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Mapping snow cover from daily Collection 6 MODIS products over Austria

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ABSTRACT

Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover maps have been successfully applied in regional snow cover mapping and hydrological modelling in many regions. The new MODIS products (i.e. Collection 6) provide information about the Normalized Difference Snow Index (NDSI) instead of simple binary information about snow cover of the former products. The objective of this study is to investigate the sensitivity and accuracy of different NDSI thresholds used for snow cover mapping and to compare the results with former snow cover classification based on a fixed NDSI threshold (NDSI = 0.4). The accuracy is tested for both Aqua (MYD10A1) and Terra (MOD10A1) daily snow cover products by using daily snow depth observations at 665 climate stations in Austria in the period 2002–2014. The results show the overall classification accuracy over 665 climate stations to be larger than 97% (97.4% for Terra and 97.6% for Aqua) in Austria. The best NDSI thresholds fitted to individual stations can differ from a fixed threshold (NDSI = 0.4) and are sensitive to the snow depth threshold indicating snow cover at the ground. The NDSI thresholds vary seasonally, decrease with increasing elevation and are lower in forested than open land cover settings. We found that the NDSI thresholds fitted to different elevation and land cover classes improve regional snow cover mapping by 3–10% in forested regions above 900 m a.s.l. in January to March.

1. Introduction

Spatial and temporal patterns of snow cover help to improve our understanding of snow melt processes, and hence improve runoff prediction during snowmelt (Grayson and Blöschl, 2001). Due to the shortage of the in-situ snowpack information for water resource management at catchment scale, remotely sensed snow cover could be a substitute for in-situ data (Dong, 2018). Optical remote sensing effectively classifies snow cover based on different reflectance of snow and land cover in the visible and shortwave infrared spectrum. The recent satellites (such as Sentinel, Landsat, Terra, Aqua, Meteosat) provide snow cover maps in high temporal (sub-daily to 3 weekly) and spatial (30 m–5 km) resolution and are one of the most attractive remote sensed datasets used for hydrological applications (Parajka et al., 2012; Parajka and Blöschl, 2008).

The MODIS (Moderate Resolution Imaging Spectroradiometer) instrument mounted on board of Terra and Aqua satellites has been mapping daily snow cover at 500 m spatial resolution globally since 2000 (Terra) and 2002 (Aqua). Hundreds of research papers (https://nsidc.org/data/modis/research.html) have shown that MODIS datasets provide accurate snow cover maps which can be used for mapping of snow cover characteristics and their changes and/or for calibration, validation and assimilation in land surface and hydrologic models. Numerous studies have been conducted to evaluate the MODIS accuracy, either based on comparisons with other satellite-derived products, reanalyses of regional climate simulations or based on comparisons with point ground based (in situ) snow depth measurements (Parajka et al., 2012).The results of these studies demonstrate that the MODIS overall accuracy during clear sky conditions usually are within the range of 85–99%, and the accuracy is related mainly to land cover (Hall and Riggs, 2007; Coll and Li, 2018), season (Simic et al., 2004; Parajka and Blöschl, 2006), persistency of snow cover (Pu et al., 2007) and snow depth (Xu et al., 2017). Coll and Li (2018) recently found that the foremost control factor of the snow cover mapping accuracy is the land cover type. Some of the validation studies, such as Simic et al. (2004), Ault et al. (2006) and Wang et al. (2008) indicate that the accuracy assessment tends to be sensitive to the snow depth threshold used to determine snow cover in the neighborhood of climate stations. In order to account for the scale gap between the MODIS pixel value and in site measurements, snow depth thresholds between 1 cm and 4 cm have been used in accuracy assessments. Some of the studies presented a sensitivity analysis investigating the impact of snow depth threshold on the accuracy (Liang et al., 2008; Wang et al., 2008; Gao et al., 2010; Marchane et al., 2015; Yang et al., 2015; Da Ronco et al., 2020), but few

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have investigated different seasons or land cover categories.

The snow cover mapping algorithm and thus also its accuracy have changed since the launch of the Terra satellite (Hall et al., 2019). The original mapping version (V001) has been replaced by version (V003) in 2003. The changes include processing refinements, instrument, and calibration stabilization (https://nsidc.org/data/modis/data_versions.html). In the next versions (V004 and V005), further changes of cloud mask, metadata extensions and data format have been implemented. More significant changes have been introduced in 2016. These include revisions in atmospheric calibration (Lyapustin et al., 2014), improvements in surface temperature screening (Riggs et al., 2017) and extending the overall quality flagging. From a practical perspective, the most significant change is that C6 (also known as V006) snow cover products do not include binary snow cover information (i.e. whether pixel is snow covered or not), but Normalized Difference Snow Index (NDSI) values. As indicated in the users' guide, NDSI values from 0.00 to 1.00 are within the theoretically possible range of snow (Riggs et al., 2016). However, clouds may also have positive NDSI values, which normally range from −0.4 to 0.4 (Stillinger et al., 2019). Hence, lower NDSI value will increase the difficulty of distinguishing cloud from snow. This means that for hydrological applications, the NDSI threshold value indicating whether a pixel is snow covered or not needs to be determined. User defined NDSI thresholds that are suited for the study area, could result in better mapping accuracy. Wang et al. (2010) compared the MODIS snow cover map from Terra using different NDSI thresholds with the Landsat-ETM + snow cover maps, and found that the relevant NDSI threshold is about 0.36 for the upper Heihe river basin in northwestern China. Zhang et al. (2019) suggested taking different NDSI threshold would improve the accuracy of snow cover data, and they demonstrated that the NDSI threshold 0.10 was more reasonable than 0.40 for use in China. Da Ronco et al. (2020) compared MODIS snow cover maps with 3 NDSI thresholds, 0.10, 0.20 and 0.40, at 7 stations in Italian Alpine catchments, and found that a NDSI threshold of 0.20 is optimal for this region from November to April. However, the fixed NDSI threshold prevented detection of snow cover that had lower NDSI value caused by the seasonally varying canopy or by complex landscape in the mid-latitude regions.

The main objective of this study is thus to investigate the accuracy and sensitivity of different NDSI thresholds for snow cover mapping from daily C6 MODIS datasets. The aim is to evaluate the spatial and seasonal patterns of the NDSI thresholds in Austria and to analyze the factors that control the mapping accuracy. The results are compared with the assessment based on a fixed NDSI threshold (NDSI = 0.4) used in previous versions of the datasets. The snow cover accuracy is evaluated against daily snow depth measurements at 665 climate stations which allows discussing and transferring the findings to similar physiographic mountain and flatland regions. We therefore propose a spatiotemporally dynamic NDSI thresholding method to improve the mapping accuracy of MODIS snow cover products and other NDSI derived products.

