



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.

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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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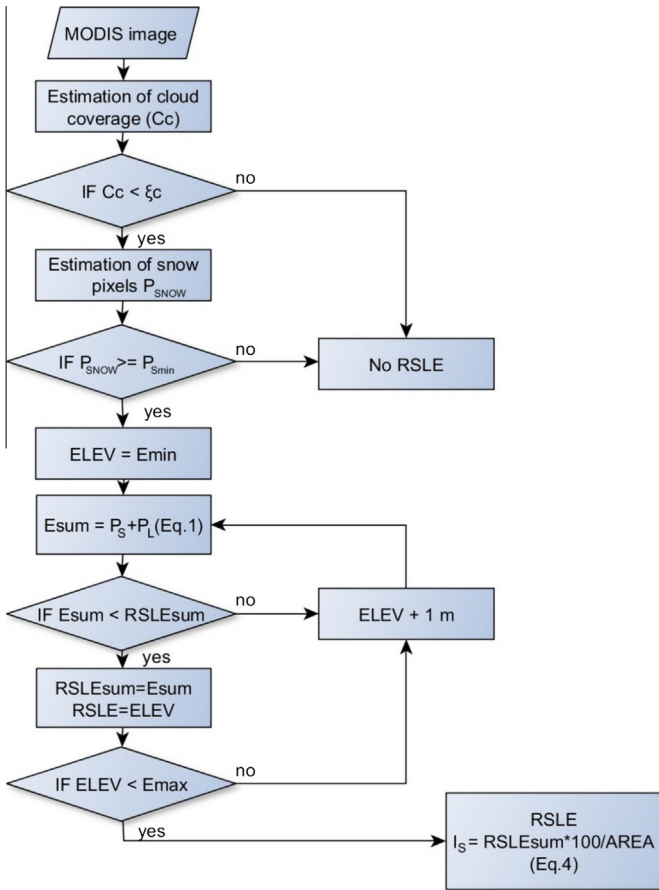


Fig. 1. Flowchart of regional snowline elevation (RSLE) methodology.

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

$$F(RSLE) = P_s(RSLE) + P_l(RSLE) \tag{1}$$

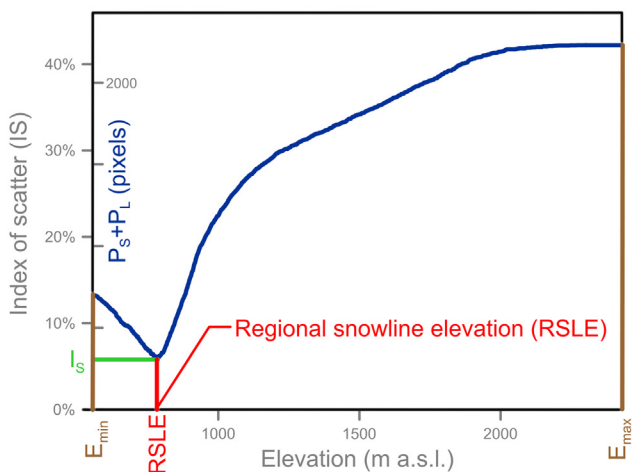
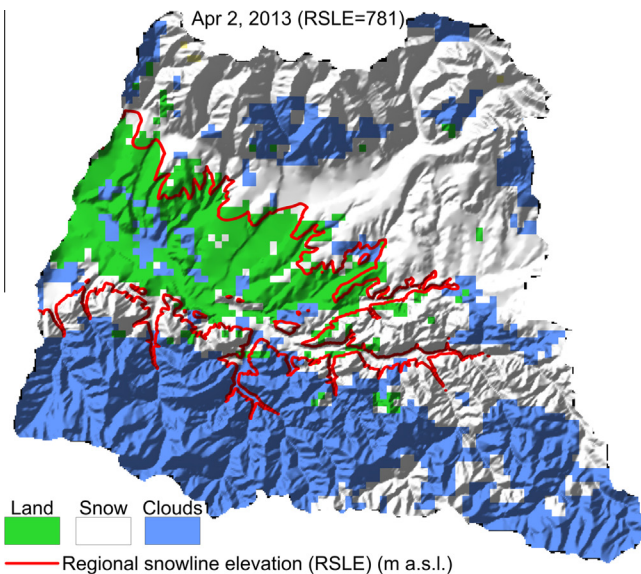


Fig. 2. Estimation of regional snow line elevation (RSLE, red line) from combined MODIS snow cover product on April, 2, 2013 (left panel). An example of estimation of regional snowline elevation (RSLE) (right panel). The red and brown colors depict the snowline elevation and minimum (E_{min}) and maximum (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 (I_s) 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.)

The analytical conditions for F (RSLE) to be minimum are given by annulling the first derivative in RSLE (steady state condition) and imposing a positive second derivative in RSLE (positive inflection) at the steady states. Mathematically, these conditions are written as:

$$\frac{\partial F}{\partial RSLE} = \frac{\partial P_S}{\partial RSLE} + \frac{\partial P_L}{\partial RSLE} = 0 \quad (2)$$

$$\frac{\partial^2 F}{\partial RSLE^2} = \frac{\partial^2 P_S}{\partial RSLE^2} + \frac{\partial^2 P_L}{\partial RSLE^2} > 0 \quad (3)$$

Solving for RSLE yields the optimal elevation $RSLE^*$ that minimizes the sum of P_S and P_L . In this study, the equations were solved numerically with finite elevation differences of 1 m interval between minimum (E_{min} , Fig. 1) and maximum elevation (E_{max} , Fig. 1) of the study area.

