WATER RESOURCES RESEARCH, VOL. 44, W03406, doi:10.1029/2007WR006204, 2008

Spatio-temporal combination of MODIS images – potential for snow cover mapping

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Received 29 May 2007; revised 5 December 2007; accepted 11 December 2007; published 8 March 2008.

[1] MODIS snow cover products are appealing for hydrological applications because of their good accuracy and daily availability. Their main limitation, however, is cloud obscuration. In this study we evaluate simple mapping methods, termed temporal and spatial filters, that reduce cloud coverage by using information from neighboring non-cloud covered pixels in time or space, and by combining MODIS data from the Terra and Aqua satellites. The accuracy of the filter methods is evaluated over Austria, using daily snow depth observations at 754 climate stations and daily MODIS images in the period 2003–2005. The results indicate that the filtering techniques are remarkably efficient in cloud reduction, and the resulting snow maps are still in good agreement with the ground snow observations. There exists a clear, seasonally dependent, trade off between accuracy and cloud coverage for the various filtering methods. An average of 63% cloud coverage of the Aqua images is reduced to 52% for combined Aqua-Terra images, 46% for the spatial filter, 34% for the 1-day temporal filter and 4% for the 7-day temporal filter, and the corresponding overall accuracies are 95.5%, 94.9%, 94.2%, 94.4% and 92.1%, respectively.

Citation: Parajka, J., and G. Blöschl (2008), Spatio-temporal combination of MODIS images – potential for snow cover mapping, *Water Resour. Res.*, *44*, W03406, doi:10.1029/2007WR006204.

1. Introduction

[2] Water stored in the snowpack represents an important component of the hydrological cycle in many regions of the world. Snow cover maps have been found very useful in hydrologic applications of assessing the snow resources, even if they give the spatial extent of the snow cover only [e.g., *Blöschl et al.*, 1991]. *Grayson et al.* [2002] noted that snow cover patterns are complementary to catchment runoff in identifying the structure of hydrologic models. *Udnaes et al.* [2007] and *Parajka et al.* [2007] demonstrated the value of snow cover data in calibrating conceptual hydrologic models. Both studies concluded that the snow cover data improved the snow estimates of the model without any significant loss in runoff model performance. Similar findings were presented by *Rodell and Houser* [2004] and *Andreadis and Lettenmaier* [2006] who assimilated MODIS snow cover data into hydrologic models in a forecasting context, concluding that the assimilation slightly improved the snow estimates in both spatial extent and temporal evolution.

[3] Various approaches to mapping the snow cover on a regional scale exist. These include the interpolation of ground based snow depth measurements [e.g., *López-Moreno and Nogués-Bravo*, 2006; *Parajka et al.*, 2007; *Brown and Braaten*, 1998], application of remote sensing techniques (in detail reviewed by *König et al.* [2001]) and the combination of the two [e.g., *Foppa et al.*, 2007]. For regional snow cover mapping, the MODIS satellite sensors are particularly appealing due to their high temporal resolution of a day and relatively high spatial resolution of about 500 m. Also, there exist two independent MODIS snow cover products (the Terra and the Aqua), whose observations are shifted by a few hours, and that could be used in a complementary way. *Parajka and Blöschl* [2006] reviewed several studies on the accuracy of MODIS snow products, either based on comparisons with other satellite-derived products or based on comparisons with ground based point snow depth measurements [e.g., *Bitner et al.*, 2002; *Klein and Barnett*, 2003; *Maurer et al.*, 2003; *Simic et al.*, 2004; *Lee et al.*, 2005; *Tekeli et al.*, 2005; *Zhou et al.*, 2005]. These studies drew two main conclusions. First, the MODIS snow cover products are, overall, in good agreement with available satellite and ground based snow data sets. The accuracy depends on region and season but, very often, it is within a range that makes the data very useful for hydrological applications. For example, *Parajka and Blöschl* [2006] found that the accuracy of the MODIS snow cover product over Austria was, on average, 95%, as measured against snow depth data at 754 climate stations. The second conclusion the studies drew is that cloud obscuration is the main limitation of the MODIS snow cover product. Again, cloud coverage depends on region and season, but, very often it is a real problem. The study of *Parajka and Blöschl* [2006] found that, on average 63% of the region was covered by clouds, and cloud coverage was even larger in the winter months where one would be particularly interested in the snow

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0043-1397/08/2007WR006204$09.00

product. A number of studies have attempted to reduce cloud obscuration in the MODIS snow data product by altering the cloud mask [e.g., *Riggs and Hall*, 2002] but the improvement is usually small as the coverage is real.

[4] The general idea this paper pursues is to reduce the cloud coverage of mapped snow cover by combining MODIS data in time and space. As clouds vary more quickly in time than the snow cover does one would expect that combining the data decreases the cloud coverage significantly. However, one would also expect that the accuracy of the snow cover maps so obtained would be lower than that of the original MODIS product because of the time shifts and space shifts introduced. Specifically, the aims of this paper are: (a) to evaluate the merging of the Terra and Aqua MODIS snow cover products; (b) to analyze different spatial and temporal combinations of MODIS snow cover images in terms of overall accuracy and spatial extent of cloud coverage; and (c) to assess the tradeoff between the MODIS snow mapping performance and the cloud coverage reduction. The ultimate goal is to obtain a combined product for near real time snow cover mapping that is robust, has minimum cloud coverage and is still accurate enough for hydrological applications. We test the MODIS daily snow cover products from the Terra and Aqua satellites against daily snow depth measurements at 754 climate stations in diverse topographic and climatic parts of Austria during January 2003 to December 2005. Such a comprehensive data set will likely allow us to draw conclusions that are more generally applicable than to the particular study region.

[5] The paper is organized as follows. First we briefly describe the MODIS snow cover products and give the details of the study area with snow depth observations. Next we present the proposed approaches of merged snow cover mapping. In the results section we give the seasonal variation in cloud coverage obtained by different mapping methods and evaluate their accuracy against in situ snow depth observations. Finally, we present the tradeoff between the snow mapping performance and cloud reduction. We conclude the paper with a discussion of the results and present some remarks on potential future applications of snow cover products.

2. Moderate Resolution Imaging Spectroradiometer (MODIS)

[6] MODIS is an imaging spectroradiometer that employs a cross-track scan mirror, collecting optics, and a set of individual detector elements to provide imagery of the Earth's surface and clouds in 36 discrete, narrow spectral bands from approximately 0.4 to 14.4 μm [*Barnes et al.*, 1998]. From a variety of geophysical products derived from MODIS observations, the global daily snow cover product is available through the Distributed Active Archive Center located at the National Snow and Ice Data Center (NSIDC, www.nsidc.org). The snow cover images used in this study have been acquired by the MODIS instrument mounted on the Terra and Aqua satellites of the NASA Earth Observation System. The Terra satellite has started the observations in February 2000, the Aqua satellite was launched in July 2002. Both satellites use the same type of MODIS instrument, but the differences in their orbits result in different viewing and cloud cover conditions. The most noticeable difference between these two satellites is the local equatorial crossing time: approximately 10:30 a.m. in a descending node for the Terra and approximately 1:30 p.m. in an ascending node for the Aqua satellite. The geolocation accuracy of MODIS instrument is about 45 m for Terra and 60 m for Aqua (*George Riggs*, personal communication, also see *Wolfe et al.* [1998]).

[7] The snow cover mapping algorithm applied to the MODIS data [*Hall et al.*, 2001] exploits the strong reflectance in the visible and the strong absorption capacity in the short-wave infrared part of the spectrum by the Normalized Difference Snow Index (NDSI). The NDSI allows to distinguish snow from many other surface features and is adaptable to a number of illumination conditions. The discrimination between snow and clouds is based on differences between cloud and snow/ice reflectance and emission properties. Clouds, typically, have high reflectance in visible and near-infrared wavelengths, while the reflectance of snow decreases toward the short-wave infrared wavelengths [*Hall et al.*, 1998]. For Terra data, the algorithm uses MODIS bands 4 (0.55 μm) and 6 (1.6 μm) to calculate the NDSI. MODIS band 6 detectors failed on Aqua shortly after launch, so band 7 (2.1 μm) is used instead to calculate the NDSI for Aqua [*Hall et al.*, 2000, 2003]. The MODIS snow cover product used here is based on a liberal cloud mask. This means that, when in doubt, the image is not masked. *Riggs et al.* [2003] suggested that a liberal cloud mask allows snow analysis on more pixels than a more conservative mask and, often, results in an increased accuracy of snow mapping in regions where there is snow and a mix of snow and clouds. On the other hand, a liberal cloud mask tends to erroneously identify some types of ice clouds as snow.