2. Study area and data

2.1. Study region

The study area is Austria. Austria is located in Central Europe and has an area of about 84000 km^2. Topography is characterized by flat or undulating topography in the East and North, and Alpine terrain in the West and South (Fig. 1). Elevations vary from 115 m a.s.l. to 3800 m a.s.l.. Climatically, Austria is located in a temperate zone, where mean annual precipitation is less than 400 mm/year in the East and more than 2800 mm/year in the West. Land use is mainly agricultural land in the lowlands, mixed and coniferous forests in the medium elevation ranges and alpine vegetation and rocks in elevations above 2000 m a.s.l.. Such diverse physiographic and landscape characteristics allows to consider territory of Austria to be representative for a wider spatial domain with similar physiographic characteristics.

2.2. MODIS snow cover datasets

The MODIS snow cover datasets tested in the study are MOD10A1 (Terra) and MYD10A1 (Aqua) products. These are daily snow cover data with 500 m spatial resolution available from Aqua (Hall andriggs, 2016a) and Terra (Hall and Riggs, 2016b) satellites. The study region is covered by two tiles: h18v04 and h19v04 which have been merged and re-projected by MODIS Reprojection Tool (Dwyer and Schmidt, 2006). The analysis is based on all available daily images from September 2002 to August 2014.

The MOD10A1 and MYD10A1 datasets provide information about the snow cover in the form of Normalized Difference Snow Index (NDSI) values (Hall and Riggs, 2011). This index compares the difference in the reflectance in the visible (band 4) and shortwave infrared (band 6) part of the spectrum and is estimated as:

$$\mathrm{NDSI} = ((\mathrm{band\ 4} - \mathrm{band\ 6})/(\mathrm{band\ 4} + \mathrm{band\ 6}))$$

If a pixel has NDSI larger than 0.0 then it indicates the presence of some snow. In the former Collection 5 version of the dataset a pixel is identified as snow if NDSI is larger than 0.4. In the previous version of MYD10A1, band 7 was used instead of band 6 because part of the detectors in Aqua band 6 were either nonfunctional or noisy. The newly developed mapping technique (Gladkova et al., 2012) allows relating Aqua MODIS band 6 data to the estimation quality, so in version C6 Aqua and Terra uses the same snow detection method. Compared to version C5, the most recent version of MYD10A1 does not use band 7 to calculate the NDSI.

2.3. Daily snow depth measurements at climate stations

The daily snow depths used for validating the MODIS datasets are taken from observations at 665 climate stations (Fig. 1). The observations are available at the data portal of the Hydrographic Service of Austria (https://ehyd.gv.at/). The snow depth readings represent point measurements at permanent staff gauges (permanently mounted snow stake) daily at 7:00 AM, and total snow depths are reported as centimeter integer values (HZB, 1992). Such measurements represent new snow that has fallen combined with snowpack already covering the ground. The spatial arrangement of the stations indicates that the snow depth measurements cover a wide range of elevation zones of the country, but in the high alpine regions the stations tend to be located at lower elevations, typically in the valleys. As indicated in Parajka and Blöschl (2006), the highest climate station used in this study is at 2290 m a.s.l. which means that approximately 6% of the region is higher and not represented by any climate station. Most of the stations (i.e. n = 602) have complete observational records and gaps longer than 5 years occur only for 10 stations.

3. Methods

The selection of the best NDSI threshold (BT_{NDSI}) is based on finding the NDSI threshold (T_{NDSI}) that has the maximum snow cover mapping accuracy expressed by the overall accuracy index (OA_T). The OA_T compares snow depth observations at climate stations with pixel values of NDSI and estimates the overall accuracy as:

$$O\mathbf{A}_T = \frac{A + D}{A + B + C + D} \cdot 100\% \quad (1)$$

where A, B, C, D represent the number of cloud-free days in each of the category of confusion matrix (Table 1). We tested 100 different T_{NDSI} from 0.01 to 1.0 with a step of 0.01. BT_{NDSI} represents the value with the highest mapping accuracy. The procedure is repeated for five different snow depth thresholds T_{SD} (1 cm, 2 cm, 3 cm, 4 cm and 5 cm).

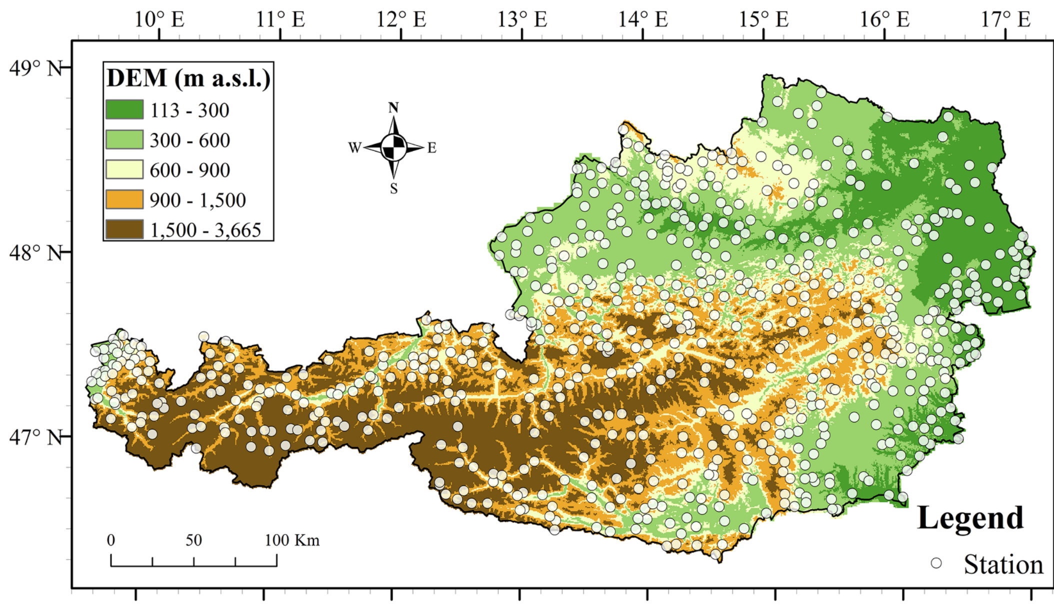

Fig. 1. Topography of Austria and spatial distribution of the 665 climate stations with daily snow depth measurements.

The assessment of the best BT_{NDSI} is performed for all individual climate stations, as well as for different groups of stations representing different physiographic conditions. The classification of different elevation, aspect and land use groups is based on previous snow cover and hydrological evaluations in Austria (Parajka and Blöschl, 2006; Parajka et al., 2009). The assessment is also applied for finding the best BT_{NDSI} for all the stations in the entire time period (September 2002 to August 2014) or for individual stations and individual months of the selected time period.

