Chapter: Remote sensing of Snow cover, Section: Snow extent, M. Tedesco (ed.)

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Introduction

Snow was easily identified in the first image obtained from the Television Infrared Operational Satellite-1 (TIROS-1) weather satellite in 1960 because the high albedo of snow presents a good contrast with most other natural surfaces. Subsequently, the National Oceanic and Atmospheric Administration (NOAA) began to map snow using satellite-borne instruments in 1966. Snow plays an important role in the Earth's energy balance, causing more solar radiation to be reflected back into space as compared to most snow-free surfaces. Seasonal snow cover also provides a critical water resource through meltwater emanating from rivers that originate from high-mountain areas such as the Tibetan Plateau. Meltwater from mountain snow packs flows to some of the world's most densely-populated areas such as Southeast Asia, benefiting over 1 billion people (Immerzeel et al., 2010).

In this section, we provide a brief overview of the remote sensing of snow cover using visible and near-infrared (VNIR) and passive-microwave (PM) data. Snow can be mapped using the microwave part of the electromagnetic spectrum, even in darkness and through cloud cover, but at a coarser spatial resolution than when using VNIR data. Fusing VNIR and PM algorithms to produce a blended product offers synergistic benefits. Snow-water equivalent (SWE), snow extent, and melt onset are important parameters for climate models and for the initialization of atmospheric forecasts at daily and seasonal time scales. Snowmelt data are also needed as input to hydrological models to improve flood control and irrigation management.

Visible / near-infrared snow products

In1966 NOAA began producing Northern Hemisphere weekly snow and ice cover analysis charts which were created manually using a combination of in-situ and satellite data (Matson and Wiesnet, 1981; Matson et al., 1986). Since 1997 the Interactive Multi-Sensor Snow and Ice Mapping System (IMS) has produced snow products daily at a spatial resolution of up to 4 km, utilizing data from various satellites and ground stations (Ramsay, 1998; Helfrich et al., 2007). The key feature that distinguishes IMS from other standard snow products is human involvement in the analysis. IMS analysts map snow extent across the globe every day regardless of the presence of clouds, for input as boundary conditions into weather forecasting models.

Snow-cover maps generated by the Rutgers University Global Snow Lab [http://climate.rutgers.edu/snowcover/] are considered a climate-data record; some inconsistencies were discovered in the early part of the data record (before 1972) and were corrected. The Rutgers snow maps, based on NOAA satellite data, constitutes a ~45-year record of snow-cover extent for the Northern Hemisphere, and is indeed used in many climate studies (e.g. Robinson et al., 1993; Frei and Robinson, 1999; Frei et al. 1999; Brown, 2000; Robinson and Frei, 2000; Déry and Brown, 2007; Brown et al., 2010; Brown and Robinson, 2011; Frei et al., in press).

The advent of the Landsat series of sensors beginning with the launch of Landsat-1 in 1972 heralded a new era of producing multispectral satellite images from which snow maps could be created at 80-m spatial resolution (Rango and Martinec, 1979). With Landsat data came the ability to create detailed basin-scale snow-cover maps when cloudcover permitted. Landsats-4 and -5 carried a Thematic Mapper (TM) sensor with 30-m resolution, and Landsat-7 carries an Enhanced Thematic Mapper Plus (ETM+) with spatial resolution of 30 m and the panchromatic band with a resolution of 15 m. Though the Landsat series has provided high-quality, scene-based snow maps, the 16- or 18-day repeat-pass interval of the Landsat satellites is not adequate for most snow-mapping requirements, especially during spring snowmelt.

In December 1999 NASA launched the Terra satellite as part of the Earth Observing System (EOS). The first of two Moderate Resolution Imaging Spectroradiometers (MODIS) was the flagship instrument of the five-instrument Terra payload. A second MODIS instrument was launched on the Aqua satellite in May of 2002. Since early 2000, snow cover has been mapped daily using MODIS data (Figure 1) with automated algorithms developed at Goddard Space Flight Center in Greenbelt, Maryland (http://modis-snow-ice.gsfc.nasa.gov) (Riggs et al., 2006; Hall and Riggs, 2007). The standard MODIS snow map products provide global, daily coverage at 500-m and 0.05° resolution, and include fractional snow cover (Salomonson and Appel, 2004) and a daily cloud-gap filled product (Hall et al., 2010). Daily snow albedo is also provided (Klein and Stroeve, 2002). Improvements to the algorithm are incorporated each time the entire dataset is reprocessed (Riggs et al., in press).