[8] The mapping of snow cover is limited in areas where snow cover is obscured by dense forest canopies [*Hall et al.*, 2001]. In the MODIS products, mapping snow in forested locations is based upon a combination of the normalized difference vegetation index (NDVI) and the NDSI [*Hall et al.*, 1998]. Application of the NDVI index allows for the use of different NDSI thresholds for forested and non-forested pixels without compromising the algorithm performance for other land cover types. However, such a mapping approach is only applied to the Terra data. The NDSI/NDVI test for snow in vegetated areas was disabled for Aqua imagery, because the use of band 7 resulted in too much false snow detection [*Hall et al.*, [2003].

[9] The MODIS snow cover data used in this study consist of daily snow cover maps from 1 January 2003 to 31 December 2005. We used Version 4 data [*Hall et al.*, 2000, 2003], where each daily map consists of a composite of multiple observations acquired for a day that are mapped to each grid cell. The combination procedure uses a scoring algorithm that is based on pixel location, area of coverage in a grid cell and solar elevation. The purpose of scoring is to select the observation nearest to nadir with greatest coverage at the highest solar elevation that was mapped into the grid cell [*Hall et al.*, 2000]. The territory of Austria is covered by the h18v04 and h19v04 tiles with 500 m spatial resolution. We combined data from both tiles and reprojected them into Lambert conformal conic projection using the MODIS Reprojection Tool [*MRT*, 2004]. After the

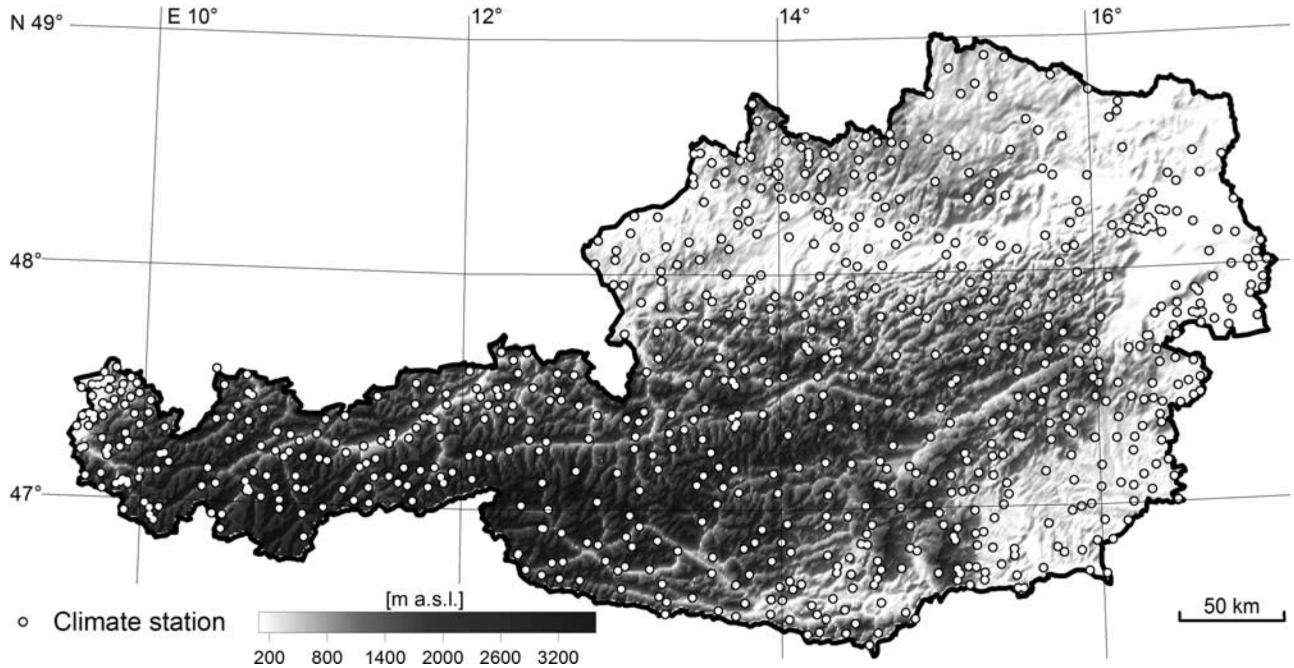

Figure 1. Topography of Austria and locations of climate stations with *in situ* snow depth measurements.

transformation, we reclassified the MODIS snow cover maps from originally 16 pixel classes [*Hall et al.*, 2000] to three categories: snow, no snow (land) and clouds. The snow class was retained as snow. The snow-free land class was retained as no snow (land). The cloud, missing and erroneous data classes were combined into clouds. However, the missing and erroneous data represent only a small portion of the total data. The remaining 11 original classes did not occur in the computations of this study. These snow cover maps were subsequently used in the spatiotemporal analysis.

3. Study Area and Snow Depth Measurements

[10] The study area covers the region of Austria. This territory has an area of about 84,000 km^2 and is characterized by flat or undulating topography in the East and North, and Alpine terrain in the West and South (Figure 1). Elevations range from 115 m a.s.l. to 3797 m a.s.l. Austria is located in a temperate climate zone, where mean annual precipitation is less than 400 mm/a in the East and almost 3000 mm/a in the West. Land use is mainly agricultural in the lowlands and forest in the medium elevation ranges. Alpine vegetation and rocks prevail in the highest mountain regions. Such diverse physiographic and landscape characteristics suggest that the territory of Austria is representative of a wider spatial domain, so the results may be applicable to larger regions with similar characteristics.

[11] The snow data set used in this study consists of daily snow depths measurements at 754 climate stations in the period from January 2003 to December 2005. The locations of these climate stations are shown in Figure 1. The snow depth readings are taken from permanent staff gauges and are hence point measurements. They are performed daily at 7:00 AM and snow depths are reported as centimeter integer values [*HZB*, 1992].

[12] For the quantitative validation of the satellite-derived snow cover product, the spatial representativeness of point measurements is important. The spatial arrangement of climate stations in Austria has been evaluated by *Parajka and Blöschl* [2006]. They demonstrated that the snow depth measurements cover a wide range of elevation zones of the country, but in the mountain regions the stations tend to be located at lower elevations, typically in the valleys. The highest climate station used in this study is at 2290 m a.s.l. which means that 6% of Austria (area above that elevation) are not represented by any climate station.

4. Methods

[13] We propose three approaches of merging MODIS data in space and/or time. The first approach, termed the combination of Terra and Aqua, merges the two MODIS snow cover products on a pixel basis. The pixels classified as clouds in the Aqua images are updated by the Terra pixel value of the same location if the Terra pixel is snow or land. This approach combines observations on the same day, shifted by several hours. The second approach, termed the spatial filter, replaces pixels classified as clouds by the class (land or snow) of the majority of non-cloud pixels in an eight pixel neighborhood. When there is a tie, the particular pixel is assigned as snow covered. The spatial filter procedure was applied to the combined Aqua-Terra images of the first approach. The third approach, termed the temporal filter, replaces cloud pixels by the most recent preceding non-cloud observations at the same pixel within a predefined temporal window. We tested temporal windows of 1, 3, 5, and 7 days. This procedure was, again, applied to the combined Aqua-Terra images of the first approach. The overall reduction of cloud coverage was then evaluated separately for all three merging approaches in terms of the

Table 1. Confusion Matrix Defining the Over- and Underestimation Errors *MO* and *MU* (Equations (1)–(2)) by Relating the Ground Based Snow Depth Observations (Ground) and the Satellite Snow Cover From MODIS[a]

Sum of Station-Days	MODIS: SNOW	MODIS: NO-SNOW
Ground: SNOW	a	b
Ground: NO-SNOW	c	d

[a]The a, b, c and d represent the number of cloud-free stations in a particular classification category. The index of overall agreement k_a (equation (3)) is defined in a similar way but relates to station-days rather than to stations.

decrease of cloud covered pixels over the territory of Austria.

