during periods when lakes remain frozen after the snow has melted on adjacent land surfaces (figure 1).

2.2 Passive microwave band observations (PMW)

Because snow grain dimensions are similar to MW wavelengths, snow is efficient at scattering MW radiation, which is naturally emitted upwards from the earth's surface. Therefore, the MW emission upward over a snow pack, which can be estimated from space-based sensors, is diminished relative to a snow-free surface (Matzler 1994; Tait 1998; Grody 2008). Furthermore, because under ideal circumstances the amount of scattering is proportional to the number of ice crystals, MW instruments offer the possibility of estimating snow amount in addition to extent. Snow amount refers to either depth, or the mass of water in the snow pack which is often measured as snow water equivalent (SWE). In contrast to VIS, PMW does not depend on the presence of sunlight and thus provides an ideal alternative at high latitudes; and, PMW is largely transmitted through clouds, offering the potential to estimate snow cover under many meteorological conditions that preclude VIS observations. In practice, research using PMW exploits the fact that MW scattering by ice crystals is frequency-dependent: higher frequencies within the MW portion of the spectrum are scattered more efficiently than lower frequencies, enabling the use of two frequency bands to account for the depletion of the MW signal caused by scattering in the overlying atmosphere (Chang et al. 1987; Grody and Basist 1996; Derksen et al. 2005; Derksen 2008).

Uncertainties in snow depth and SWE estimates are associated with the physical structure of snow packs (the presence of liquid water, ice lenses, grain size variations, impurities) which vary in space (Sturm et al. 1995) and time (Langham 1981) and can alter the scattering and emission characteristics of the snow pack. Metamorphosis of the crystalline structure of a snow pack, which over time typically develops larger crystals such as a layer of depth hoar near the bottom of the pack (figure 2), results in more efficient scattering of MW radiation. Thus, a signal change measured at the satellite sensor due to snow metamorphosis may be indistinguishable from a signal change due to a change in snow amount. Vegetation within and above the snow pack emits microwave radiation, and can confound any detection algorithm (Chang et al. 1996; Foster et al. 1997). Also, as a snow pack reaches a certain critical depth, the relationship between snow-amount and scattering efficiency changes (Derksen 2008).

3. Snow Products

A number of digital products, or data sets, that are based on some combination of *in situ* measurements, remote observations, and model simulations are available to researchers (Rango et al. 2000; Kelly et al. 2004). These are produced for either operational or research purposes, and some fulfill both purposes. Operational products are produced in near real time (i.e. within one day) and are used as input into weather or hydrologic forecast models, and can include only information that is reliably available in near real time. Research products, in contrast, can include information from historical sources and those that are not available in real time, and can prioritize improved accuracy and quality control over timeliness. Satellite products whose production is completely automated can be available for both operational and research purposes. The focus here is on the two products most widely used for large scale climate research: The Interactive Multisensor Snow and Ice Mapping System (IMS) (section 3.1) and Moderate Resolution Imaging Spectroradiometer (MODIS) (section 3.2). PMW (section 3.3) and combined (section 3.4) products are briefly discussed, followed by a review of product evaluation studies (section 3.5). Many products are available from the U.S. National Snow and Ice Data Center (NSIDC). Table 1 provides some helpful URLs.

3.1 IMS snow extent product

The data set that has historically been most widely used for the operational charting and climatological analysis of large-scale snow extent (not mass or water equivalent) has been produced by the US National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite and Data Information Service (NESDIS), and has recently been transferred to the National Ice Center (NIC), which is jointly supported by NOAA, the Navy, and the Coast Guard. This has been based primarily on VIS observations, and covers the period from around 1967 to present, constituting the longest remotely sensed environmental time series that has been derived in a *near-consistent* fashion (Matson and Wiesnet 1981; Robinson et al. 1993; Helfrich et al. 2007). The term *near-consistent* used because, due to changing operational requirements and evolving technical capabilities, this product has undergone, and continues to undergo, improvements and refinements (Ramsay 1998; 2000; Helfrich et al. 2007; Robinson 2008) as summarized briefly here. The two reasons for this product's importance - as operational input into atmospheric forecast models and as a long-term climatic record - are also discussed.

Although a number of improvements and corrections in the production of the NOAA product occurred in the earlier years (Robinson 2008), the biggest methodological change was implemented in the late 1990s. Until that time, NOAA snow charts were produced on a weekly basis by trained meteorologists who would visually interpret photographic copies of visible band imagery, and manually produce charts that would subsequently be digitized with spatial resolution between 150 km and 200 km. In 1997 NOAA began producing snow charts using the Interactive Multisensor Snow and Ice Mapping System (IMS), with improved spatial (24 km) and temporal (daily) resolutions. IMS is operated by trained analysts who produce a daily digital product utilizing Geographic Information System (GIS) technology and incorporating a variety of, and an ongoing expansion of, technological capabilities as well as sources of information. Since 1999, when weekly manual charting was discontinued, only daily IMS charts continue to be produced (Robinson et al. 1999). A number of technological advancements since 1999 have led to even higher resolution (4 km) and more accurate snow mapping (Helfrich et al. 2007). A key feature of the IMS product is that human judgment as to which data sources are most reliable in different conditions and regions remains an integral part of the process. The IMS product can be visualized at the IMS web site; and the data files can be obtained from NSIDC (see table 1 for URLs)

There exists an inherent tension between the two main uses of this product. The primary purpose of this product is to provide input to atmospheric forecast models. As a record for evaluating long term environmental change, however, the value of any product is diminished if methodological changes (including those that provide more accurate data) result in inconsistencies in the data set that might be difficult to distinguish from actual changes in snow extent. To maintain product continuity and a viable long-term record, IMS continues to produce a coarse (24 km) resolution version of the data set. And, in collaboration with IMS, David Robinson at the Rutgers University Global Snow Lab (GSL) produces a climate data record that has accounted for inconsistencies between the earlier maps and the IMS product, and can be used for analysis of historical variations (see table 1 for URL).