The approach for RSLE estimation consists of several steps, which are presented in a flowchart in Fig. 1. In the first step, the percentage of pixels classified as clouds (C_c) in a satellite image is estimated for the study region. If clouds do not cover a large extent of study area, i.e. are less than threshold ξ_c , then the amount of pixels classified as snow is determined. In order to estimate RSLE particularly for cases with larger snow cover extent and to reduce

Table 1

Contingency table relating the ground based snow depth observations (Ground) and the snow estimation from regional snowline (RSLE). The A, B, C and D represent the number of station-days when snow line was determined in a particular classification category.

| Sum of station-days | RSLE snow | RSLE no snow |
|---------------------|-----------|--------------|
| Ground snow | A | B |
| Ground no snow | C | D |

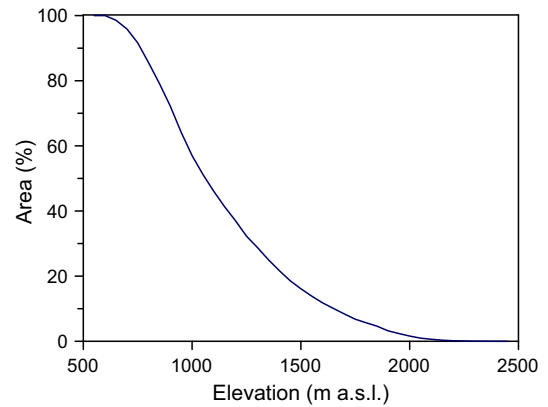


Fig. 4. Hypsometric curve of the upper Váh basin. The curve is derived from 10 m digital elevation model of the region.

cases with some misclassification of clouds as snow (see e.g. Parajka and Blöschl, 2006), the snowline elevation is estimated only if the relative amount of snow pixels (P_{SNOW}) in particular day in the study area exceeds P_{Smin} (discussed in Section 4.1.). The RSLE is then estimated by minimizing the amount of pixels which are classified as snow and land (E_{sum} , Fig. 1), but located below and above RSLE, respectively. The procedure starts with the minimum elevation ($ELEV = E_{min}$, Fig. 1) of the study territory. E_{sum} is calculated with the increment of 1 m of the altitude ($ELEV + 1m$, Fig. 1) until the maximum elevation (E_{max} , Fig. 1) is reached. The elevation ($ELEV$, Fig. 1) with the smallest number of P_S and P_L pixels then determines the RSLE. The variability of snow cover around the RSLE is expressed by the index of scatter I_s :

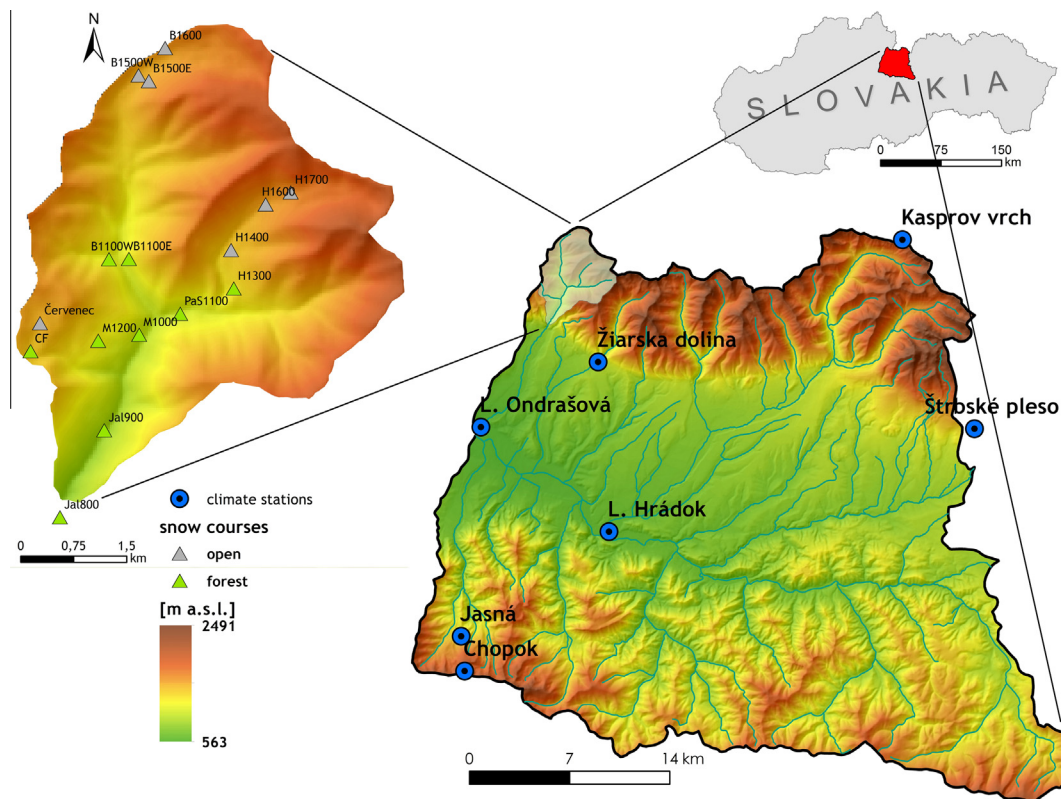


Fig. 3. Topography of the upper Váh (right map) and Jalovecky creek (left map) basins and location of sites with snow depth observations (climate stations – circles, snow courses – triangles).

$$I_S = \frac{(P_S + P_L)}{A} 100 \quad [\%] \quad (4)$$

which relates the sum of P_S and P_L pixels to the area (A – total number of pixels) of study region (in per cent).

An example of a satellite image and RSLE estimation is presented in Fig. 2. Left panel shows a typical snow cover map from a satellite. The estimated cloud coverage (C_C) is around 40% and snow pixels (P_{SNOW}) cover approximately 46% of the study area. Right panel of Fig. 2 presents the sum of P_S and P_L pixels for different elevations ($ELEV$), indicating the lowest sum ($RSLE_{sum}$, Fig. 1) for elevation 781 m a.s.l., which is the final RSLE for that day. I_S varies between 14% (E_{min}) and 46% (E_{max}) and it is at 6% minimum for estimated RSLE. The setup and estimation of cloud threshold ζ_C and P_{Smin} are regionally dependent and their effect on RSLE and amount of available information is, for the selected study area, presented in detail in the Section 4.