4. Results

4.1. Evaluation of the best NDSI threshold

The distribution of the Terra and Aqua NDSI values stratified by snow depth categories is presented in Fig. 2. The box-whiskers plot shows the distribution of NDSI pixel values for the locations of climate stations in the period September 2002 to August 2014. It is clear that the NDSI values tend to increase and their variability tends to decrease with increasing snow depth. Interestingly, even if the snow depth at the climate stations exceeds 1 m of snow, the median of the NDSI values is about 30% lower (0.71 for Terra and 0.73 for Aqua) than the theoretically possible maximum NDSI value (NDSI = 1.00). On the other hand, during snow-free conditions at the climate stations, only 3% of MODIS pixels values have NDSI larger than 0. A comparison of the Aqua and Terra satellites indicates that the median and variability of the Terra NDSI values are somewhat smaller than those of Aqua. This is likely related to the different processing chain used for snow detection in the Aqua product (Kraatz et al., 2017). The snow reflectance is slightly lower in band 7 than in band 6 (Wang et al., 2006). This results in higher NDSI value of Aqua, which band 6 value used for NDSI calculation is retrieved from Band 7. The most noticeable difference between Aqua and Terra occurs for patchy snow conditions (snow depth in range 1–5 cm). The median of the Aqua NDSI values is about 0.11 smaller and the variability is about 50% larger than the variability of Terra NDSI values. The main reason for the difference is the Aqua images the same area approximately three hours later than Terra, the patchy snow covered area shrinks between this gap.

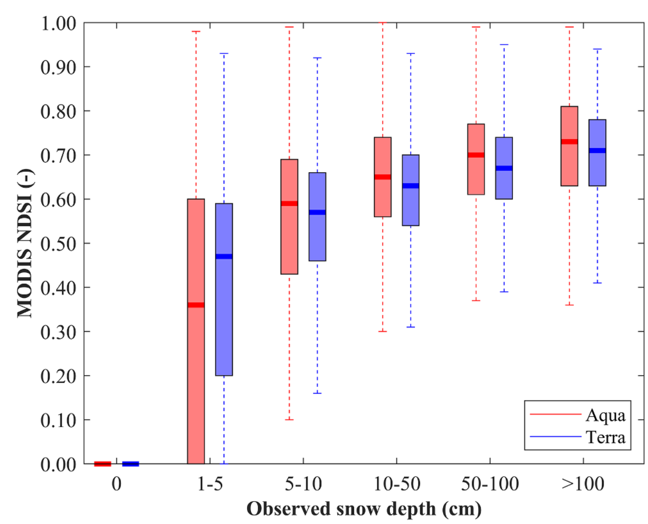

Fig. 2. Distribution of NDSI values for different categories of observed daily snow depth at 665 stations in the period September 2002 – August 2014. Red and blue boxes show the space–time variability (i.e. 75%- and 25%-percentiles) in the Aqua (MYD10A1) and Terra (MOD10A1) snow cover products.

The best threshold for snow cover mapping (BT_{NDSI}) fitted for each individual climate station is evaluated in Fig. 3. The cumulative distribution functions of the BT_{NDSI} are presented for different snow depth thresholds T_{SD} indicating the limit above which the ground

Table 1
Confusion matrix defining the snow cover mapping accuracy index (OA_T). T_{NDSI} represents the MODIS NDSI threshold and T indicates the snow depth threshold at the climate stations.

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

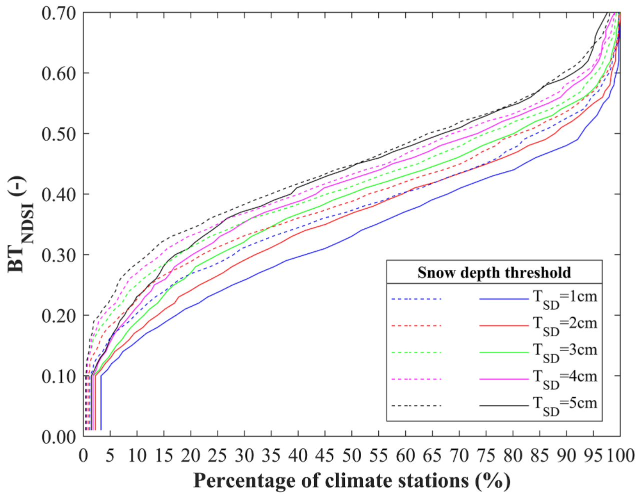

Fig. 3. Cumulative distribution functions of the best NDSI threshold BT_{NDSI} estimated for Aqua (dashed line) and Terra (solid line) snow cover products by using different (1 cm, 2 cm, 3 cm 4 cm and 5 cm) snow depth thresholds at 665 stations in the period September 2002 to August 2014.

Table 2
The best NDSI threshold optimized from the overall accuracy using all stations and the median value of the best NDSI threshold selected for individual stations.

Snow depth threshold T_{SD}/Station groups with T_{SD} = 1 cm		Best NDSI threshold for all stations		Best NDSI threshold for median stations	
		Aqua	Terra	Aqua	Terra
Snow depth threshold T_{SD}	T_{SD} = 1 cm	0.37	0.30	0.37	0.34
	T_{SD} = 2 cm	0.37	0.32	0.39	0.37
	T_{SD} = 3 cm	0.38	0.34	0.41	0.40
	T_{SD} = 4 cm	0.40	0.37	0.43	0.43
	T_{SD} = 5 cm	0.40	0.38	0.45	0.45
Elevation	< 300 m a.s.l.	0.48	0.40	0.45	0.43
	300–600 m a.s.l.	0.40	0.34	0.40	0.36
	600–900 m a.s.l.	0.35	0.31	0.36	0.33
	900–1500 m a.s.l.	0.34	0.24	0.34	0.27
	> 1500 m a.s.l.	0.35	0.19	0.35	0.27
Landuse type	non-forest	0.38	0.32	0.39	0.36
	coniferous forest	0.34	0.27	0.32	0.29
	other forest	0.33	0.26	0.32	0.28
Aspect	N-NE	0.36	0.32	0.35	0.35
	NE-E	0.37	0.32	0.37	0.34
	E-SE	0.36	0.32	0.39	0.35
	SE-S	0.35	0.32	0.36	0.32
	S-SW	0.32	0.24	0.35	0.29
	SW-W	0.34	0.29	0.38	0.33
	W-NW	0.43	0.32	0.42	0.33
	NW-N	0.42	0.37	0.42	0.39
Month	November	0.43	0.39	0.33	0.32
	December	0.34	0.32	0.31	0.31
	January	0.29	0.28	0.24	0.27
	February	0.26	0.24	0.20	0.24
	March	0.31	0.25	0.24	0.29

(neighborhood of climate station) is considered as snow covered. The results show that the BT_{NDSI} tends to increase with increasing snow depth threshold T_{SD}. The variability of BT_{NDSI} caused by different T_{SD} is somewhat larger for the Terra than the Aqua products, mainly for shallow snowpack described by smaller thresholds (i.e. T_{SD} = 1 cm and 2 cm). The median of BT_{NDSI} over 665 climate stations (Table 2) varies between 0.34 (T_{SD} = 1 cm) to 0.45 (T_{SD} = 5 cm) for Terra and between 0.37 (T_{SD} = 1 cm) and 0.45 (T_{SD} = 5 cm) for the Aqua daily dataset.

