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Operative estimation of snow covered area for the needs of hydrological modelling

Sari Metsämäki, Jenni Vepsäläinen, Markus Huttunen & Mikko Hynninen
Finnish Environment Institute, Geoinformatics and Land use Division, Helsinki, Finland

Jouni Pulliainen
Helsinki University of Technology, Laboratory of Space Technology, Finland

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ABSTRACT: In hydrological cycle, snow acts as a seasonal water storage, from where water is released during the melting period. Predicting this process is important for flood prevention and hydropower industry. It is accomplished by hydrological models, where the areal extent and the water equivalence of the snow pack are often included as state variables. The problem with the models is the low spatial and/or temporal resolution of input data. This defect can be alleviated by employing remote sensing techniques to produce spatially (and temporally) well-distributed information on snow cover and taking this information into the model. Optical and near-infrared sensors are useful for monitoring the extent of snow cover. We have developed a feasible remote sensing method for operative monitoring of snow covered area (SCA), with the aim of using the results in hydrological forecasting. The implementation of the method was carried out for NOAA/AVHRR data, starting from melting period 2001. SCA estimates are calculated whenever cloudiness permitting and published also as thematic snow maps in WWW-pages of the Finnish Environment Institute. The operative Finnish national hydrological modelling system is currently under modification in order to optimally utilize the remote sensing based information on SCA.

1 INTRODUCTION

The information about the extent of the snow cover is essential in regions where the seasonal snow pack is thick and the volume of water produced from the melting snow is high. During springtime, the snow melt produces runoff and raises the water level in lakes and rivers. At the final state of melting, large volumes of water can be rapidly released from drainage basins to the lakes and rivers. This often causes a risk of flooding and is also a matter of major importance for hydropower management.

The general behavior of visible and near-infrared reflectance of snow is rather well known (Wiscombe and Warren, 1980; Warren, 1982). The highest values are observed from pure dry snow at visible wavelengths. The reflectance decreases as snow ages, mainly due to the impurities and growing grain size, related to snow melt. At near-infrared region, reflectance is almost as high, but the decrease caused by the growing grain size is more distinct. Other natural objects, on the other hand, have clearly lower reflectance at both visible and near-infrared regions. With remote sensing data, several ground objects contribute to observed reflectance within a pixel: snow, bare ground, vegetation etc. Therefore, the observed reflectances change according to regional proportions of these. With full snow cover, highest reflectances are observed, but they gradually decrease as snow disappears. By monitoring this decrease, the regional fraction of Snow Covered Area (SCA) can be estimated. However, forest canopy reduces the signal from the ground and snow underneath. Therefore, we estimate the SCA by applying an empirical reflectance model that includes different contributors to reflectance, including the forest transmissivity as an important factor (Metsämäki et al., 2001; Vepsäläinen et al., 2001a).

In our study, drainage basins of Finland serve as calculation areas for remote sensing of SCA. The same areas are used in an nationwide operative hydrological modelling system run by the Finnish Environment Institute. The system produces forecasts for water level and discharge for more than 5000 drainage basins (with mean acreage of ~60 km^2), including SCA as a state variable (Vehviläinen, 1994). The objective of our study is to evaluate the feasibility of a combined use of the two information sources, remote sensing and hydrological modelling.

2 STUDY AREA AND DATA

2.1 *Study area for operative remote sensing SCA estimation*

Finland is located in the Northern Europe, between latitudes 60 and 70. Coniferous forest dominates the landscape of Finland with areal coverage of 72%. Wide non-forested areas locate only in the northernmost parts of Finland, north from the Eurasian boreal coniferous forest zone.

The seasonal snow cover settles down during October-November, and stays until April-June. The average annual water equivalent volume is as high as 140-200 mm in northern Finland and 80-140 mm in southern Finland (Kuusisto, 1984). The operative monitoring of SCA starts in March, when melting begins, usually starting from southern-western coast.

2.2 *Study area for joint use of hydrological model and remote sensing*

The hydrological model of Kemijoki river basin was chosen to serve as a test model for investigation of utilization of SCA estimates produced with remote sensing. Kemijoki basin, mostly covered by boreal forests, is located in northern Finland and compounds an area of 50 000 km^2. The typical altitude is below 300 meters.

