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Estimating northern hemisphere snow water equivalent for climate research through assimilation of space-borne radiometer data and ground-based measurements

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ABSTRACT

The key variable describing global seasonal snow cover is snow water equivalent (SWE). However, reliable information on the hemispheric scale variability of SWE is lacking because traditional methods such as interpolation of ground-based measurements and stand-alone algorithms applied to space-borne observations are highly uncertain with respect to the spatial distribution of snow mass and its evolution. In this paper, an algorithm assimilating synoptic weather station data on snow depth with satellite passive microwave radiometer data is applied to produce a 30-year-long time-series of seasonal SWE for the northern hemisphere. This data set is validated using independent SWE reference data from Russia, the former Soviet Union, Finland and Canada. The validation of SWE time-series indicates overall strong retrieval performance with root mean square errors below 40 mm for cases when SWE <150 mm. Retrieval uncertainty increases when SWE is above this threshold. The SWE estimates are also compared with results obtained by a typical stand-alone satellite passive microwave algorithm. This comparison demonstrates the benefits of the newly developed assimilation approach. Additionally, the trends and inter-annual variability of northern hemisphere snow mass during the era of satellite passive microwave measurements are shown.

1. Introduction

The seasonal snow cover of the northern hemisphere has a major effect on climate, the water cycle, and biogeochemical cycling. The winter season surface albedo in northern land areas is controlled by snow extent, as the difference in the reflectance of snow and snow-free ground is high. Terrestrial run-off is dominated by snow and glacier mel at mid- and high latitudes and high elevation areas across Eurasia and North America regions (Barnett et al., 2005). The carbon balance at northern latitudes is influenced by the length of the snow season, particularly the timing of snow melt. The respiration of soil, as well as the thickness of the seasonally thawing active layer in permafrost areas is related to the timing of snow melt as well as the seasonal evolution of snow mass (Grogan and Jonasson, 2006). Improved information on snow cover, therefore, provides a tool to further investigate climatological, hydrological, and greenhouse gas processes (such as CO2 and CH4) at middle and high latitudes.

Snow water equivalent (SWE) is the product of snow depth (SD) and snow density (ρ) and represents the resulting water column should a snowpack melt in place. For the purposes of climate research, SWE or SD can be estimated using the interpolation of ground-based observations (for example, Dyer and Mote, 2006; Kitaev et al., 2002) although these interpolation methods can lack temporal resolution and are negatively impacted by the sparse spatial coverage of observations particularly in northern regions. Improvements to interpolation techniques by applying various kriging approaches have been suggested e.g. by Hudson and Wackernagel (1994), Erxleben et al. (2002) and Brown and Tapsoba, (2007). Information on snow cover extent (SE) and SWE/SD can be also obtained from atmospheric reanalysis datasets (for example, as described in Brown et al., 2010) or by assimilating data from different sources. For example, the Canadian Meteorological Centre (CMC) produces a daily gridded global snow depth analysis by combining all available snow observations with a simple snow model (Brasnett, 1999) while the National Weather Service produces daily snow information for the continental United States and parts of southern Canada through a snow analysis system that also combines observations with a snow model (Carroll et al., 2006; Rutter et al., 2008). The point-wise nature of in situ measurements, however, remains in these products. For instance, the CMC analysis has a tendency

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towards early loss of snow cover in the spring due to the shallow bias of snow depths reported from observing sites that tend to be located in clearings (Brown et al., 2010).

For climate applications, long time series are needed in order to produce meaningful statistics on trends and variability. Satellite passive microwave data are commonly used for the retrieval of snow information because of a wide swath (which produces frequent repeat coverage), insensitivity to illumination and decreased influence of clouds, multi-frequency response to the presence of snow on land, and of the availability of a continuous time series that extends back to 1978 (Table 1). The limiting factor for the climatological use of passive microwave derived SWE information is the high uncertainty in SWE and SD retrievals at the hemispheric scale both in terms of systematic and random error (i.e. Kelly et al., 2003). Most passive microwave SWE retrieval algorithms exploit the negative spectral gradient between a measurement frequency sensitive to snow grain volume scattering (~37 GHz) and a measurement frequency considered largely insensitive to snow (~19 GHz; Chang et al., 1987, 1990; Goodison and Walker, 1995; Kelly et al., 2003; Mognard and Josberger, 2002; Pulliainen, 2006). The larger the difference between brightness temperature (T_B) measurements at these two frequencies, the higher the estimate of SWE.