3.2 MODIS snow extent product

In 1999, NASA's Earth Observing System (EOS) Terra satellite was launched. Terra contains five instruments, including the Moderate Resolution Imaging Spectroradiometer (MODIS) which measures VIS radiation. MODIS snow cover products, available since 2000, are derived in a fully automated procedure which provides high spatial resolution (500m), cloud detection, and frequent coverage (daily at mid to high latitudes) (Hall et al. 1995; Riggs et al. 2000; Hall et al. 2002). NASA provides a hierarchy of products based on MODIS snow observations, which are designed to satisfy the needs of a variety of users (all available at NSIDC). These include a swath product which contains images with data from regions associated with actual satellite overpasses; daily and 8-day composite tile products which are mapped onto a sinusoidal projection and available in 10 degree lat/lon tiles; as well as daily, 8-day composite, and monthly products available in the Climate-Modeling Grid (CMG, which is a latitude-longitude projection), at two spatial resolutions (0.05 or 0.25 degree) (Hall et al. 2002; Riggs et al. 2005). An 8-day composite is considered useful because in many regions, particularly at high latitudes, persistent cloudiness limits the number of days available for surface observations (see section 4). The CMG was developed to be useful for the evaluation of climate models and for studies at large spatial scales.

3.3 PMW snow extent and snow amount products

Global PMW measurements are available from the Scanning Multichannel Microwave Radiometer (SMMR) instrument (1978 through 1987), and the Special Sensor Microwave / Imager (SSM/I) instrument (1987 through present) although some compatibility issues between the two products exist (Armstrong and Brodzik 2001; Derksen and Walker 2003; Brodzik et al. 2007). The new generation EOS instrument that measures PMW is the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E), available since 2002. This instrument provides a full suite of measurement bands to make it spectrally compatible with both SMMR and SSM/I at higher spatial resolution (Kelly et al. 2004; Derksen et al. 2005). Due to the inherent difficulties and regional variations in the interpretation of PMW signals (section 2), the production of a data set that is consistently accurate across all Northern Hemisphere regions requires regionally-based algorithms (Foster et al. 1997) which have yet to be developed for most regions. Nevertheless, NSIDC provides global SWE products based on SMMR and SSM/I, on AMSR-E using the algorithm of Kelly et al. (2003) as well as a product that combines both AMSR-E SWE and MODIS snow extent (Brodzik et al. 2007).

Environment Canada produces a regional PMW SWE product for central Canada, including the Prairies and part of the boreal forest back to 1978. Until December, 1999, this product relied on a single algorithm that was calibrated for the prairies region (Goodison and Walker 1995); since that time an algorithm that corrects for the effects of different forest types on the PMW signal has been included (Goita et al. 2003). This product is available from the Canadian State of the Cryosphere web site (table 1).

3.4 Other products

Kelly et al. (2004) and Tait et al. (2000) provide valuable overviews of the issues involved in the spatial modeling of snow depth and the development of combined products. Although a more detailed discussion is beyond the scope of this article, it is worth mentioning a few such products. One widely used example is NOAA's National Operational Hydrologic Remote Sensing Center (NOHRSC) Snow Data Assimilation System (SNODAS), which operationally incorporates input from snow models, station reports, and airborne sensors to estimate daily SWE at 1 km resolution across the continental US (Carroll et al. 2001) (available from NSIDC).

Weather prediction models require some sort of operational snow information (Drusch et al. 2004). The product by Brown et al. (2003), which employs the operational snow depth routine of the Canadian Meterological Center model (Brasnett 1999), has been used for evaluation of climate models (Frei et al. 2005). Grundstein et al. (2002) developed a research-oriented SWE climatology for the Great Plains of the United States by combining station observations with the 1-dimensional snow pack model SNTHERM (Jordan 1991). A research-oriented product based on spatial interpolation of *in situ* depth measurements over North America (Dyer and Mote 2006) has recently been used (Ge and Gong 2008b). A recent study used QuickSCAT active microwave scatterometer data to estimate the timing of snow melt across Arctic lands (Wang et al. 2008). These products are available

3.5 Comparisons and evaluations of products

Which of these products is best? Two key impediments to a conclusive evaluation are that the answer depends on spatial scale, and that there is no perfect “ground truth.” The complexities of validation efforts related to spatial scale (Brubaker et al. 2005; Chang et al. 2005) are similar to those associated with combining products (section 3.4 and Kelly et al., 2004). Brubaker et al. (2005) discuss the difficulties in comparing point measurements to spatially integrated satellite retrievals, especially in areas of sparse station networks, which are typically at high elevations and northerly regions (exactly the areas where snow is most prevalent). They find that there is no single accepted method to perform validation of remotely sensed snow products. Chang et al. (2005) provide an informative review of how varying station densities and different satellite footprints are not equally spatially representative, and how the differences can complicate evaluations and comparisons of different products. They employ geostatistical techniques, as suggested by Kelly et al. (2004), to quantitatively define the spatial density of station observations required to provide sufficient information for validation studies. Riggs et al. (2005) confirm that even between different versions of the same product (MODIS), analyses at different spatial resolutions provide conflicting results in some regions.

