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The value of MODIS snow cover data in validating and calibrating conceptual hydrologic models

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Summary The objective of this study is to test the potential of snow cover data from the MODIS satellite sensor for calibrating and validating a conceptual semi-distributed hydrological model. The methodology is based on an indirect comparison of snow water equivalent simulated by the hydrologic model and the MODIS snow cover data. The analysis is performed for 148 catchments in Austria using the original Terra and Aqua MODIS images as well as MODIS snow cover products based on the combination of Terra and Aqua and on different spatial and temporal filters that reduce cloud coverage by using information from neighbouring non-cloud covered pixels in space or time. The results indicate that the use of the MODIS snow cover data improves the snow model performance as measured against independent ground snow depth data. In a verification mode, the median snow cover overestimation error of 7.1% of mismatch decreases to 5.6% and the corresponding underestimation error decreases from 4.7 to 4.1% if the combined MODIS data are used for calibration as compared to the case where no MODIS data are used. MODIS snow cover data also slightly improve the runoff model performance. In a verification mode, the median runoff model efficiency increases from 0.67 to 0.70 if MODIS data are used for calibration as compared to the case where no MODIS data are used. Sensitivity analyses indicate that the magnitude of the model efficiency is sensitive to the choice of the threshold of snow covered area used in estimating the snow underestimation errors, and the cloud cover threshold used in deciding whether a MODIS image can be used for model analysis. Evaluation of the model performance against merged MODIS snow products shows that the combination and filtering of the Aqua and Terra images does not significantly affect the runoff and snow model efficiency.

Introduction

Water stored in the snow pack represents an important component of the hydrologic balance in many regions of

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the world, especially in mountain regions. Monitoring and modelling of snow accumulation and melt is particularly difficult in these areas because of the large spatial variability of snow characteristics and, often, limited availability of ground based hydrologic data. Satellite imagery is an attractive alternative to ground based data, in particular in mountainous areas, as their resolution and availability does not depend much on the terrain characteristics.

In recent years, a range of MODIS instruments have been used for snow cover monitoring. 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. Numerous comparisons of MODIS snow cover images with other satellite-derived snow products and with ground based point snow depth measurements have confirmed their high accuracy and consistency (see 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, Pu et al., 2007, Wang et al., 2008). As summarized by Hall and Riggs (2007), the overall absolute accuracy is about 93%, but varies by land-cover type and snow condition. The study of Parajka and Blöschl (2006) has shown that the accuracy depends also on the season, mainly in correspondence with the seasonal variation of snow and cloud coverage. In many parts of the world, cloud obscuration has been found as the main obstacle to applying the MODIS snow cover product. The average spatial extent of clouds over Austria, for example, was 63% during 2000–2005 and cloud coverage was even larger in the winter months where one would be particularly interested in the snow product. However, as recently demonstrated by Parajka and Blöschl (2008) a reduction of cloud coverage is possible. Their basic idea proposed for the cloud reduction merges the two independent MODIS snow cover products (Terra and Aqua), whose observations are shifted only by a few hours. The study of Parajka and Blöschl (2008) evaluates simple mapping methods, termed temporal and spatial filters, that reduce cloud coverage by using information from neighbouring non-cloud covered pixels in time or space, and by combining MODIS data from the Terra and Aqua satellites. Interestingly, their 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.

Only a few studies in the literature have exploited the potential of MODIS snow cover data for calibrating and validating hydrological models (e.g. Rodell and Houser, 2004, Déry et al., 2005, Tekeli et al., 2005, Andreadis and Lettenmaier, 2006, Udnaes et al., 2007). Most of these studies indicated that the integration of MODIS snow data into hydrologic models improved the snow cover simulations and did not change much the model performance with respect to runoff. For example, Udnaes et al. (2007) studied the operational use of satellite-observed snow covered area (SCA) in the HBV model in order to improve spring flood prediction. They calibrated the hydrologic model using runoff and snow cover data and compared the model performance against a traditional calibration to runoff only. They found that snow cover data included in the HBV model calibration slightly decreased the runoff model efficiency, but improved the SCA simulations of hydrologic model. Rodell and Houser (2004) and Andreadis and Lettenmaier (2006) assimilated the MODIS snow cover observations into the snow water storage of a hydrologic model and assessed the assimilation efficiency against snow ground observations. They found that snow assimilation resulted in more accurate snow coverage simulations and compared more favourably with ground snow measurements. Each of these studies, however, used a limited number of catchments and limited duration of the observation period in their analyses. As the effects of using MODIS data on model performance tend to be small, they are difficult to detect with a limited number of catchments as they may depend on particular catchment conditions and the observation period. It is hence of interest to examine a larger number of catchments to draw more generic inferences than has been possible in previous research. The aim of this paper therefore is to assess the effect of using MODIS data on hydrological simulations for a total of 148 catchments and, specifically, to examine their value in terms of snow model and runoff model performance.