An analysis of the relationship between BT_{NDSI} fitted for each individual climate station and selected physiographic characteristics of pixels where climate stations are located is presented in Fig. 4 using a snow depth threshold T_{SD} = 1 cm. The evaluation shows that the BT_{NDSI} tends to decrease with increasing altitude of climate stations (Fig. 4, left panel). The median of BT_{NDSI} for stations below 300 m a.s.l. and above 1500 m a.s.l. ranges from 0.45 to 0.35 for Aqua, and from 0.43 to 0.27 for Terra. The thresholds fitted for each individual station are generally larger for non-forest land cover (i.e. urban areas and grassland) than for coniferous and other forests (Fig. 4, middle panel). Interestingly, there is no large difference between different forest type categories in Austria. The variability of BT_{NDSI} between different aspects of 500 m pixels (Fig. 4, right panel) indicates smaller BT_{NDSI} values for pixels with S and SW aspects in the Terra dataset. The difference in the median between S-SW and W-N aspects is 0.07 for Aqua and 0.10 for Terra. Interestingly, the Aqua BT_{NDSI} values are larger in all aspect categories and the median of the southern aspects has a similar magnitude as the median of the pixels with northern aspects in the Terra dataset. The best threshold represents a tradeoff between minimizing under- and overestimation errors. Larger Aqua BT_{NDSI} values are affected by a larger frequency of clouds and an approximately 10% lower mapping accuracy during shallow snowpack conditions (snow depth between 1 and 5 cm), which has likely an impact on the determination of the final thresholds. The spatial patterns of the BT_{NDSI} for different snow depth thresholds are presented in the Supplement (Fig. S1).

The seasonal variability of BT_{NDSI} fitted for each individual station in individual months is presented in Fig. 5. The results indicate that there is a distinct difference between larger BT_{NDSI} values fitted for the winter months (i.e. November to March) and almost zero threshold values in the summer months (i.e. June to September). An exception is the BT_{NDSI} threshold for the Aqua dataset in September and October, which, for most of the stations, is significantly larger than the thresholds fitted for the Terra dataset. This is likely related to the fitting procedure of the best thresholds, where a wide range of thresholds has a very similar mapping accuracy and thus only few cases influence the final estimate. Time shifts between Terra and Aqua during the onset of the snow cover, which can be one of the reasons for a higher Aqua threshold, are very rare (only 7 cases for all stations in the selected time period), so it is unlikely that the difference in overpass time has a significant effect on the estimated best thresholds in Austria.

A different strategy is evaluated in Table 2 and Fig. 6. In contrast to the previous assessment that evaluates the thresholds fitted for individual stations (and months), Table 2 presents a summary of thresholds fitted as a single value representative of all stations in Austria. Table 2 shows that, if the MODIS threshold is fitted to all stations, the NDSI threshold value is somewhat smaller than the median BT_{NDSI}. The exception is BT_{NDSI} fitted for the Aqua product and snow depth threshold T_{SD} = 1 cm, which has the same value of 0.37.

A different pattern is observed for single threshold fitted separately for six groups of stations. The thresholds in each group are fitted to maximize the overall accuracy in individual months. The groups split stations into two elevation and three land cover groups. While the left panels (Fig. 6) show thresholds for the group of stations situated at altitudes equal or lower than 900 m a.s.l. (i.e. are representative for lowland and hilly regions), the right panels show stations situated in the mountains (i.e. stations above 900 m a.s.l.). Three land cover classes represent the main vegetation types in Austria. The results show a clear seasonal pattern of the best thresholds. Interestingly, compared to thresholds fitted for each station in individual months (Fig. 5), the best thresholds for all groups are significantly larger in the summer months. This is likely the result of fitting procedure to minimize overestimation of snow cover due to misclassification of clouds as snow (Parajka and Blöschl, 2006). The thresholds are fitted to maximize the overall accuracy, so thresholds exceeding 0.65 in the summer months help to eliminate the relatively higher possibility of overestimation of snow cover in the summer months. The thresholds fitted for the mountain

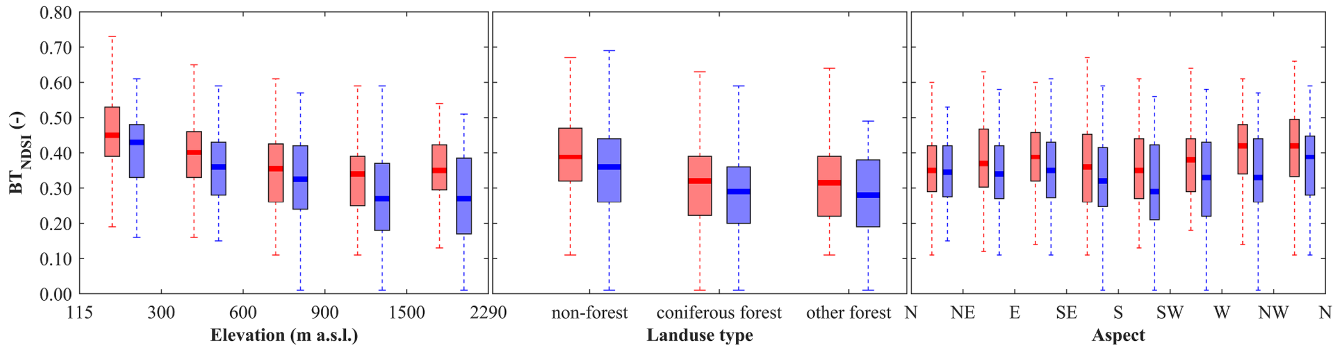

Fig. 4. Boxplots of Best NDSI threshold for MYD10A1 (Aqua, red) and MOD10A1 (Terra, blue) with 1 cm in-situ snow depth for different classifications (elevation, aspect, landuse type) of the 665 Austrian stations in the period September 2002 to August 2014. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

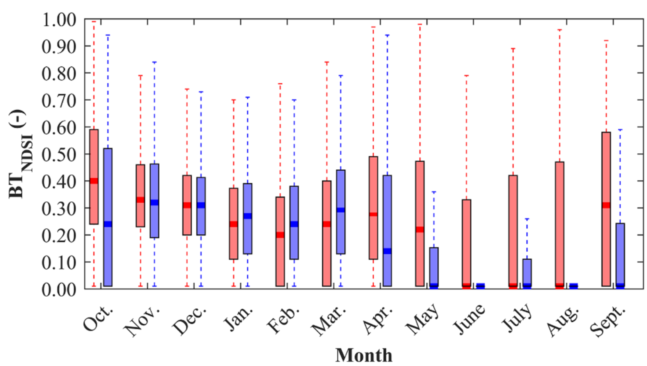

Fig. 5. Boxplots of Best NDSI threshold for MYD10A1 (Aqua, red) and MOD10A1 (Terra, blue) with 1 cm in-situ snow depth for different months of the 665 Austrian stations in the period September 2002 to August 2014.

groups (all vegetation classes) are generally smaller than those fitted for flatland stations. The thresholds tend to be larger for non-forest classes, and the difference between the coniferous and other forest classes is obvious in the mountain groups. The thresholds are the smallest (less than 0.15 in January to March) in the mountains for the other forest group. In this group there are also the largest differences between the Terra and Aqua datasets, particularly in the period between April and July. Aqua and Terra show a similar variance tendency in the winter, but disagreement in the summer, for the other forest group.