Despite the inherent difficulties, comparative studies are able to draw some conclusions (Basist et al. 1996; Tait and Armstrong 1996; Foster et al. 1997; Armstrong and Brodzik 2001; Bitner et al. 2002; Romanov et al. 2002; Derksen et al. 2003; Mote et al. 2003; Drusch et al. 2004; Mialon et al. 2005; Brown et al. 2007; Savoie et al. 2007). For example, evaluations of the NOAA visible-based and the passive microwave products find most disagreement during the swing seasons than during mid-winter, with particular differences under forest canopies, over rugged terrain, in areas of persistent clouds, patchy snow, wet snow (Basist et al. 1996; Armstrong and Brodzik 2001), and over the Tibetan Plateau (Savoie et al. 2007). Brown et al. (2007) identify discrepancies in the central Canadian Arctic between IMS and station observations during spring ablation. They find more consistency between QuickSCAT results (section 3.4) and station observations than with IMS, but can not with certainty diagnose the causes of these differences. In general, it appears that the greatest discrepancies between products are found during periods of accumulation and ablation, and in particular during spring.

4. Examples

This section shows examples of how MODIS and IMS can be used to examine the climatology of snow cover. Prior to discussing snow, some of the problems inherent in the interpretation of VIS imagery discussed in section 2.1 are revisited.

Figure 3, derived from the MODIS daily CMG 0.25 degree product (see section 3.2), shows, for each grid cell, the median number of days per month with clear skies for October, January, and April from the 2000-2001 through 2007-2008 snow seasons. The October (top) panel demonstrates that many of the land areas north of ~45N are plagued by persistent cloudiness during fall, with most pixels in northern regions having either 1-3 or 4-8 clear days per month.

The January (middle) panel demonstrates the severity of problems in winter associated with clouds, low sun angle, and polar night. Many mid-latitude regions experience few clear days per month. Over eastern Asia, a significant area has median values of zero clear days per month, meaning that in at least half of the years analyzed there were no clear days in January. The orange colored region in the north includes those cells which experience polar night during any day in January, and is therefore excluded from this analysis. An interesting feature of this panel is the latitudinal band of white grid cells just south of the polar night region for which the median number of clear days in January is zero. This is not a true representation of cloudiness, but is rather an artifact of the problem with VIS interpretation posed by low sun angles.

The April (bottom) panel demonstrates how these problems are significantly diminished during spring, when more of the Northern Hemisphere skies are clear, allowing for more frequent VIS surface observations. Nevertheless, areas colored green in the figure still have only 8 clear days per month, meaning that frequent periods of persistent cloudiness for several days at a time are common over many regions even in spring. Thus, when developing time series of snow cover based on VIS imagery, the detection of snow onset in the fall, and snow ablation in the spring, may be delayed by several days or more depending on cloudiness.

Figure 4 shows an example of using non-parametric statistics to display climatological snow extent features. The median percentage of days that each IMS pixel is snow covered is shown for the fall (September through November) and spring (April through June) seasons. Some of the seasonal and spatial characteristics of snow variations can be demonstrated in this figure. For example, the frequency of snow coverage is much lower during fall, because snow over many regions tends to accumulate relatively late in the fall, with the largest monthly area of snow accumulation occurring in October. Snow is more frequent in spring because, while continental snow extent peaks in January or February, large areas remain snow covered well into June, with the month of most widespread ablation occurring in April.

The spatial patterns of snow extent displayed in figure 4 result primarily from temperature and precipitation patterns. Most obvious is the more frequent snow cover in mountainous regions. One also can detect the influence of large scale geographic features in regions where the contour lines depart from zonality (i.e. where contour lines are not parallel to lines of latitude). For example, this is evident as regions of low snow frequency over continental interiors which receive less moisture; and as regions of low frequency over northern Europe where circulation patterns in the North Atlantic Ocean maintain higher European temperatures than over comparable latitudes in the Asian interior. Note that IMS, in contrast to MODIS, provides snow information at each grid point every day (as is required for operational forecasting purposes) even where clouds are present, whether the information is obtained from ancillary data sources or simply assuming persistence from the most recent cloud-free observation.

The final example is from the MODIS monthly mean CMG 0.05 degree product (figure 5), which has five times finer spatial resolution than the 0.25 degree product shown in figure 3. Figure 5 includes the same number of grid points in both longitude and latitude directions as figure 3, but covers a much smaller region (from Alaska to north-central Canada). The October (top) and May (bottom) panels demonstrate how both the onset and ablation of snow are affected by geography. The cold northern regions are snow covered more frequently than the dry continental interiors. The maritime influence of the Pacific Ocean results in lower snow frequencies (due to higher temperatures) over southwestern Alaska; while north and east of the Gulf of Alaska, frequent storm and frontal passages transport copious moisture into the steep, high elevation mountain range, resulting in frequent snowfall and persistent (and deep) snow cover. The numerous missing observations in the winter (middle) panel demonstrate, again, the problem with VIS snow observations during polar night and at low sun angle.