The paper is organized as follows. The methods section describes the concept used for the validation of the conceptual hydrologic model and introduces the integration of MODIS data into the model calibration. The data section gives the details of the study area and the ground and MODIS data used in this paper. The results section consists of three parts – a sensitivity analysis to evaluates the thresholds on snow model performance; validation of the snowmelt simulations (without calibration to MODIS snow cover) against different MODIS snow cover data; validation of the snowmelt simulations (with calibration to MODIS snow cover data). The final section discusses the results and concludes with remarks on potential future applications of snow cover products.

Data

The integration of MODIS snow data into a conceptual hydrologic model is tested and evaluated in 148 catchments in Austria (Fig. 1, Table 1). These catchments are located in different physiographic and climatic zones and have different sizes, ranging from 25 km^2 to 9770 km^2 with a median size of 369 km^2. Elevations of the study region range from 115 m a.s.l. to 3797 m a.s.l.. Mean annual precipitation ranges from less than 400 mm/year in the East to almost 3000 mm/year 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 study region is representative of a wider spatial domain and the results may be applicable in catchments with similar characteristics.

The hydrologic data set used in this study includes runoff data of the 148 catchments to calibrate and validate the hydrological model for different periods. The data also include daily precipitation at 1091 stations and daily air temperature at 240 climatic stations as an input to the hydrological model. The precipitation data were spatially interpolated by external drift kriging and the air temperature data were interpolated by the least-squares trend prediction method (Pebesma, 2001), using elevation as an

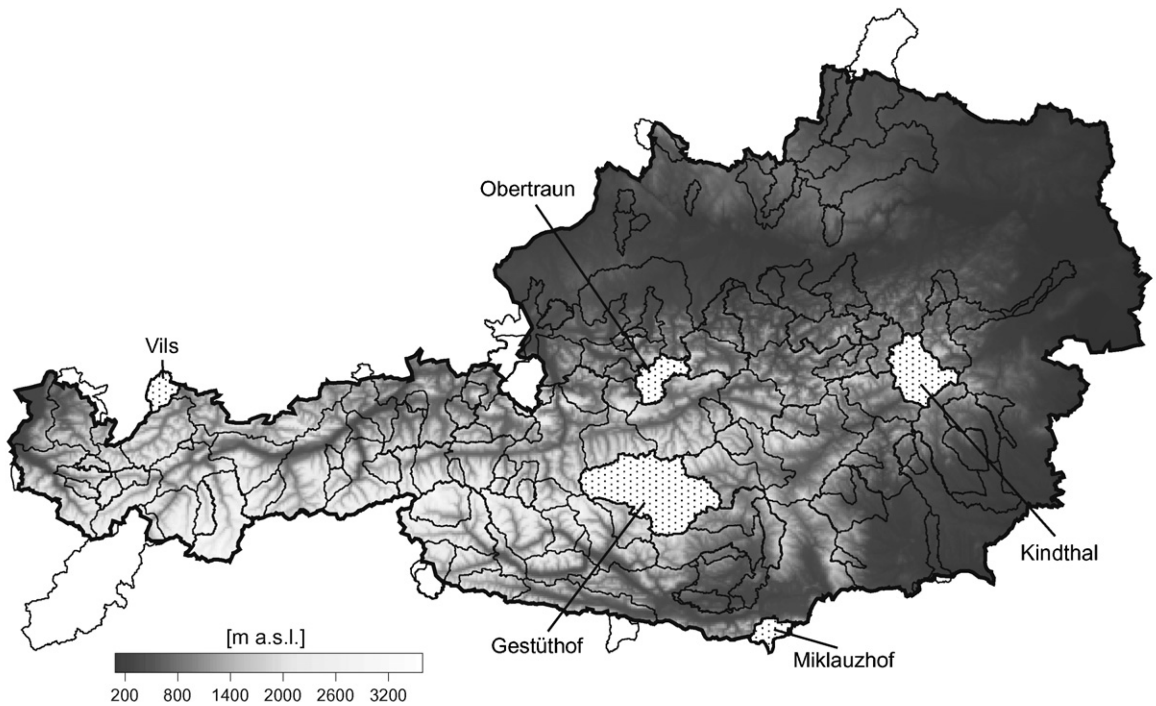

Figure 1 Topography of the study region and boundaries of the 148 catchments analyzed in this paper. Thick lines highlight the catchments used for a detailed comparison of the MODIS snow cover data and the hydrologic model simulations. Their basic characteristics are presented in Table 1.