[14] The accuracy of different spatial and temporal combinations of MODIS snow cover images was quantitatively evaluated using the ground snow depth measurements. Snow depth observations at the climate stations were considered as ground truth for the pixel that was closest to each station. The ground truth for these pixels was regarded as snow covered if the measured snow depth equaled or exceeded a threshold value ξ, and snow free otherwise. In the MODIS validation, two types of errors were evaluated: the MODIS misclassification of snow as land termed here the MODIS underestimation error (*MU*) and the misclassification of land as snow, termed the MODIS overestimation error (*MO*), both in %:

$$MU = \frac{b}{a+b+c+d} \cdot 100 \quad (1)$$

$$MO = \frac{c}{a+b+c+d} \cdot 100 \quad (2)$$

where a, b, c and d represent the number of cloud-free stations in a particular classification category as of Table 1. The MO and MU errors were estimated for each day and statistically evaluated in terms of the median and percentile difference (p75%–p25%) over the entire period 2003–2005, stratified by month. The overall degree of agreement between MODIS and snow depth measurements in the study period was represented by an accuracy index of overall agreement, k_a, defined as the sum of correctly classified station-days (snow, snow and no snow, no snow) divided by the total number of cloud-free station-days in percent:

$$k_a = \frac{A+D}{A+B+C+D} \cdot 100 \quad (3)$$

where A, B, C and D are defined in a similar way as in Table 1, but represent the number of station-days rather than

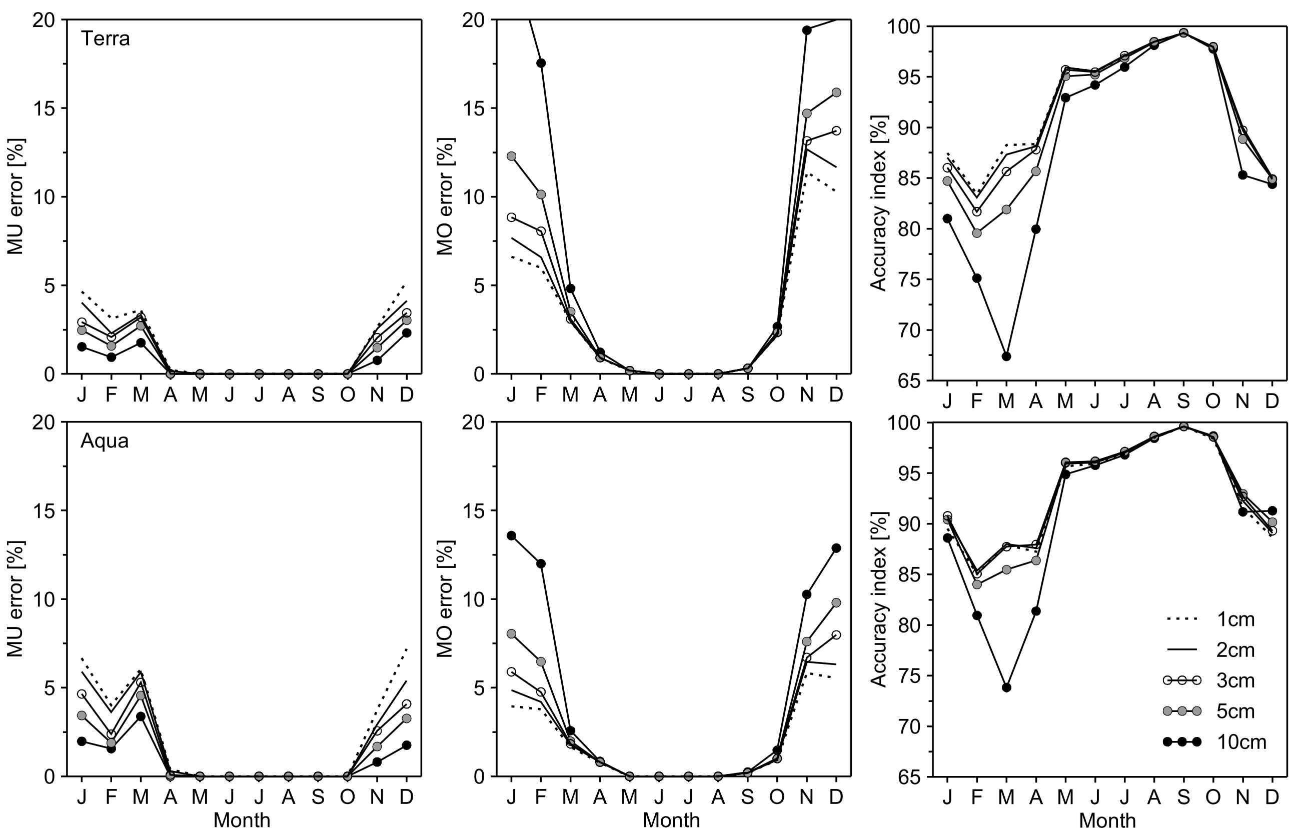

Figure 2. Sensitivity analyses of the effect of different snow depth thresholds ξ (1 to 10 cm) on the MODIS overestimation (*MO*) and underestimation (*MU*) errors and the index of overall accuracy. The sensitivity is evaluated separately for the Terra (top panels) and the Aqua (bottom panels) snow cover products.

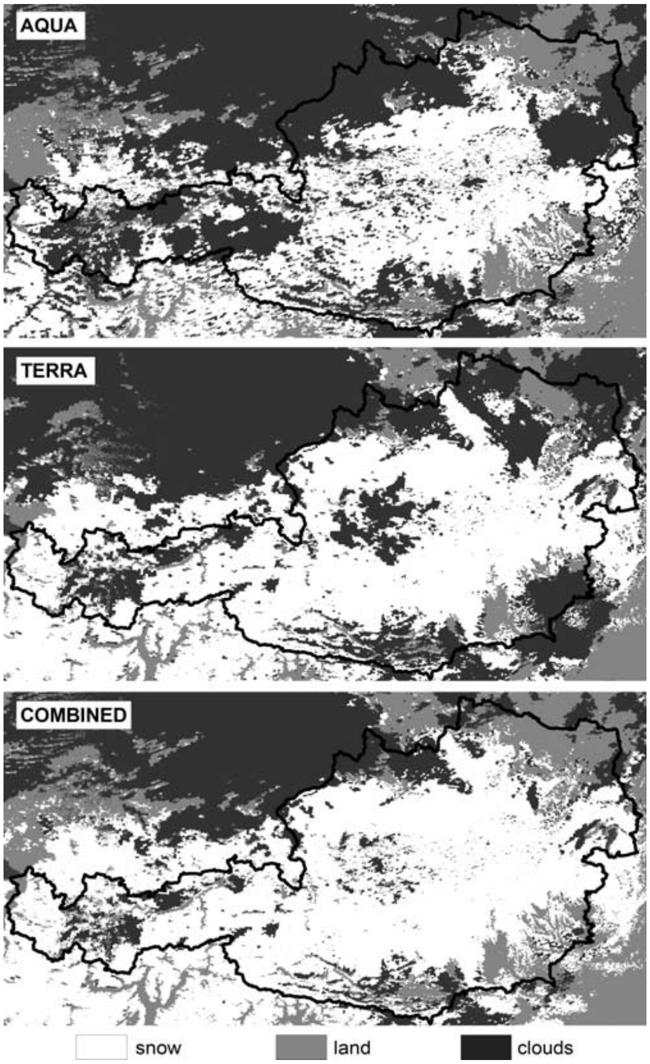

Figure 3. Example of merging the Aqua (top) and Terra (center) snow cover images for Austria on 25th October 2003.

the number of stations. The station-days are defined here as the number of days of misclassification or correct classification summed over all stations and evaluated for the entire period 2003–2005.

[15] In general, a suitable snow depth threshold ξ for the MODIS accuracy assessment may depend, e.g., on elevation, topographic variability, season and the resolution of the snow depth measurements. To determine a suitable value for this study, we performed a sensitivity analysis that relates different snow depth thresholds and the MODIS accuracy. Figure 2 shows the effect of the choice of the ξ thresholds on the Terra and Aqua *MU* and *MO* errors, and the overall accuracy k_a. The comparison indicates that the overall MODIS accuracy (right hand panels) is not sensitive whether 1, 2 or 3 cm thresholds are chosen and there is a slight decrease in the overall accuracy as the threshold increases. The MU and MO errors are more sensitive. For ξ = 1 cm the under- and overestimation errors are of similar magnitude, which implies that the biases are small. On the basis of this sensitivity assessment and given that in Austria the snow depths are reported as centimeter integer values, a snow depth threshold of ξ = 1 cm was selected for the MODIS evaluations.

5. Results

5.1. Combination of Terra and Aqua Snow Cover Maps

[16] An example of merging Terra and Aqua snow cover maps is presented in Figure 3. The top panel shows a snow cover map on 25th October 2003 acquired by the Aqua satellite; the middle panel shows the Terra image for the same day. The combined snow cover map presented in the bottom panel indicates a significant decrease in cloud coverage. On this day, the cloud coverage was 61.4% (Aqua), 55.6% (Terra) and 46.2% for the combined product. This corresponds to a reduction in the number of cloud covered pixels of 51,141 (12,785 km^2) in comparison to Aqua, and 31,618 (7904 km^2) in comparison to Terra.

[17] The seasonal distribution of cloud coverage and the effect of merging Terra and Aqua is presented in Figure 4. Terra has slightly lower cloud coverage than Aqua, and there is a remarkable decrease in cloud coverage when the two are combined. Merging the two snow cover products on the same day reduces cloud coverage by approximately 4% in February (Terra) and more than 21% in August (Aqua). More detailed statistics are given in Table 2 including the percentile difference (75%-25%) of the distribution of daily cloud coverage in each month. The percentile differences tend to increase when merging the products indicating a strong daily variation in cloud frequencies within each month. This may enable more reliable identification of the onset and melting of the snow cover, because more pixels are available for the snow cover mapping on a particular day.

