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Estimation of regional snowline elevation (RSLE) from MODIS images for seasonally snow covered mountain basins

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SUMMARY

We present a method for estimation of regional snowline elevation (RSLE) from satellite data for seasonally snow covered mountain basins. The methodology is based on finding an elevation for which the sum of snow covered pixels below and land pixels above the RSLE is minimized for each day. The methodology is tested with MODIS daily snow cover product in the period 2000–2013 in the upper Váh basin (Slovakia). The accuracy is evaluated by daily snow depth measurements at seven climate stations and additional snow course measurements at 16 profiles in the period 2000–2013.

The results show that RSLE allows accurate estimation of snowline elevation. For the RSLE estimation, two thresholds need to be considered. The thresholds of maximum cloud coverage and minimum number of snow pixels considerably affect the number of days (images) available for estimation. The sensitivity evaluation indicates that the cloud threshold has less effect on the accuracy than the minimum snow threshold. Setting cloud and minimum snow thresholds to 70% and 5% respectively, results in an average RSLE estimation accuracy of 86% at climate stations. The accuracy in the forest is 92% in the winter months and drops to 70% in April. The main factors that control the accuracy and scatter around the snowline are vegetation cover and shading of terrain. The results show that spatial patterns of misclassification correspond well with forest cover and potential insolation duration in winter.

The developed RSLE method is more accurate than the previously used methods of snowline elevation estimation, it decreases the scatter around the snowline and can be potentially applied in an improved cloud reduction in MODIS products as well.

1. Introduction

The availability of water is becoming an important issue in the changing world. Snow accumulation and melt is a significant component of hydrologic water balance in many regions, especially in the mountains. The seasonality of river discharge is controlled by snowmelt not only in northern basins (e.g. Gusev and Nasonova, 2014), but also in temperate climates, such as mountain regions in central Europe (Holko et al., 2011; Parajka et al., 2010a).

Regional snowline elevation and its inter- and intra-annual variability are key characteristics indicating temporal changes in snow cover and duration of snow melt. The concept of snowline estimation for assessing snow cover variability depends on the applications. In geography and climate studies, the snowline (or snow limit) defines the lowest altitude of the perennial snow cover, which is an equivalent to the lower boundary of the snow covered area at the end of summer (Fierz et al., 2009, Price et al., 2013). In glacier studies, the regional transient snowline approximates the equilibrium line altitude for estimation of glacier mass balance changes (Pelto, 2010; Shea et al., 2013). In meteorological literature, median snowline is also used for describing the relative number of days with snow cover above a specified snow depth (e.g. Hantel and Maurer, 2011).

In hydrological applications, the snowline is identified for estimation of snow covered area and its temporal evolution, which is hence used as an input for hydrological modeling (e.g. for SRM model, Holzer et al., 1995; Martinec et al., 2008) or for validation of snow model simulations (Baumgartner and Apfl, 1997; Zappa, 2008). Recently, snowline elevation estimates have also been applied as an alternative method for cloud reduction in satellite snow cover products (Gafurov and Bárdossy, 2009; Da Ronco and

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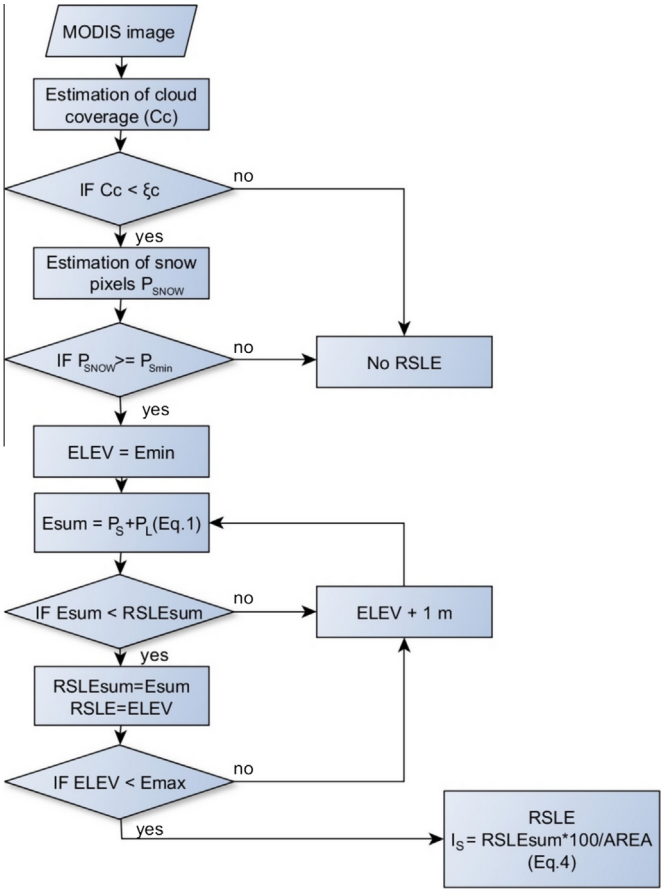

Fig. 1. Flowchart of regional snowline elevation (RSLE) methodology.

