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# Validation of VIIRS snow cover in Central European Highlands

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**Abstract.** The Moderate Resolution Imaging Spectroradiometer (MODIS) is one of the most attractive remote sensing datasets used for mapping snow cover. The MODIS product is expected to be replaced by the Visible Infrared Imaging Radiometer Suite (VIIRS) snow cover product in the near future. Therefore, a reliable and accurate evaluation of this product is needed for future hydrological applications. This study aims to assess the mapping accuracy of the VIIRS snow product at the regional scale (i.e., at 631 climate stations in Austria) and within a small experimental catchment, the Jalovecký Creek catchment in northern Slovakia, using extensive snow course measurements conducted at both open and forested sites between January 2012 and December 2020. In the VIIRS snow cover product, the Normalized Difference Snow Index (NDSI) is used to detect snow. A threshold of NDSI ($T_{NDSI}$) is needed for distinguishing snow from snow-free land. Based on the daily snow depth observations from climate stations/snow course locations, the optimal NDSI threshold ($OT_{NDSI}$) is first determined through a detailed sensitivity test (100 different $T_{NDSI}$ from 1 to 100 with a step of 1). The overall accuracy (OA) of VIIRS data is then evaluated based on the $OT_{NDSI}$. The assessment of the $OT_{NDSI}$/OA is performed for all climate stations/snow profiles, as well as for different groups of stations/snow profiles representing different physiographic and land cover conditions.

The findings demonstrate that the classification accuracy for 631 Austrian stations using the optimal thresholds ranges from 52.3% to 99.3%, with a median of 92.5%. The NDSI thresholds vary seasonally and decrease with increasing elevation. The NDSI thresholds fitted to different months and elevations show the smallest differences to $OT_{NDSI}$ in overall accuracy. The NDSI thresholds fitted to different elevations improve regional snow cover mapping by 1.5% between 900 – 1200 m a.s.l. and by 3.1% above 1200 m a.s.l. At the catchment scale, the difference is found between open and forested sites, where the mapping accuracy is lower in the forest. VIIRS enables snow mapping accuracy from 71.5 to 95.9% at the open site (during winter, median OA is up to 98.8%) and from 58.1 to 93.7% at the forest site (during winter, median OA is up to 91.5%). The overall accuracy at the site with the most measurements is 95.9% (Červenec – open site) and 93.7% (Červenec – forest site), respectively. The accuracy at the forest is more sensitive to seasonal variation compared to the open area, where the accuracy is more stable and accurate across the year.

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## 1 Introduction

Many studies have shown that satellite data on snow cover help to understand and simulate the water cycle, particularly snow accumulation and melt (e.g., Parajka and Blöschl, 2006, 2008; Parajka et al., 2012; Krajčí et al., 2014, 2016; Tong et al., 2020). MODIS from the Terra satellite is one of the most widely used snow cover products in hydrological research (Román et al., 2024). However, the mission is going to end, with the Terra satellite entering a new orbit that will affect data quality. The VIIRS (Visible Infrared Imaging Radiometer Suite) sensor installed on the Suomi NPP satellite is designed to be a successor to MODIS (Skakun et al., 2018; Riggs et al., 2019), but its accuracy and the factors that control its performance are still not well understood.

The most common way to classify snow cover from optical remote sensing is based on a Normalized Difference Snow Index (NDSI). The NDSI represents a difference in reflectance between visible and shortwave infrared light, which enables an effective mapping of snow cover and distinguishing it from clouds, vegetation, or bare soil. The existing global snow cover products either provide snow classification based on a fixed NDSI threshold (Härer et al., 2018), or the NDSI threshold needs to be estimated by the user (Zhang et al., 2020; Tong et al., 2020). A typical threshold value for mapping snow is 0.4, but various studies have evaluated the mapping accuracy across a range of values. For instance, Wang et al. (2010) indicated that the NDSI threshold of 0.36 was optimal for MODIS snow cover data in the upper Heihe River basin (China). According to Zhang et al. (2019), the NDSI threshold of 0.10 is reasonable for detecting snow using MODIS data in China. Da Ronco et al. (2020) found that a NDSI threshold of 0.20 is optimal for seven stations in Italian Alpine catchments. Tong et al. (2020) showed that an NDSI threshold of 0.4 provides reliable estimates of snow cover from MODIS data in Austria. Studies have indicated that the optimal Terra MODIS threshold changes according to altitude and season, affecting mapping accuracy (Da Ronco et al., 2020; Tong et al., 2020). With this threshold, mapping accuracies of 0.81 (F-score) in China (Zhang et al., 2019), 97.4% in Austria (Tong et al., 2020), and 89% in Italy (Da Ronco et al., 2020) have been reported. However, the optimal thresholds and their impact on VIIRS snow cover mapping accuracy remain poorly understood.

The main objective of this study is to analyse and estimate the optimal NDSI threshold for VIIRS and its impact on snow cover mapping accuracy. We aim to test the snow cover mapping over the Central European Highlands by assessing the mapping accuracy: (1) at the regional scale using daily snow depth observations at 631 climate stations across Austria, and (2) at the small catchment scale using snow course measurements in the forest and open locations within an experimental mountain catchment (the Jalovecký Creek catchment in the Western Tatra Mountains).

The paper is organized as follows: The data section provides details about the study region (Austria vs experimental mountain catchment situated in the Western Tatra mountains) and the dataset (VIIRS snow cover data, snow depth measurements at climate stations/snow courses) used in the study. The method section defines the strategy adopted for comparing VIIRS snow cover data with ground observations. The result section compares the optimal NDSI thresholds/overall VIIRS accuracy at climate stations and land cover classes. The factors that influence the VIIRS mapping accuracy are then discussed in the Conclusions and discussion section.

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## 2 Data

### 2.1 Study area

The study is performed at two scales – regional and more detailed, i.e., catchment scale (Fig. 1). At the regional scale, Austria is selected as the study region. Austria is located in Central Europe and has an area of about 84000 km$^2$. This region is Alpine (mountainous) in the west and south, and flat in the east and north. The elevation ranges from < 200 m a.s.l. to > 3000 m a.s.l. Mean annual precipitation ranges from 400 to 3000 mm/year. Land cover is dominated by agriculture in lowland areas and tree cover in the medium elevation ranges. Alpine vegetation prevails in catchments in the Alps. The varied physiographic and landscape characteristics of Austria suggest that this territory serves as a representative example of a broader geographic area, making the results relevant to other regions with similar conditions.

At the catchment scale, the VIIRS accuracy is tested in the Jalovecký Creek catchment (Fig. 1). This catchment is an experimental catchment of the Institute of Hydrology, Slovak Academy of Sciences. It lies in northern Slovakia, in the highest part of the Carpathians. Hydrological research in the catchment started in 1986, and its main aim is to improve understanding about the water balance components and snow cover variability in the mountain environment (Holko et al., 2021). This well-documented, forested mountain catchment serves as a natural laboratory in which the course of hydrological processes and snow cover evolution can be studied in detail (Holko and Kostka, 2006, 2008; Holko et al., 2020; Parajka et al., 2012; Danko et al., 2015; Krajčí et al., 2016). Catchment size is 22.2km$^2$ and elevation ranges between 820 and 2178 m a.s.l. The catchment's mean altitude is 1500 m a.s.l. Catchment mean annual precipitation (study period 2012 – 2020) is 1467 mm, mean annual runoff is 1048 mm, and mean annual air temperature at catchment mean elevation is 3.5 °C. The main soil types are cambisols, podzols and lithosols. Rendzinas occur on Mesozoic rocks. All soils have a high skeleton content, often reaching values of 40–50% and more (Hlaváčiková et al., 2019). Forest (mostly spruce), dwarf pine, and alpine meadows, including bare rocks on the steepest slopes, cover 44, 31, and 25% of the catchment area, respectively. Most of the forest is over 100 years old. Since the catchment is situated in the Tatra National Park, human activities are restricted to tourism only.