5. Discussion

Information about terrestrial snow cover from satellites is available since the late 1960s, making the documentation of hemispheric-scale snow extent one of the longest remotely-sensed environmental records. The information available historically as well as from the new generation of satellite products have proven useful in documenting snow variations for use as an index of climate variation, as well as for investigating the role of snow in the climate system. In an era of rapid and dramatic cryospheric changes, continued monitoring of snow is a priority for weather and climate prediction as well as for water resource management. Numerous opportunities exist for applications using satellite based snow observations, as well as for the development of more accurate remotely sensed snow products.

One major application is the use of snow observations to calibrate more accurate representations of snow in climate models (Roesch et al. 2001; Slater and others 2001). A major challenge in climate modeling is the quantification of the snow-albedo feedback which is expected to play a major role in determining the magnitude and spatial characteristics of climate change. Several studies (Dery and Brown 2007; Qu and Hall 2007) point out a huge discrepancy between the magnitudes of the snow-albedo feedbacks in different models, which are at least partially responsible for the wide spread in twenty-first century snow predictions (Frei and Gong 2005; Raisanen 2007). Land surface routines used in Global Climate Models (GCMs) have not yet been refined to the point of including all the processes associated with high latitude snow variations such as blowing snow, snow pack metamorphic processes, and vegetation interactions (Pomeroy et al. 2007). Vegetation changes can significantly modulate the response of snow cover to climatic changes (Sturm et al. 2005). Thus, the availability of accurate snow information for the calibration and validation of improved snow models is vital for reducing uncertainties in climate change predictions.

Another application of snow observations is to identify and evaluate snow’s impact on atmospheric circulation. This area of research has a long history as suggested by the number of review articles over the years (Walsh 1984; Cohen 1994; Barry 2002; Barry et al. 2007), studies of the possible influence of snow on monsoon systems (Hahn and Shukla 1976; Dey and Kumar 1983; Barnett et al. 1988; Kripalani et al. 1996; Sankar-Rao et al. 1996; Bamzai and Shukla 1999; Bamzai and Marx 2000; Ye and Bao 2001; Hawkins et al. 2002; Robock et al. 2003; Ye et al. 2005), as well as other recent studies (Clark and Serreze 2000; Ye 2000; 2001; Dery et al. 2005; Elgundi et al. 2005; Grundstein et al. 2005; Ge and Gong 2008a; Klingaman et al. 2008). One fascinating and current branch of this field of study has identified the influence of north Asian autumn snow cover on the dominant pattern of winter, Northern Hemisphere atmospheric circulation (the AO or NAO). A number of authors have identified such an impact in both emipirical and modeling studies (Gong et al. 2003; Saito and Cohen 2003; Cohen et al. 2007; Fletcher et al. 2007), which is attributed to the effect of snow-modulated surface conditions over Siberia during fall on long wave circulation patterns in the overlying troposphere; the subsequent propagation of these wave anomalies vertically into the stratosphere and horizontally over the North Atlantic Ocean; and downward propagation of these impacts into the troposphere in winter. One recent study indicates that GCMs are not sufficiently sensitive to one or more of the myriad of processes responsible for this teleconnection, and are therefore unable to simulate this feedback unless the simulations are artificially forced with extremely anomalous snow cover (Hardiman and Kushner 2008). This has implications for climate predictions across the Northern Hemisphere, even far from snowy regions.

Despite the recent technological advances discussed here, opportunities remain for the development of improved snow products. For example, improvements can be made with regards to the retrieval of snow amount from PMW sensors (Tedesco et al. 2004), the refinement of snow extent estimates from VIS sensors (Parajka and Bloschl 2008), and the estimation of sub-grid scale information. One promising avenue is to refine our abilities to combine products (see section 3.5 and Kelly et al. (2004). The IMS product is an example of such a product that is not completely automated. Tait et al. (2000) provide a helpful review, and describe a prototype of a fully automated product that includes station observations as well as both visible and microwave retrievals. Tedesco and Miller (2007) explore the relative merits of active and passive microwave retrievals, using MODIS as their reference "truth." Although, overall, passive is superior to active, they find that over certain regions active retrievals can provide additional information. A number of researchers are investigating the potential for finer scale information on snow extent or amount (Salomonson and Appel 2004; Derksen et al. 2005), snow melt (Wang et al. 2008), as well as on snow pack properties (Nolin and Dozier 2000; Rango et al. 2000; Schmugge et al. 2002; Painter et al. 2003; Painter and Dozier 2004; Kinar and Pomeroy 2007; Dozier et al. 2008).

Thus, a number of research areas that have implications for climate change detection and attribution require the development and improvement of snow observations. In light of the decreasing number of *in situ* observations in recent years, and remaining shortcomings and discrepancies in snow products, integrated remotely-sensed snow observations offer great opportunities and challenges in the years to come.

