SNOWTOOLS: RESEARCH AND DEVELOPMENT OF METHODS SUPPORTING NEW SNOW PRODUCTS

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ABSTRACT

The main objective of the work described here has been to identify what type of research and development that is needed to support the user needs for new snow parameter information derived from optical, synthetic aperture radar (SAR), passive microwave radiometer (PMR) and multisensor remote sensing data. A review of both existing algorithms and available and near-future has been done. Snow products have been defined based on a user requirement investigation. The products cover the parameters snow cover area, snow water equivalent, snow surface albedo, snow depth, snow surface temperature, liquid water within the snowpack and snow surface wetness. The snow product specification has been used as a "driving force" to identify the type of methodology which needs to be developed.

INTRODUCTION

Monitoring of the seasonal snow is important for several purposes. In northern regions, the snow may represent more than half the annual runoff, putting specific demands on the models and other tools employed in managing this water resource. Risk of flooding enhances this demand, both in areas with stable winter coverage, and in areas only occasionally covered with snow. Snow is also an important natural resource for the hydropower industry. In the mountainous areas and in the whole North of Europe, snowfall is a substantial part of the overall precipitation. In Finland 27%

and in Norway about 50% of the annual average total precipitation is snow. Snow covered ground affects the energy exchange processes developing weather and climate, both locally and in large regions, and is an important element in meteorological modelling tools. The snowpack itself causes avalanches every year in alpine regions, enforces a high priority road clearing service both in cities and in rural areas, and affects many other aspects of human life.

Remote sensing instruments are the means of continuous monitoring of the snow cover, as successfully demonstrated (Kuttinen 1992; Solberg and Andersen 1994). In the future, remote sensing, mainly by polar orbiting satellites, will play a key role in deriving information about the snow.

The work presented here has been performed within the SNOWTOOLS project and is fully documented in Solberg et al. (1997). The project is within the Commission of the European Communities' Environment and Climate research and technological development program. The main objective of SNOWTOOLS is to develop new remote sensing methodology to extract snow parameters.

USER NEEDS FOR SNOW PARAMETERS

The approach to determine what kind of remote sensing data needed and algorithms to develop has been first to determine the relevant snow products and then identify data and algorithms that support the products best. The products proposed have been determined from the user requirement investigation performed in another part of the SNOWTOOLS project (Kolberg et al. 1997), from direct interaction with the users and from knowledge about spaceborne remote sensing sensors that are expected in the foreseeable future.

Most users need digital, spatial products — GIS layers — for further analysis by their own analysis tools (usually a GIS). Table 1 summarises the proposed digital map products for the applications climate and meteorology (C&M), water resource management (WRM) and flood risk forecasting (FRF). The snow parameters are snow-covered area (SCA), snow water equivalent (SWE), snow surface albedo (SSA) and snow liquid volume wetness (SVW). SVW is a binary product signalling whether liquid water is present or not in the snowpack. It may be used to predict the onset of snow melting and the current area where melting takes place. Spatial resolution is equivalent to pixel resolution. The temporal resolution is the coverage cycle (repetition cycle for a satellite or group of satellites). Delivery time is the time from acquisition until the user has received the product. Precision is the quantification level, e.g. the number of classes (cls.) or size of unit in millimetres (mm). All the classes are of equal size. Accuracy has to be interpreted as overall accuracy of the product. The overall accuracy is calculated as the weighted percentage of correct classification, where the weighting compensates for the variation of the number of pixels within each class. An accuracy of, e.g., 50 mm relates to root-mean-square (RMS) error. The spatial accuracy is specified to 0.5 pixel RMS error for all products.

Table 1. Primary spatial snow products.

Name	**Parameter**	**Application**	**Spatial resolution**	**Temporal resolution**	**Delivery time**	**Precision**	**Accuracy**
SCA-HDAY	SCA	C&M	500 m	1/2 day	2 hours	10 cls.	80%
SCA-DAY	SCA	WRM/FRF	250 m	1 day	0.5 day	10 cls.	80%
SCA-WEEK	SCA	WRM/FRF	250 m	1 week	1 day	10 cls.	80%
SCA-MONTH	SCA	WRM/FRF	250 m	1 month	1 week	10 cls.	80%
SWE-DAY	SWE	WRM/FRF/C&M	250 m	1 day	0.5 day	100 mm	50 mm
SWE-WEEK	SWE	WRM/FRF/C&M	250 m	1 week	1 day	100 mm	50 mm
SSA-DAY	SSA	C&M	500 m	1 day	2 hours	10 cls.	80%
SVW-DAY	SVW	WRM/FRF	500 m	1 day	0.5 day	binary	80%

These are the products given highest priority by the users, except for the avalanche risk forecasting application which has requirements far exceeding what are possible by current and near-future remote sensing techniques.