[18] Merging the Aqua and Terra snow cover images was performed on a pixel basis. Figure 5 shows the relative number of changes made for each pixel, i.e., how many times cloud pixels were replaced by snow or land. The largest frequencies (more than 20%) and hence the largest

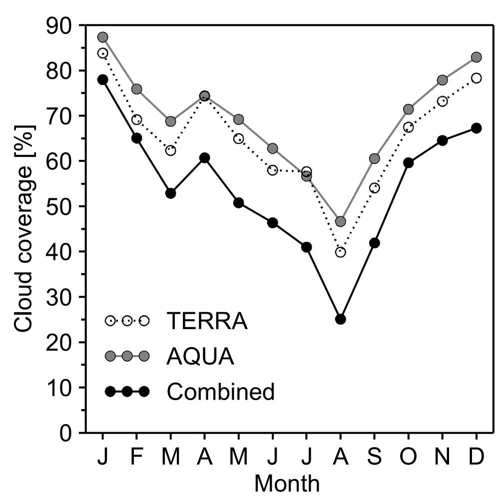

Figure 4. Cloud coverage of the Terra, Aqua and the combined Terra-Aqua MODIS snow maps in terms of the median of the daily distribution of cloud coverage over Austria (in %) within each month of the period 2003–2005.

Table 2. Cloud Coverage of the Terra, Aqua and the Combined Terra-Aqua MODIS Snow Maps[a]

Month	Terra	Aqua	Combined
January	83.8/29.1	87.4/31.2	78.0/36.9
February	69.1/45.4	75.9/43.6	65.1/51.7
March	62.3/59.6	68.7/55.7	52.9/67.4
April	74.4/38.7	74.4/34.0	60.7/46.0
May	64.9/60.4	69.2/44.5	50.8/60.3
June	58.0/57.4	62.8/44.2	46.4/58.3
July	57.7/54.5	56.7/45.3	41.0/53.6
August	39.9/57.3	46.7/57.4	25.1/53.6
September	54.0/66.8	60.5/68.1	41.9/73.2
October	67.5/53.1	71.4/53.3	59.6/58.9
November	73.2/38.0	77.9/40.0	64.5/39.6
December	78.3/42.7	82.9/37.0	67.3/48.0
Annual	66.1/53.9	70.1/48.1	55.0/59.2

[a]Median (first value) and percentile difference (p75%–p25%, second value) of the daily distribution of cloud coverage over Austria (in %) within each month of the period 2003-2005 as well as annual values.

benefits of merging the two snow cover products occur in the south of Austria which is the region south of the main ridge of the Alps. This is likely due to less persistent cloud coverage compared to the Alpine regions where clouds tend to be more continuous in time.

[19] The MODIS snow cover maps were verified against the ground observations at 754 climate stations. Table 3 summarizes the relative frequencies of stations where the MODIS snow products misclassified the snow presence or absence. The distribution of overestimation (MO) and underestimation (MU) errors shows typical seasonal patterns of winter highs and summer lows. There is very little snow in summer, so the errors are small too. Terra is biased in early winter (November and December) with median underestimation errors of 3–5% and overestimation errors of 10–11%. The remaining months show very little bias. Aqua has a slight bias toward underestimating snow. In December the median under- and overestimation errors are 7.2% and 5.5% respectively. This is likely due to the disabled NDSI/NDVI test for snow in vegetated areas in the Aqua snow mapping algorithm. As Aqua and Terra show tendencies for opposite biases, the combined product is less biased than Terra, although some biases remain. In November, for example, the median of over- and underestimation errors are 10.4% and 3.4%, respectively, when expressed as percent of the cloud-free stations. This means that, in these months, the combined MODIS product is biased with a tendency for classifying pixels as snow that were in fact snow free.

5.2. Spatial and Temporal Combination of Terra and Aqua Snow Cover Maps

[20] Figures 6 and 7 shows the spatial combination of the MODIS products where cloud pixels are replaced by their neighbors. This spatial filter approach produces a consistent decrease in the median of cloud frequency from Terra and Aqua of about 7%. Application of the spatial filter to the combined Terra-Aqua images (Table 4, first column) results in an additional decrease of 6% to 14% in cloud coverage, as compared to the merged unfiltered snow maps. The magnitude of cloud reduction depends on the season. The largest decrease (13.6%) is obtained for July when the median (merged) cloud coverage is 27.4%. In September and October, the reduction in cloud coverage is smaller (about 6%) leading to 35% cloud coverage in September and 53.6% cloud coverage in October. Terra has slightly lower cloud coverage than Aqua. Interestingly, 1-day temporal filtering of Terra gives a slightly larger cloud reduction than just combining Terra and Aqua for the same day,

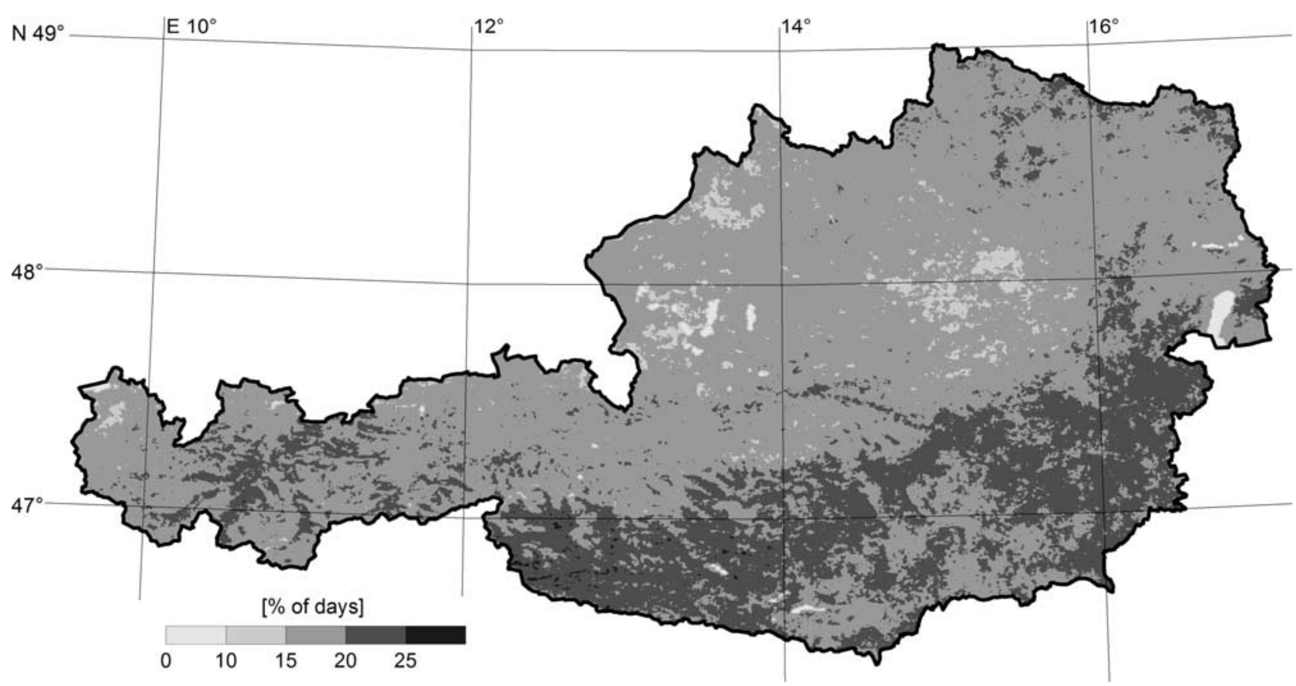

Figure 5. Frequency of change made by merging the Aqua and Terra snow cover images evaluated on a pixel basis. Values represent the relative number of replacements performed in the period 2003–2005.