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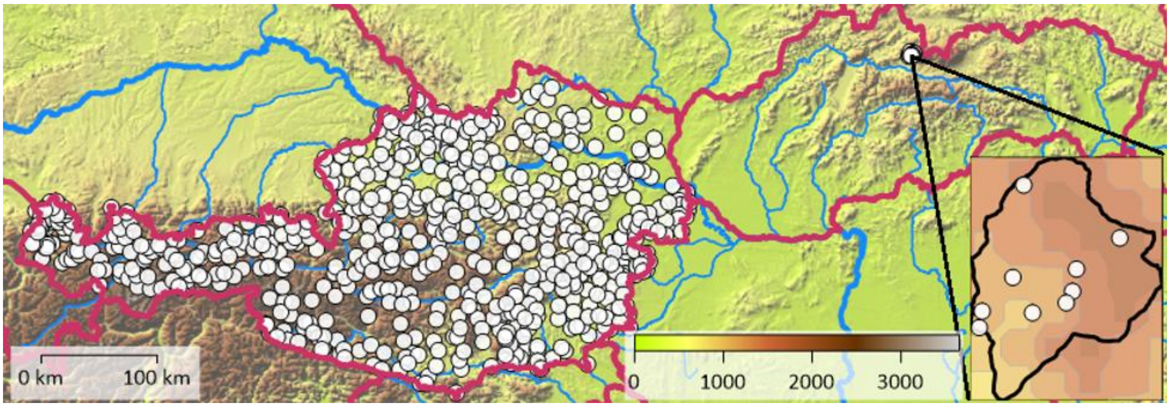


90 **Figure 1: Topography of Austria and Slovakia, location of 631 climate stations with daily snow depth measurements and 9 snow profiles used for VIIRS data assessment.**

## 2.2 VIIRS snow cover dataset

The Visible Infrared Imaging Radiometer Suite (here referred to as "VIIRS") snow cover dataset is evaluated in this study. VIIRS is a multispectral sensor located on the Suomi NPP (launched in 2011) and NOAA-20 (launched in 2017) satellites. It is the successor to the MODIS instrument and plays an important role in Earth monitoring, including snow cover mapping (Zhang et al., 2020). VIIRS datasets are accessible at 375 m spatial resolution, providing improved spatial detail compared to MODIS. VIIRS records data in 22 spectral bands, including visible, near-infrared, and thermal infrared, enabling detailed detection of snow cover via the Normalized Difference Snow Index (NDSI) in combination with brightness temperature thresholds and spatial filters. The NDSI is calculated using the reflectance difference between the green (~0.55 µm) and shortwave infrared (SWIR, ~1.6 µm) bands, and in the VIIRS snow product, it is estimated as:

$$\mathrm{NDSI} = (\mathrm{Green} - \mathrm{SWIR}).100/(\mathrm{Green} + \mathrm{SWIR}) \quad \text{(Eq. 1)}$$

where Green and SWIR represents the reflectance in the green and shortwave infrared bands.

Snow has a high reflectance in the green band and a low reflectance in the SWIR – this is used to distinguish it from clouds, water, or vegetation. If the NDSI value exceeds a certain threshold, the pixel is classified as snow-covered. The values of NDSI are in the VIIRS product, given in the range between 1 to 100. More details of the VIIRS snow cover data are described in the VIIRS Snow Products User Guides (Riggs et al., 2016; Riggs et al., 2019).

### 2.3 Daily snow depth measurements at climate stations

Daily snow depth data during 1 January 2012 – 31 December 2020 from 631 climate stations across Austria are used to validate the VIIRS dataset. Figure 1 shows the geographic distribution of these climate stations. The snow depth measurements cover a broad range of elevation zones across the country. However, in high alpine regions, the stations are generally situated at lower elevations, usually within valleys. The observations are available at the data portal of the Hydrographic Service of Austria (https://ehyd.gv.at/). The snow depth observations at climate stations are performed daily at 7:00 AM. These are point measurements taken from permanent staff gauges (HZB, 1992). Before the processing, all data have been well quality controlled, and gaps longer than 5 years occurred only for 10 stations (Tong et al., 2020).

### 2.4 Snow measurements in Jalovecký Creek catchment

Expeditionary manual measurements have been conducted in the Jalovecký Creek catchment since 1987 to obtain snow data (depth, water equivalent) for evaluating snow cover variability (Holko and Kostka, 2008; Danko et al., 2015; Holko et al., 2021). Such long-term measurements carried out in this catchment are not commonly measured in headwater mountain catchments in Slovakia. Spatial and temporal variability of snow depth and snow water content within the catchment are measured at snow courses located at different elevations (750 – 1900 m a.s.l.). Fortnightly measurements are carried out at the catchment mean elevation at the open site Červenec (1500 m a.s.l.) and in the nearby forest (1420 m a.s.l.) during the snow accumulation period. Weekly or more frequent measurements are carried out there during the snowmelt period. Measurements at other snow courses located at altitudes between 750 and 1900 m a.s.l. are conducted at the end of January, February, and March. The timing of measurements is selected to capture the changes in snow accumulation and melt in different altitudinal and vegetation zones (Parajka and Blöschl, 2012). 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.

## 3 Methods

Based on daily observations of snow depth from 631 climate stations and 9 snow profiles, the optimal NDSI threshold ($OT_{NDSI}$) with the highest mapping accuracy is determined for VIIRS snow cover data through a detailed sensitivity test. We tested 100 different thresholds ($T_{NDSI}$) from 1 to 100 with a step of 1. The procedure is repeated for snow depth threshold $T_{SD}$ = 0 cm. The snow depth observations from stations/snow course locations are directly compared with the snow cover data of the VIIRS pixels where the stations/snow courses are located. A commonly used confusion matrix (Tab. 1) is adopted for comparing VIIRS snow cover data with ground observations. The overall degree of agreement between VIIRS and snow depth measurements is represented by an accuracy index of overall agreement (OA), defined as follows:

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$$OA = \frac{A + B}{A + B + C + D} \cdot 100\% \qquad \text{(Eq. 2)}$$

where A, B, C, D represent the number of cloud-free days in each of the category of confusion matrix (Table 1).

Tab. 1 Confusion matrix defining the snow cover mapping accuracy (OA). $T_{NDSI}$ is the VIIRS NDSI threshold and $T_{SD}$ represents the snow depth threshold at the climate stations/snow profiles.

| | VIIRS NDSI > = $T_{NDSI}$ (SNOW) | VIIRS NDSI < $T_{NDSI}$ (LAND) |
|---|---|---|
| Station snow depth > =$T_{SD}$ (SNOW) | A | B |
| Station snow depth < $T_{SD}$ (LAND) | C | D |

The assessment of the $OT_{NDSI}$ is performed for all individual climate stations/snow profiles, as well as for different groups of stations/snow profiles representing different physiographic and land cover conditions, as well as for the group that includes all stations. The classification of different elevation groups is based on previous snow cover and hydrological evaluations in Austria (Parajka and Blöschl, 2006; Parajka et al., 2009; Tong et al., 2020). Land cover classes within the experimental mountain catchment are represented by open and forest sites (Parajka et al., 2012). The $OT_{NDSI}$ is evaluated for the entire period as well as for individual seasons: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February).