Some snow parameters obtainable currently or in the near future were not requested by the users. The authors feel it right to mention the parameters here since they may be of relevance to users in the near future (see Table 2). Snow depth (SD) could be used to estimate SWE. Like SVW, both snow surface temperature (SST) and snow surface wetness (SSW) may be used to predict the onset of snow melting and the current areas where melting take place. The last two rows in the table show low spatial resolution products (SCA and SWE) that probably will receive interest in climate modelling.

Table 2. Secondary spatial snow products.

Name	**Parameter**	**Application**	**Spatial resolution**	**Temporal resolution**	**Delivery time**	**Precision**	**Accuracy**
SD-DAY-L	SD	C&M	5 km	1 day	0.5 day	0.5 m	0.2 m
SST-DAY	SST	WRM/FRF	1000 m	1 day	0.5 day	1.0 K	0.5 K
SSW-DAY	SSW	WRM/FRF	500 m	1 day	0.5 day	binary	80%
SCA-DAY-L	SCA	C&M	5 km	1 day	0.5 day	10 cls.	80%
SWE-DAY-L	SWE	C&M	5 km	1 day	0.5 day	100 mm	50 mm

There may also be an interest in the future for receiving maps of snow parameters on a continuous scale rather than grouped into classes, at least for advanced users. This should not require any significant changes in the methodology to be developed.

Several users want snow parameters per elevation zone. The size of the zones varies between the users. Therefore, it is proposed to provide a digital elevation model (DEM) as an ancillary data product for each snow product. The user will then be able to derive parameters for elevation zones according to specific needs.

Almost all users want or are satisfied with Internet as the way of data distribution. It is proposed to use both web pages and FTP sites in parallel. Web pages are well suited for browsing, while FTP is most efficient for routine data transfer.

Users with limited or no tools for GIS processing want ”one step” higher level products in the form of tables. The products needed are summarised in Table 3. The products cover the snow parameters SCA and SWE, and the corresponding products for the time periods day and week.

Table 3. Tabular snow products.

SCA-TAB-DAY SCA per elevation zone. Elevation-zone interval 200 m. Products produced daily (derived from SCA-DAY). Delivery time, precision and accuracy as for SCA-DAY.	**SWE-TAB-DAY** SWE per elevation zone. Elevation-zone interval 200 m. Products produced daily (derived from SWE-DAY). Delivery time, precision and accuracy as for SWE-DAY.
SCA-TAB-WEEK SCA per elevation zone. Elevation-zone interval 200 m. Products produced weekly (derived from SCA-WEEK). Delivery time, precision and accuracy as for SCA-WEEK.	**SWE-TAB-WEEK** SWE per elevation zone. Elevation-zone interval 200 m. Products produced weekly (derived from SWE-WEEK). Delivery time, precision and accuracy as for SWE-WEEK.

CURRENT ALGORITHMS FOR SNOW PARAMETER EXTRACTION

The current operational snow products are based on optical and PMR data. The optical products are all for SCA, and the spatial resolution are for most of them 1 km. There are PMR products for SCA and SD, and the spatial resolution for these are 25 km and coarser. There are no products based on SAR yet.

Many algorithms for determining the snow cover from optical data are based on standard techniques, like unsupervised and supervised classification (e.g., see Baumgartner and Rango 1995; Harrison and Lucas 1989), and various indices based on arithmetic combinations of image bands