Table 3. MODIS Over- (MO) and Underestimation (MU) Errors Evaluated for Cloud Free Days[a]

	Terra		Aqua		Combined	
Month	MU	MO	MU	MO	MU	MO
January	4.6/6.2	6.6/5.9	6.7/9.7	3.9/5.7	5.6/6.9	6.5/5.3
February	3.1/3.9	6.0/5.6	4.0/8.0	3.8/6.2	3.5/4.8	6.0/5.8
March	3.6/4.6	3.0/4.0	6.0/8.0	1.6/2.3	4.5/4.7	3.2/4.2
April	0.23/1.0	0.9/3.5	0.4/1.5	0.8/1.9	0.4/1.2	1.2/3.7
May	0.0/0.3	0.2/1.2	0.0/0.3	0.0/1.1	0.0/0.3	0.4/1.5
June	0.0/0.0	0.0/0.3	0.0/0.0	0.0/0.3	0.0/0.0	0.0/0.3
July	0.0/0.0	0.0/0.2	0.0/0.0	0.0/0.0	0.0/0.0	0.0/0.3
August	0.0/0.0	0.0/0.0	0.0/0.0	0.0/0.1	0.0/0.0	0.0/0.3
September	0.0/0.0	0.3/2.1	0.0/0.0	0.2/1.2	0.0/0.0	0.5/2.2
October	0.0/1.3	2.2/7.5	0.0/0.3	0.9/4.0	0.0/1.3	2.7/6.1
November	2.6/4.7	11.4/12.0	3.7/7.8	5.8/7.9	3.4/5.3	10.4/9.9
December	5.2/3.3	10.3/7.1	7.2/7.5	5.5/7.1	5.9/3.9	9.4/6.7
Annual	0.0/3.2	1.7/7.4	0.0/4.5	0.8/3.9	0.2/3.9	2.0/6.8

[a]Median (first value) and percentile difference (p75%–p25%, second value) of the errors (in %) within each month of the period 2003–2005 as well as annual values.

as presented in Figure 4. The 3-day temporal filtering yields a significant reduction in cloud coverage which is further reduced by the 5- and 7-day temporal windows.

[21] The reduction in cloud coverage obtained by the temporal filtering of the merged Terra and Aqua images is even larger (Table 4, columns 2–5). For the winter months (December and January), when cloud coverage is largest, the cloud coverage decreases to about 50% with 1-day temporal filtering (Table 4, column 2). The 3-day filter brings the cloud coverage down to less than 30% in December. The 5- and 7-day filters result in cloud coverages of less than 15% and 5%, respectively. The significant reduction in cloud coverage is also reflected in a decrease in the daily variability of cloud frequencies. The percentile differences in January to March decrease from around 50% for the 1-day filter to less then 10% for the 7-day filter.

[22] The spatially or temporarily merged Terra and Aqua snow cover images are quantitatively evaluated in Table 5. Overall there is a good agreement between the merged snow cover images and ground snow depth observations. There are, again, typical summer lows and winter highs. The errors of the spatially filtered combined Terra and Aqua snow cover images are almost the same as those of the combination of unfiltered snow maps. The magnitude of the bias for the winter season ranges, approximately, from 4% underestimation (MU) errors in February to more than 10% overestimation (MO) errors in November. Application of different temporal filters results in similar seasonal patterns, but the magnitude of the errors increases slightly. The largest overestimation error in November is 15% for the 1-day temporal filter and decreases to 10.4% for the 7-day filter. The underestimation errors are largest in January (12.1%) for the 3-day filter and approximately 7% for the 5- and 7-day filters. The magnitude and seasonal variability of the errors indicate that the main source of bias stems from the MODIS snow classification algorithm and not from the application of different filtering techniques.

5.3. Regional Variability in MODIS Accuracy and Trade Off Between Accuracy and Cloud Reduction

[23] The effect of vertical zonality on the agreement between different MODIS products and ground snow depth measurements was assessed by the evaluating the MODIS underestimation (MU) and overestimation (MO) errors in different elevation zones of Austria. Figure 8 displays the median of the MU (top panels) and MO (bottom panels) errors calculated separately for climate stations divided into four elevation zones. The MU errors show no consistent relationship to elevation. The largest MODIS underestimation errors occur for the stations located in the zone from 800 to 1500 m a.s.l. Seasonally, the largest MU errors occur in December, January and March, which corresponds well to the overall seasonal patterns of MODIS accuracies. When comparing the different MODIS products, the Aqua snow product gives the largest MU errors of about 15% in March. The MO errors show a clear dependence on elevation. The largest MO errors occur for the stations in the highest elevation zone (above 1500 m a.s.l.), where the median of the MO errors is more than 15% in the winter months. In contrast, the smallest MO errors are obtained for the lowlands (the lowest elevation zone), where the MO median is less than 5% for most of the MODIS snow cover products. In the period from April to October, there are practically no MO errors in this elevation zone. Snow cover very rarely occurs in this zone during these months.

[24] The overall degree of agreement between the different snow cover maps and the snow depth measurements was quantified in Figures 9 and 10 by the accuracy index k_a separately at 754 climate stations. Figure 9 gives the results of the Terra and Aqua images, their combination and the spatial filter applied to the combined images. Both the Terra and Aqua snow cover products are in very good agreement with the in situ snow depth measurements. More than 91% of all stations yield indices of more than 90% MODIS overall accuracy and there are only seven climate stations with MODIS accuracy of less than 80%. The combined and spatially filtered images yield slightly poorer performance. 90% (combined Aqua Terra images), and 88% (spatially filtered) of the climate stations have accuracies larger than 90%, and eight stations have accuracies of less than 80%.

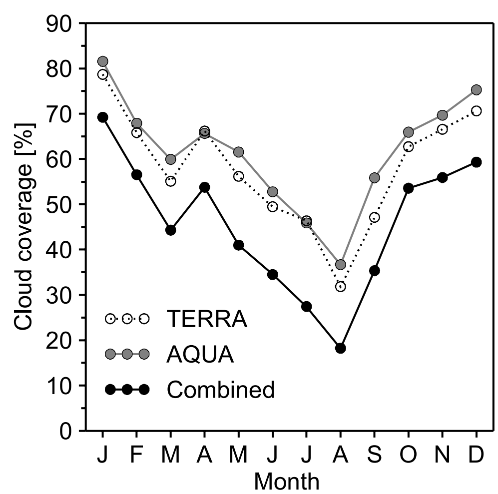

Figure 6. Cloud coverage of the Terra, Aqua and the combined Terra-Aqua MODIS snow maps subjected to the spatial filter approach in terms of the median of the daily distribution of cloud coverage over Austria (in %) within each month of the period 2003–2005.

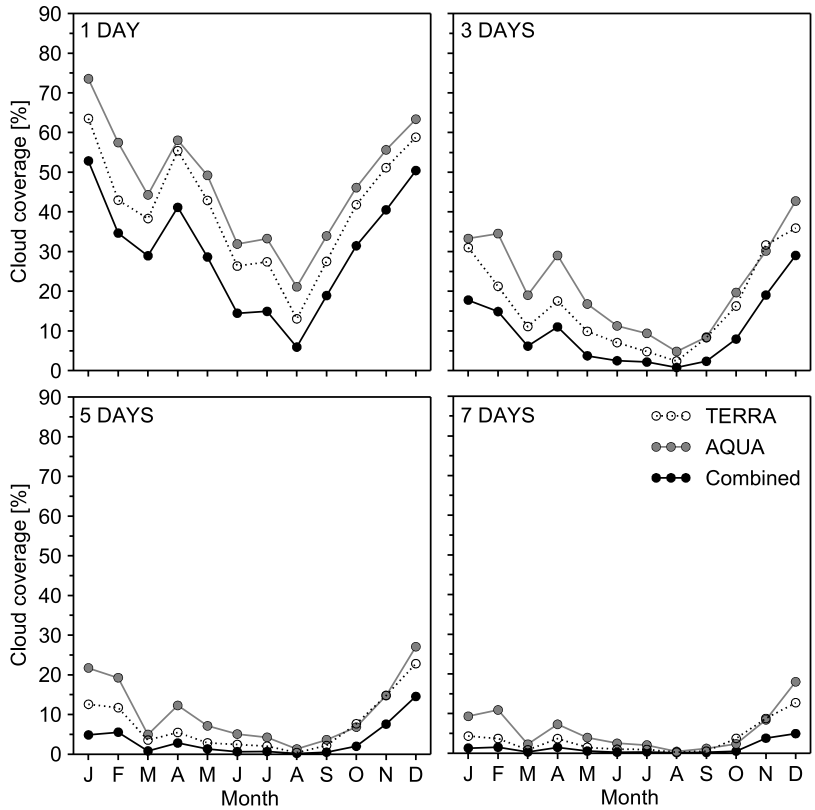

Figure 7. Cloud coverage of the Terra, Aqua and the combined Terra-Aqua MODIS snow maps subjected to the temporal filter approaches in terms of the median of the daily distribution of cloud coverage over Austria (in %) within each month of the period 2003–2005.

The spatial locations of the stations with poorer agreement do not exhibit a consistent pattern, but many of them are located in alpine valleys, where topographic and climate variability is large. The accuracy of the temporal filters is evaluated in Figure 10. The performance of the 1-day temporal filter is very similar to those of the mapping approaches in Figure 9. The total number of stations with an accuracy of less than 80% is eight. A decreasing trend in overall accuracy continues with the increasing width of the temporal window. The number of stations with an overall accuracy of less than 80%, increases from 10 (3-day filter) to 15 (5-day filter), and 17 (7-day filter). For the 3- and more days temporal filters, a distinct group of stations with poorer performance (less than 85%) is apparent at the boundary between the flat and mountain regions in the Eastern part of Austria.