4.2. *Accuracy assessment*

The mapping accuracy of the snow cover maps classified by using the fitted BT_{NDSI} thresholds is evaluated in Figs. 7 to 10 and Table 3. Fig. 7 shows cumulative distribution functions of the overall accuracy (OA) for five different snow depth thresholds applied to the Aqua and

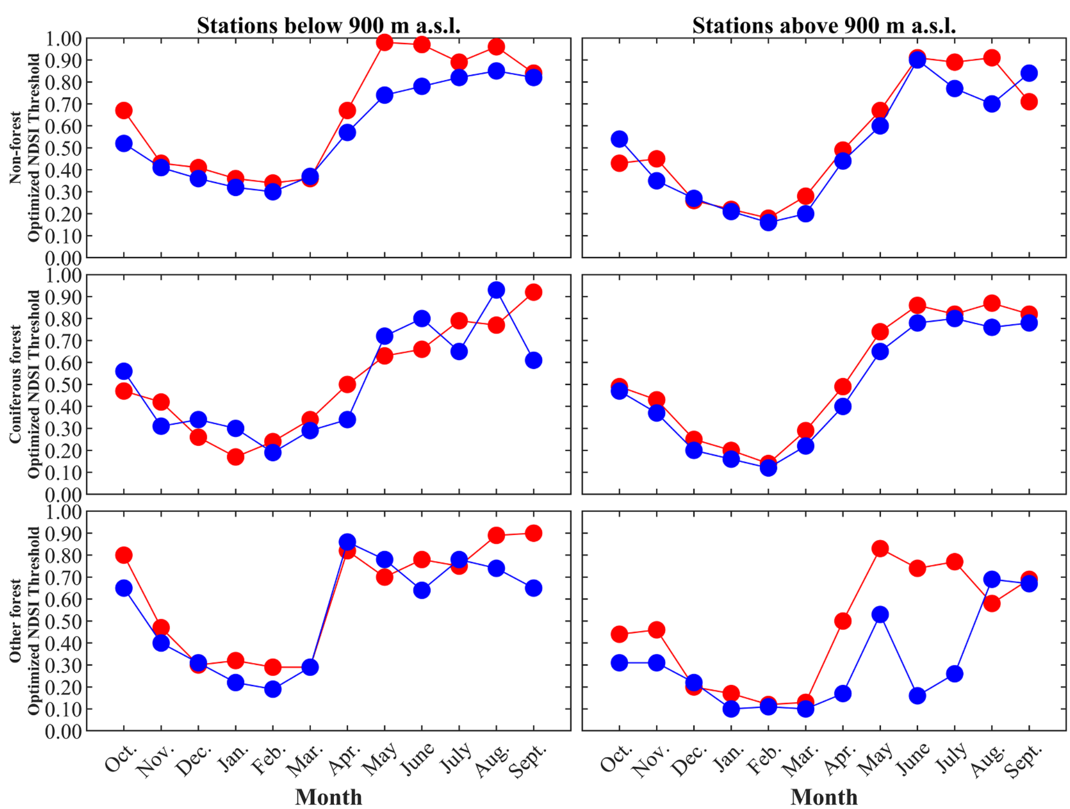

Fig. 6. Optimized NDSI threshold for 6 classification of 665 Austrian stations by below/above 900 m a.s.l and 3 landuse types in each month for MYD10A1 (Aqua, red) and MOD10A1 (Terra, blue) in the period September 2002 to August 2014. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

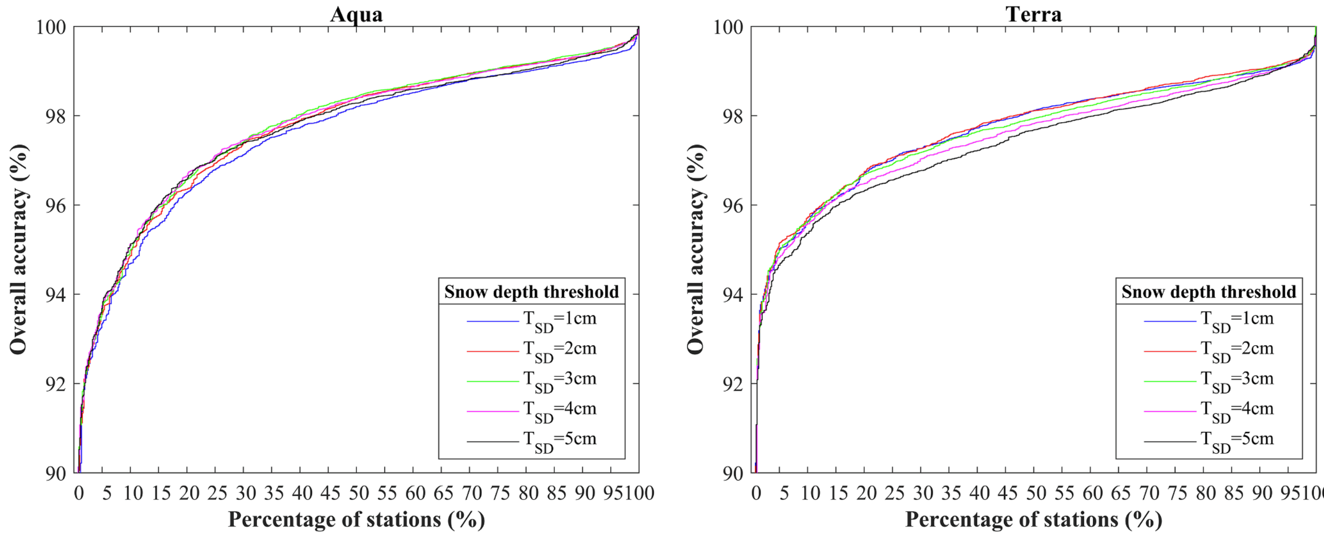

Fig. 7. Cumulative distribution functions of the overall accuracy of Aqua (left panel) and Terra (right panel) snow cover products estimated for best NDSI thresholds in individual stations and for 5 snow depth (SD) thresholds (Table 1). Overall accuracy is estimated for all 665 stations in the period September 2002 to August 2014.

Terra datasets. The results demonstrate a very high snow cover mapping accuracy and very similar accuracy values obtained for different snow depth thresholds. This indicates that, for a given snow depth threshold, one can fit NDSI thresholds that give similar mapping accuracies. The median of OA over all stations is very high and similar for the Terra and Aqua datasets. The median overall accuracy slightly decreases with increasing snow depth threshold for Terra (from 98.1% to 97.6%) but the median OA slightly increases for increasing thresholds between 1 and 3 cm for Aqua (from 98.2% to 98.4%). The variability of OA for different snow depth thresholds is slightly larger for the Terra dataset, which reflects also a slightly larger variability of BT_{NDSI} thresholds (Fig. 3). Interestingly, the relative variability of mapping accuracy is smaller than the relative variability of the BT_{NDSI} thresholds, which means that a similar overall accuracy can be obtained by different NDSI and snow depth thresholds.