(Dozier 1989). There are two main subpixel snow-cover algorithms, the Norwegian Linear Reflectance-to-Snow-Cover Algorithm (NLR) (Andersen 1982; Solberg and Andersen 1994) and spectral unmixing (Nolin et al. 1993). There are serious drawbacks with all existing algorithms with respect to accuracy and level of automation. Interpolation of snow cover can be used to predict the snow cover under clouds (Xu et al. 1993). The interpolation techniques are so far not thoroughly tested for the snow application, but well-developed techniques that may also be applied for snow exist. Albedo measurements are heavily affected by atmospheric, terrain and snow anisotropic reflectance effects (Dozier 1984). To predict the albedo for a wide spectrum, spectral reflectance models have to be used (Warren and Wiscombe 1980; Wiscombe and Warren 1980). A robust algorithm has been developed for snow surface wetness measurements based on a spectral absorption feature (Green and Dozier 1995). However, the algorithm needs narrow-band coverage of certain regions in the near-infrared spectrum. It is possible to predict the snow depth with current methodology, but the predictions are only useful for smooth terrain, areas with homogeneous surface cover, homogeneous snow conditions and a thin snow layer (Xu et al. 1993).

The most promising applications for SAR instruments are monitoring of snow melt (SVW) and discrimination of snow-free areas and areas covered by wet snow (SCA). Single polarisation and single frequency SAR, like ERS SAR, is able to discriminating between wet snow and other categories (Gunneriussen 1997). Koskinen et al. (1997) shows its capability for snow-melt monitoring at subpixel level by using multitemporal SAR images. Bernier and Fortin (1992) have previously reported on the relation between the snow thermal resistance and backscattering coefficient, which suggest a possibility to estimate the snow water equivalent from the backscattering coefficient. However, this approach is far from operational. The backscattering coefficient decreases remarkably as the incidence angle increases (Mäzler et. al 1993; Stilles et al. 1980), which makes it necessary to correct for this effect using a digital elevation model (DEM). Multiband SAR, however, offers vital information of layers at various depths in the snowpack. Shi and Dozier (1996) studied the relation between polarimetric C-band signatures and snow wetness. Shi and Dozier also tested the capability of multiparameter SAR (SIR-C/X-SAR), and found that multiparameter SAR is very useful in monitoring spatial and temporal variability of snow water equivalent.

Algorithms developed for PMR data are mainly based on the application of linear combinations of brightness temperatures measured at low and higher frequencies using well-known semi-empirical approaches. An algorithm for the detection of wet snow solely by microwave radiometry is used currently (Chang 1986), though for that purpose, the inclusion of active microwave data is more realistic. There have been developed algorithms using PMR data for mapping of snow cover area, liquid water content, snow depth and snow water equivalent (Hiltbrunner 1996; Hallikainen 1984; Aschbacher 1989; Grandell et al. 1994), however, the accuracy of the algorithms varies much for different natural conditions.

CURRENT AND NEAR-FUTURE SENSORS

Current and near-future sensors that may be of interest to snow-parameter mapping have been identified and reviewed. The known optical sensors of interest, available currently or in the near future, are shown in Table 4.

Table 4. Most important satellites and sensors for snow mapping.

Optical	**SAR**	**PMR**
1. NOAA AVHRR	1. ERS-2 SAR	1. DMSP SSM/I
2. IRS WiFS	2. RADARSAT	2. PRIRODA IKAR
3. Resurs	3. JERS	3. EOS PM-1 AMSR
4. ERS ATSR	4. ENVISAT ASAR	
5. SeaWiFS		
6. EOS MODIS		
7. SPOT VEGETATION		
8. Envisat MERIS		

Optical sensors 1-5 are in orbit now and deliver data routinely. The future sensors are expected to be in orbit within the period 1998-2000. The spatial resolution of these are in the range 0.2-1 km. EOS MODIS is the most interesting of these supporting algorithms that are able to fulfil the product requirements very far.

SAR sensors 1-3 employ only one frequency and one polarisation. Therefore, the number of snow applications is limited to SCA. However, ENVISAT employs co-polarisation and, based on results obtained from airborne SARs, this feature can offer vital information about snow parameters like SWE and SVW.

The PMR sensors SSM/I and IKAR are currently available, while AMSR should be available in 2000. These sensors have spatial resolution in the range 4-75 km, and cover the frequency range of about 5-90 GHz.

RESEARCH NEEDED FOR IMPROVED ALGORITHMS

Even if remote sensing of snow has been a research area for more than 25 years, there are still a lot of unsolved problems. Some of these remaining problems are due to the complexity of the phenomenon, others are due to the new requirements of higher accuracy, higher spatial resolution and automatic processing for production of the snow products. In addition, algorithms have to be adapted to a new generation of satellite sensors.