Table 1 Summary of catchments selected for a detailed assessment of the calibration variants

ID	Gauge/stream	Area (km^2)	Gauge elev. (m a.s.l.)
212852	Miklauzhof/Vellach	194.3	459
201111	Vils/Vils	198.1	807
211086	Gestüthof/Mur	1700.3	776
211243	Kindthal/Mürz	727.7	569
205104	Obertraun/Traun	334.4	526

auxiliary variable in both cases. To validate the snow model when no MODIS snow cover data were available, ground snow depth data at 1091 stations were also used.

The MODIS data integrated in this study are based on observations acquired by the MODIS optical instrument mounted on the Terra and Aqua satellites of the NASA Earth Observation System. 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 observation, the global snow cover product is freely available through the Distributed Active Archive Center located at the National Snow and Ice Data Center (NSIDC, www.nsidc.org). This center publishes technical documents presenting a detailed description of the snow mapping algorithm, data formats and their spatial and temporal resolutions and references to validation studies. The MODIS snow cover dataset applied in this study contains all variants derived in the study of Parajka and Blöschl (2008). In their study they propose three approaches of merging original Terra (here termed as the T) and Aqua (A) MODIS products in space and/or time (Table 2). The first approach, termed the combination (CM) 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 (SF), replaces pixels classified as clouds by the class (land or snow) of the majority of non-cloud pixels in an eight pixel neighbourhood. 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 (D), replaces cloud pixels by the most recent preceding non-cloud

Table 2 MODIS snow cover products used in this paper (see Parajka and Blöschl, 2008)

Short	MODIS product
T	Terra
A	Aqua
CM	Combination of Terra and Aqua
SF	Spatial filter of CM
1D	Temporal filter (1 day) of CM
3D	Temporal filter (3 days) of CM
5D	Temporal filter (5 days) of CM
7D	Temporal filter (7 days) of CM

observations at the same pixel within a predefined temporal window of 1, 3, 5 and 7 days. This procedure was, again, applied to the combined Aqua-Terra images of the first approach.

The dataset used in this study consists of two parts. The first is a calibration dataset, which includes the hydrologic and MODIS data in the period from October 1, 2002 to December 31, 2005. The second is a verification dataset, which includes the hydrologic data in the period from November 1, 1986 to December 31, 1997. In the verification period, MODIS data are not available, thus ground based snow depth observations were applied in validation instead.

Methods

Model

The hydrologic model tested for the MODIS data integration is a semi-distributed conceptual rainfall runoff model, following the structure of the HBV model (Bergström, 1976) and uses elevations zones of 200 m. The model runs on a daily time step and consists of snow, soil moisture and flow routing routines. The snow routine simulates snow accumulation and melt using a concept of threshold air temperatures and a simple degree-day melting approach. Mean daily precipitation in an elevation zone is partitioned into rain and snow, based on the mean daily air temperature and the rain (T_R) and snow (T_S) air temperature thresholds. The catch deficit of the precipitation gauges during snowfall is corrected by a snow correction factor (CSF). Snow accumulation starts at air temperatures below a melt air temperature threshold (T_M). The amount of water stored in a snow pack is described by the snow water equivalent (SWE), which is a state variable of the model and is simulated independently in each elevation zone of a catchment. Snow melt starts at air temperatures above a T_M threshold and is proportional to a degree day factor (DDF) and the difference between air temperature and a T_M threshold. The soil moisture routine represents runoff generation and changes in the soil moisture state of the catchment. It is characterised by three model parameters: maximum soil moisture storage (FC), soil moisture state above which evaporation is at its potential rate (LP) and a parameter relating runoff generation to the soil moisture state (B). Runoff routing on the hillslopes is represented by an upper and a lower soil reservoir. Excess rainfall enters the upper zone reservoir and leaves this reservoir through three paths, outflow from the reservoir based on a fast storage coefficient (K_1); percolation to the lower zone with a constant percolation rate (C_P); and, if a threshold of the storage state (LS_{UZ}) is exceeded, through an additional outlet based on a very fast storage coefficient (K_0). Water leaves the lower zone based on a slow storage coefficient (K_2). The outflow from both reservoirs is then routed by a triangular transfer function using a free model parameter (C_R). From a total of 14 model parameters, 3 parameters were fixed ($T_R = 2\,°C$, $T_S = -2\,°C$, $C_R = 26.5$, for details see e.g. p. 5 and Figure 6 of Parajka et al., 2007b) and 11 parameters (Table 3) were estimated by automatic model calibration. More detailed information about the model structure and the model equations are given in the appendix of Parajka et al. (2007a); and examples of its application in hydrological modelling in Austria is presented, e.g., in Parajka et al. (2005a,b, 2007b).