[25] It is clear that, as the spatial and temporal filters are applied, the cloud coverage decreases, but so does the

Table 4. Cloud Coverage of the Combined (Aqua and Terra) MODIS Snow Maps Subjected to Spatial and Temporal Filters[a]

Month	Spatial Filter	Temporal Filter [1 day]	Temporal Filter [3 days]	Temporal Filter [5 days]	Temporal Filter [7 days]
January	69.2/43.1	52.8/50.2	17.8/40.8	4.8/28.0	1.3/9.6
February	56.5/55.2	34.6/49.6	14.9/32.3	5.5/18.9	1.5/9.5
March	44.3/69.3	28.9/51.6	6.2/24.0	0.8/7.4	0.3/1.2
April	53.8/51.8	41.1/48.9	11.0/29.5	2.8/12.0	1.5/5.5
May	41.0/60.8	28.6/52.8	3.7/22.9	1.3/3.7	0.6/1.1
June	34.5/57.6	14.5/34.1	2.5/8.8	0.6/1.7	0.3/0.6
July	27.4/53.6	14.9/38.4	2.2/10.6	0.7/1.6	0.3/0.5
August	18.2/51.3	5.9/28.3	0.8/4.2	0.2/1.0	0.2/0.1
September	35.3/72.8	18.9/56.5	2.3/25.6	0.5/10.3	0.2/1.2
October	53.6/57.2	31.5/55.8	7.9/33.5	2.0/7.6	0.5/2.5
November	55.9/40.6	40.5/31.9	19.0/21.8	7.6/13.0	3.8/6.2
December	59.3/51.7	50.4/43.7	29.0/38.3	14.5/29.1	4.9/18.5
Annual	46.3/59.3	29.4/51.7	6.9/26.9	1.6/9.1	0.6/3.0

[a]Median (first value) and percentile difference (p75%–p25%, second value) of the daily distribution of cloud coverage over Austria (in %) within each month of the period 2003-2005 as well as annual values.

Table 5. Over- (MO) and Underestimation (MU) Errors of the Combined (Aqua and Terra) MODIS Snow Maps Subjected to Spatial and Temporal Filters, Evaluated for Cloud Free Days[a]

	Spatial Filter		Temporal Filter [1 Day]		Temporal Filter [3 Days]		Temporal Filter [5 Days]		Temporal Filter [7 Days]	
Month	MU	MO	MU	MO	MU	MO	MU	MO	MU	MO
January	7.0/8.1	6.7/5.5	10.2/9.7	8.7/8.6	12.1/14.3	9.0/7.8	6.7/9.6	6.9/4.6	7.1/10.7	7.1/5.4
February	4.1/5.1	6.1/5.6	6.0/4.2	10.1/5.9	7.4/4.9	9.7/5.6	5.3/5.5	6.8/4.5	5.4/5.8	6.6/4.1
March	5.0/5.1	3.8/4.8	7.0/6.3	7.2/4.8	7.7/8.2	7.1/4.6	4.8/4.4	5.0/3.9	4.8/4.8	5.3/3.8
April	0.6/1.5	1.9/3.7	1.7/3.4	3.5/5.0	1.8/3.8	3.4/4.0	0.8/1.9	1.8/2.5	0.8/2.1	2.0/2.2
May	0.2/0.4	0.9/2.3	0.4/0.9	1.4/2.6	0.5/0.8	1.3/1.8	0.3/0.4	0.6/0.9	0.3/0.4	0.7/1.0
June	0.0/0.0	0.2/0.6	0.1/0.2	0.5/1.0	0.1/0.2	0.4/0.9	0.0/0.1	0.1/0.4	0.0/0.1	0.1/0.4
July	0.0/0.0	0.1/0.6	0.0/0.0	0.3/0.7	0.0/0.0	0.4/0.4	0.0/0.0	0.1/0.4	0.0/0.0	0.1/0.4
August	0.0/0.0	0.0/0.6	0.0/0.0	0.4/1.0	0.0/0.0	0.3/0.7	0.0/0.0	0.0/0.3	0.0/0.0	0.0/0.3
September	0.0/0.0	0.9/3.6	0.0/0.2	2.0/4.7	0.0/0.5	1.9/3.8	0.0/0.0	0.7/1.6	0.0/0.0	0.6/1.6
October	0.0/1.7	3.2/7.2	2.1/5.8	6.4/9.5	3.0/8.2	5.5/8.8	0.1/4.3	1.9/4.4	0.1/4.3	1.8/4.0
November	4.1/5.3	10.7/10.8	7.0/6.6	15.0/8.4	7.8/10.6	14.4/8.8	4.9/5.6	10.6/9.2	4.9/6.0	10.4/8.5
December	6.7/4.3	9.5/6.8	7.9/5.4	13.7/12.1	8.8/12.9	12.4/9.1	6.9/6.1	10.2/5.5	7.2/8.2	9.9/4.9
Annual	0.3/4.4	2.6/7.2	0.4/4.4	2.0/6.8	0.7 /4.9	2.0/6.5	0.8/5.2	2.0/6.1	0.8/5.5	2.0/6.1

[a]Median (first value) and percentile difference (p75%−p25%, second value) of the errors (in %) within each month of the period 2003-2005 as well as annual values.

accuracy. It is hence of interest to examine the tradeoff between accuracy and the potential for cloud reduction which is shown in Figure 11 and Table 6. The tradeoff curve is a clear, almost linear, relationship between cloud coverage and overall accuracy. An exception is December, where the cloud coverage can be decrease without any loss in accuracy. In all months, the best performance can be achieved for the original Aqua and Terra snow cover products. However, for these products the cloud coverage is large, especially in winter. Merging these two data sets (combined maps) gives very similar overall accuracy with a loss of only 0.2% and 0.6% with respect to the Terra and Aqua snow products, respectively. At the same time, the cloud coverage decreases by 7% and 11%, respectively. For the spatial filter and the 1-day temporal filter, the decrease in overall accuracy is 0.7% and 0.9%, respectively. However, there is a substantial reduction in cloud coverage of 13% and 25%, respectively, with respect to the Terra snow product. The 3-, 5-, and 7-day temporal filters reduce the cloud coverage by 44%, 52% and 55% respectively. This is at the expense of a decrease in accuracy of 1.8%, 2.6% and 3%, respectively (Table 6).

6. Discussion and Conclusions

[26] The aim of this study was to test simple and robust approaches for improving the existing MODIS daily snow products by reducing cloud coverage. Our motivation was to enable accurate near real time snow cover mapping to produce snow cover maps with a minimum of cloud coverage. Other potential applications include operational snowmelt runoff forecasting, data assimilation and the calibration or validation of hydrologic models. Cloud obscuration and the accuracy of the snow classification scheme are considered the crucial issues in using MODIS data sets for these purposes.

[27] We tested various approaches that replace the missing information, mostly due to cloud coverage, by the neighboring pixels in time or space. First, we merged the similar MODIS snow cover products available on the two platforms, the Terra and the Aqua satellites. As indicated by *D. Hall* [personal communication, 2006]: "There should be very little difference between the two products, but there are some. First of all, the Terra and Aqua products are acquired at different times during the day and therefore cloud coverage and even potentially snow cover conditions may be different. Secondly, the Aqua snow-mapping algorithm uses MODIS band 7 instead of band 6 and this produces a slightly different map under some conditions." A systematic evaluation of differences between these two showed that they are really similar in terms of cloud coverage and accuracy. Overall, Aqua is slightly more accurate but cloud coverage is slightly larger. The most noticeable differences in the accuracy assessment are the slightly lower overestimation errors in the winter months for Aqua, which is compensated by a somewhat larger underestimation of snow cover, in comparison to snow depth measurements at the ground. Interestingly, the simple combination of the Terra and Aqua snow cover images resulted in a 9% (January) to 21% (August) decrease in cloud coverage, in comparison to the Aqua snow cover product. If we assume similar classification accuracy of the two snow products, this may indicate the extent of temporal cloud continuity within a day. As the results indicated, the spatial patterns of cloud substitution frequencies are likely related to local meteorological conditions, suggesting more persistent cloud cover in the high alpine regions expressed by higher cloud frequencies and lower clouds substitution rates.