## 4 Results

### 4.1 The optimal NDSI threshold

#### 4.1.1 The optimal NDSI threshold at climate stations

The most optimal NDSI threshold for snow cover mapping found for the group that includes all climate stations is 40. Compared to the optimal threshold fitted to the entire group of stations, Fig. 2 shows the variability of the optimal threshold ($OT_{NDSI}$) fitted individually to each climate station and a month. The results of the optimal thresholds in individual stations are in Fig.2 grouped into five selected elevation zones. While a group of stations situated at altitudes equal to or lower than 900 m a.s.l. is representative for lowland and hilly regions, a group of stations above 900 m a.s.l. is representative for mountains. We can see that the $OT_{NDSI}$ thresholds decrease with increasing elevations. The median of $OT_{NDSI}$ for stations below 300 m a.s.l. and above 1200 m a.s.l. is from 81 to 100, and from 12 to 100, respectively. The $OT_{NDSI}$ thresholds vary seasonally, i.e., lower $OT_{NDSI}$ values are observed in winter months (i.e., December–February) and highest values in the summer months (June–August). The median winter $OT_{NDSI}$ for stations below 300 and above 1200 m a.s.l. ranges from 81 to 100 and from 12 to 34, respectively. In spring (March–May), thresholds increase compared to winter. For stations below 300 m a.s.l., the median

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values remain high ($OT_{NDSI}$ = 100). For stations above 1200 m a.s.l., the median $OT_{NDSI}$ increases from 18 in March to 100 in April–May, indicating a rapid seasonal transition. Over the autumn months (September–November), thresholds are high across all elevation zones. A decrease occurs in November, particularly at higher elevations, where the median $OT_{NDSI}$ decreases to 34 above 1200 m a.s.l., indicating the start of snow cover.

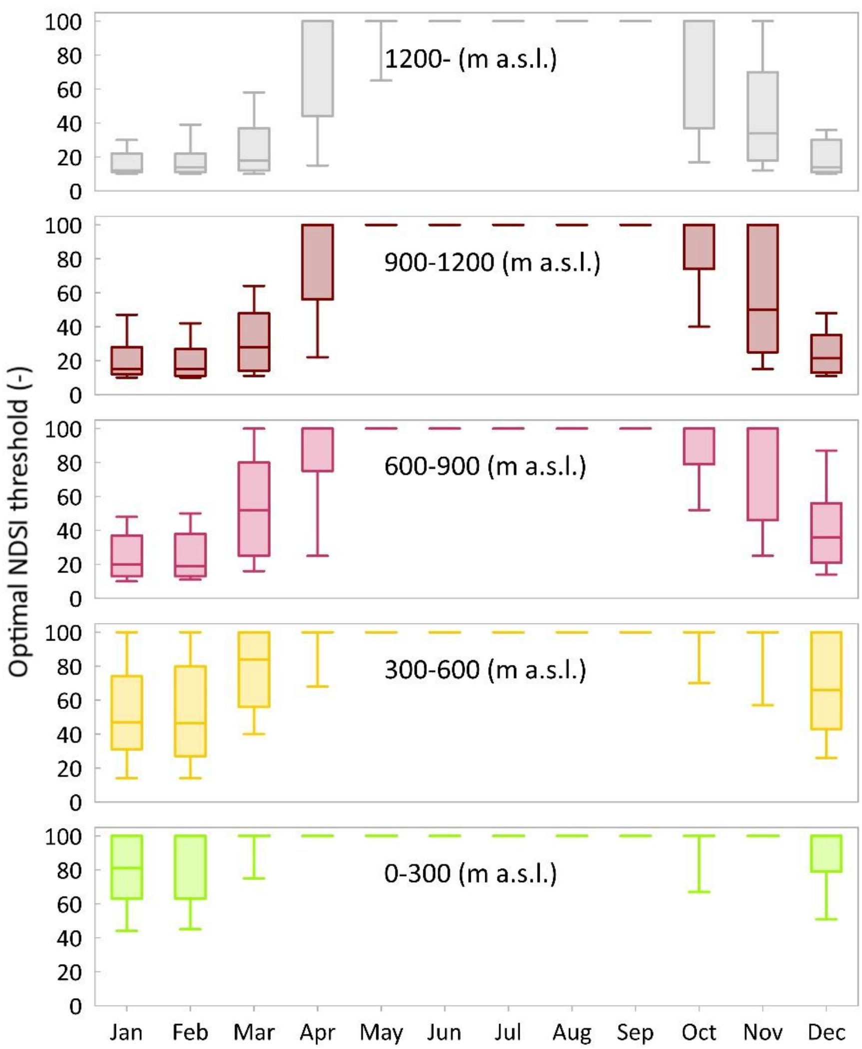


**Figure 2: Variability of the optimal NDSI threshold in different months and elevation groups of the 631 Austrian stations for VIIRS in the period from January 2012 to December 2020.**

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The variability of the optimal threshold ($OT_{NDSI}$) for snow cover mapping, fitted for each climate station in five elevation groups, is presented in Fig. 3. The evaluation shows that the $OT_{NDSI}$ and its magnitude tend to decrease with increasing altitude of the climate stations. The median of $OT_{NDSI}$ for stations below 300 m a.s.l. and above 1200 m a.s.l. is 100 and 11, respectively. A more pronounced decrease in median $OT_{NDSI}$ is seen between stations located in the lowlands (<300 m a.s.l., median 100) and stations at mid-altitudes (600–900 m a.s.l., median 25). Above 900 m a.s.l., the decrease in thresholds is less pronounced, with a small difference between the 900–1200 m a.s.l. (median 15) and >1200 m a.s.l. (median 11) elevation groups. This suggests that $OT_{NDSI}$ values are relatively stable at higher elevations, while differences exist between stations in the lowlands and mid-altitudes.

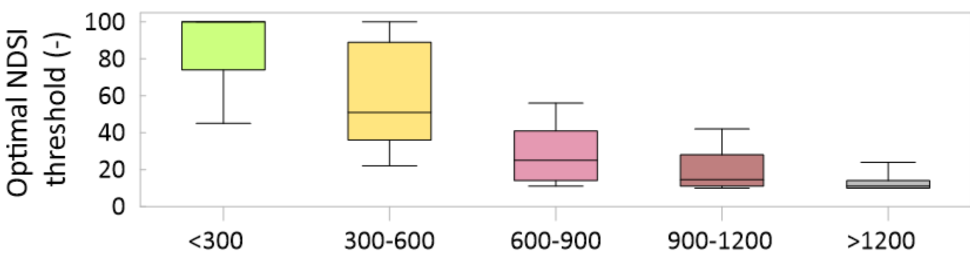


**Figure 3: Variability of the optimal NDSI threshold in different elevation groups of the 631 Austrian stations for VIIRS in the period from January 2012 to December 2020**

In contrast to the previous assessment that evaluates the thresholds fitted for individual stations in different months or elevations, Table 2 and 3 and Figure 4 present a single threshold fitted separately only for individual months (Fig. 4 top) or only to the elevation groups of stations (Fig. 4 middle) or their combination (i.e. fits to months and elevation, Fig. 4 bottom). The thresholds in each group are fitted to maximize the overall accuracy in individual months, elevations, and their combination (i.e., months and elevation groups together).

Figure 4 (top) indicates that there is a distinct difference between lower $OT_{NDSI}$ values (10 – 88 from) fitted for the winter months and the highest threshold values ($OT_{NDSI}$ = 100) in the summer months. The $OT_{NDSI}$ tends to be larger (97 – 100) for stations <600 m a.s.l. For the group of stations situated at altitudes >600 m a.s.l. the $OT_{NDSI}$ values vary from 10 to 30 (Fig. 4, middle).