Efficiency and error measures for runoff and snow covered area

Calibration and validation of the model is based on a number of efficiency measures and error measures that represent the match (or mismatch) of the simulation and the data. For runoff, the Nash–Sutcliffe Model efficiency has been used in two variants, M_E and $M_E^{\log}$, that emphasize high and low flows, respectively:

$$M_E = 1 - \frac{\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i} - \overline{Q_{obs}})^2} \tag{1}$$

and

$$M_E^{\log} = 1 - \frac{\sum_{i=1}^{n}(\log(Q_{obs,i}) - \log(Q_{sim,i}))^2}{\sum_{i=1}^{n}(\log(Q_{obs,i}) - \log(\overline{Q_{obs}}))^2} \tag{2}$$

where $Q_{sim,i}$ is the simulated runoff on day i, $Q_{obs,i}$ is the observed runoff, $\overline{Q_{obs}}$ is the average of the observed runoff

Table 3 Hydrologic model parameters and lower (p_l) and upper (p_u) bounds used in model calibration

Model parameter j	Model component	p_l	p_u
CSF (-)	Snow	0.8	1.5
T_M	Snow	−2.0	2.0
DDF (mm/°C day)	Snow	0.0	5.0
LP/FC (-)	Soil	0.0	1.0
FC (mm)	Soil	0.0	600
B (-)	Soil	0.0	20
K_0(days)	Runoff	0.0	2.0
K_1(days)	Runoff	2.0	30
K_2(days)	Runoff	30	250
C_P(mm/day)	Runoff	0.0	8.0
LS_{UZ}(mm)	Runoff	1.0	100

over the calibration (or verification) period of n days. Also a relative volume error V_E of runoff has been analysed:

$$V_E = \frac{\sum_{i=1}^{n} Q_{\mathrm{sim},i} - \sum_{i=1}^{n} Q_{\mathrm{obs},i}}{\sum_{i=1}^{n} Q_{\mathrm{obs},i}} \quad (3)$$

For snow covered area, the comparison is less straightforward as the model is based on elevation zones while MODIS are raster data. A schematic example of SWE simulation for a hypothetical catchment with four elevation zones (A, B, C, D) is presented in Fig. 2. This example shows that the model simulates a uniform distribution of SWE in each elevation zone, which is in contrast with the gridded representation of MODIS snow cover map (right panel of Fig. 1). Another difference between these two snow representations stems from the fact that the model simulates the amount (volume) of water stored in the form of snow, while the MODIS snow cover data shows only whether the spatial unit of the snow mapping (pixel) is covered by snow, land or is classified as missing information (mostly representing the clouds). This indicates that comparison of MODIS snow cover data with the SWE model simulations is possible only in an indirect way. The comparison is performed in individual elevation zones of a catchment. Two types of snow errors are evaluated. The first, termed model overestimation error (S_E^O), counts the number of days m_O when the hydrologic model simulates zone SWE greater than a threshold but MODIS indicates that no snow is present in the zone, i.e.:

$$S_E^O = \frac{1}{m \cdot l} \sum_{j=1}^{l} m_O \wedge (\mathrm{SWE} > \xi_{\mathrm{SWE}}) \wedge (\mathrm{SCA} = 0) \quad (4)$$

where SWE is the simulated snow water equivalent in one zone, SCA is the MODIS snow covered area within this zone, m is the number of days where MODIS images are available (with cloud cover less than a threshold ξ_C), l is the number of zones of a particular catchment, and ξ_{SWE} is a threshold that determines when a zone can be essentially considered snow free in terms of the simulations. An example of a day that would contribute to the snow overestimation error is presented in zone C of Fig. 2.

The second error, termed model underestimation error (S_E^U) counts the number of days m_U when the hydrologic model does not simulate snow in a zone but MODIS indicates that snow covered area greater than a threshold is present in the zone, i.e.:

$$S_E^U = \frac{1}{m \cdot l} \sum_{j=1}^{l} m_U \wedge (\mathrm{SWE} = 0) \wedge (\mathrm{SCA} > \xi_{\mathrm{SCA}}) \quad (5)$$

where ξ_{SCA} is a threshold that determines when a zone can be essentially considered snow free in terms of the MODIS data. An example of a day that would contribute to the snow underestimation error is presented in zone A of Fig. 2.