Acknowledgements: The author began work on this article while on sabbatical at the Climate Research Division of Environment Canada in Downsview, ON, and would like to thank his colleagues there for their graciousness in hosting him. These include Chris Derksen, Anne Walker, Ross Brown, Libo Wang, Murray MacKay, Arvids Silis, Peter Toose, Francis Zwiers, and numerous others. I would also like to thank the following for helpful comments on early versions of this manuscript: …

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Figure Captions

Figure 1. Aerial view of open canopy boreal forest in northern Northwest Territories, Canada. The VIS surface brightness perceived from a remote viewpoint depends on the characteristics of the overlying vegetation, slope, aspect, insolation and viewing angles, image footprint size, and presence of lake ice. Photo by A. Frei, April, 2008.

Figure 2. Depth hoar conglomerate taken from the bottom of a snow pack in Northern Northwest Territories. The picture is approximately the size of a hand. Large crystals develop due to metamorphic processes in the snow. Sample taken by A. Silis, Environment Canada. Photo by A. Frei, April 2008.

Figure 3. Median number of clear days per month with MODIS-defined cloud cover <= 10% per cell for October (top), January (middle), and May (bottom). The temporal domain includes the 2000-2001 through 2007-2008 snow seasons. The spatial domain includes the Northern Hemisphere north of 20N. Ranges of values are color coded: 0 days (white); 1-3 days (magenta); 4-8 days (blue); >8 days (green); no data for one or more days (orange). Derived from the 0.25 x 0.25 (latitude x longitude) daily Climate Modeler's Grid (CMG) version of the data set, these panels are each 1440 x 280 grid cells.

Figure 4a. Median monthly snow extent (percentage of days each pixel is snow covered) for fall (September-October-November) from IMS. The temporal domain includes the 1999-2000 through 2007-2008 snow seasons. The spatial domain includes the Northern Hemisphere north of

20N. Ranges of values are color coded: 0% (white); 1-10% (magenta); 11-25% (blue); 26-50% (dark green); 50-75% (light green); 75-90% (yellow); 90-100% (orange). Derived from the 24km resolution version of the data set. Greenland is excluded from this analysis.

Figure 4b. Same as figure 4a, except for the spring (April-May-June) season.

Figure 5. Mean monthly snow extent (percentage of days each pixel is snow covered) for October (top), January (middle), and May (bottom) from MODIS. The temporal domain includes the 2000-2001 through 2007-2008 snow seasons. The spatial domain includes Alaska and northwestern Canada. Ranges of values are color coded: 0% (green); 1-25% (magenta); 26-50% (blue); 51-75% (yellow); 76-100% (orange); no data due to clouds or polar night for one or more days (white). Derived from the 0.05 x 0.05 (latitude x longitude) monthly Climate Modeler's Grid (CMG) version of the data set, these panels are each 1440 x 280 grid cells.

Figure 1. Aerial view of open canopy boreal forest in northern Northwest Territories, Canada. The VIS surface brightness perceived from a remote viewpoint depends on the characteristics of the overlying vegetation, slope, aspect, insolation and viewing angles, image footprint size, and presence of lake ice. Photo by A. Frei, April, 2008.

Figure 2. Depth hoar conglomerate taken from the bottom of a snow pack in Northern Northwest Territories. The picture is approximately the size of a hand. Large crystals develop due to metamorphic processes in the snow. Sample taken by A. Silis, Environment Canada. Photo by A. Frei, April 2008.