Fig. 4 (bottom) clearly shows that the thresholds vary seasonally and also with altitude. In lower elevations (<300 m a.s.l.), they are stable throughout the year and mostly reach maximum (96–100). With increasing altitude in the winter months, thresholds decrease, while in stations >1200 m a.s.l. they decrease to a minimum ($OT_{NDSI}$ = 10) in January and February. During the spring months, thresholds are higher at high-elevation stations. In the autumn (October–November), thresholds

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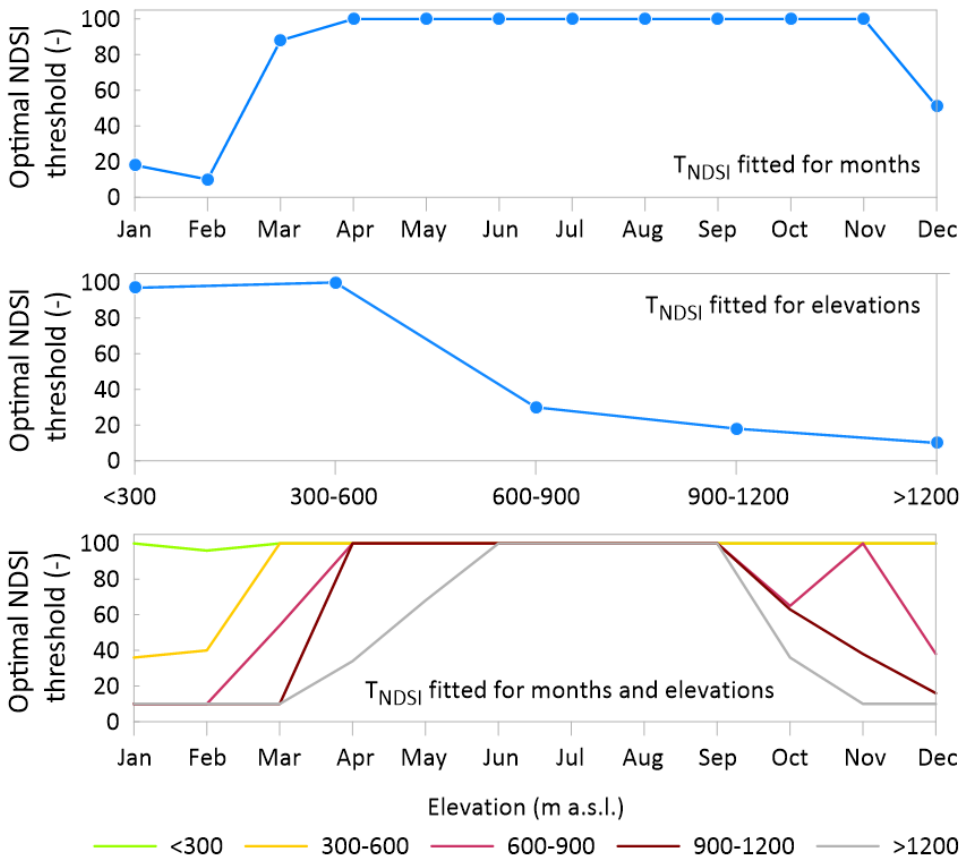
decrease, especially at higher altitudes. In November and December, $OT_{NDSI}$ values at high altitudes return to the winter minimum, while at lower altitudes they remain high.




215 **Figure 4: Single optimal NDSI threshold fitted separately for individual months (top panel), elevation groups (middle panel), or months and elevation groups together of Austrian stations in the period from January 2012 to December 2020.**

Tab. 2. Threshold fitted separately for individual months or elevation groups of 631 Austrian stations

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $OT_{NDSI}$ | 18 | 10 | 88 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 51 |
| Elevation | <300 | 300-600 | 600-900 | 900-1200 | >1200 | | | | | | | |
| $OT_{NDSI}$ | 97 | 100 | 30 | 18 | 10 | | | | | | | |

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Tab. 3. Threshold fitted for individual months and elevation groups together of 631 Austrian stations

| | Elevation (m a.s.l.) | | | | |
|---|---|---|---|---|---|
| Month | <300 | 300-600 | 600-900 | 900-1200 | >1200 |
| January | 100 | 36 | 10 | 10 | 10 |
| February | 96 | 40 | 10 | 10 | 10 |
| March | 100 | 100 | 54 | 10 | 10 |
| April | 100 | 100 | 100 | 100 | 34 |
| May | 100 | 100 | 100 | 100 | 68 |
| June | 100 | 100 | 100 | 100 | 100 |
| July | 100 | 100 | 100 | 100 | 100 |
| August | 100 | 100 | 100 | 100 | 100 |
| September | 100 | 100 | 100 | 100 | 100 |
| October | 100 | 100 | 65 | 63 | 36 |
| November | 100 | 100 | 100 | 38 | 10 |
| December | 100 | 100 | 38 | 16 | 10 |

#### 4.1.2 The optimal NDSI threshold for open and forest sites

Variability of optimal threshold ($OT_{NDSI}$) for snow cover mapping fitted for each snow profile at different land cover classes (i.e., open and forest sites) is depicted in Fig. 5. The Figure indicates that the $OT_{NDSI}$ are larger for open site compared to forest. Seasonal pattern of the optimal thresholds shows lower $OT_{NDSI}$ values in winter months and forest site. During the winter and spring months, thresholds are relatively low, ranging from 12 to 41 at the open site and from 11 to 14 at the forest site. From June to October, the $OT_{NDSI}$ values reach their maximum 100. In November and December, the thresholds drop back to lower values (12–18 open site, 10–11 forest site).

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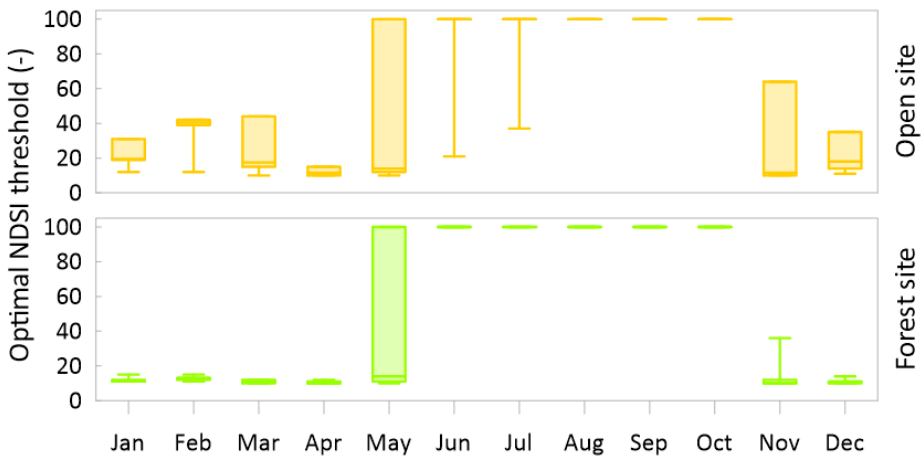


**Figure 5: Variability of the optimal NDSI threshold in months and land cover classes (open and forest sites) for VIIRS in the period from January 2012 to December 2020.**

### 4.2 Mapping accuracy

#### 4.2.1 Mapping accuracy at climate stations

The median VIIRS accuracy obtained for the optimal thresholds over 631 stations is 92.5%. The evaluation of seasonal variability of mapping accuracy for the optimal thresholds fitted in individual stations is presented in Fig. 6. The comparison indicates that there is a decrease in the overall accuracy as the elevation of the stations increases. The mapping accuracy has a strong seasonal variability. In winter, the accuracy is lower, especially at stations at higher altitudes (OA from 58 to 62% at stations above 1200 m). The lowest median accuracy (58%) in winter is found for stations above 1200 m a.s.l., particularly in January (58%) and February (59%). For stations < 300 m, the accuracy remains relatively high (81 – 93%), but decreases with increasing altitude. At the beginning of the spring season, the accuracy is from 40 (stations above 1200 m) to 98% (stations below 300 m), but from April it reaches almost 100% in all elevation zones. In summer, the accuracy is highest and stable across all altitudes. In autumn, the accuracy is still very high (especially at stations up to 900 m), but at higher-elevation stations it starts to decrease already in November, which indicates the influence of early snowfall.