The percent or fraction of snow covered area, SCA, within each zone was calculated from the MODIS data as

$$\mathrm{SCA} = \frac{S}{S + L} \quad (6)$$

where S and L represent the number of pixels mapped as snow and land, respectively, for a given day and a given zone. The reliability and accuracy of the SCA estimation depends on the spatial extent of clouds occurring in an elevation zone. Only those days of the SCA images were hence used for a particular day and elevation zone if the cloud coverage was less than a threshold ξ_C:

$$C < \xi_C \quad (7)$$

where C is the fractional cloud cover for a particular day and elevation zone.

The thresholds ξ_{SWE}, ξ_{SCA} and ξ_C have been chosen on the basis of a sensitivity analysis (see Section 4.1). In this study, different MODIS snow products are examined. The sensitivity of SCA thresholds is thus evaluated for different MODIS snow cover products.

As no MODIS data are available in the verification period, ground based snow depth observations were applied for the validation of the snow model instead. The model errors S_D^O

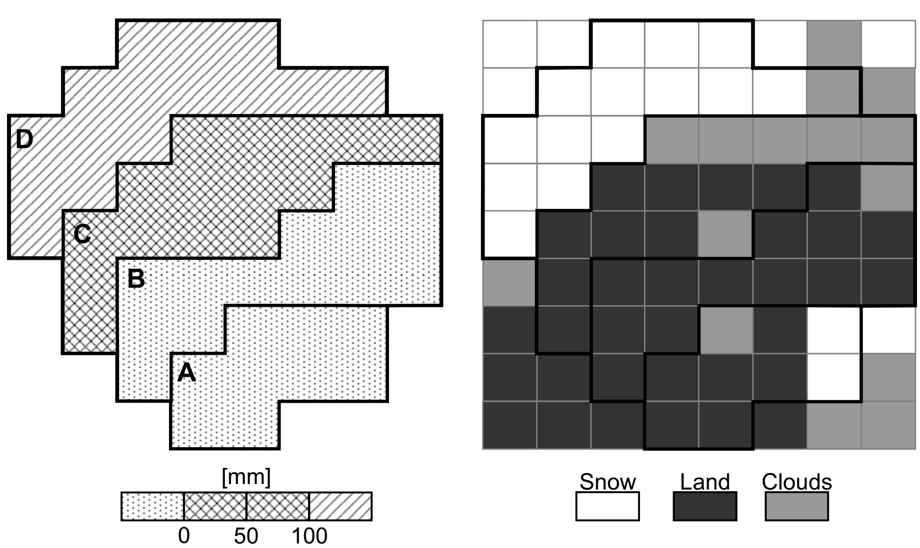

Figure 2 Schematic comparison of simulated snow water equivalent SWE (left) and MODIS snow cover (right). The A, B, C and D polygons represent the elevation zones of a catchment. Both maps are illustrative examples.

and S_D^U are defined in a similar way as in Eqs. (4) and (5) but instead of using MODIS SCA, the ground snow depth data were spatially interpolated from which the snow covered area was calculated for each elevation zone. The pixels were mapped as snow covered when the interpolated snow depth exceeded 1 cm and considered as land otherwise. Snow depth maps were interpolated by the external drift kriging method, using elevation as auxiliary variable.

Calibration to runoff alone

In a first variant, termed single-objective calibration, we emulate the usual model calibration and estimate the parameters of the hydrologic model using measured runoff only. The runoff objective function is defined as

$$Z_Q = w_Q \cdot (1 - M_E) + (1 - w_Q) \cdot (1 - M_E^{\log}) \qquad (8)$$

where the weight w_Q is set to 0.5. The idea of Eq. (8) is to combine two agreement measures M_E and $M_E^{\log}$, that emphasize high and low flows, respectively. The SCE-UA automatic calibration procedure (Duan et al., 1992) is used to minimize Eq. (8). No MODIS snow data are used for the calibration in this variant but they are used for assessing the errors of the snow simulations by analyzing the S_E^O and S_E^U errors for all catchments.

Calibration to both runoff and MODIS snow cover

In a second variant, termed multiple-objective calibration, we use both runoff data and MODIS snow cover data to calibrate the model by minimizing a compound objective function Z_M, which involves two parts Z_Q and Z_S that are related to the runoff and the snow cover, respectively:

$$Z_M = w_S \cdot Z_S + (1 - w_S) \cdot Z_Q \qquad (9)$$

The w_S is chosen on the basis of sensitivity analyses (see Section 'Sensitivity of SCA availability and snow model performance to the thresholds ξ_C, ξ_{SWE} and ξ_{SCA}'). The snow part Z_S of the compound objective function represents the sum of the over- and underestimation snow errors:

$$Z_S = w_1 \cdot S_E^O + w_2 \cdot S_E^U \qquad (10)$$

which were equally weighted in this study, so w_1 and w_2 were both set to 1.0. The same calibration and verification periods were used in the two variants of model calibration.