2.3 *Remote sensing data*

The AVHRR dataset consists of non-cloudy scenes during the melting period in years 2000-2001. The study site covers the whole Finland, compounding an area of 1320 x 720 km^2. Pre-processing of the data included radiometric calibration for visible (0.58-0.68 µm) and near infrared (0.725-1.1µm) channels as well as atmospheric correction with SMAC method (Rahman et al. 1994). After image rectification, cloud masking was performed.

3 HYDROLOGICAL MODELLING IN FINLAND

In Finland, the hydrological forecasting and real-time monitoring is carried out by the Watershed Simulation and Forecasting System (WSFS) of the Finnish Environment Institute (Vehviläinen, 1994). Its several hydrological models operate for more than 5000 drainage basins covering 86 % of the area of Finland. Standard meteorological data is used as input. The principal output includes water discharge, water level and snow water equivalence, and the state of the model is corrected with respect to *in situ* measurements of those three. The future use of remotely sensed SCA in the correction scheme will be feasible as it is included in the model a state variable. The principle idea of the snow part of the hydrological model is presented in the Fig. 1.

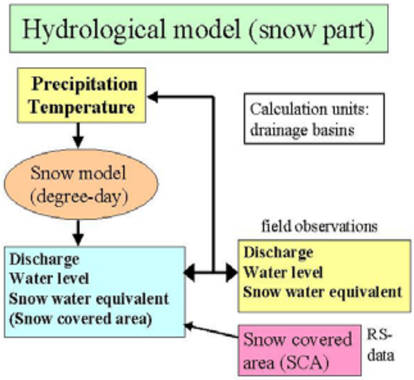


Figure 1. The snow part of the hydrological model (remote sensing data will be used in model correction in near-future).

Hydrological model calculations as well as SCA estimates from AVHRR data are constantly utilised in water management by a Finnish hydropower company, in national flood forecasting and as important information for other nature sciences.

4 REMOTE SENSING OF SCA

4.1 *Methodology*

Our remote sensing method for SCA estimation is based on a very high reflectance of snow compared with other natural targets. In the estimation, we apply an empirical reflectance model where SCA is included to describe the relative proportion of the radiative contributors underneath the forest canopy. In the model, reflectance from target is expressed as a function of forest canopy transmissivity and generally applicable reflectance values for wet snow, snow-free ground and forest canopy:

$$\rho(SCA) = (1-t^2)*\rho_{forest} + t^2\left[SCA*\rho_{snow} + (1-SCA)*\rho_{ground}\right] \quad (1)$$

where ρ_{snow}, ρ_{ground} and ρ_{forest} are the reflectances for wet snow, snow-free ground and forest canopy, respectively. *ρ(SCA)* stands for observed reflectance at current SCA. The value for transmissivity *t* is characteristic for each calculation area, i.e. drainage basin in this case. It describes how much of the upwelling radiance is originated underneath the forest canopy. With full snow cover (SCA=1), a simple expression for t^2 is obtained from (1):

$$t^2 = \frac{\rho(SCA) - \rho_{forest}}{\rho_{snow} - \rho_{forest}} \quad (2)$$

For each basin, the transmissivities $\hat{t}^2_i$ were estimated from (2) using regionally averaged reflectance data from AVHRR mosaic (years 1999-2000) under full snow cover conditions (Robinson and Kukla, 1985; Metsämäki et al., 2001). Formula (2) yields a low transmissivity for areas with dense forests and high transmissivity for totally open areas. The results were compared with forest cover statistics derived from National Forest inventory (Vuorela, 1997), indicating a good agreement. The transmissivities for basins are presented in Fig. 2.

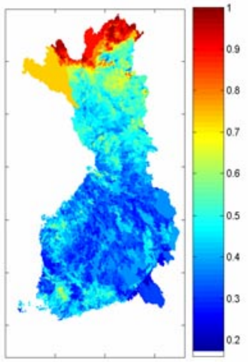


Figure 2. Regional average forest transmissivities.

In non-vegetated or scrub land areas, found only in northern Finland, the averaged reflectances were close to the value of plain snow, while in the other parts of Finland, lower reflectances were observed due to the contribution of forest canopy. Assuming the consistent reflectance of full cover dry snow throughout the study area, the proportion of forest canopy can be estimated using the observed reflectances.