[28] In a next step, attempts at improving the combined Aqua and Terra snow cover images were made. We tested different approaches for replacing pixels assigned as clouds on both platforms. Replacement using the majority of non-cloud classes in the eight closest pixels, termed the spatial filter, resulted in an additional 6 to 13% decrease in cloud coverage, as compared to the simple combination of Terra and Aqua. On average, the clouds obscured only 45% of Austria using the spatial filter, which is approximately 18% lower than what has been obtained by *Parajka and Blöschl* [2006]. Interestingly, the use of neighboring pixels only

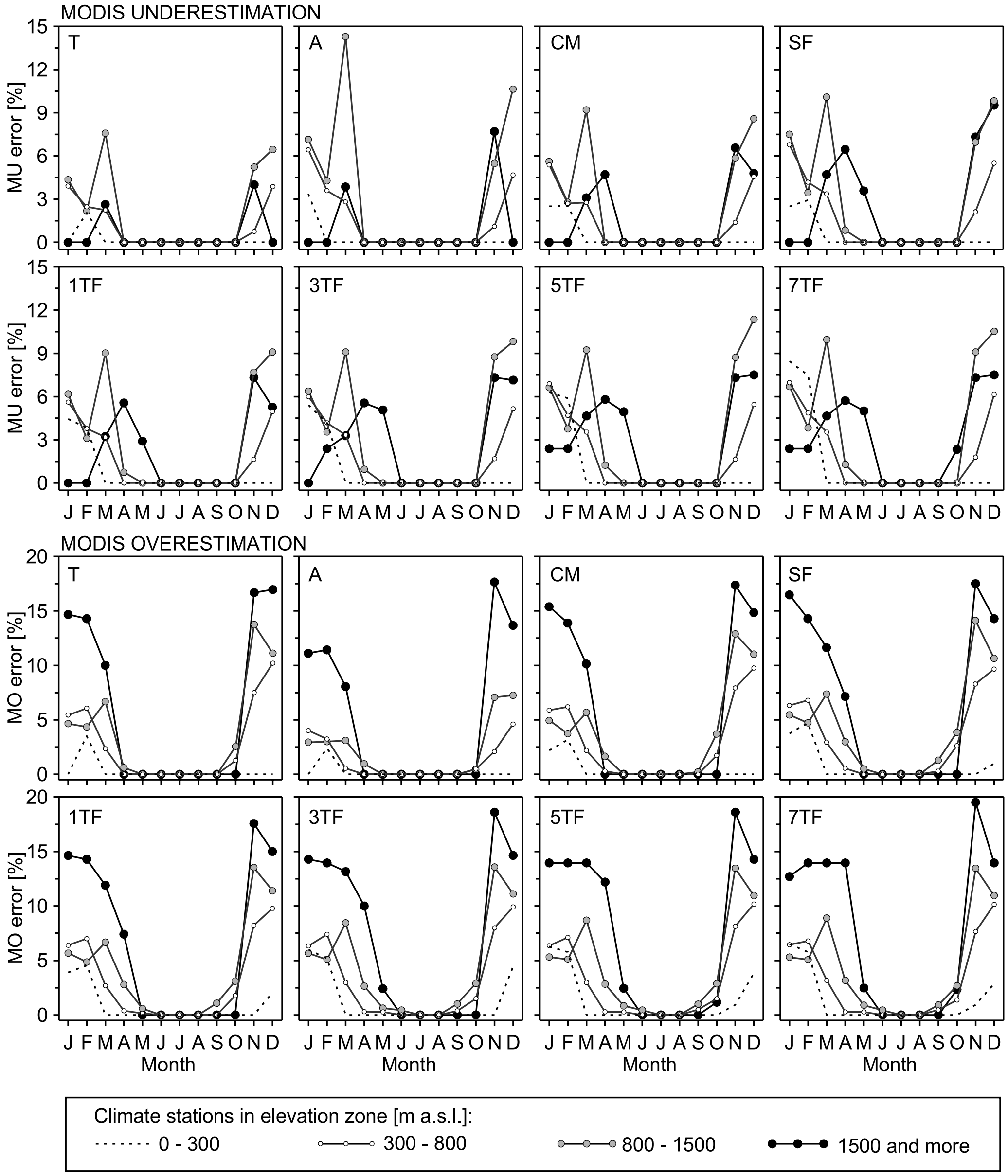

Figure 8. Evaluation of MODIS underestimation (*MU*) and overestimation (*MO*) errors in different elevation zones. The errors given are the medians over 118 (elevation zone 0–300), 381 (elevation zone 300–800), 234 (elevation zone 800–1500) and 43 (elevation zone above 1500 m a.s.l.) climate stations. The T and A relate to the original Terra and Aqua products, respectively. The CM relates to the combined product, the SF to the spatial filter, and the TF to the temporal filters (1 to 7 days).

slightly decreased the mapping performance. The seasonal patterns of the overestimation errors and underestimation errors obtained for the spatial filter are similar to those of the combined images. On average, the decrease in annual overall accuracy was only 0.9%, with a maximum decrease of 1.4% in February. Application of different spatial windows to MODIS data and evaluation of their accuracy in a similar fashion has been reported by *Zhou et al.* [2005]. Although they employed only four SNOTEL stations for comparison, they found almost the same classification accuracy, regardless of the size of the spatial window applied. The maximum difference in the classification accuracies between the 1 × 1, 3 × 3, and 5 × 5 spatial windows was 1.1%, varying for different stations from 50.3% to 56.8%. This compares fairly well with our results for the spatial filter, as their classification accuracy did not discriminate clear days from cloudy days. If we recalculate our overall accuracy index in a similar way (considering the clouds as classification error), the 94.2% accuracy of the spatial filter translates into an accuracy of 50.6% as measured by the accuracy index of *Zhou et al.* [2005].

[29] The temporal filter that uses preceding observations to replace cloud covered pixels enabled a further reduction in cloud coverage. Our results showed that using the previous observations from both platforms (1 day filter) reduced the average cloud coverage over Austria from

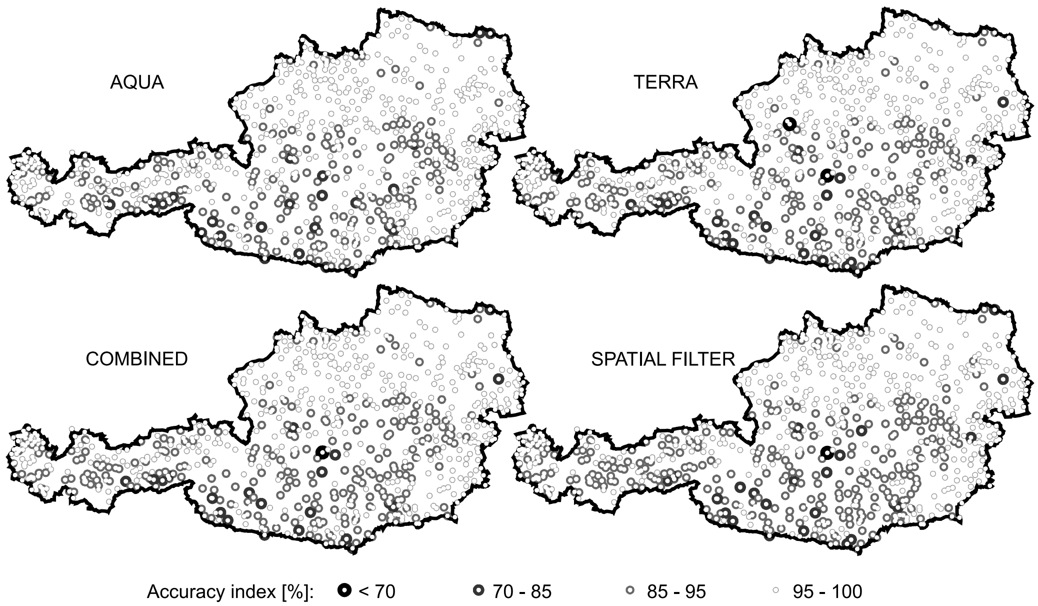

Figure 9. Spatial variability in the overall accuracy obtained for different MODIS snow cover combinations (Aqua, Terra, combined Aqua-Terra, spatial filter applied to combined Aqua-Terra). The index of overall accuracy k_a (Equation 3) is computed against ground based snow depths at 754 climate stations in the period 2003–2005.

51.7% to 33.5%, while the overall annual accuracy decreased from 94.9% to 94.4%. A similar temporal filtering was tested by *Şorman et al.* [2007] in the upper Euphrates River Basin in Turkey. They applied a shift of 1 and 2 days before or after the date of ground observations and reported that it resulted in a reduction in cloud coverage from 37% to 28% (1 day) and 18% (2 day filter). Their classification accuracy measured against 98 ground observations increased from 62% to 71% (1 day) and 82% (2 day filter) but it did not discriminate clear days from cloudy days. If we recalculate our overall accuracy index in a similar way (considering the clouds as classification error), our decrease of 94.9% to 94.4% by the 1-day filter translates into an increase in accuracy from 45.7% to 62.8%.