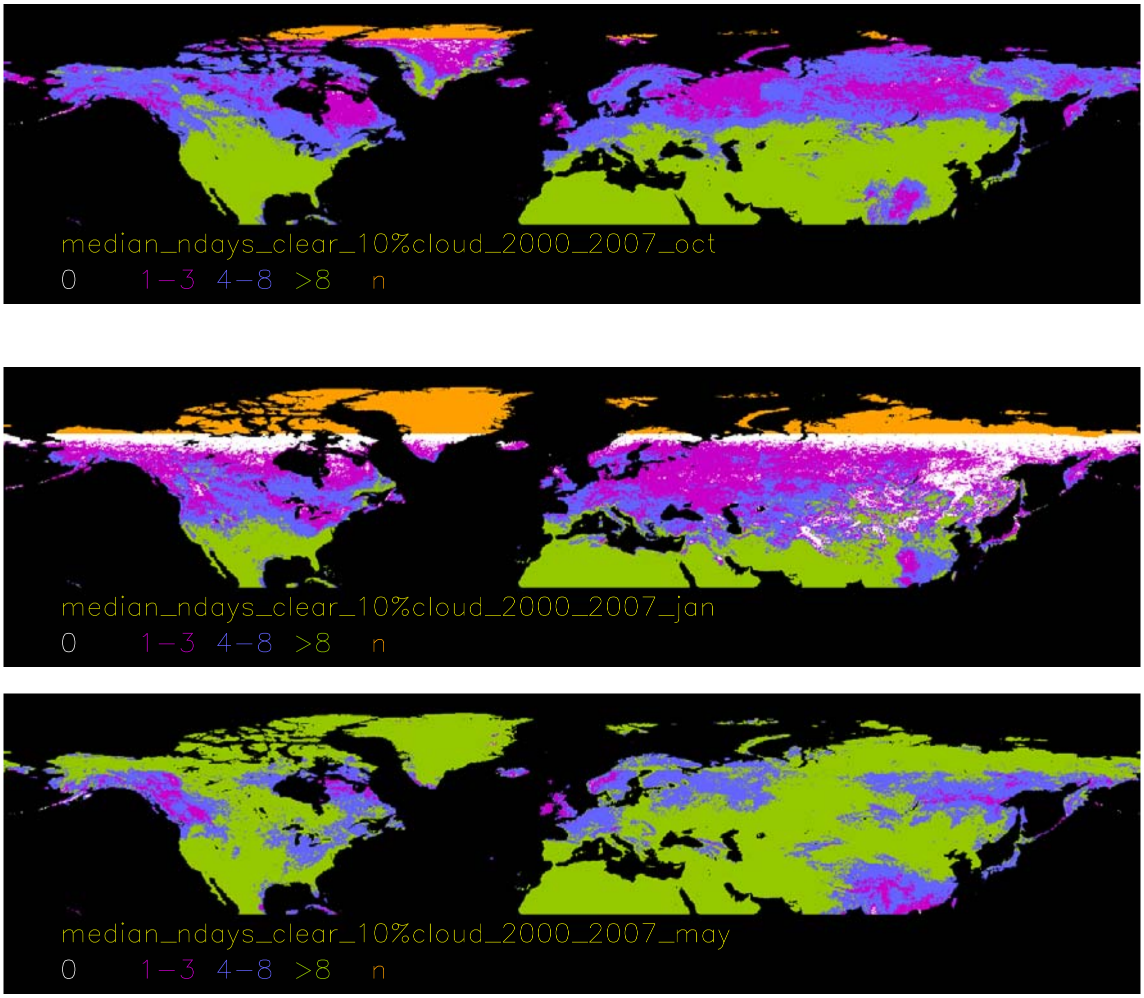

Figure 3. Median number of clear days per month with MODIS-defined cloud cover <= 10% per cell for October (top), January (middle), and May (bottom). The temporal domain includes the 2000-2001 through 2007-2008 snow seasons. The spatial domain includes the Northern Hemisphere north of 20N. Ranges of values are color coded: 0 days (white); 1-3 days (magenta); 4-8 days (blue); >8 days (green); no data for one or more days (orange). Derived from the 0.25 x 0.25 (latitude x longitude) daily Climate Modeler's Grid (CMG) version of the data set, these panels are each 1440 x 280 grid cells.