Results

Sensitivity of SCA availability and snow model performance to the thresholds ξ_C, ξ_{SWE} and ξ_{SCA}

As the reliability of the snow covered area SCA estimate from MODIS for each zone will depend on the fraction of the zone obscured by clouds we used a cloud cover threshold ξ_C above which the SCA is not used in the analysis. The magnitude of the threshold ξ_C will affect the number of days for which MODIS images are available, so there will be a trade-off between reliability and availability. This is shown in Fig. 3 in terms of the median number of days that are available for SCA estimation. For the combined Terra/Aqua product (CM) and a threshold of ξ_C = 20%, for example, SCA images are available on at least 33% of the days in half of the catchments (crosses, CM in Fig. 3). As the threshold ξ_C increases (i.e. is relaxed), the availability increases. The availability also increases as one moves from individual Terra/Aqua images to the various combinations of the images, and the effect of the threshold ξ_C decreases. A typical example of the SCA estimation is presented for the Obertraun catchment in Fig. 4. The top triplet of panels shows the SCA for the case when the whole catchment has less than 10% cloud cover (ξ_C = 10%), while the bottom triplet shows the case for a 60% cloud threshold. The top panels of each triplet give the SCA from the original Aqua and Terra snow cover products and their combination (CM), the middle panels give the SCA from the spatial and temporal 1 day filter, and the bottom panels give the SCA from the various temporal filters. Application of a less restricted clouds criterion (bottom triplet) enables more frequent estimation of the SCA, especially for the original Terra, Aqua and combined snow cover product (CM). The estimates from the 60% threshold seem to be robust as compared to those of the 10% threshold. During most of the season, they are very similar. The exception is early December and April, when the

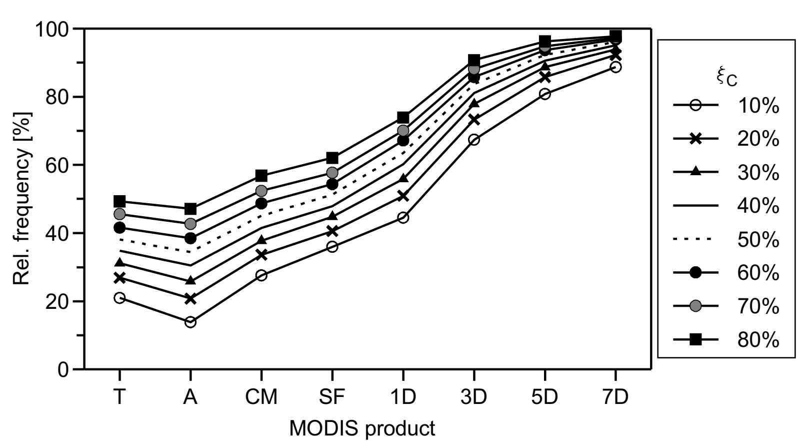

Figure 3 Number of days available for calculating snow covered area (SCA) from MODIS for different cloud thresholds ξ_C ranging from 0.10 to 0.80. Days are expressed as the frequency relative to the total number of days in the period 2003–2005. MODIS product see Table 2. Median of days evaluated over 148 selected catchments.