2.2. Accuracy assessment

The accuracy of estimated snowline elevation is quantitatively evaluated using ground snow depth measurements. The overall degree of agreement between snow estimated from regional snowline elevation (RSLE) and snow depth measurements is represented by an accuracy index of overall agreement k_a . If the elevation of a site with ground snow depth measurements is above RSLE then the station (ground) is considered as snow covered and considered without snow cover (no snow) otherwise. The k_a is defined as the sum of correctly classified station-days (snow at ground – snow from RSLE, no snow at ground – no snow from RSLE) divided by the total number of station-days in per cent:

$$k_a = \frac{A + D}{A + B + C + D} \cdot 100 \quad [\%] \quad (5)$$

where A , B , C and D represent the number of station-days when snow line is determined ($C_C < \zeta_C$, Fig. 1) in a particular classification category as of Table 1. The frequency of station-days is statistically evaluated on a monthly basis and for the entire period used in the analyses.

3. Data

3.1. Study area

The regional snowline elevation is evaluated in the upper Váh basin (Slovakia), which is situated in the highest part of the

Table 2

List of sites with snow depth measurements in the period 2000–2013. Measurements at climate stations (ClimSt) represent open conditions, snow course data (SC) include profile measurements at open and forest sites. Number of days indicates snow measurements in winter seasons (November–May) 2000–2013.

| Site | Elevation (m a.s.l.) | Type | No. of days with measurements |
|----------------|----------------------|-----------|-------------------------------|
| L. Ondrašová | 569 | ClimSt | 4877 |
| L. Hrádok | 640 | ClimSt | 4871 |
| Žiarska dolina | 900 | ClimSt | 3160 |
| Jasná | 1185 | ClimSt | 4874 |
| Štrbské pleso | 1322 | ClimSt | 4828 |
| Kasprov vrch | 1987 | ClimSt | 4653 |
| Chopok | 2005 | ClimSt | 4650 |
| Jal800 | 800 | SC/Forest | 18 |
| Jal900 | 900 | SC/Forest | 8 |
| M1000 | 1000 | SC/Forest | 40 |
| B1100E | 1100 | SC/Forest | 25 |
| B1100W | 1100 | SC/Forest | 32 |
| PaS1100 | 1100 | SC/Forest | 23 |
| M1200 | 1200 | SC/Forest | 17 |
| H1300 | 1300 | SC/Forest | 35 |
| H1400 | 1400 | SC/Open | 32 |
| CF | 1420 | SC/Forest | 147 |
| B1500E | 1500 | SC/Open | 23 |
| B1500W | 1500 | SC/Open | 24 |
| Červenec | 1500 | SC/Open | 199 |
| B1600 | 1600 | SC/Open | 17 |
| H1600 | 1600 | SC/Open | 23 |
| H1700 | 1700 | SC/Open | 31 |

Carpathian Mountains. The size of the basin is 1216 km² and the elevation ranges from 560 to almost 2500 m a.s.l. (Fig. 3). The topography is described by a digital elevation model (DEM) with spatial resolution of 10 m (EUROSENSE and GEODIS Slovakia, 2013). The hypsometric curve of the basin (Fig. 4) indicates that the mean basin elevation is 1092 m a.s.l. and more than 15% of the basin is above 1500 m a.s.l. Land-use types in the study area are mainly agricultural fields and pastures in the valleys, forest in the elevations below 1500 m a.s.l. and alpine meadows and rocks in the highest mountain parts.

The upper Váh is located in a cold climate zone (Dfb and ET zones, Peel et al., 2007). The mean annual precipitation is less than 700 mm year⁻¹ in valleys and more than 2000 mm/year in the highest parts. Seasonally, the largest precipitation occurs in June or July, minimum monthly precipitation typically occurs in February. Mean annual air temperature varies between 6 °C in valleys to less than –1 °C in the mountains. The coldest month is January and a typical lapse rate in winter is 0.3 °C 100 m⁻¹.

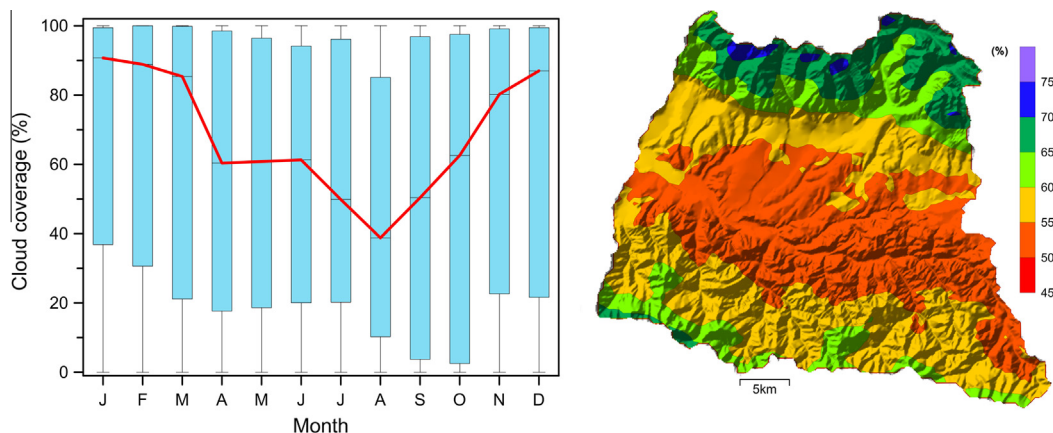


Fig. 5. Seasonal frequency (left panel) and spatial pattern (right panel) of cloud coverage from combined MODIS product in the upper Váh basin. Combined MODIS images represent merged Terra and Aqua daily snow cover products. The box-whiskers plot shows quantiles (minimum, 25-percentile, median, 75-percentile and maximum) of daily cloud coverage in the period 2000–2013. The red line indicates median cloud coverage in different months. The map (right panel) shows mean cloud coverage in the period 2000–2013. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