With more than 12 years of MODIS snow-cover maps now available, many time-series studies are being undertaken. For example, focusing on Southeast Asia, Immerzeel et al. (2009) used MODIS standard snow-cover maps to show a significant negative winter snow-cover trend in the Indus River basin, from 2000 – 2008 ; a similar trend from 2000 – 2006 was found in the western Himalaya region by Prasad and Singh (2007). Meltwater from snow in the mountains is extremely important in the Indus River basin for water resources. Using only seven years of MODIS snow-cover data, Pu et al. (2007) found large spatial variability between years in the amount of snow cover over the Tibetan Plateau, with a possible slight decrease in snow-cover over the time period from 2000 – 2006. With only 12 years of record, it is not possible to make meaningful statements regarding climate trends based solely on MODIS snow-cover data.

Passive microwave products

Historical PM 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 snow products from the two instruments exist (Armstrong and Brodzik, 2001; Derksen and Walker, 2003; Brodzik et al., 2007). The NASA EOS Aqua platform also provided science data from the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) from 2002 until the instrument failed in October 2011 (Kelly et al., 2003; Derksen et al., 2005; Tedesco et al., 2011), after outliving its expected lifetime by >3 years. PM imaging does not depend on the presence of sunlight. It is largely (but not completely) transmitted through non-precipitating clouds, offering the potential to estimate snow cover under conditions that preclude the acquisition of VNIR observations.

Snow is efficient at scattering microwave radiation emitted from the Earth's surface since snow grain dimensions are often similar to microwave wavelengths, resulting in a diminished signal measured at the satellite from snow-covered surfaces (Chang et al., 1976; Shanda et al., 1983; Matzler, 1994). Microwave scattering by ice crystals is frequency-dependent, enabling the use of two or more bands to estimate SWE (Chang et al., 1987; Grody and Basist, 1996), although other methods have been evaluated such as one based on the inversion of a snow emission model (e.g., Pulliainen and Hallikainen, 2001). A thorough discussion of the measurement of SWE from space appears elsewhere in this chapter.

Limitations to the monitoring of snow extent and SWE using PM sensors result from a variety of factors, including the presence of liquid water, ice lenses, grain size variations (such as resulting from depth hoar (Hall et al., 1986), and vertical heterogeneities within the snowpack (Chang et al. 1996; Foster et al., 1997 and 2005; Tedesco et al., 2005). Though these factors influence the measurement of SWE, near-surface moisture in the snow affects measurement of snow-covered area.

Due to the inherent difficulties and regional variations in the interpretation of PM signals, the production of a data set that is consistently accurate across all Northern Hemisphere regions requires either (1) a physical approach, which includes robust representations of snowpack processes and their parameterization in retrieval schemes (Pulliainen and Hallikainen, 2001), or (2) a regional approach, which includes regionally-tuned algorithms (Foster et al., 1997) that statistically represent regional snowpack processes but are not applicable in different snow accumulation regimes.

Blended VNIR / PM products

Data from different satellite instruments, ground observations and models can be combined to enhance information content about snow cover. A recent example of a blended product is the Air Force Weather Agency (AFWA) / National Aeronautics and Space Administration (NASA) Snow Algorithm (ANSA) blended, global snow product (Foster et al. 2011) that utilizes MODIS and AMSR-E (Kelly et al., 2003; Tedesco et al., 2011) standard data products (Figure 2). This blended product improves mapping of snow-cover extent, fractional-snow cover, SWE, the onset of snowmelt, and of actively melting snow covers (Foster et al., 2011). The blended-snow products are currently at 5- or 25-km resolution but the inherent resolution of the AMSR-E precludes the SWE or snow cover (during cloudy periods) being finer than 25 km, though snow cover can be mapped by MODIS at 5 km (or finer) resolution under clear skies. The product accuracy has been assessed in the lower Great Lakes region of the U.S. (Hall et al., 2012), in the mountains in Turkey (Akyurek et al., 2011), and in Finland (Casey et al., 2009). The confidence for mapping snow cover extent is greater with the MODIS product than with the microwave product when cloud-free MODIS observations are available, therefore the MODIS product is used as the default for detecting snow cover. Other examples of combined products include the Canadian Meteorological Centre snow product (Brasnett, 1999), GlobSnow (Pulliainen, 2006; Takala et al., in press), and others (Tait et al., 2000; Derksen et al., 2004; Biancamaria et al., 2011).