The relationships between the overall accuracy and the physiographic characteristics of the pixels the stations are located (Fig. 8) show that the OA tends to decrease with increasing elevation of the stations and is larger for open (non-forest) areas than for stations situated in coniferous forest. There are no significant relationships between OA and the aspect of the pixels, the medians of OA for 8 different aspect classes vary between 97.55% and 98.53% (Table 3). The variability of OA is larger for northern than for southern and eastern slopes. Overall the accuracies and relationships are very similar for the Terra and Aqua datasets.

The mapping accuracy has a strong seasonal variability. Fig. 9 shows the seasonal variability of OA for thresholds fitted in each station for each month. The results indicate that the accuracy is similar for Terra and Aqua and is the lowest in December. The median of OA in December is 92.31% (Aqua) and 91.67% (Terra), and in 10% of stations

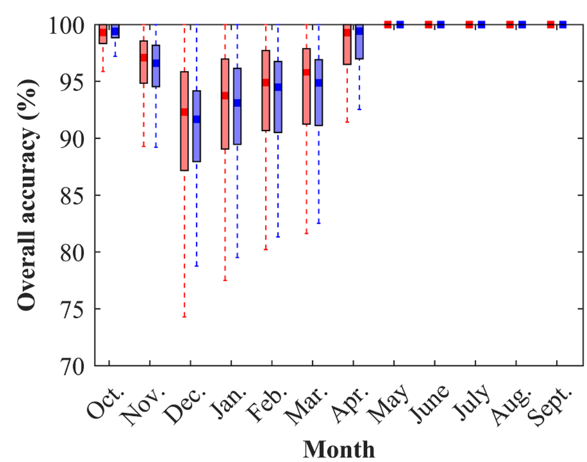

Fig. 9. Boxplots of overall accuracy for MYD10A1 (Aqua, red) and MOD10A1 (Terra, blue) with using the optimized NDSI threshold showing in Fig. 6 for different month of the 665 Austrian stations in the period September 2002 to August 2014. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

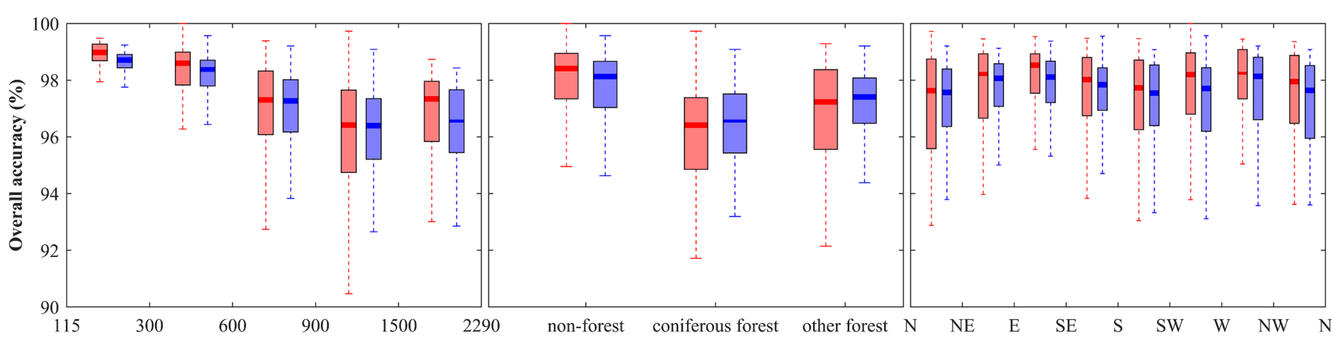

Fig. 8. Boxplots of overall accuracy for MYD10A1 (Aqua, red) and MOD10A1 (Terra, blue) with using the optimized NDSI threshold showing in Fig. 6 for different groups (elevation, aspect, landuse type) of the 665 Austrian stations in the period September 2002 to August 2014. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

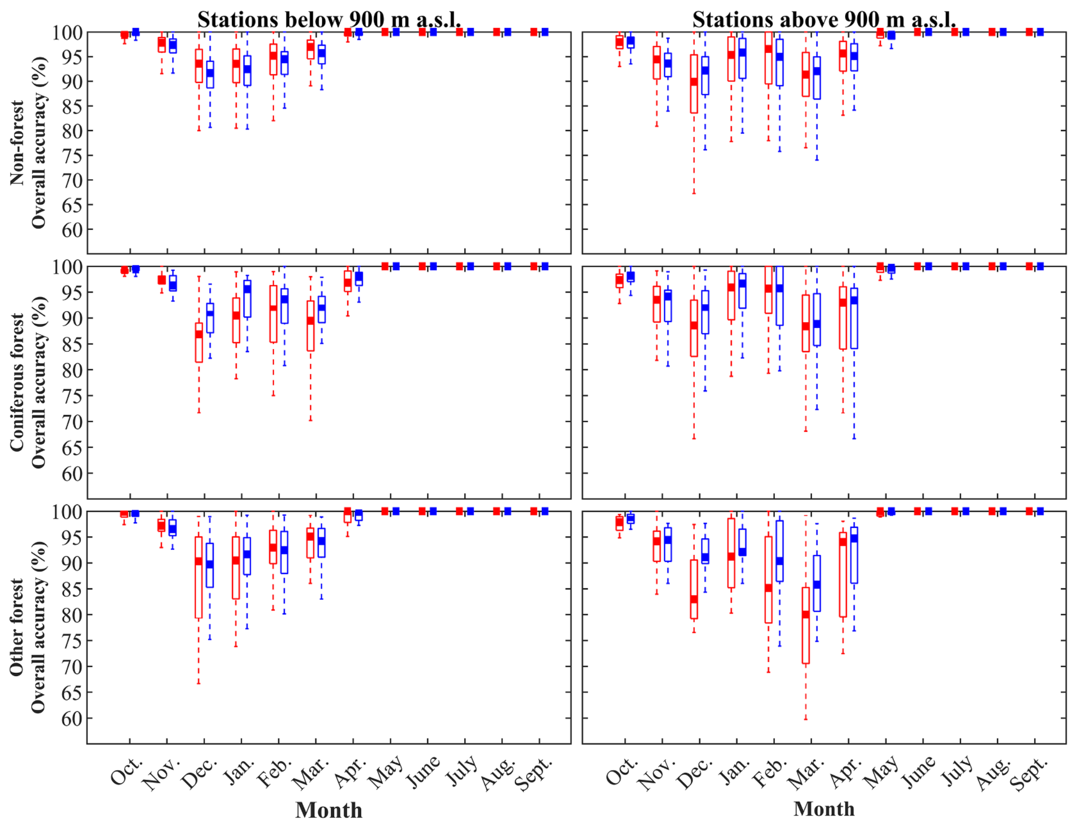

Fig. 10. Accuracy of MODIS snow cover maps MYD10A1 (Aqua, red) and MOD10A1 (Terra, blue) (with optimized NDSI threshold as shown above, snow depth threshold 1 cm) for different classifications (elevation, landuse type) of the 665 Austrian stations in the period September 2002 to August 2014. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Mapping accuracy obtained for different snow depth stations and different groups of stations. The NDSI threshold applied here is using the best NDSI threshold for all stations as shown in Table 2 for snow depth threshold T_{SD} 1–5 cm; using the optimized NDSI threshold with 6 classification as shown in Fig. 6 for the station groups with snow depth threshold T_{SD} = 1 cm.