After determining the apparent transmissivity $\hat{t}^2_i$ for each drainage basin, the value of SCA is calculated by inverting (1), as follows:

$$SCA_i = \frac{\frac{1}{\hat{t}_i^2} * \rho(SCA) + (1 - \frac{1}{\hat{t}_i^2}) * \rho_{forest} - \rho_{ground}}{\rho_{snow} - \rho_{ground}} \quad (3)$$

In this study, valid values for ρ_{snow} , ρ_{ground} and ρ_{forest} were derived from AVHRR dataset by carefully selecting the representative areas, using The National Land Use and Forest Map of Finland (Vuorela, 1997) as a reference. A good agreement with values found in literature was achieved. Note that in (3), ρ_{snow} refers to wet snow, explicitly. For wet snow and bare ground, the representativiness of AVHRR data was validated with *in situ* snow data from weather stations and snow courses.

At the very end of the melting season, the appearance of seasonal vegetation increases the observed reflectance, easily leading to overestimations of SCA. This is considered by employing a particular threshold rule for normalized difference vegetation index (NDVI=*(ρ_2-ρ_1)/ρ_2+ρ_1)),* calculated from the AVHRR observations.

$$NDVI_{th} = a * \hat{t}^2_i + b \quad (4)$$

a and *b* are empirical parameters (Vepsäläinen et al., 2001b). With this rule, areas with too high NDVI are automatically classified as snow-free.

4.2 *Operative monitoring of SCA*

Starting from melting season 2000, Finnish Environment Institute has calculated SCA estimates from NOAA/AVHRR on daily basis. Data processing is mostly automated, including pre-processing described in section 2.3. After a calibrated and rectified image with cloud mask is ready, the SCA estimation method is applied, resulting to estimates for all cloud-free basins. This data are delivered to the developers of the hydrological model, but are also prepared into a thematic Snow Map available for public in FEI's web-site. A sample set of the Snow Maps is presented in Fig. 3.

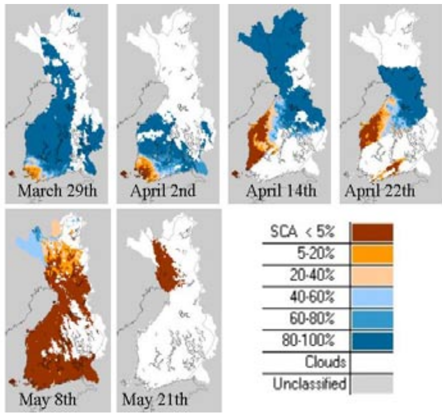


Figure 3. A sample of remote sensing based operative Snow-Maps from melting season 2001.

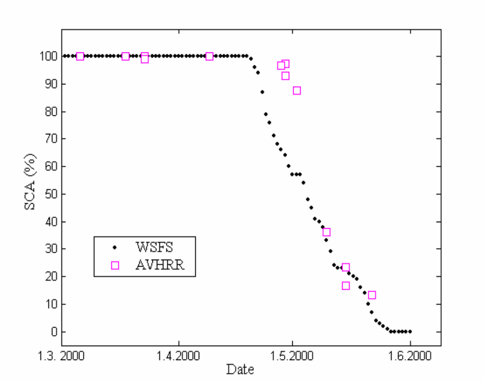
Considering the bidirectional reflectance anisotropy of snow (Jin and Simpson, 1999) and snow-free land (Cihlar et al., 1994), a procedure for correcting the reflectances should be included in the model. At the moment, the effect of viewing geometry to the reflectances and transmissivity has not been included. Therefore, image data with only a limited set of viewing geometries has been employed in method testing. Data with view zenith angle $2_v < 30^o$ for both forward and backward scattering directions have been accepted.

5 THE JOINT USE OF REMOTELY SENSED SCA AND THE HYDROLOGICAL MODEL

The joint use of remote sensing and hydrological modeling started with model calibration. Presently, the Kemijoki test model is calibrated using the remotely sensed SCA as one source of observation data. In the calibration, the simulation results are compared to the observed water levels, discharges, snow water equivalent and now also to the SCA estimates. This enables the future use of remotely sensed SCA-values also in model corrections and forecasting.

In the previous version of the Kemijoki model where the remotely sensed SCA was not used in the calibration, the simulated and remotely sensed SCA-values differed considerably during the melting period. In such situation, SCA estimates were not usable for model correction. Now, in the calibrated version, the simulated and remotely sensed SCA values are closer to each other and their joint use is beneficial especially in the end of the melting period if the snow water equivalent (SWE) in the hydrological model is simulated correctly. On the other hand, error in the estimate of SWE essentially leads into error in discharge forecasts.