Satellite snow extent as input to hydrological models

Over the past decade, there have been rapid developments in land surface and hydrological modeling. With the amplification of climate change in polar (Serreze and Francis, 2006; Déry and Brown, 2007) and alpine (Bradley et al., 2004) regions driven in part by the snow/ice-albedo feedback, there is renewed interest in improving the representation of snow inland surface and hydrological models. To this end, the assimilation of remotely-sensed snow cover extent by numerical models provides a strong constraint in retrospective or (near) real-time simulations of land surface and hydrological processes at the watershed- to continental-scale.

For example, Déry et al. (2005) improved their snow and streamflow simulations for the Kuparuk River Basin of Alaska's North Slope by constraining the Catchment-based Land Surface Model (CLSM) (Koster et al., 2000) with snow areal depletion curves from MODIS. Andreadis and Lettenmaier (2006) used an Ensemble Kalman Filter (EnKF) to assimilate MODIS snow cover extent data into the Variable Infiltration Capacity (VIC) macroscale hydrological model with application to the Snake River Basin of the western United States. Sun et al. (2004) demonstrated the feasibility of using an EnKF to assimilate remotely-sensed snow cover extent data for simulations of continental-scale land surface conditions. MODIS snow-cover products have also been used to develop statistical models that predict the timing of the spring freshet for the Quesnel River of western Canada (Figure 3) (Tong et al., 2009) and for the Upper Euphrates River of Turkey (Akyurek et al., 2011). Other recent efforts have explored the potential to assimilate fractional snow coverage information from MODIS to reconstruct SWE in Sierra Nevada watersheds (Rice et al., 2011) and for snowmelt energy balance modeling in Alaska (Homan et al., 2011).

Rodell and Houser (2004) used MODIS snow-cover maps in the Mosaic land surface model driven by the NASA/NOAA Global Land Data Assimilation System to directly correct SWE fields when there was a mismatch between observations and model predictions. A suite of data-assimilation experiments using the Land Information System (LIS) framework of Kumar et al. (2008) was also performed. Output from this simulation was compared to that from a control (not updated) simulation, and both were assessed using a conventional snow-cover product and data from ground-based observation networks over the continental U.S. Output from the updated simulations generally displayed more accurate snow coverage and compared more favorably with in-situ snow time series than did the models without assimilation of MODIS snow-cover maps as reported in Hall et al. (2010).

Future prospects suggest techniques for snow cover data assimilation are likely to be improved and optimized, allowing (near) real-time land surface and hydrological simulations. This will provide enhanced modeling of potential flooding events caused by rapid snowmelt. Continued improvements in remotely sensed snow cover products and numerical models ensure the expanding use of both to accurately depict land surface and hydrological processes at the watershed- to continental-scale.

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Figures:

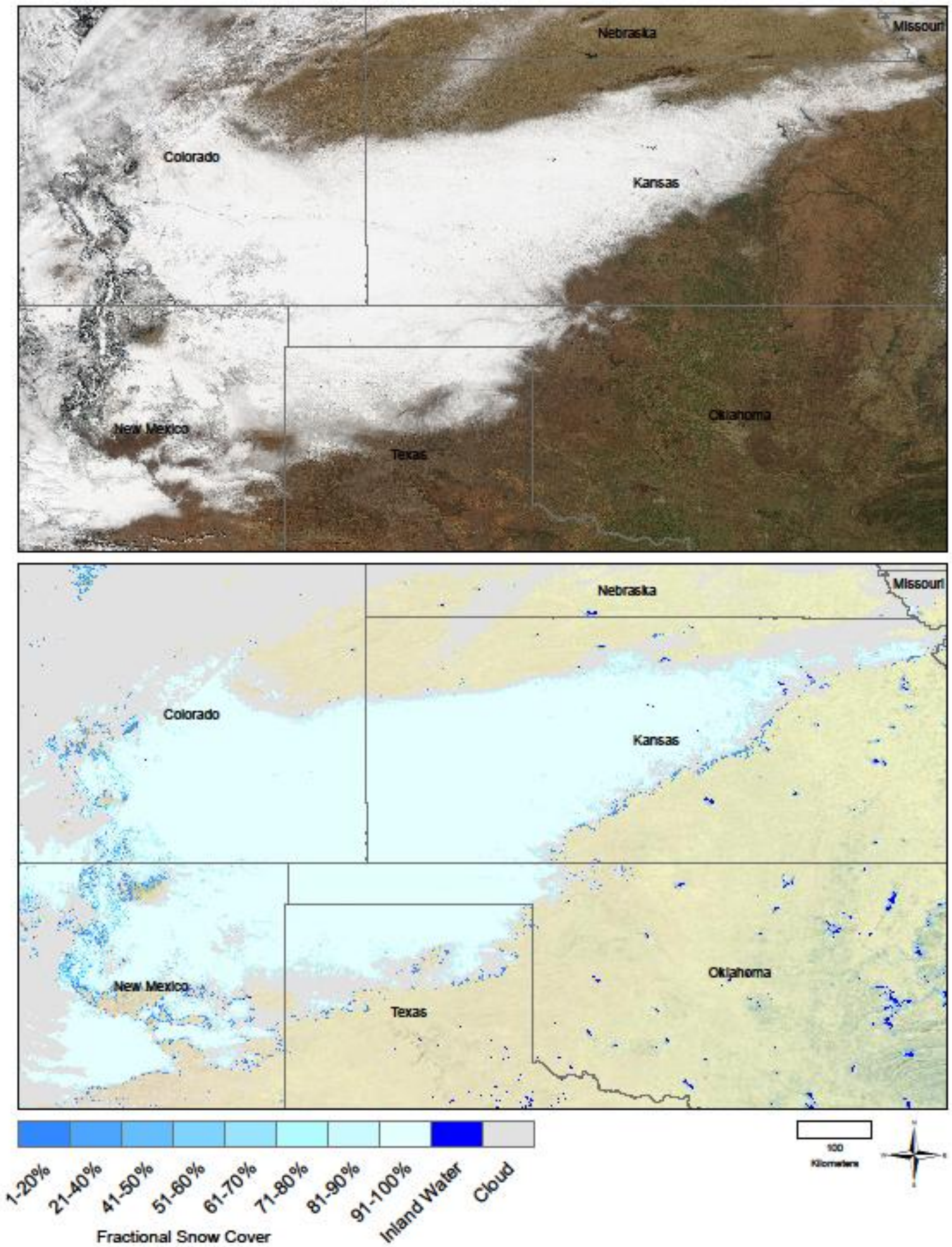

Figure 1.MODIS Aqua image (top) and snow map (bottom) acquired on 23 December 2011.