By comparing the specifications of the snow products with the performance of the state-of-the-art methodology, the following major problems have been identified for analysis of optical data:

SCA: The most demanding requirements are the short delivery time and the accuracy needed for several products. Completely automatic processing is necessary to fulfil the time requirement. The accuracy is especially demanding in mountainous terrain, for areas which have very heterogeneous ground cover, and for forested areas.

SSA: Again, the most demanding requirements are the short delivery time and the accuracy. Effects from anisotropic reflectance of snow and terrain effects make SSA especially difficult to measure in mountainous terrain.

SSW: Available algorithm seems to be very accurate. However, an imaging spectrometer is needed. It may be possible to use MODIS, so this should be investigated.

SST: The main problem with the current algorithms is the accuracy. Accuracy down to 1/10th K may be needed to get a reliable prediction of the presence of liquid water. An alternative approach is to predict/warn snowmelt onset by using a time series of images. This will require less accuracy.

SD: The main challenge is the accuracy needed. Current algorithms need far more testing and improvements before one can conclude whether they are suitable for operational use.

SAR data are relevant for the estimation of SCA, SSW and SWE. The estimation of other parameters than SCA will require multiparameter SAR systems and, due to the lack of such spaceborne sensors, the highest priority should be given to SCA. The following major problems have been identified for the relevant products:

SCA: The most demanding requirements are the short delivery time, the coverage and the accuracy. At least a high degree of automatic processing is needed. The accuracy is especially demanding in mountainous terrain, for areas which have very heterogeneous ground cover, and for forested areas.

Starting from the specifications of the snow products based on the user requirements, one has to state that the spatial resolution of these products is the major challenge with PMR algorithms. The advent of new satellite-based radiometers will provide a best spatial resolution of 6 km × 4 km (AMSR, 89 GHz and PRIRODA, 90 GHz). Comparing this with the required spatial resolution of the snow products, PMR data will mainly contribute to low spatial resolution products. We recommend the development of algorithms for the snow products described below.

SWE: A new algorithm for the retrieval of SWE from microwave brightness temperature should be developed using an approach based on measured microwave signatures of different snow types, which will better account for the heterogeneous surface type composition than previous algorithms.

SCA: The generation of snow maps should be based on the experience from signature studies where linear combinations of emissivities should be tested and improved by comparing the results with ground measurements and optical satellite data.

SD: Algorithms with a global validity do not exist. Therefore, new approaches should be directed towards regional applications. Additionally, one should focus on developing regional algorithms including seasonal peculiarities.

SST: The effective temperature is equal to the physical temperature at the base of the snowpack. This temperature is close to or below the freezing point of water in regions with seasonal snow cover, which inhibits the retrieval of snow surface temperatures by means of microwave radiometry, with the exception of wet snow. In this case, the effective temperature can be inferred from surface type classification.

Some of the snow parameters can to some degree be measured by means of more than one remote sensing data type (optical, SAR or PMR). The data types may contain complementary information, or one data type works best under one condition, while another type works best under a different condition. The multisensor approach may be fruitful for improving spatial and temporal coverage, e.g. due to the cloud cover problem with optical data, or improve the accuracy by measuring the same parameter by different methods.

CONCLUSIONS

We have in the previous pages given a review of the current state-of-the-art methodology for remote sensing of snow parameters, defined snow products according to the needs, presented the relevant remote sensing sensors that will be available in the foreseeable future, and identified problems and insufficiencies which require further research in order to satisfy the user needs. From the discussion in the previous section, topics for further research are concluded below.

For analysis of optical data, we can conclude that more research is needed on: Subpixel classification of SCA; modelling and compensation for temporal, topographic and anisotropic reflectance effects; compensation for vegetation/forest; validation of SSW algorithm; and improvement of SST accuracy.

For SAR, more research are needed on: Capability to measure snow-covered ground and melting snow; effect of vegetation; use of polarimetry; combined use of various frequencies; and use of SAR interferometry.

Similarly, we can for PMR conclude that more research is needed on: Algorithms for multitemporal and low and high frequency data; effects of mixed signatures, vegetation, atmosphere and rugged terrain; investigation of error sources; development of new algorithms for the SWE retrieval; and assessment of interpolation techniques.

For the multisensor approach, research on the following combinations is recommended: Optical and SAR for SCA mapping; optical and SAR for snow wetness measurements; optical and PMR for SST estimation; PMR and SAR for SCA mapping; and optical and PMR for SD estimation.

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