From the data of the melting seasons 2000 and 2001, a large set of SCA-values estimated by AVHRR-algorithm and calibrated Kemijoki model was compared. In the Fig. 4, two samples of the comparisons are presented.



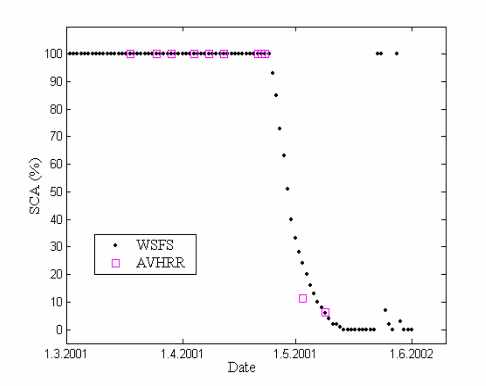


Figure 4. Model simulated and Remote Sensing based SCA during melting periods 2000 and 2001.

The national WSFS hydrological model is corrected before making forecasts. This correction is made by changing the inputs of the model, i.e. daily precipitation and temperature. The goal of the correction is to make the model simulation results as close to the observed discharges, water levels, snow water equivalents and SCA estimates as possible. The idea of the correction is that when the model simulates according to the observed values, we also have the unobserved storages, such as soil moisture and ground water storage close to the correct values.

The remotely sensed SCA estimates are beneficial especially in the end of the melting period, when they can be used for correcting the simulated snow water equivalent. The two most favourable situations for correcting the model with remotely sensed SCA occurs when making discharge forecast at the very end of the melting season: (1) we can see from remotely sensed SCA that there is no snow on the basin any more while there is still snow in the model and (2) there is snow according to the remotely sensed SCA but no snow in the model. In both of these cases the incorrect snow water equivalent would lead to erroneous discharge forecast, but based on the near-real time SCA estimates this can be at least partly corrected.

When the remotely sensed SCA estimates are used in the correction of the model, the information of the accuracy of the estimates is essential. The estimates can be used in the model correction only when we are sure that the difference between remotely sensed SCA and model simulated SCA is notable. If the accuracy of the each SCA estimate is not known, we have to compare the difference of each estimate to the mean difference between simulated and observed SCA values. But if the accuracy of each estimate is known, the more reliable estimate can be weighted.

Currently, the nationwide operational hydrological model does not use the remotely sensed SCA estimates for the model correction. This would require calibration of the whole model, preferably with several years remote sensing data. This will probably succeed on the next melting period, spring 2003. The current status of the system is presented in Fig.5.

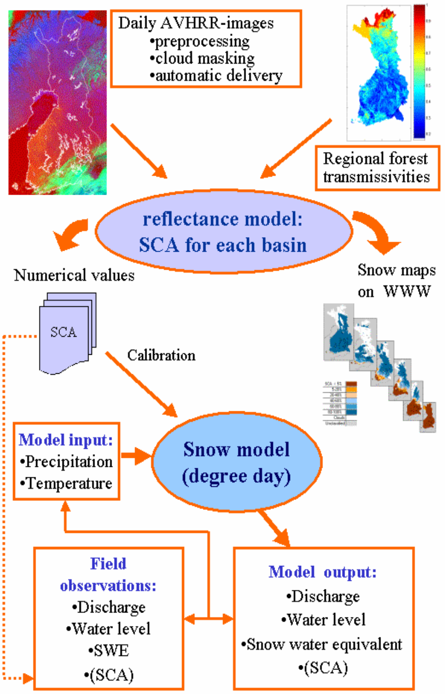


Figure 5. The scheme of the combined use of the two operative systems: remote sensing based SCA-production and hydrological model.

6 CONCLUSIONS

In this paper, a method for estimating regional values for Snow Covered Area (SCA) from optical remote sensing data for the needs of Finnish operative hydrological modeling was presented.

In the future, SCA estimates will be assimilated to the daily hydrological model calculations. Due to the continuous nature of the method presented here, the mathematical methods for assimilation should be relatively easy to find.

Our method for SCA estimation has been tested for NOAA/AVHRR data. However, the method is applicable for other optical data (like TERRA/MODIS) and calculation areas as well. The fact that no information on land cover or forest statistics is needed makes it easy to use also outside our calculation area (boreal forest zone, mountainous areas excluded).

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