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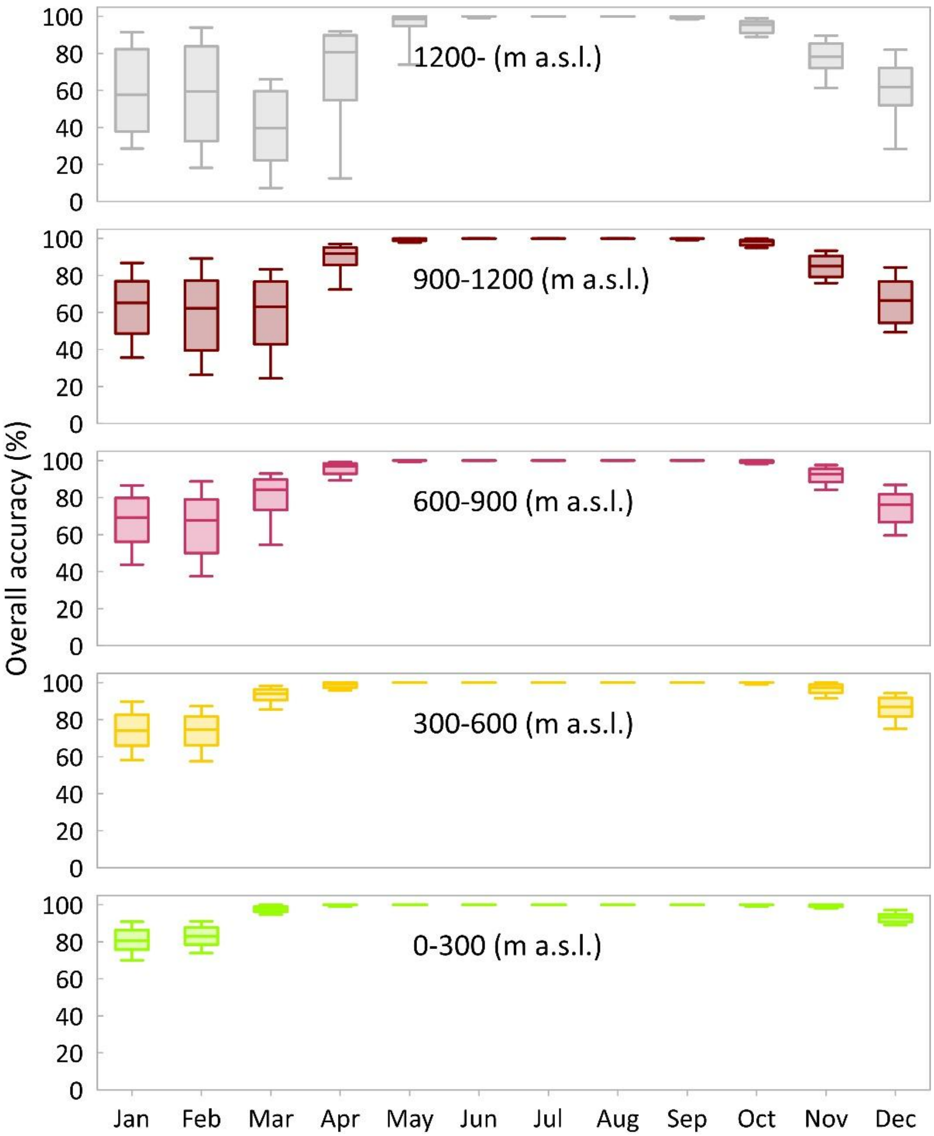


**Figure 6: Accuracy of VIIRS snow cover maps with optimal NDSI threshold for different months and elevation groups of the 631 Austrian stations in the period January 2012 to December 2020.**

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Tab. 4. Median accuracy of the VIIRS product for individual months and elevation groups of 631 Austrian stations

| | Elevation (m a.s.l.) | | | | |
|---|---|---|---|---|---|
| Month | <300 | 300-600 | 600-900 | 900-1200 | >1200 |
| January | 81 | 74 | 69 | 65 | 58 |
| February | 83 | 75 | 68 | 62 | 59 |
| March | 98 | 94 | 84 | 63 | 40 |
| April | 100 | 99 | 97 | 92 | 81 |
| May | 100 | 100 | 100 | 100 | 98 |
| June | 100 | 100 | 100 | 100 | 100 |
| July | 100 | 100 | 100 | 100 | 100 |
| August | 100 | 100 | 100 | 100 | 100 |
| September | 100 | 100 | 100 | 100 | 100 |
| October | 100 | 100 | 99 | 98 | 95 |
| November | 100 | 97 | 93 | 85 | 78 |
| December | 93 | 87 | 76 | 67 | 62 |

The overall accuracy (OA) obtained with thresholds fitted for different elevations is presented in Figure 7. We can see that the OA decreases with increasing elevations. Median accuracy is highest for stations <300 m, where it reaches up to 96%. With increasing altitude, overall accuracy decreases - in the range of 900–1200 m, the OA is 86%, and in high-elevation stations (above 1200 m), the OA is 83%. The difference in OA between the lowest and highest elevation zone is approximately 13%.

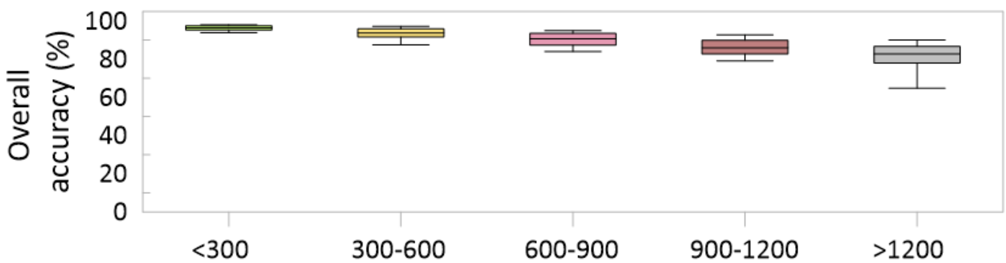


**Figure 7: Accuracy of VIIRS snow cover maps with optimal NDSI threshold for different elevation groups of the 631 Austrian stations in the period January 2012 to December 2020.**

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Tab. 5. Median accuracy of the VIIRS product for elevation groups of 631 Austrian stations

| Elevation | <300 | 300-600 | 600-900 | 900-1200 | >1200 |
|---|---|---|---|---|---|
| OA (%) | 96 | 94 | 91 | 86 | 83 |

Fig. 8 evaluates overall VIIRS accuracy obtained with a single threshold fitted separately for individual months (Fig. 8 top), elevation groups of stations (Fig. 8 middle), or their combination (i.e., fits to months and elevation together, Fig. 8 bottom). Seasonal course of the overall accuracy (Fig. 8 top) indicates that during the winter months (December to February), the median accuracy is lowest (60–70%). During the spring months, the accuracy increases (87% in March and 97–100% in April–May). The summer months represent a period of maximum stability, when the accuracy is 100%. In the autumn, the values decrease slightly, but they remain high (94–100%) in September–November.