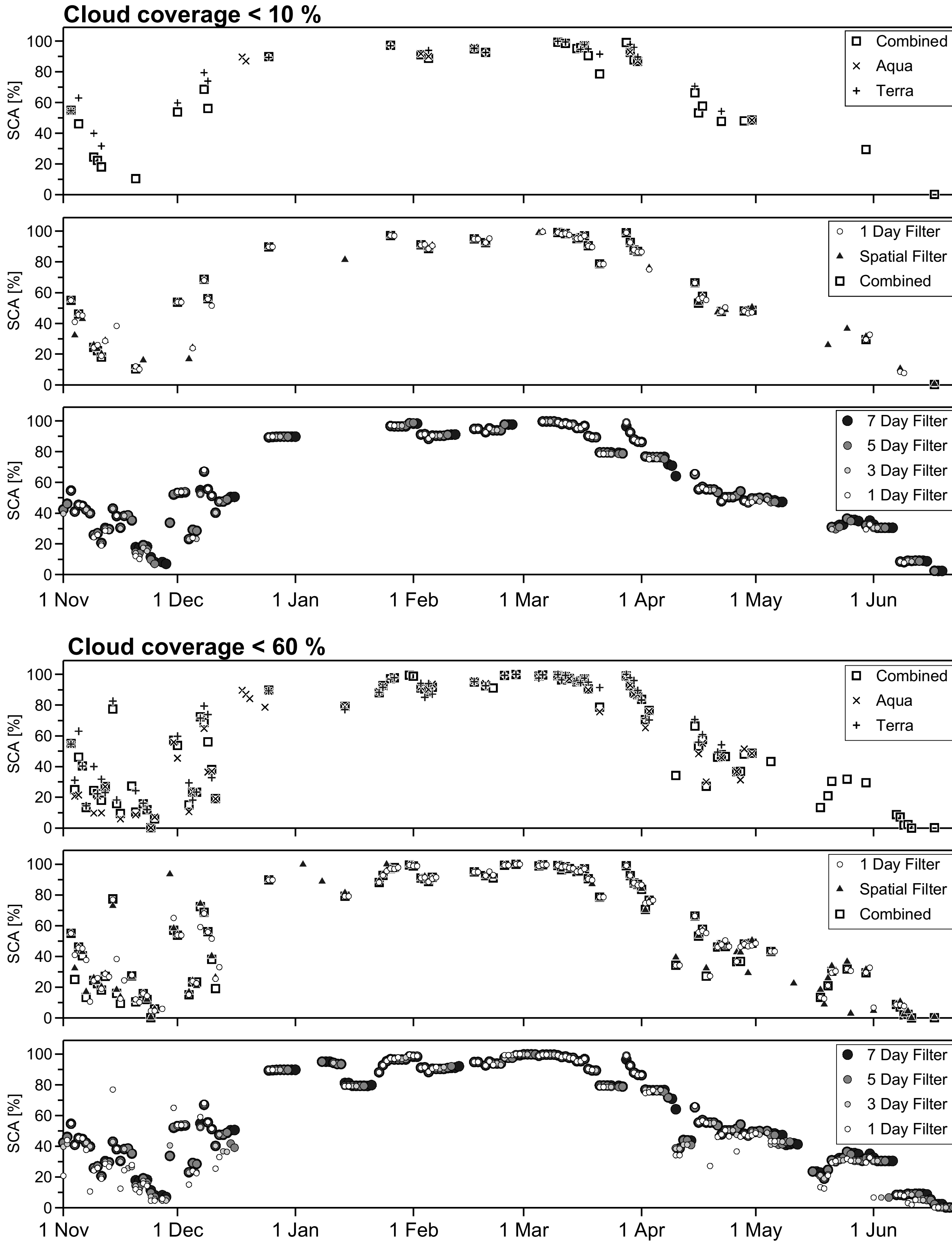

Figure 4 Example of MODIS snow cover area (SCA) in the Obertraun catchment (see Fig. 1) in the snow season 2004. The SCA was estimated for different MODIS snow products, only using images with less than 10% ($\xi_C = 0.10$, top triplet of panels) and 60% ($\xi_C = 0.60$, bottom triplet of panels) cloud cover.

scatter of SCA on subsequent days is a little larger in the case of the 60% threshold. The larger scatter may be related to the more frequent snow melt and rain-on-snow events during these periods. However, the difference is small. Thus based on these evaluations and additional error analyses of Parajka and Blöschl (2008), a threshold of $\xi_C = 60\%$ was selected for the SCA estimation in the snow efficiency evaluations of the remainder of this paper.

The thresholds ξ_{SWE} and ξ_{SCA} are used in the comparison of the model simulations and the MODIS snow cover observations to define the snow model errors (S_E^O and S_E^U). Fig. 5 explores how sensitive are the snow model errors to these thresholds. Specifically, the errors relate the CM MODIS product and the snow simulations obtained by the single-objective calibration over the 148 basins. The cumulative distribution functions (CDFs) of the S_E^O overestimation errors are almost insensitive to the thresholds ξ_{SWE} ranging from 0 to 10 mm (left panel). The median decreases slightly as ξ_{SWE} increases, but the larger values of the CDF change very little. In contrast, the CDFs of the S_E^U underestimation errors are very sensitive to the threshold ξ_{SCA} (right panel). The S_E^U errors are largest for $\xi_{SCA} = 0$ (i.e. a restrictive threshold) and are less than about 12% for half the basins (open circles in Fig. 5 right). As the threshold gets less restrictive (larger ξ_{SCA}), the errors decrease, as one would expect. For example, for $\xi_{SCA} = 10\%$ the S_E^U errors are less than 3.4% for half the basins (dark dashed line). To provide more insight into the nature of this sensitivity, Fig. 6 shows the seasonal distribution of the S_E^U errors. Fig. 6 indicates that the small ξ_{SCA} thresholds lead to largeS_E^U errors even in the summer months. This is clearly due to the misclassification errors of the MODIS mapping approach caused mainly by false classification of tiny ice clouds as snow (Parajka and Blöschl, 2006). This suggests that, for the further analyses, $\xi_{SCA} > 5$ should be chosen.