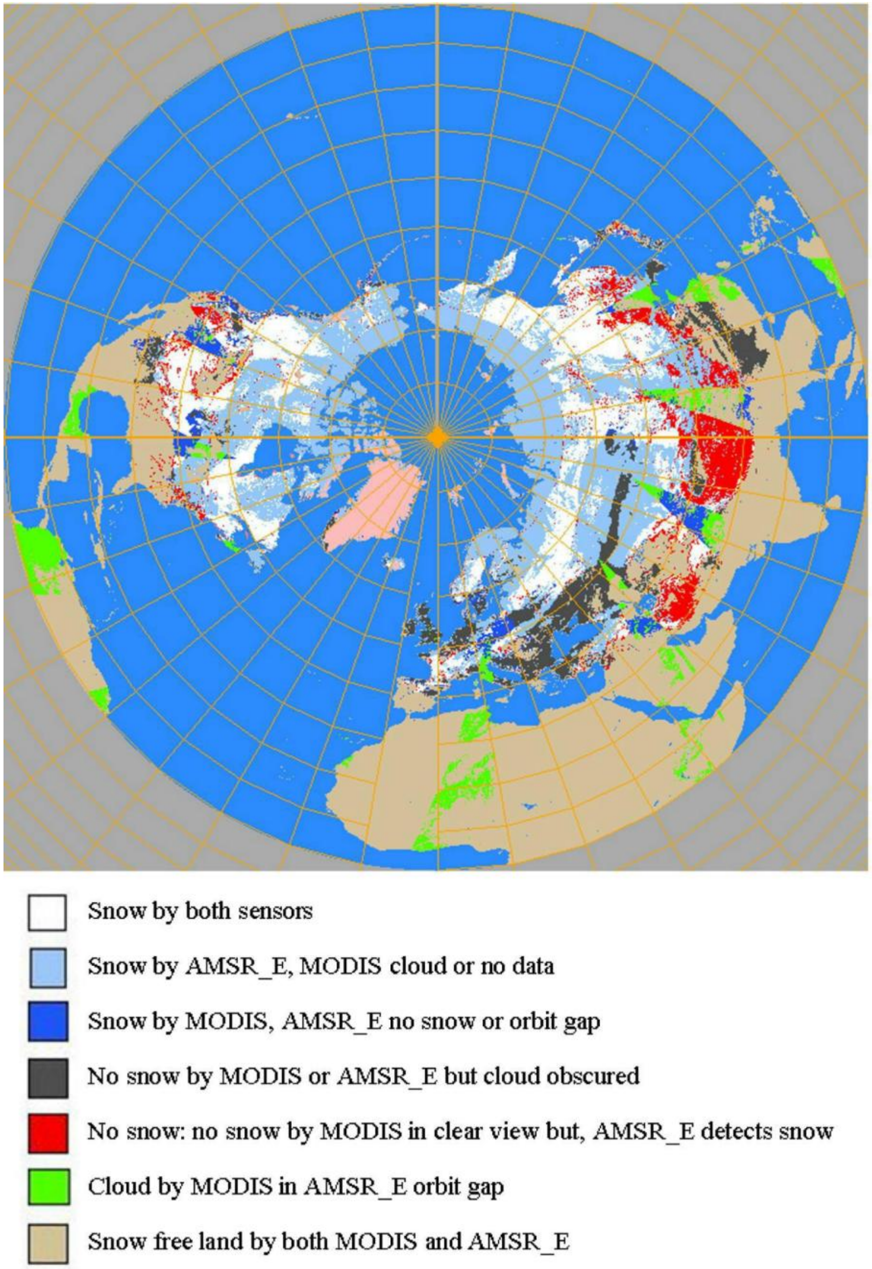

Figure 2

Figure 2. ANSA blended-snow product for 26 January 2007 in the Lambert Azimuthal polar projection (from Foster et al., 2011).

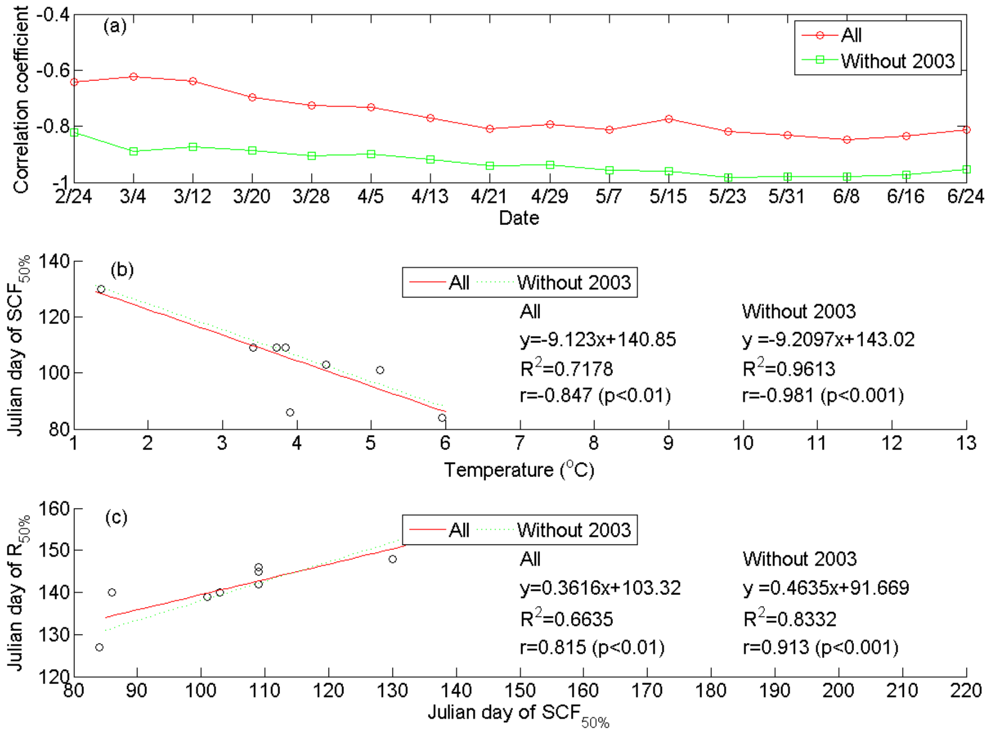

Figure 3. (a) Correlation coefficients and (b) scatter plots between average air temperature within different periods and Julian day of a snow cover fraction of 50% ($SCF_{50\%}$), and (c) between Julian day of $SCF_{50\%}$ and normalized accumulated runoff ($R_{50\%}$) during snow ablation seasons 2000-2007 in the Quesnel River Basin(QRB) of western Canada (Tong et al. 2009). The scatter plots reveal an inverse linear relationship between spring air temperatures and the date for which half of the QRB remains snow covered, with the latter preceding the freshet by about a month.