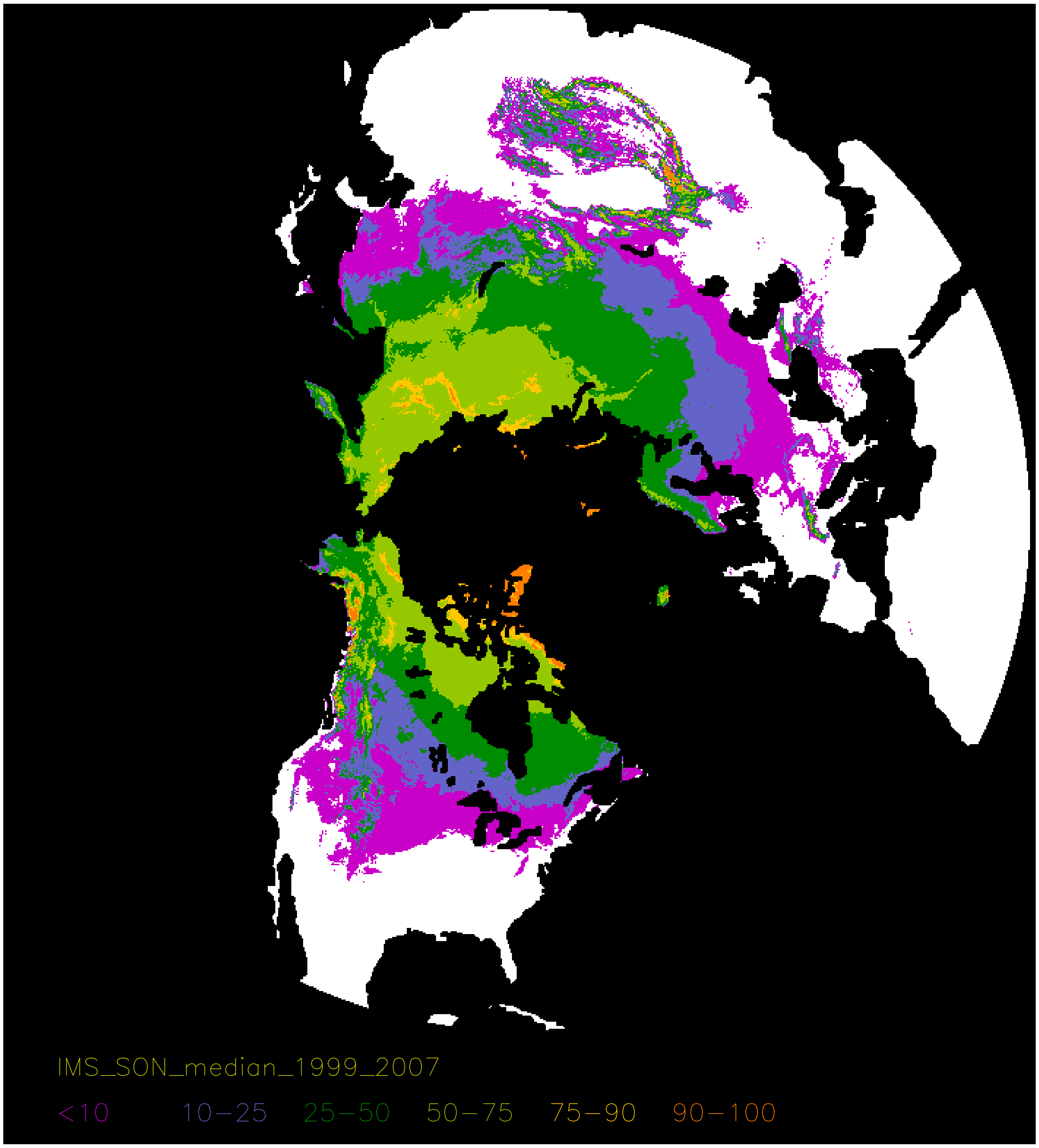

Figure 4a. Median monthly snow extent (percentage of days each pixel is snow covered) for fall (September-October-November) from IMS. The temporal domain includes the 1999-2000 through 2007-2008 snow seasons. The spatial domain includes the Northern Hemisphere north of 20N. Ranges of values are color coded: 0% (white); 1-10% (magenta); 11-25% (blue); 26-50% (dark green); 50-75% (light green); 75-90% (yellow); 90-100% (orange). Derived from the 24km resolution version of the data set. Greenland is excluded from this analysis.

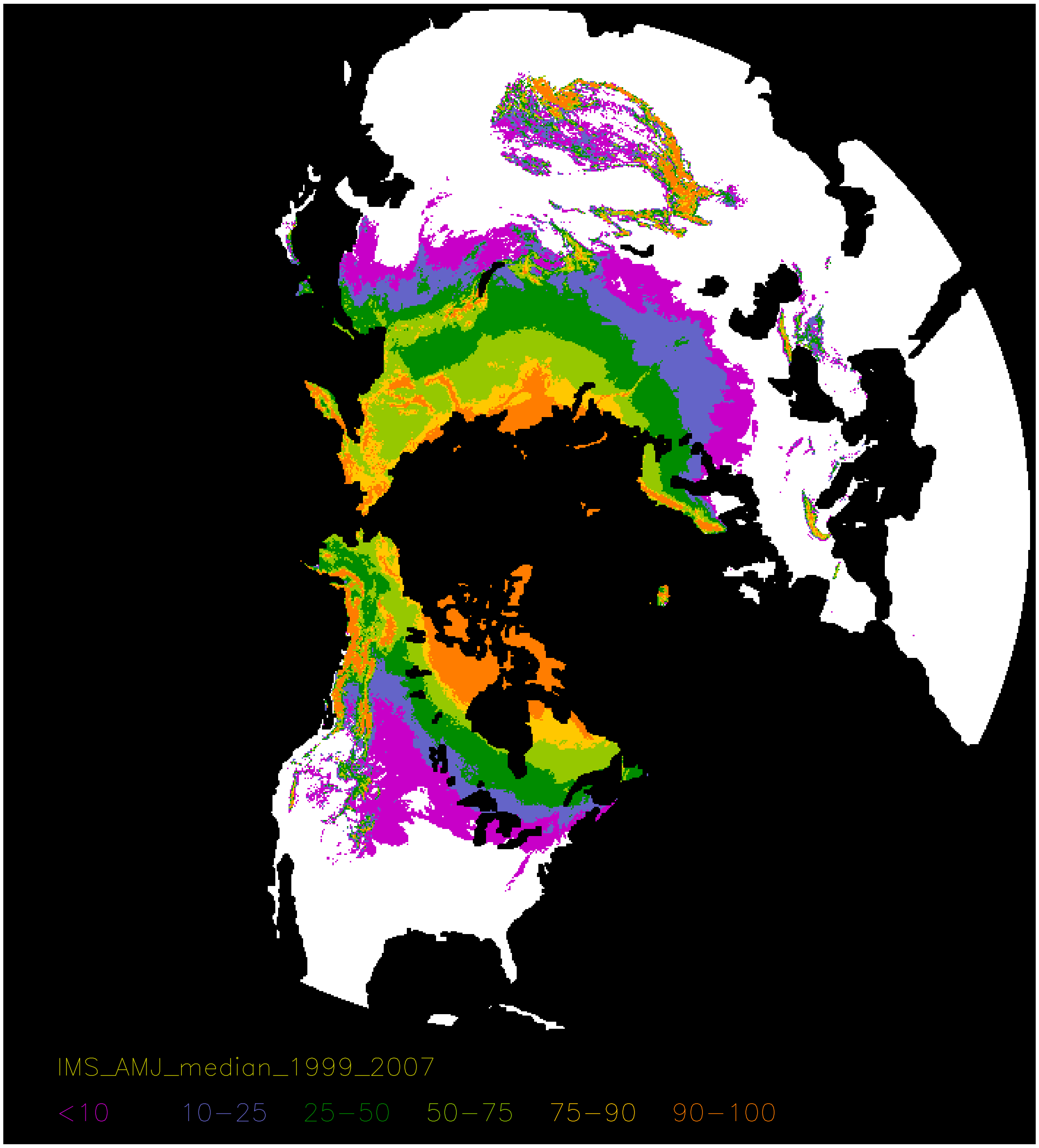

Figure 4b. Same as figure 4a, except for the spring (April-May-June) season.