The evaluation of the median overall accuracy by altitude (Fig. 8, middle) shows a slight but distinct decrease in accuracy with increasing altitude. The highest accuracy (up to 95%) is achieved for stations below 300 m a.s.l. For stations in altitudes between 300 and 600 m, the accuracy decreases to 90%, with the largest decrease (83%) occurring at altitudes between 600 – 900 m a.s.l. For stations in altitudes between 900 and 1200 m and above 1200 m, the accuracy increases (87% and 86 %), but does not reach the level of the lower-elevation stations.

The evaluation of the median overall accuracy in months and altitudes (Fig. 8, bottom) shows significant seasonal and altitude differences. During the winter months (December to February), accuracy is lowest across all elevations, with values at stations <300 m dropping to 39–43%, while at higher elevations it is slightly higher (around 60–63%). In spring, accuracy is higher in all elevation zones. In March, accuracy increases to 76–87%, and from April onwards it reaches 97–100% without significant differences between altitudes. The summer months bring maximum accuracy of 100% in all elevation zones. In autumn (September–November), accuracy is still high (99–100%) in September and October, but a slight decline is observed in November (85–90%), especially at higher-elevation stations.

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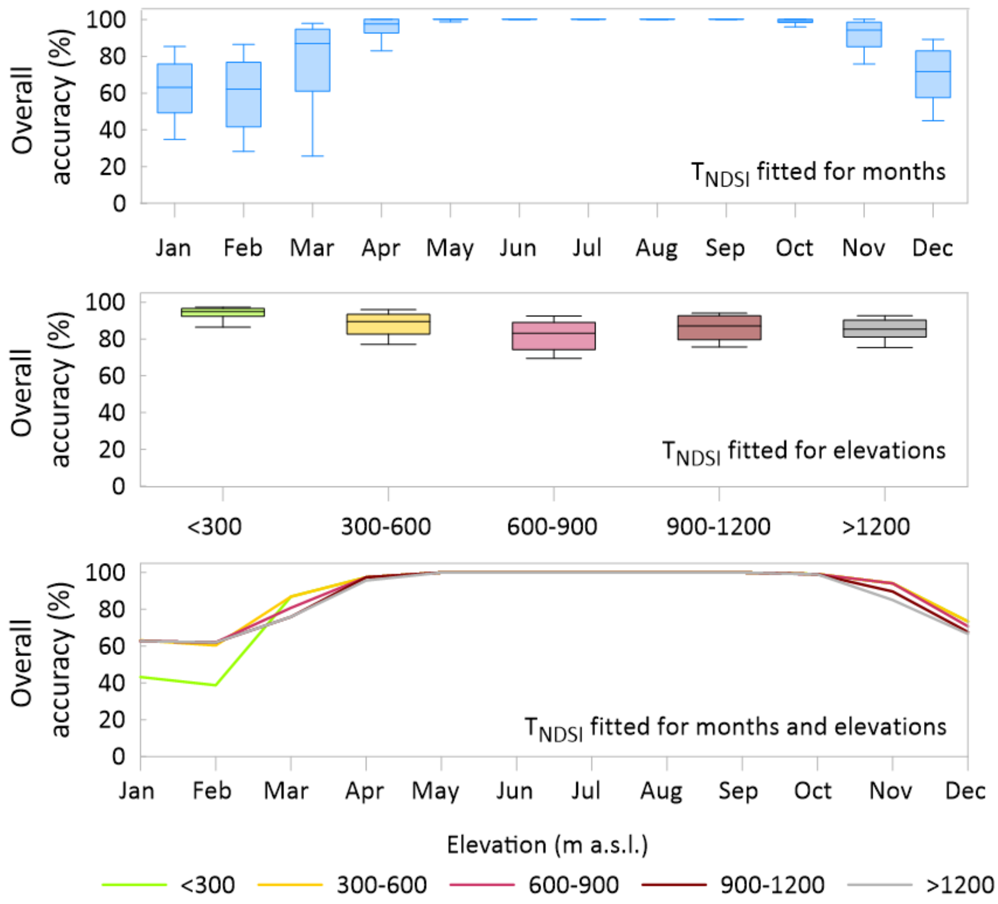


**Figure 8: Accuracy of VIIRS snow cover maps obtained with single optimal NDSI threshold fitted separately for individual months (top panel), elevation groups (middle panel), or months and elevation groups together of Austrian stations in the period from January 2012 to December 2020.**

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Tab. 6. Median overall accuracy obtained with thresholds fitted separately for individual months or elevation groups of 631 Austrian stations

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OA (%) | 63 | 62 | 87 | 97 | 100 | 100 | 100 | 100 | 100 | 99 | 94 | 71 |
| Elevation | <300 | 300-600 | 600-900 | 900-1200 | >1200 | | | | | | | |
| OA (%) | 95 | 90 | 83 | 87 | 86 | | | | | | | |

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Tab. 7. Median overall accuracy obtained with thresholds fitted for individual months and elevation groups together of 631 Austrian stations

| | Elevation (m a.s.l.) | | | | |
|---|---|---|---|---|---|
| Month | <300 | 300-600 | 600-900 | 900-1200 | >1200 |
| January | 43 | 63 | 63 | 63 | 63 |
| February | 39 | 60 | 62 | 62 | 62 |
| March | 87 | 87 | 81 | 76 | 76 |
| April | 97 | 97 | 97 | 97 | 96 |
| May | 100 | 100 | 100 | 100 | 100 |
| June | 100 | 100 | 100 | 100 | 100 |
| July | 100 | 100 | 100 | 100 | 100 |
| August | 100 | 100 | 100 | 100 | 100 |
| September | 100 | 100 | 100 | 100 | 100 |
| October | 99 | 99 | 99 | 99 | 99 |
| November | 94 | 94 | 94 | 90 | 85 |
| December | 73 | 73 | 71 | 68 | 67 |

### 4.2.2 Mapping accuracy at open and forest sites

Variability of mapping accuracy of the snow cover maps classified by using the fitted $OT_{NDSI}$ thresholds for each snow profile at open and forest site is evaluated in Fig. 9. The mapping accuracy shows seasonal and site-dependent differences. The comparison indicates that accuracy is larger for open areas than for sites situated in forest. The overall accuracy estimated for individual sites varies between 72% and 96% at the open site and between 58% and 94% at the forested site. The accuracy at the sites with the most measurements is 96 % (Červenec 1500 – open site) and 94% (Červenec 1420 – forest site). For the open site, the median accuracy is very high for most of the year, frequently close to 100%. However, there are three drops: May (42%), November (44%), and April (87%). The OA at the forest site is more sensitive to seasonal variation, with particularly low accuracy in spring and late autumn. The accuracy is highest (100%) in summer and early autumn, but shows lower values in spring (28%) and in November (38%). During the winter months, the OA is from 93% to 99% at the open site and from 80% to 91% at the forest site.