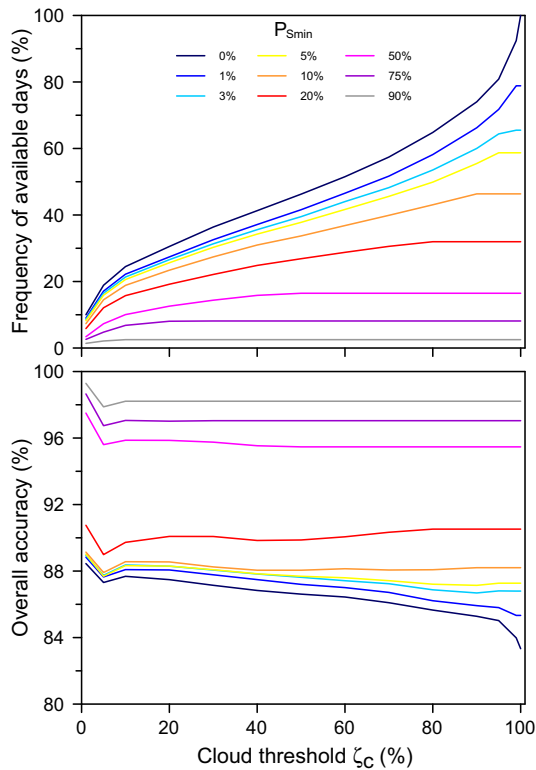


Fig. 6. Sensitivity of cloud (ζ_c) and minimum snow cover (P_{Smin}) thresholds on data availability (top panel) and overall accuracy (k_a , Eq. (5), bottom panel) of RSLE estimation in the upper Váh basin. The overall accuracy is estimated over all climate stations in the period 2000–2013.

3.2. Snow cover observations

The study region represents a typical seasonally snow covered basin in the Carpathian Mountains. Snow cover usually occurs in the period between November and May. Snowmelt starts in the main river valley typically in February and March, while the main snowmelt period in the mountains starts in April (Holko et al., 2011).

The estimation of snowline elevation is based on daily MODIS Terra (MOD10A1, V005) and Aqua (MYD10A1, V005) (Hall et al., 2006) snow cover products in the period February, 2000 to June, 2013. In order to reduce the effects of clouds, both datasets are

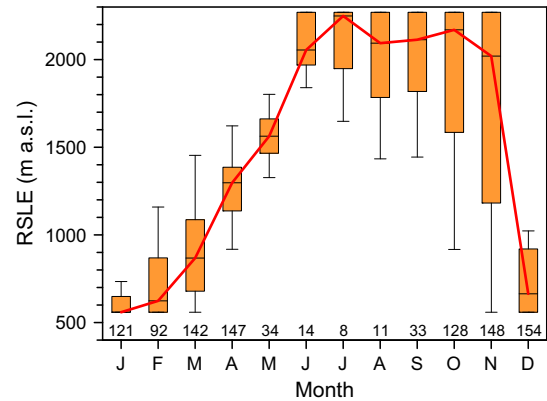


Fig. 7. Seasonal frequency of regional snowline elevation (RSLE) in the upper Váh basin. Box-whiskers plot shows quantiles (minimum, 25-percentile, median, 75-percentile and maximum) of RSLE in the period 2001–2013. Red line indicates median RSLE. Figures above months indicate number of days with determined RSLE. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

merged as described in Parajka and Blöschl (2008). The pixels classified as clouds (pixel value = 50) in the Terra product are replaced by the Aqua product values, if the Aqua classes are snow or land. The merged product is, in this study, termed the combined MODIS product. The merging of Terra and Aqua is performed since the launching of the Aqua satellite in 2002. Before this period, the combined MODIS product is represented by single Terra images. Further information about the processing and reprojecting of the combined MODIS snow cover product for Slovakia is presented in Parajka and Blöschl (2012).

The RSLE methodology is evaluated by snow depth observations at seven climate stations and by additional snow course measurements in the experimental Jalovecky creek basin (Fig. 3, and Table 2). Table 2 indicates the number of days with snow observations at each site and whether the site represents open or forest conditions. The snow depth observations at climate stations are typically performed daily at open grassy plots at 7:00 AM. These are point measurements taken from permanent staff gauges. The additional snow course measurements represent snow depth and snow water equivalent measured along 16 snow course profiles. Each snow profile consists of 20 snow depth measurements conducted along approximately 25 m long transect and one SWE measurement conducted approximately in the middle of the transect. The timing of measurements is selected to capture the

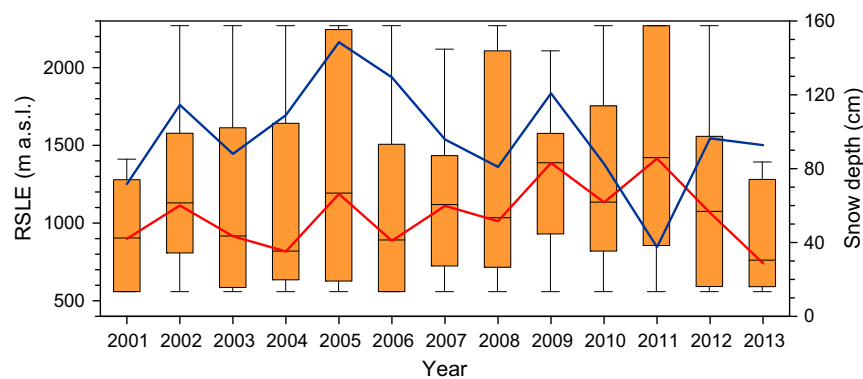


Fig. 8. Inter-annual variability of regional snowline elevation in the upper Váh basin. The box-whiskers plot shows the quantiles (minimum, p25%, p50%, p75% and maximum) of RSLE within a year. Red and blue lines indicate median of RSLE and median of maximum snow depth over all climate stations (Table 1) in March, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

changes in snow accumulation and melt in different altitudinal and vegetation zones, depending on weather conditions and personnel availability (Parajka and Blöschl, 2012).

4. Results

4.1. Selection of cloud and minimum snow cover thresholds

The assessment of relative cloud frequencies in the upper Váh basin is presented in Fig. 5. The left panel (Fig. 5) shows seasonal

frequency of MODIS cloud classes in the period 2000–2013. It is clear that there is a larger cloud coverage in the study area. On average, the clouds cover more than 57% of the study area, however on more than 50% of winter days, the clouds exceed 85%. The assessment of average spatial extent of the clouds (Fig. 5, right panel) indicates that the main river valley is covered by clouds on less than 55%. Larger cloud coverage is observed in mountains, where clouds exceed 65%, particularly on northern slopes.