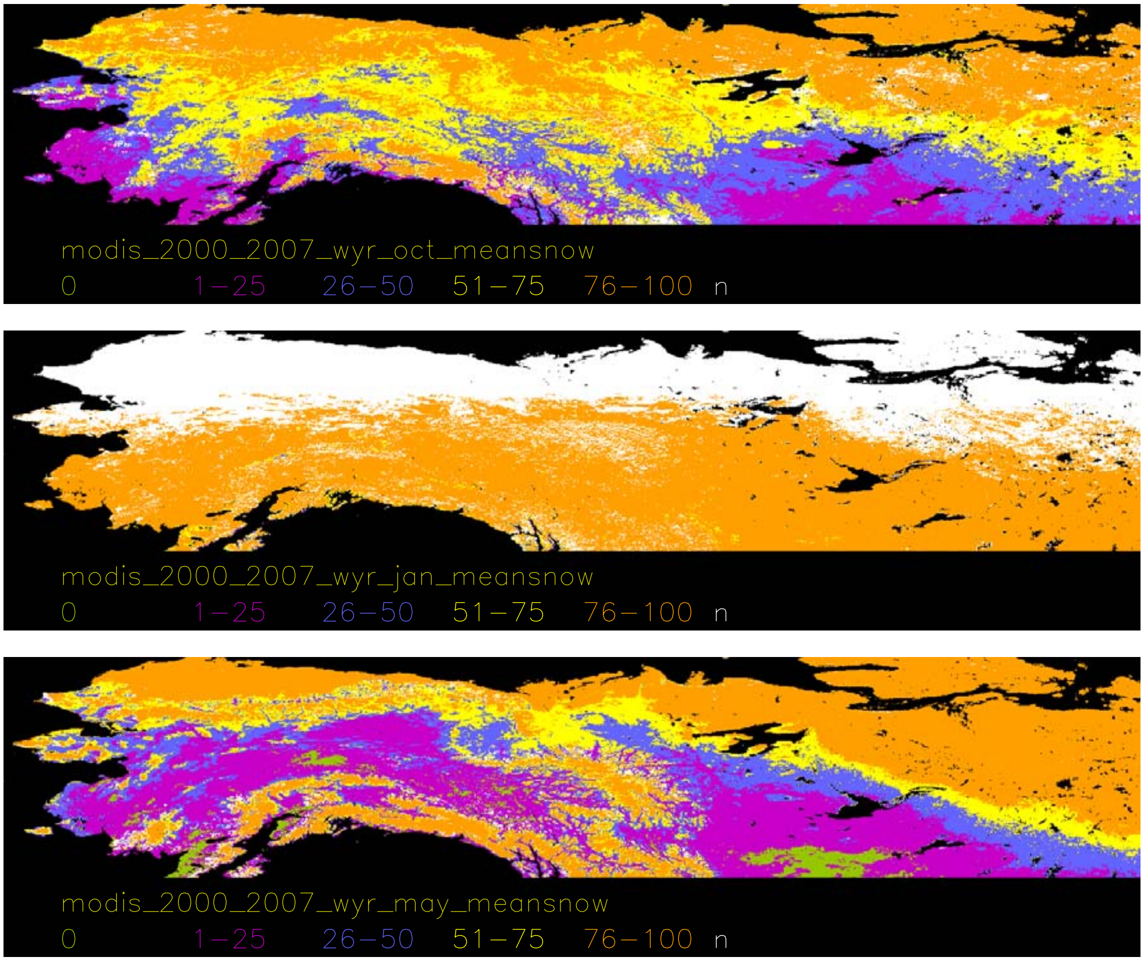

Figure 5. Mean monthly snow extent (percentage of days each pixel is snow covered) for October (top), January (middle), and May (bottom) from MODIS. The temporal domain includes the 2000-2001 through 2007-2008 snow seasons. The spatial domain includes Alaska and northwestern Canada. Ranges of values are color coded: 0% (green); 1-25% (magenta); 26-50% (blue); 51-75% (yellow); 76-100% (orange); no data due to clouds or polar night for one or more days (white). Derived from the 0.05 x 0.05 (latitude x longitude) monthly Climate Modeler's Grid (CMG) version of the data set, these panels are each 1440 x 280 grid cells.

Table 1. Some Helpful URLs for obtaining and visualizing snow data

Site Description	**URL**
U.S. National Snow and Ice Data Center (NSIDC)	nsidc.org
State of the Canadian Cryosphere (SOCC)	www.socc.ca/index_intro_e.cfm
Canadian Cryosphere Information Network (CCIN)	www.ccin.ca
MODIS	modis-snow-ice.gsfc.nasa.gov/modis.htm
IMS	www.natice.noaa.gov/ims
National Operational Hydrologic Remote Sensing Center (NOHRSC)	www.nohrsc.nws.gov/
Rutgers University Global Snow Lab (GSL)	climate.rutgers.edu/snowcover/