De Michele, 2014), i.e. for improving the availability and accuracy of snow cover products developed for assimilation in operational hydrologic models (Bach et al., 2004; Parajka et al., 2010a,b).

From the methodological point of view, snowline elevation from satellite images is typically estimated as a minimum, mean or selected fixed percentile elevation of pixels classified as snow, by taking into account the amount of clouds. For example, Gafurov and Bárdossy (2009) estimated snowline from MODIS as the elevation above which all pixels are classified as snow and clouds are less than 70%. Parajka et al. (2010b) estimated regional snowline as a mean elevation of snow pixels, considering cloud coverage less than 90%. Lei et al. (2012) extracted snowline from pixels with at least 80% frequency of snow coverage in a season. For their analysis, they used a multi-temporal 8-day MODIS product to reduce the effects of clouds. Shea et al. (2013) evaluated seasonal variability of 10% and 20% percentiles of elevation for snow classes and weighted the seasonal variability of snowline by the amount of cloud free pixels.

The objective of this paper is to propose and evaluate a simple method for estimation of regional snowline elevation (RSLE), which is not based on fixed statistical quantiles of elevation for pixels classified as snow. The idea is to estimate RSLE in a seasonally snow covered basin without permanent glaciers by using MODIS images and to investigate the accuracy and factors which control temporal and spatial variability of RSLE in the last decade.

The paper is organized as follows. First, we introduce the RSLE methodology. Next, the method is applied and evaluated in a typical river basin of Western Carpathians region. Finally, we discuss the factors controlling accuracy of proposed methodology and present some implications for further research.

2. Methodology

2.1. Regional snowline elevation (RSLE) estimation method

The proposed methodology estimates regional snowline elevation from satellite snow cover data. The cornerstone of the approach is to find an elevation (RSLE) for which the sum of snow covered pixels below (P_S) and land pixels above (P_L) the RSLE is minimized. Mathematically, this is a variation problem, consisting on finding the optimal elevation RSLE = RSLE* that minimizes the objective function

$$F(\mathrm{RSLE}) = P_S(\mathrm{RSLE}) + P_L(\mathrm{RSLE}) \quad (1)$$

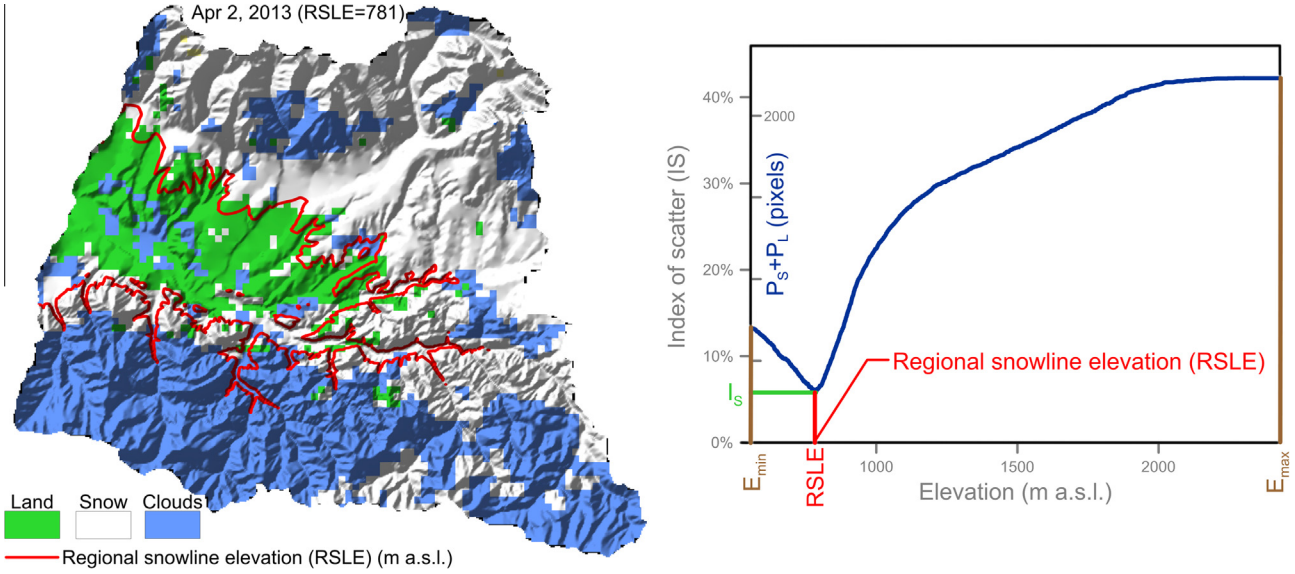

Fig. 2. Estimation of regional snow line elevation (RSLE, red line) from combined MODIS snow cover product on April, 2, 2013 (left panel). An example of estimation of regional snowline elevation (RSLE) (right panel). The red and brown colors depict the snowline elevation and minimum (E_{min}) and maximum (E_{max}) elevation of study area, respectively. The blue line depicts the sum of snow pixels below (P_S) and land pixels above (P_L) the RSLE. The index of scatter (IS) expresses the relative frequency of P_S and P_L within the study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)