The assessment of cloud coverage clearly indicates some limits of optical satellite sensors for snow cover mapping. In order to

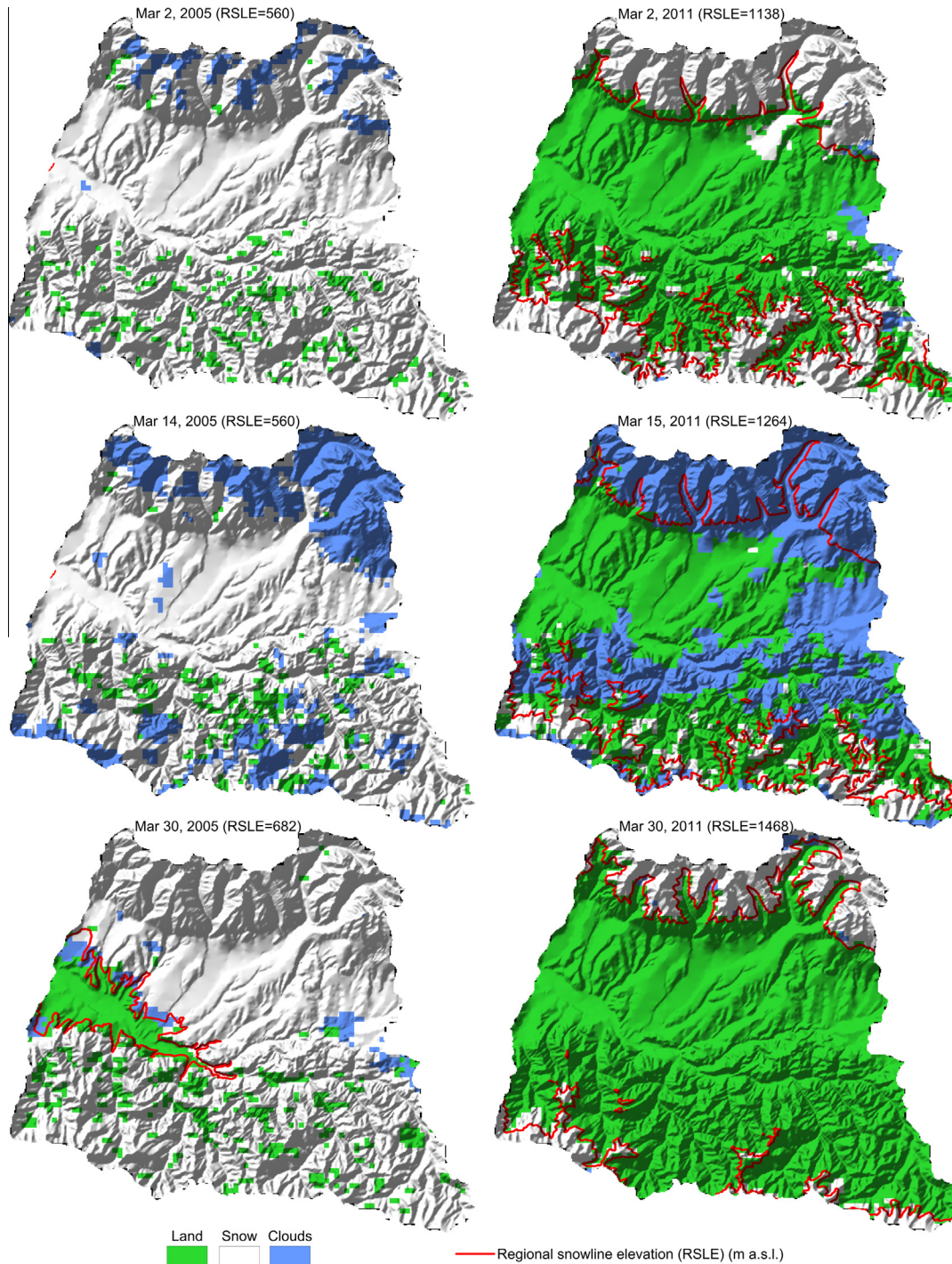


Fig. 9. Maps of snow cover distribution and estimated regional snowline elevation (RSLE, red line) in the upper Váh basin. Maps on the left and right show selected days in March for snow rich (left) and poor (right) winter, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

investigate the effect of clouds on the regional snowline estimation, a sensitivity of different cloud thresholds ξ_c and thresholds indicating minimum snow coverage P_{Smin} on data availability and mapping accuracy is evaluated. The top panel of Fig. 6 shows how different cloud thresholds affect the amount of days available for RSLE estimation. For example, the criterion of using only MODIS images with less than 60% of clouds allows for the estimation of RSLE on approximately 50% of days of the period 2000–2013. If an additional threshold of minimum snow coverage (P_{Smin}) is applied, then the relative frequency of days further decreases, i.e. to 40% if P_{Smin} equals 5%.

The bottom panel of Fig. 6 shows the effect of the choice of cloud thresholds ξ_c on the overall accuracy over all climate stations (k_a). The results indicate that k_a decreases only slightly with increasing ξ_c . On the other hand, k_a is larger for increased P_{Smin} . There is a clear tradeoff of increasing accuracy but decreasing frequency of available data with increasing P_{Smin} and decreasing ξ_c .

Based on this sensitivity assessment, a cloud cover threshold of $\xi_c = 70\%$ and $P_{Smin} = 5\%$ is selected for further RSLE evaluations. This choice allows for the estimation of RSLE and its variability in more than 40% of days with reasonable accuracy.