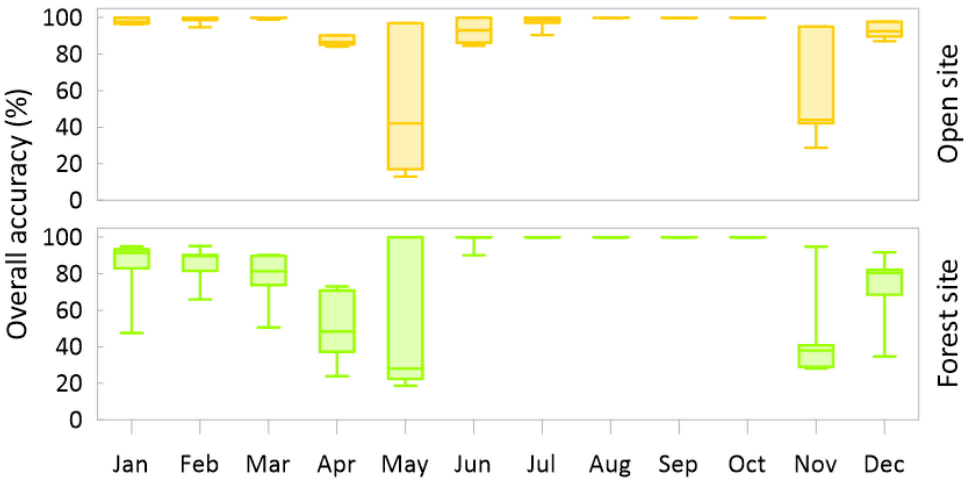


**Figure 9: Accuracy of VIIRS snow cover maps with optimal NDSI threshold for different months and land cover classes (open and forest sites) in the period from January 2012 to December 2020.**

## 5 Discussion and conclusions

This study evaluates VIIRS snow cover mapping accuracy and its sensitivity to snow classification thresholds. While some earlier versions of satellite snow cover products (such as MODIS) used a fixed NDSI threshold for snow cover classification, current datasets provide NDSI estimates, and the user must decide which NDSI threshold to use for classification. We found that when we fit the threshold using all stations and days in the Central European Highlands, the optimal threshold is 40 (or equivalent of 0.4 in some products). This is the same as used in earlier versions of MODIS (i.e., collection 5 and older), but higher than the 0.14 threshold estimated by Zhang et al. (2020) across 330 stations in China or the 0.23 estimated by Dietz and Roessler (2025) using 381 Landsat scenes. We found that the optimal snow-mapping threshold for VIIRS at the regional scale decreases with increasing elevation, varies seasonally, and is smaller in forests than at open sites. This finding is in contrast with the previous study by Zhang et al. (2020), who reported that the optimal NDSI threshold at climate stations is not correlated with geographic and meteorological variables, including elevation, longitude, latitude, snow depth, precipitation, air temperature, wind speed, and relative humidity. In the Central European Highlands, the correlation between the optimal threshold and elevation of the stations exceeds 0.67. If we compare the optimal thresholds for VIIRS with those reported for MODIS in Tong et al. (2020), the thresholds in MODIS are somewhat lower (median for Terra and Aqua is 0.3 and 0.37, respectively), but there is a very close correlation between them (i.e., exceeding 0.92). A similar relation between the MODIS and VIIRS thresholds has been reported by Thapa et al. (2019), who, for the Midwestern United States and southern Canada, found that MODIS snow cover maps were the closest to VIIRS if the MODIS threshold of 0.3 is used. Interestingly, we found

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that at the catchment scale in the forest, the optimal threshold is around 0.14, which corresponds well to the threshold suggested for China in Zhang et al. (2020).

The median mapping accuracy of VIIRS, using optimal thresholds fitted at individual climate stations, is 92.5%. This is slightly lower than the median of 93.5% estimated for MODIS (Terra) for the same period and climate stations and lower than the median of over 97% reported for MODIS for a different time period in Tong et al. (2020). If the overall agreement between VIIRS and snow depth at the stations is translated into Cohen's Kappa index used in Zhang et al (2020), then the median Cohen's Kappa for stations in Austria is 0.43, which is slightly lower than reported by Zhang et al. (2020) for stations over Tibetan Plateau (0.50), but notably lower than for other stations in China (0.77). The Cohen's Kappa index, however, is sensitive to class imbalance (Stehman, 1997), which is large in Austria because stations cover a wide range of physiographic and climatic conditions.

The variability of the optimal threshold at the regional scale also affects the VIIRS mapping accuracy. Figure 10 shows how the mapping accuracy reduces if optimal thresholds are fitted to (1) all stations and days in Austria, (2) to individual months, or (3) groups of stations in different elevation zones, compared to the optimal thresholds fitted over individual stations. If only one threshold is used (green bars in Fig. 10), the mapping accuracy decreases by 10-13% in the winter months. If the threshold is fitted seasonally across different elevation zones (blue bars in Fig. 10), the reduction in mapping accuracy is only about 3-5%. This is consistent with the results of Tong et al. (2020), who reported a 3-10% improvement of MODIS mapping accuracy if the thresholds are fitted in different seasons, elevations, and land cover groups.

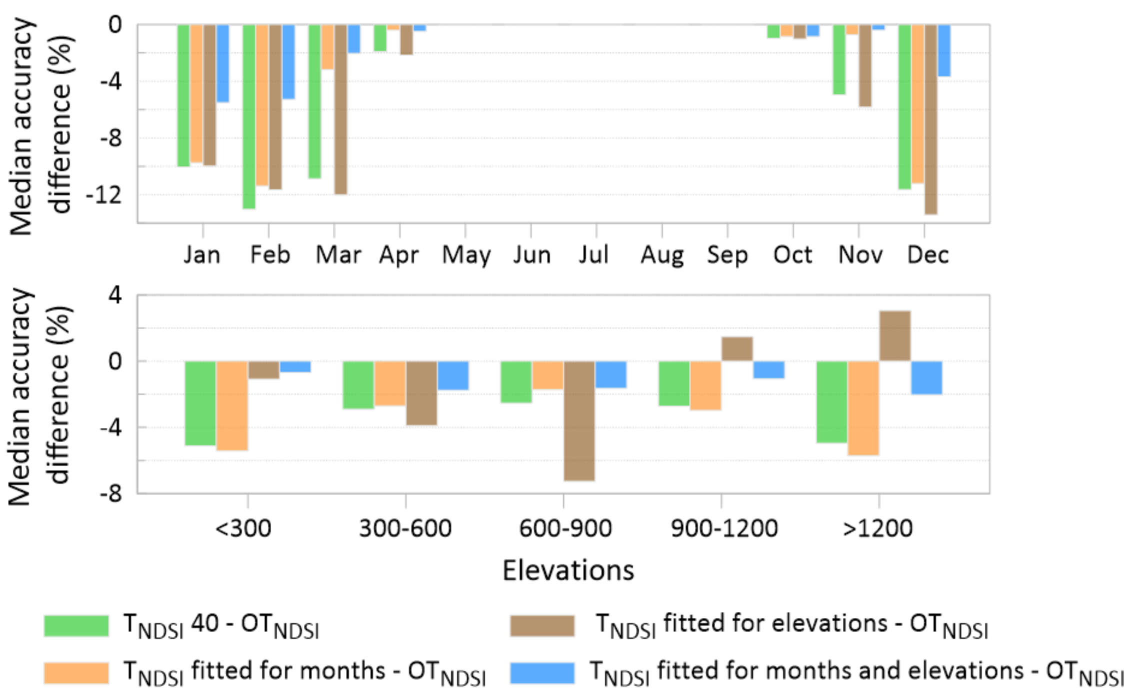

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**Figure 10: The difference in VIIRS mapping accuracy for different variants used for fitting the optimal NDSI thresholds. The mapping accuracy change represents the difference between accuracy obtained for NDSI thresholds fitted over individual stations ($OT_{NDSI}$) and accuracy if the optimal threshold is fitted for all days over the entire Austria ($T_{NDSI}$40, green colour), for individual months over the entire Austria (orange colour), for all days and stations grouped into selected elevation zones (brown colour) and for individual months and selected elevation zones (blue colour).**

Comparing the satellite mapping accuracy between open and forest sites is rare in the literature. We evaluated VIIRS mapping accuracy in the forest in the same experimental catchment as used for the MODIS evaluation in Parajka et al. (2012). We found that the optimal thresholds are lower than those found in the assessment for the regional scale and that there is a significant difference, i.e., a decrease in mapping accuracy in the forest, particularly when the snow accumulation starts (October-November) and at the end of the melting season (April-May). The VIIRS mapping accuracies are about 1% higher in the forest and about 2.4% lower at open sites, compared to the MODIS assessment in Parajka et al. (2012). Comparison of the mapping accuracies obtained with optimal thresholds fitted individually and those fitted separately for the open and forest sites (Fig.11) indicates remarkable differences, particularly during the onset of snow cover. During the winter and spring months, the optimal thresholds and associated mapping accuracy are very similar. The comparison of VIIRS and MODIS mapping accuracy at open and forest sites (Fig. 12) indicates similar results, but not a clear pattern. During the winter, VIIRS sometimes classifies clouds as snow, and during the snowmelt phase, MODIS and VIIRS sometimes differ in classifying snow and clouds.