The algorithm originally proposed by Chang et al. (1987) estimated snow depth from horizontally polarized Scanning Multichannel Microwave Radiometer (SMMR) measurements. The algorithm has a physical basis — the parameterization was based on forward simulations with a radiative transfer model. This algorithm has been widely adopted for estimating SWE from different space-borne microwave radiometers (Armstrong and Brodzik, 2001) including modifications to account for variable surface and snowpack characteristics (Foster et al., 1997, 1991; Tait, 1998). Armstrong and Brodzik (2002) compared the performance of several traditional algorithms (Chang et al., 1987, Goodison, 1989; Nagler and Rott, 1992; Rott et al., 1991) and found large errors at the hemispheric scale when compared to available in situ data. The general tendency was for the algorithms to underestimate SWE, especially under deep snow conditions, while algorithm performance broke down completely under wet snow conditions. Large errors (approaching 100%) were reported in the hemispheric application of T_B difference algorithms by Kelly et al. (2003) with lake-rich tundra areas proving especially problematic for this approach (Derksen et al., 2010; Koenig and Forster, 2004). When applied regionally, land cover specific T_B difference algorithms have reported lower uncertainties (Derksen, 2008; Derksen et al., 2010, 2005), although consistent underestimation of SWE occurs in heavily forested areas and the accuracy characteristics are subject to inter-seasonal variability due to changes in snowpack physical properties (e.g. when ice lenses are present).

Table 1
Summary of satellite passive microwave sensors.

Platform	Sensor	Frequency (GHz)	Swatch width (km)	Incidence angle (degrees)	Field of view (km)
Nimbus-7 (1987)	SMMR	6.6	800	50.3	95 × 148
		10.69			70 × 109
		18.0			43 × 68
		21.0			36 × 56
		37.0			18 × 27
DMSP F8 to F-15 (1987)	SSM/I	19.4	1400	53	45 × 70
		22.2			40 × 60
		37.0			30 × 38
		85.5			14 × 16
Aqua (2002)	AMSR-E	6.9	1445	54.8	43 × 75
		10.7			29 × 51
		18.7			16 × 27
		23.8			18 × 32
		36.5			8 × 14
		89.0			4 × 6

A different approach is the use of theoretical or semi-empirical radiative transfer models for snow cover, coupled with atmospheric and vegetation models, to simulate microwave emission and inversely calculate snow characteristics from satellite measurements (e.g. Pulliainen et al., 1999, Wiesmann and Matzler, 1999). The more complicated models are computationally expensive and require precise ancillary data in order to give accurate predictions (i.e. Durand and Margulis, 2006). These factors restrict their operational applicability on a global scale.

Improving the performance of passive microwave retrieval algorithms by means of data assimilation has also been investigated. Pulliainen (2006) presents an assimilation technique which weighs passive microwave data combined with a semi-empirical radiative transfer model, and prior snow information from ground measurements, with their respective statistical uncertainties. This technique successfully reduced systematic errors related to the saturation of T_B difference algorithms when SWE exceeds approximately 120 mm. In regional studies by Pulliainen and Hallikainen (2001) and Pulliainen (2006) unbiased RMSE values of 15 to 40 mm were achieved when compared to in situ data.

In this study, we implement the methodology of Pulliainen (2006) across the northern hemisphere to exploit the benefits of both conventional measurements and passive microwave data to produce a Climate Data Record (CDR) for SWE. The approach of Pulliainen (2006) is enhanced by integrating the methodologies of Hall et al. (2002) and Takala et al. (2009) to discriminate the region of dry seasonal snow cover and estimate the date the land surface becomes snow free. As it is based on the assimilation of ground-based synoptic observations of SD and space-borne radiometer data, benefits of the approach are that SWE (and SD) estimates are produced for wet snow cover, and statistical error variance estimates are provided for every individual SWE estimate (produced on a grid with a resolution of 25 km).

Because this study is concerned with the production of snow cover information for climate trend analyses and for the evaluation of climate models, an essential aspect is the validation of the 30 year SWE time series. Typically, snow course observations representative for coarse grid cell evaluation are lacking at a continental scale over long time periods. In this study, however, we utilize the Russian INTAS-SCCONE (International Association for the promotion of co-operation with scientists from the New Independent States of the former Soviet Union — Snow Cover Changes Over Northern Eurasia) snow surveys as independent reference data for validation. These data are available throughout the former Soviet Union between 1980 and 2000, with observations from a total of 1292 snow courses. The Russian sites are complemented by Finnish snow surveys including SWE observations from years 2005–2008, and Canadian research data sets on SWE for tundra, boreal forest, and prairie environments also for 2005–2008.

The specific objectives of this study are to:

1. provide an overview of the SWE retrieval technique (based on Pulliainen, 2006) now applied across the northern Hemisphere within the European Space Agency (ESA) GlobSnow project (Luojus et al. 2010).
2. assess these SWE retrievals against reference SWE measurements and compare the retrieval accuracy to other available algorithms.
3. develop a climatological time series (1979 to 2010) of northern hemisphere SWE (and total/continental snow mass).

2. Methods and data

2.1. Algorithm overview

The methodology for SWE retrieval employed in this study utilizes a Bayesian non-linear iterative assimilation approach first described