4.2. Regional snowline elevation variability in the upper Váh basin

The seasonal frequency of regional snowline elevation (RSLE) is presented in Fig. 7. Box-whiskers plot shows quantiles of seasonal variability of RSLE in the period 2000–2013. The median of RSLE is less than 665 m a.s.l. in winter months (December to February), which indicates that almost the whole study area is covered by snow in 50% of the days. As expected, the largest variability in RSLE is in October and November, which are months when seasonal snow cover starts. Occasionally, there is some snow coverage also in summer, but RSLE is typically above 2000 m a.s.l.

The inter-annual variability in RSLE is presented in Fig. 8. The red line shows the median of RSLE in different years, the blue line indicates the median of maximum snow depth in March. Snow cover in March is used as a descriptor whether the winter is rich or poor in snow. Fig. 8 indicates that there is no significant trend in RSLE and maximum snow depth in March in the last 13 years. Snow rich winters (i.e. 2005, 2006 or 2012) tend to have median of RSLE at lower elevations than snow poor winters (i.e. 2011), but the relationship between statistical quantiles of RSLE and snow depth characteristic is not very close. The variability of RSLE (i.e. as described by quantile difference) is not related to the amount of snow in spring, i.e. is large for the richest (2005) as well as the poorest winter (2011).

Examples of typical spatial patterns of snow cover distribution, their seasonal variability and estimated RSLE are presented in Fig. 9. The panels display a different snow cover situation, i.e. cloud conditions and snowline elevation in March for a snow rich (Fig. 9, left panels) and poor (Fig. 9, right panels) winter. MODIS clearly indicates almost the whole basin as snow covered in the beginning of March 2005. There are only a few pixels classified as land, but estimated RSLE equals minimum elevation of the basin. In the middle of March, the amount of land pixels slightly increases particularly at the southern slopes, but the RSLE remains at minimum elevation and there is some typical cloud coverage covering the highest parts of the area. By the end of March 2005, snow has melted in the main valley and RSLE increases to higher elevation. On the other hand, on March 2, 2011, there is snow only in the upper part of the basin, i.e. above approximately 1100 m a.s.l., as also indicated by the RSLE. The clouds in the middle of March do not allow the precise estimation of RSLE, particularly in the northern part of the basin. By the end of March 2011, snow occurs only at higher elevation, but the snowline very closely follow the topography with minimum scatter around RSLE.

As indicated in example maps (Fig. 9), there is always some scatter of snow or land pixels, which are below or above the RSLE. The relative frequency of these pixels in different seasons is evaluated in Fig. 10. The green and purple lines show the average monthly frequency of P_L and P_S pixels, respectively. A comparison of the number of land pixels above and snow pixels below RSLE indicates a different seasonal distribution. The P_L frequencies are small in summer months but increase to more than 10% in the December–February period. On the other hand P_S gradually increases from January to November and then it drops to less than 2%. As expected, the index of scatter (I_S) is larger during the onset of snow accumulation than during the snowmelt period or in the summer. The average I_S is 12%, which means that there is on average 12% of pixels scattered around the snowline. The largest I_S is observed in November and December, where the median I_S somewhat exceeds 15%. The lowest scatter (the median below 7%) is between June and August. It should be noted, however, that the number of days with snow cover and estimated RSLE is significantly lower in summer than in winter months.

The spatial patterns of the P_L and P_S frequencies are presented in Fig. 11. Most of the scatter is clearly observed in the southern part of the basin (bottom part of the maps) where P_L and P_S frequencies exceed 20% and 10%, respectively. The spatial distribution of forest cover and evaluation of the scatter for the forest and open areas (Fig. 12) indicates, that most of the scatter is observed for forested parts of the basin. The median of P_S and P_L is 7%, which is noticeably larger than the median for open areas (less than 2%). The larger frequency of P_L , observed particularly in the forested southern part, corresponds well with the lower values of potential insolation duration in winter. This indicates that the lower agreement of RSLE with elevation might also be affected by misclassification of snow in forested regions shaded by local topography. The largest P_L values are observed for pixels with potential insolation duration less than 2 h per day in the winter months.

4.3. Assessment of regional snowline elevation accuracy

The evaluation of the accuracy of the RSLE method at selected climate stations and snow course measurements (Table 2) is presented in Fig. 13. In general, the overall accuracy (k_a) tends to increase with increasing elevation of stations and snow courses. The k_a for climate stations varies between 73% (station Ziarska dolina, 900 m a.s.l.) and 92% (Kasprov vrch, 1987 m a.s.l.). The

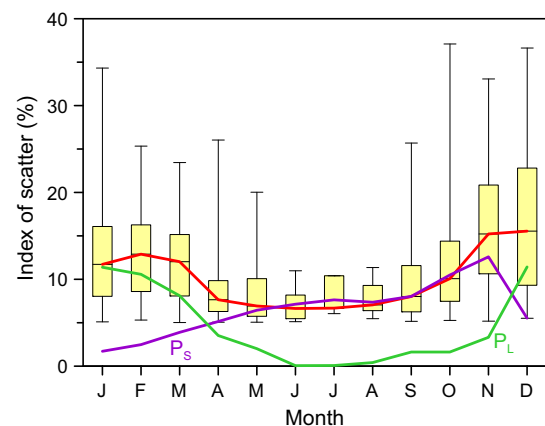


Fig. 10. Seasonal frequency of scatter, i.e. relative number of snow pixels below (P_S , purple line) and land pixels above (P_L , green line) the regional snowline elevation. Index of scatter (I_S) is estimated for the upper Váh basin in the period 2000–2013. Median of I_S is displayed by a red line. P_S and P_L lines represent monthly average of relative frequency. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