[30] The National Snow and Ice Data Center provides a similar composite snow cover product, the Global 8-Day Snow Cover data set [*Hall et al.*, 2006], which contains the maximum snow cover extent over an 8-day compositing

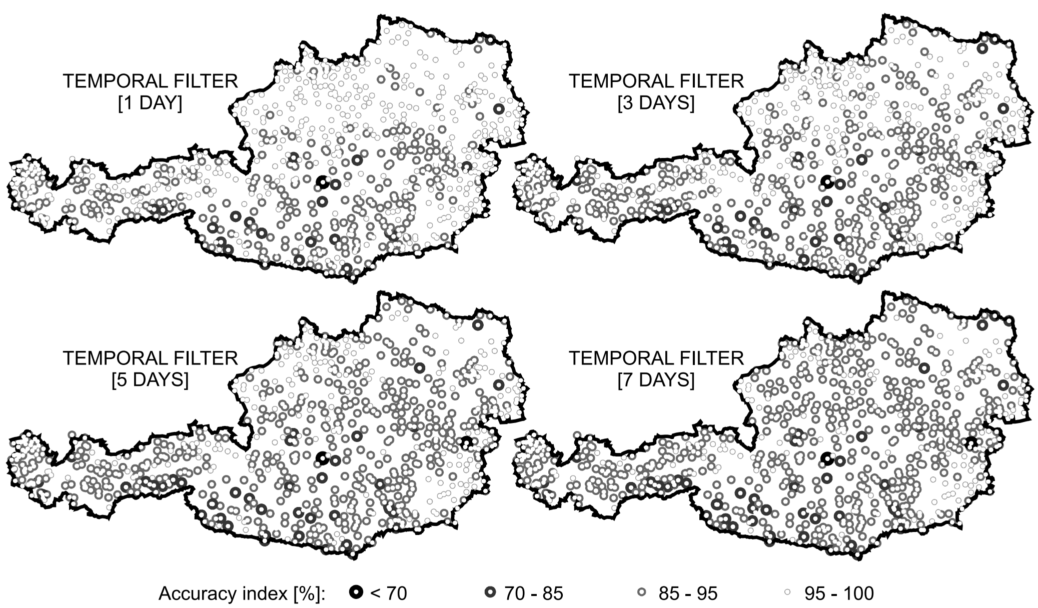

Figure 10. Spatial variability in the overall accuracy obtained for different MODIS snow cover combinations (temporal filters applied to combined Aqua-Terra). The index of overall accuracy k_a (equation (3)) is computed against ground based snow depths at 754 climate stations in the period 2003–2005.

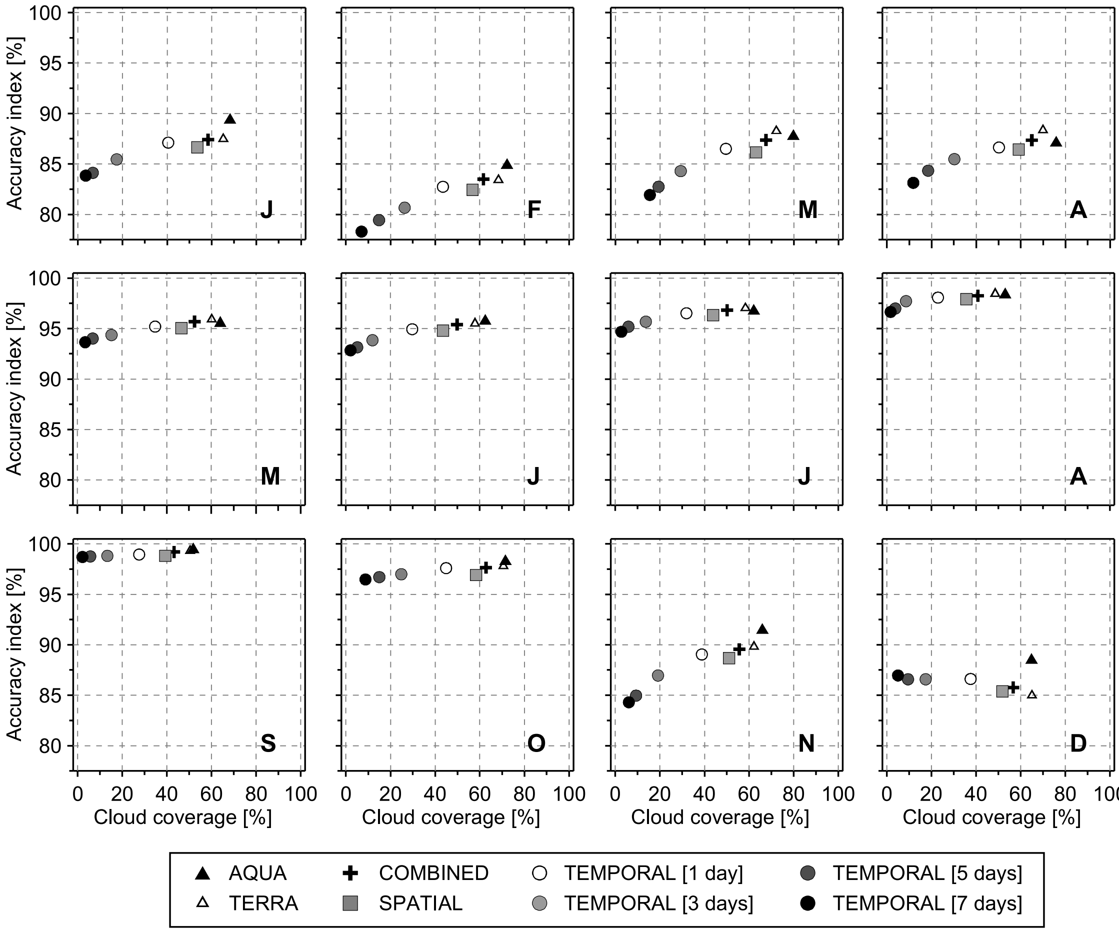

Figure 11. Trade off between the overall accuracy k_a (equation (3)) and cloud coverage obtained by different spatial and temporal merging approaches of MODIS. Spatial and temporal filters are applied to the combined Aqua-Terra images. Period 2003–2005, stratified by month (J is January, D is December).

period. In contrast to our mapping approach they map the maximum snow cover extent within a predefined 8-day temporal window, and do not replace the clouds by the latest non-cloud information. Our study demonstrated that mapping of the snow cover with a 7-day temporal filter allows a reduction in cloud coverage of more than 95%, with an overall annual accuracy of more than 92%. The same overall accuracy evaluation was applied by *Pu et al.* [2007] who tested the MODIS 8-day composite snow product against ground snow depth data on the Tibet Plateau. They reported an average of 90% overall accuracy in the period 2000–2003. The results of the 7-day temporal filter in this study (92.1% overall accuracy) compare favorably with these findings, although snow conditions in Tibet and Austria are different, so the magnitudes of the accuracy are not strictly comparable. The evaluation of the accuracy of the Global 8-Day Snow Cover product within the framework of hydrological modeling is foreseen in our next research.

[31] The assessment of the effect of vertical zonality on the agreement between different MODIS products and ground snow depth measurements has shown that the overestimation errors are related to topography. The overestimation errors of MODIS tend to increase with elevation and are up to 15% in the elevation zone above 1500 m a.s.l. in the winter months. In contrast, the underestimation errors show no consistent relationship to elevation for all tested MODIS snow products.

[32] The results of this study show that there exists a clear, seasonally dependent, trade off between cloud coverage and mapping accuracy. As progressively more data are merged, the cloud coverage decreases but so does the accuracy. The largest decrease in snow mapping performance occurs in November, February and March, which are the transition periods, representing the start of snow accumulation and melt respectively. These periods are most

Table 6. Trade Off Between the Overall Accuracy k_a (Equation 3) and Cloud Coverage Obtained by Different Spatial and Temporal Merging Approaches of MODIS[a]

	Overall Accuracy k_a	Cloud Coverage
Terra	95.1	59.2
Aqua	95.5	63.0
Combined	94.9	51.7
Spatial filter	94.2	46.1
Temporal filter [1 day]	94.4	33.5
Temporal filter [3 days]	93.3	15.5
Temporal filter [5 days]	92.5	7.5
Temporal filter [7 days]	92.1	4.0

[a]Spatial and temporal filters are applied to the combined Aqua-Terra images. Period 2003–2005.

sensitive to the replacement of pixels, especially when using preceding observations. The general benefits of the proposed mapping approaches however indicate that simple mapping techniques are remarkably efficient in cloud reduction and still in good agreement with ground snow observations. The main strength of the merging approaches proposed here probably lies in their simplicity and robustness. They can be easily applied in an operational context without additional data as would be needed in assimilation schemes. The choice of approach among those presented here will depend on the purpose of application and how much accuracy one is prepared to trade in for a reduction in cloud coverage. The results in this paper give guidance on this choice.

[33] **Acknowledgments.** The authors would like to thank the European Commission (AWARE project, contract No. SST4-CT-2004-012257) and the Austrian Science Foundation (FWF project no. P18993-N10) for financial support. At the same time we would like to acknowledge the Austrian Hydrographic Service (HZB) for providing the snow depth data and three anonymous reviewers for their constructive comments.

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