Snow depth threshold T_{SD}/Station groups with T_{SD} = 1 cm		OA for all stations (%)		OA for median stations (%)	
		Aqua	Terra	Aqua	Terra
Snow depth threshold T_{SD}	T_{SD} = 1 cm	97.17	97.23	97.90	97.78
	T_{SD} = 2 cm	97.32	97.21	98.10	97.77
	T_{SD} = 3 cm	97.35	97.02	98.12	97.51
	T_{SD} = 4 cm	97.30	96.82	98.02	97.28
	T_{SD} = 5 cm	97.20	96.61	97.91	97.08
Elevation	< 300 m a.s.l.	98.90	98.60	98.98	98.71
	300–600 m a.s.l.	98.31	98.11	98.60	98.36
	600–900 m a.s.l.	96.96	96.91	97.30	97.27
	900–1500 m a.s.l.	95.79	96.01	96.42	96.40
	> 1500 m a.s.l.	96.58	96.39	97.34	96.60
Landuse type	non-forest	97.84	97.58	98.41	98.13
	coniferous forest	95.92	96.34	96.41	96.60
	other forest	96.79	97.06	97.23	97.41
Aspect	N-NE	97.05	97.05	97.63	97.57
	NE-E	97.67	97.58	98.24	98.06
	E-SE	97.95	97.74	98.53	98.11
	SE-S	97.45	97.36	98.02	97.84
	S-SW	97.35	97.21	97.73	97.55
	SW-W	97.63	97.39	98.20	97.71
	W-NW	98.01	97.81	98.29	98.13
	NW-N	96.97	96.81	97.95	97.64
Month	November	95.96	95.67	97.09	96.61
	December	90.43	90.56	92.31	91.67
	January	92.45	92.32	93.75	93.10
	February	93.43	93.15	94.90	94.50
	March	93.65	93.23	95.76	94.87

it is less than 80%. In the spring months (March, April) the median accuracy increases to over 95%.

The thresholds fitted to individual stations can be considered as a baseline for comparison but are difficult to apply in a regional use of MODIS snow cover maps. So, best thresholds for groups of stations in different elevation and land cover classes are representative (Fig. 6). The accuracy of these thresholds is evaluated in Fig. 10. The results show that a median accuracy over 90% is found in all three land cover groups for elevations below 900 m a.s.l. and for open (non-forest) land cover above 900 m a.s.l.. The lowest accuracy is found for stations above 900 m a.s.l. for other forest group, particularly in December, February and March. The median accuracy in this group is lower for the Aqua than the Terra dataset and varies between 80–85% for Aqua and 86–90% for Terra.

As can be seen from Table 4, the mapping accuracy for snow free condition increased but not significant with the optimized T_{NDSI} comparing to T_{NDSI} = 0.40. For patchy snow (1–5 cm) conditions the accuracy increased 4.29% for Aqua and 7.53% for Terra. There is also approximate 3% accuracy improvement for thick snow condition. If one is interested in the accuracy of snow classification, it can be improved to 88.08% and 92.03% for Aqua and Terra, respectively, with the optimized T_{NDSI}.

5. Discussion and conclusions

The main objective of this study is to evaluate the accuracy and applicability of the new MODIS snow cover datasets, i.e. Collection 6, for regional snow cover mapping in Austria. The key improvement of the new datasets are the NDSI values instead of binary snow-land-cloud classes based on fixed NDSI value (NDSI = 0.4). This provides some flexibility for users to create their own regional snow cover map, but requires selection of the NDSI thresholds, which can vary in time and/or space. Some of the previous studies (Härer et al., 2018) found a fixed threshold T_{NDSI} = 0.4 to be accurate, but this study shows that the

Table 4
The mapping accuracy for different snowpack conditions based on in-situ snow depth with NDSI threshold (T_{NDSI}) 0.40 and optimized T_{NDSI} (Fig. 6) in this study.

Snowpack condition	Snow free		Patchy snow		Thick snow		Snow covered		Overall	
In-situ snow depth SD (cm)	0		1–5		> 5		> 0		~	
T_{NDSI}	0.40	optimized	0.40	optimized	0.40	optimized	0.40	optimized	0.40	optimized
Aqua	98.78%	98.91%	52.67%	56.96%	91.61%	94.15%	85.25%	88.08%	97.14%	97.59%
Terra	98.56%	98.32%	64.52%	72.05%	92.26%	96.17%	87.50%	92.03%	96.97%	97.42%

thresholds, if allowed to vary in space and time, can be fitted to maximize the mapping accuracy. Our results show that the best NDSI thresholds in Austria have a strong seasonality and tend to decrease with increasing elevation. The best thresholds are lower in forested regions than in an open land cover setting and in these locations are generally lower than the fixed threshold (T_{NDSI} = 0.4). This is consistent with the recent results of Da Ronco et al. (2020) who quantified and compared optimal NDSI thresholds for 7 stations in the Central Apennines (Italy). They found that the optimal NDSI threshold for this region was 0.20, which resulted in a 15% increase in the snow-cover extent in all seasons. The snow cover mapping accuracy of the new dataset is very high. The median over 665 stations in Austria is larger than 97%, which is approximately 2% larger than that of the previous version (Parajka and Blöschl, 2006). The results indicate a similar decrease of mapping accuracy with increasing elevation and somewhat smaller accuracies in forested regions similar to previous assessments (Arsenault et al., 2014; Parajka et al., 2012). We found that the selection of the NDSI threshold is sensitive to the selection of snow depth threshold indicating snow coverage around the at site measurements. The analysis demonstrates that the different NDSI thresholds can be fitted to obtain very similar mapping accuracies. The question of how to select the NDSI threshold for regional snow cover mapping then depends on the snow depth threshold and land cover and topography of the region. Fig. 11 shows that, if a single threshold is fitted to all of Austria, a wide range of thresholds, i.e. between 0.2 and 0.4, results in a very similar mapping accuracy. The difference between the originally used threshold 0.4 and somewhat smaller thresholds is very small. If one refines the thresholds in different seasons and elevation and land cover groups (Fig. 12), the mapping accuracy can be increased for the period January to March by approximately 3–10% in forested regions above 900 m a.s.l..

Our results demonstrate that the new MODIS Collection 6 daily products have improved in comparison to the previous version and allow a flexible regional adjustment of mapping accuracy. The accuracy assessment particularly indicates an improvement of the mapping accuracy in spring which is expected to improve hydrological predictions during snowmelt events. In January to March, a lower NDSI threshold could reduce the MODIS underestimation error. While higher NDSI thresholds were found to avoid the MODIS overestimation error in the summer, accuracy improvements were not obvious. We therefore suggest that for future snow cover mapping applications in regions with similar physiographic conditions the previously used threshold (NDSI = 0.4) can be, in general, used for robust estimates of snow cover from MODIS (C6) datasets. In forested alpine regions, however, the lower threshold will improve snow cover mapping particularly during spring months. For fitting of such thresholds additional snow cover, snow depth or snow fraction data can be used.