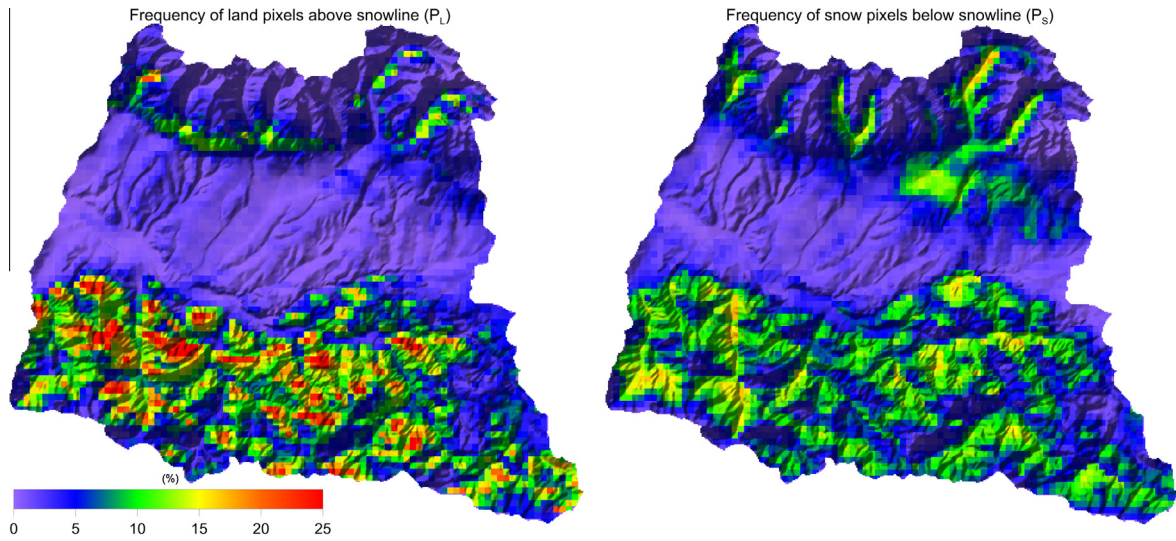


Fig. 11. Spatial patterns of the relative number of snow (P_s , right panel) and land (P_L , left panel) pixels below and above regional snowline elevation in the upper Váh basin in the period 2000–2013.

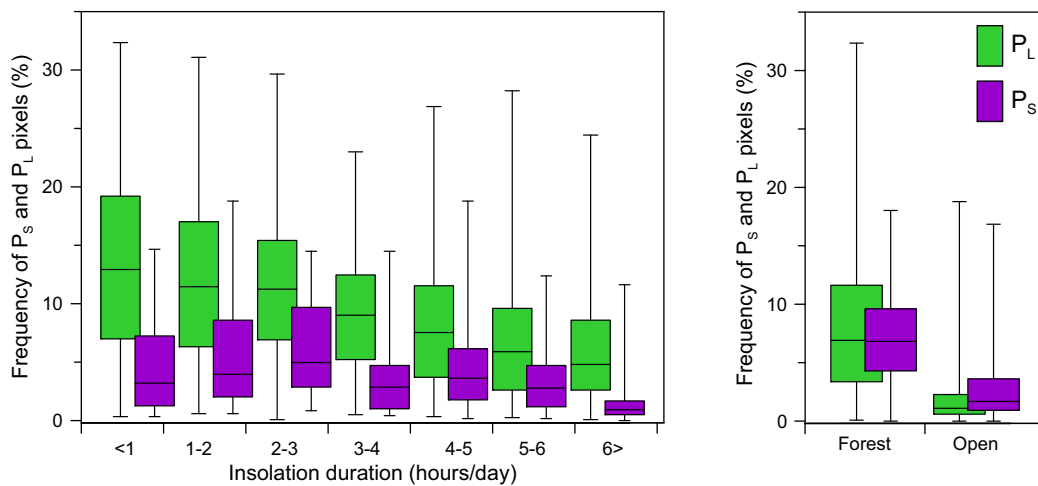
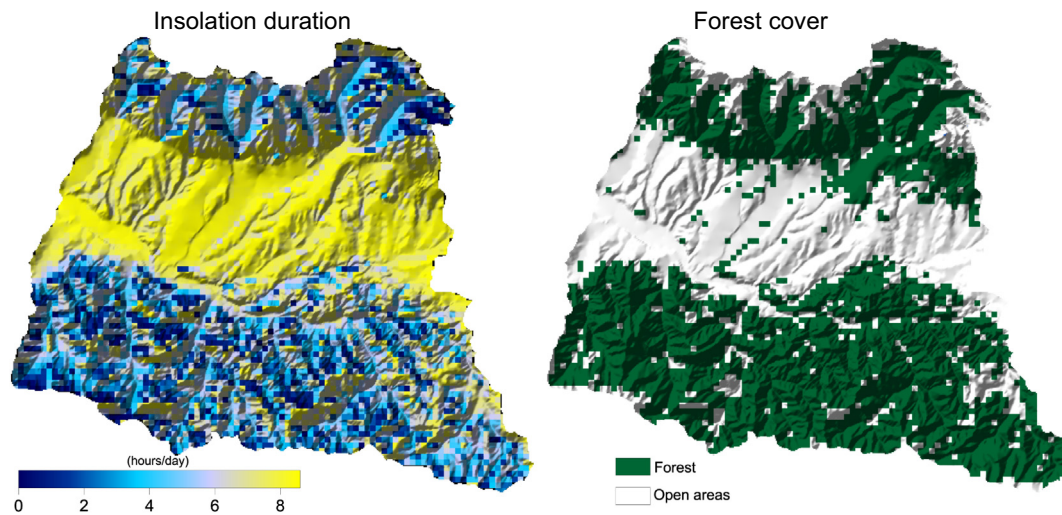


Fig. 12. Forest cover map (top right panel) and map of potential insolation duration (top left panel) in winter months (December to February). The evaluation of the relative number of snow (P_s) and land (P_L) pixels below and above regional snowline elevation is shown for different classes of insolation duration (bottom left panel) and forest and open areas (bottom right panel). Potential insolation duration was calculated by the r.sun module of Grass GIS (Hofierka and Šúri, 2002).

accuracy is larger at open sites, where it exceeds 90%. Interestingly, the accuracy in the forest is comparable to that at climate stations, and exceeds 82% for most of the snow courses. It should be noted, however, that in comparison to climate stations, the snow course measurements are much less frequent and are available only for the snowmelt period.