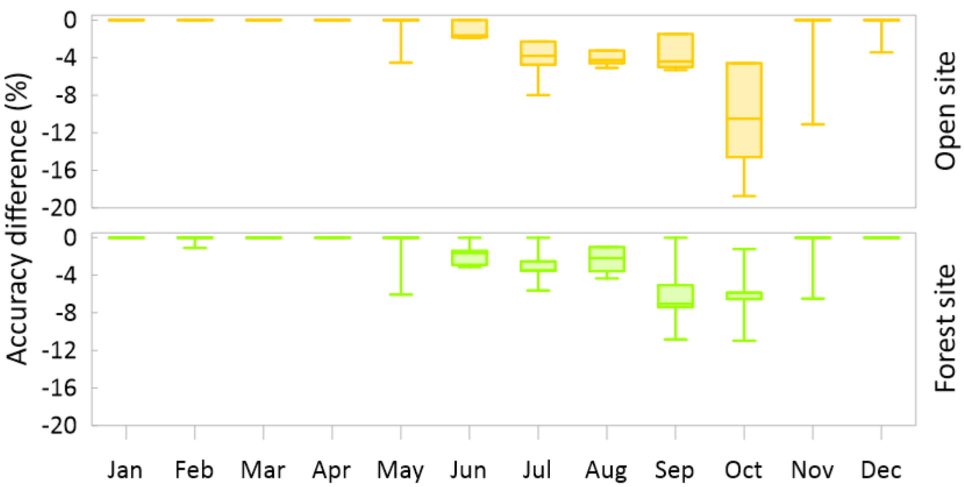


**Figure 11: Difference in VIIRS accuracy when using a single threshold value representative for all days and snow courses ($T_{NDSI}$ 10) compared to the optimal threshold ($OT_{NDSI}$) obtained at each site individually.**

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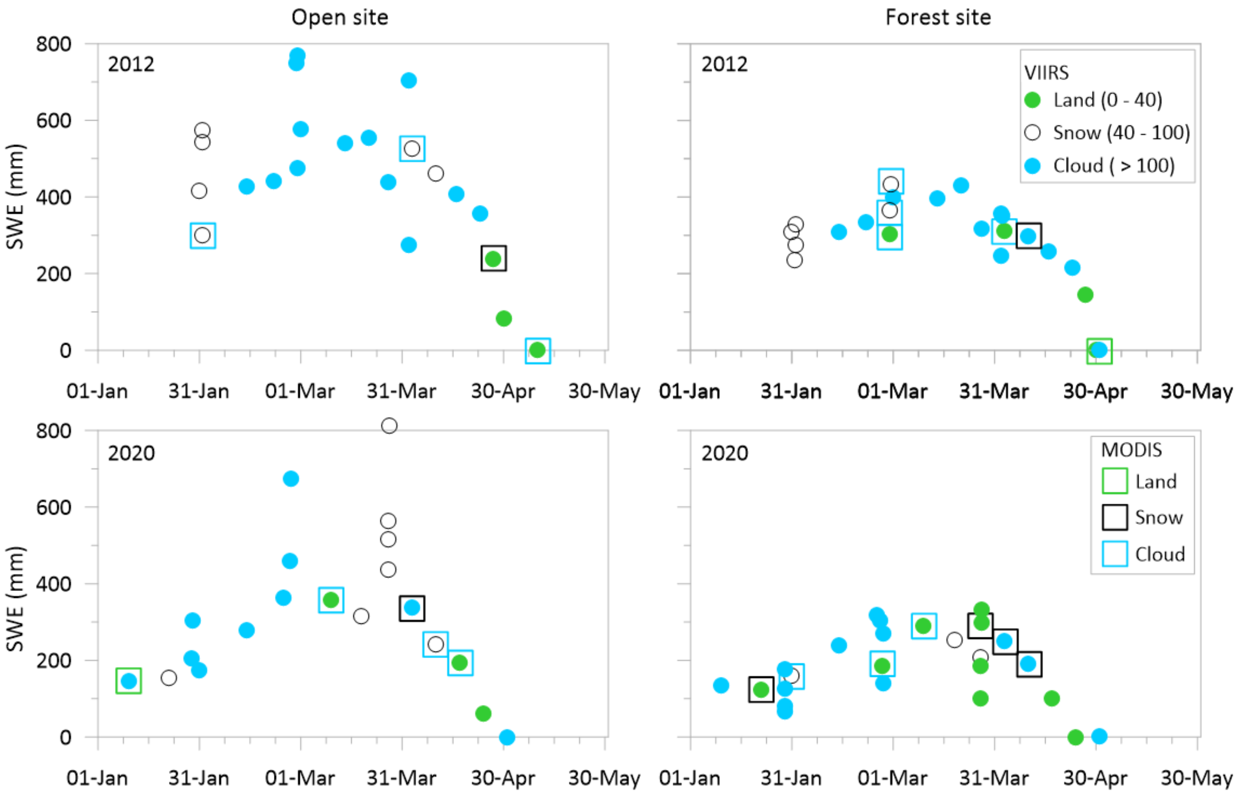


**Figure 12. Snow water equivalent (SWE) observations at open/forest sites and VIIRS (circle) and MODIS (square) classification at the respective pixels in selected snow seasons (2012 and 2020). Colors indicate snow (white), land (green) and cloud (blue) classifications.**

Our results indicate that VIIRS can be used for mapping of snow cover as a successor of MODIS after the end-of-mission. Similarities in the sensor characteristics and snow cover mapping based on NDSI result in similar but not identical mapping performance. Our VIIRS assessment for the Central European Highlands indicates that the optimal thresholds for snow cover mapping are somewhat higher than obtained for MODIS (in Tong et al., 2020) and that snow cover classification is more accurate if the optimal thresholds are estimated separately in different months and for different elevation zones. In the next phase, we plan to compare the application of MODIS and VIIRS datasets in hydrological model calibration and validation. This can provide additional information about their consistency for enhancing hydrological predictions.

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**Code availability**

R script used for VIIRS snow accuracy analysis is provided in the Supplement.

**Data availability**

The VIIRS snow cover data were downloaded from the National Snow and Ice Data Center (NSIDC) (https://nsidc.org/data/vnp10a1/versions/1). Processed data can be provided by the corresponding author upon request.
NDSI data derived from the VIIRS product for individual snow profiles located in open areas and forested sites within the Jalovecký Creek catchment, as well as snow water equivalent (SWE) measurements for the individual profiles, are provided in the Supplement.

**Author contributions**

PS and JP conceived and designed the study, wrote the codes, performed the analyses, and prepared the paper. MD and MJ were responsible for the data management, including quality control. LH provided feedback on the manuscript. All authors discussed the results and commented on the manuscript.

**Competing interests**

The contact author has declared that none of the authors has any competing interests.

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