We found that NDSI values provided in new MODIS snow cover product allow a flexible estimation of snow cover area. The uncertainties related to fitting of the best thresholds include the selection of snow depth threshold, particularly when the snow is patchy, or there is large topographical variability within a MODIS pixel or under the dense forest vegetation (Parajka et al., 2012). As it is indicated in Parajka and Blöschl (2006) time shift between snow depth and MODIS observations can also lead to some differences and uncertainty in the mapping of final thresholds. Such uncertainties can be reduced by using satellite products with finer resolution or by using new mapping algorithms that use vegetation characteristics (Wang et al., 2018). In future studies we plan to implement and evaluate different regionalization methods for regional snow cover mapping and to test their value and uncertainty for calibration and validation of rainfall-runoff models as well as for potential assimilation of new MODIS products in operational snowmelt forecasting methods.

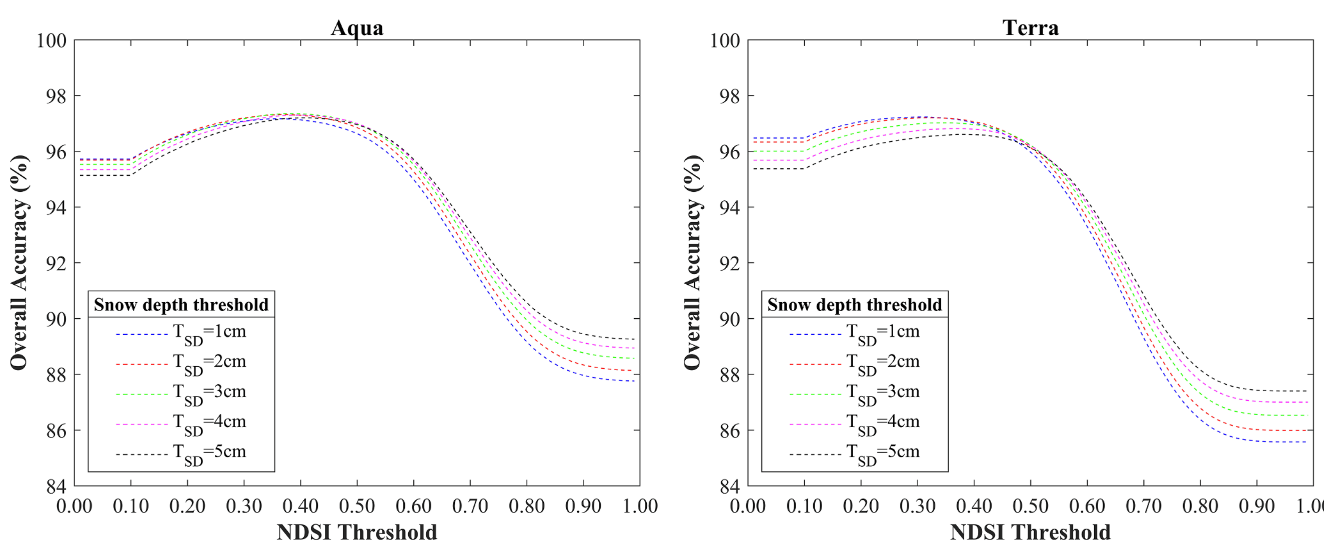

Fig. 11. Overall accuracy of Aqua (left panel) and Terra (right panel) snow cover products estimated for different NDSI and snow depth (SD) thresholds (Table 1). Overall accuracy is estimated for all 665 stations in the period September 2002 to August 2014.

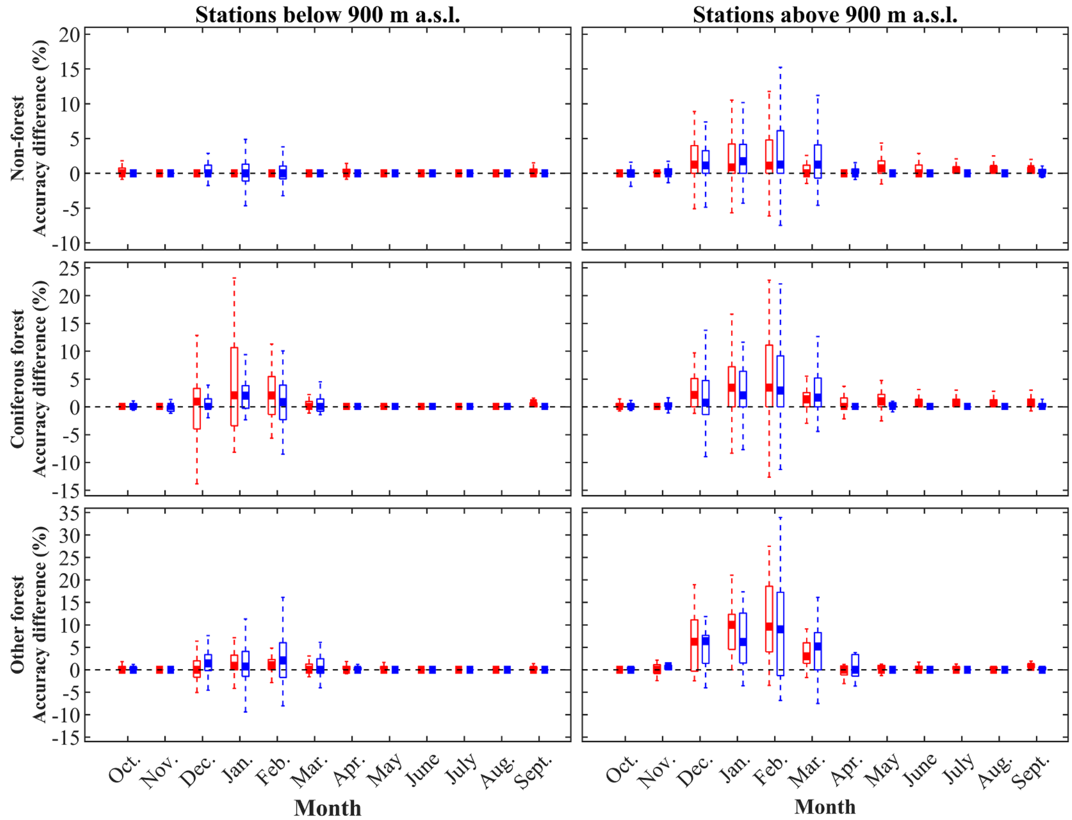

Fig. 12. Boxplot of accuracy difference between using NDSI threshold optimized and 0.40 for MYD10A1 (Aqua, red) and MOD10A1 (Terra, blue) over Austria according to the elevation of the stations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

CRediT authorship contribution statement

R. Tong: Conceptualization, Methodology, Software, Data curation, Writing - original draft. **J. Parajka:** Conceptualization, Methodology, Software, Validation, Writing - review & editing. **J. Komma:** Software, Validation, Data curation. **G. Blöschl:** Conceptualization, Resources, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data (Figs. S1 and S2) to this article can be found online at https://doi.org/10.1016/j.jhydrol.2020.125548.

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