The seasonal variability of the k_a is presented in Fig. 14. Fig. 14 shows that the RSLE accuracy is the largest in winter months and tends to be larger for snowmelt than the snow onset period. The median k_a is larger than 90% in January, February and March and around 80% in October and November. This is likely related to some extent to the lower accuracy of MODIS snow product and to the less close relationship between snow cover and elevation in November (i.e. as documented by larger scatter, Fig. 10) than it is at the end of the snowmelt season. When comparing seasonal accuracy of RSLE at profile snow measurements, the results (not shown here) show that the k_a is almost 100% at most of the profiles (open and forested sites) in January and February and some decrease of accuracy is observed mainly in April. Part of this difference is likely related to patchy snow conditions at the end of snowmelt seasons, as it is already indicated by Parajka and Blöschl (2012).

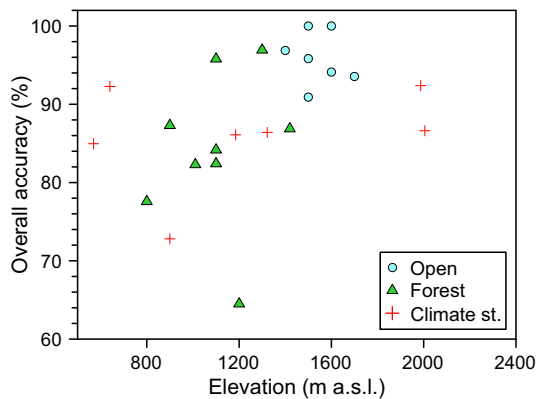


Fig. 13. The overall accuracy of the regional snowline elevation method. Blue circles, green triangles and red crosses represent the open, forested areas and climate stations, respectively. The graph shows the relationship between the overall accuracy and elevation of snow measurements. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

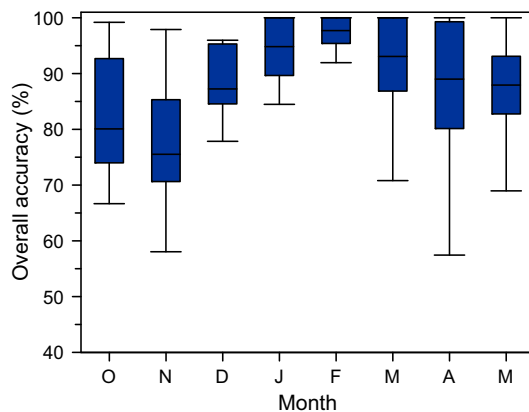


Fig. 14. The overall accuracy of regional snowline elevation method at seven climate stations (Table 1) in the upper Váh basin. Box-whisker plot shows minimum, 25%, 50%, 75%-percentiles and maximum of overall accuracy in different months of the period 2000–2013.

5. Discussion and conclusions

This study proposes a methodology for estimation of regional snowline elevation (RSLE) from satellite images for basins with seasonal snow cover. The approach is tested and evaluated in a mountain basin in central Slovakia, which represents the typical climate and physiographic conditions of the Carpathian Mountains.

The analyses are based on combined daily MODIS snow cover product. The snow mapping accuracy of this product is large, as has been evaluated and documented in numerous studies (i.e. Parajka et al., 2010a,b). The main limiting factor of MODIS application is cloud coverage, which is particularly large in mountain regions. The median of cloud frequency in the analyzed region exceeds 85% in the winter months, which is very similar to cloud frequencies found in MODIS assessments in the Austrian Alps (Parajka and Blöschl, 2006) and Po river basin in Italy (Da Ronco and De Michele, 2014). A sensitivity analysis indicates a clear tradeoff between increasing cloud threshold and increasing number of days (satellite images) available for RSLE estimation. Increasing of cloud threshold, however, does not affect the accuracy very much. The accuracy is more sensitive to the threshold of the minimum number of pixels classified as snow. Increasing this threshold improves the snowline elevation accuracy with respect to snow observations. The final thresholds for acceptable cloud coverage and minimum snow pixels are set to 70% and 5%, respectively, which is consistent with studies looking on reducing clouds in satellite products (Gafurov and Bárdossy, 2009; Parajka et al., 2010b).

The choice of the thresholds is a multi-objective problem. It depends on weights given to different objectives (accuracy and amount of available days) by the user. The minimum snow pixels threshold 5% is selected because it provides a relatively high number of days available for the analysis of snow line elevation seasonal variability (more than the 10% threshold). At the same time the accuracy of snow line estimation is larger than for the 3% threshold. If one would be interested in more accurate RSLE estimation, i.e. only for cloud-free days in the period of maximum snow storage, the choice for cloud and the minimum number of snow pixel thresholds might be lower and larger, respectively.

The overall accuracy (k_a) of RSLE estimated at climate stations ranges between 73% and 92%, with an average k_a of 86% in the upper Váh basin. This is about 14% larger than k_a obtained by the snowline elevation estimation method of Parajka et al. (2010b) or Da Ronco and De Michele (2014). Importantly, the RSLE is not only more accurate than these methods, but also decreases the scatter around the snowline. When estimating the snowline from the mean elevation of snow and land pixels, there are about 21% cases in the upper Váh basin when some part of the area (pixels) is located below the snowline, but above the landline elevation at the same time. In these cases, the methodology of Parajka et al. (2010b) does not allow one to uniquely estimate snowline elevation, whereas the new iterative approach does. We plan to test and evaluate the implementation of RSLE for cloud reduction in MODIS products in the near future.

The analysis of the factors that control the variability and scatter of snowline elevation indicates that the scatter is larger in forested areas and areas shaded with surrounding terrain, particularly during winter months. This is likely a result of darker conditions caused by the shading of terrain and vegetation cover. Partly, it also reflects the natural difference in snow cover distribution in mountain terrain caused by the different distributions of energy fluxes and snow redistribution. The comparison of RSLE accuracy in the forest indicates a good agreement with the snow profile measurements. The average k_a is 92% in the forest for the period January to March. Some differences are observed only at the end

of snowmelt seasons, when snow cover tends to be patchy and the average k_a drops to 70%. This is consistent with 93% accuracy of MODIS in Jalovecky creek basin (Parajka and Blöschl, 2012), which uses the same snow profile measurements for evaluation.

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