Similar sensitivity analyses were performed for all MODIS snow cover products considered in this paper and are shown in Tables 4 and 5 in terms of the median and the percentile difference of the S_E^O and S_E^U errors over the 148 catchments. For all products, the pattern of the S_E^O errors is similar to Fig. 5 in that they decrease with increasing threshold ξ_{SWE} (Table 4) but the decrease is small. The S_E^O errors slightly increase as one move from the original Terra product to the filtered products. For example, with $\xi_{SWE} = 1$ mm the Terra product gives a median S_E^O error of 0.7% while a seven day filter gives an error of 1.2%. This increase is likely related to the reduction in accuracy with increasing duration of the filter which is traded in for a smaller cloud cover (see Parajka and Blöschl, 2008). The percentile difference (P75% − P25%) over 148 catchments is remarkably stable around 2.5% indicating that the shape of the CDF does not change much with changing thresholds and the use of filters. There is a tendency for Aqua to produce larger errors and larger percentile differences than Terra and filtered products. Interestingly, the Aqua images have been found more accurate with respect to ground snow depth measurements than Terra (see Parajka and Blöschl, 2008), which means that the hydrologic model calibrated against runoff only, tends to overestimate snow as compared to the observed snow depth data.

The sensitivity of the S_E^U errors (Table 5) to ξ_{SCA} for the various filters is similar to that of the combined product (Figs. 5 and 6). The errors decrease significantly with increasing ξ_{SCA} and this is true of all MODIS products. The percentile differences (P75% − P25%) over 148 catchments are of the same order of magnitude as the medians. For the threshold $\xi_{SCA} = 25\%$ the median underestimation errors S_E^U are around 1.6% with a percentile differences of 2.7% (Table 5). This is very similar to the median and the percentile differences of median overestimation errors S_E^O for

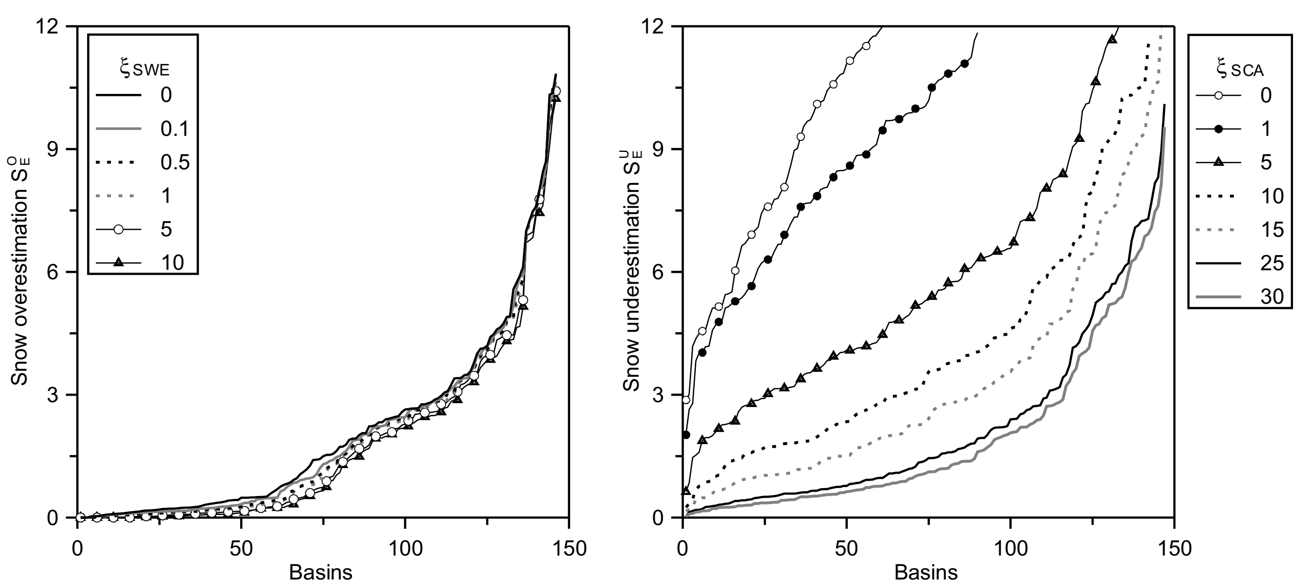

Figure 5 Cumulative distribution functions of the snow over- (S_E^O) and underestimation (S_E^U) errors to different thresholds ξ_{SWE} (in mm) and ξ_{SCA} (in%) based on the combined MODIS (CM) snow product using data from 148 basins in the calibration period. Snow simulations are obtained by single-objective calibration to measured runoff only.

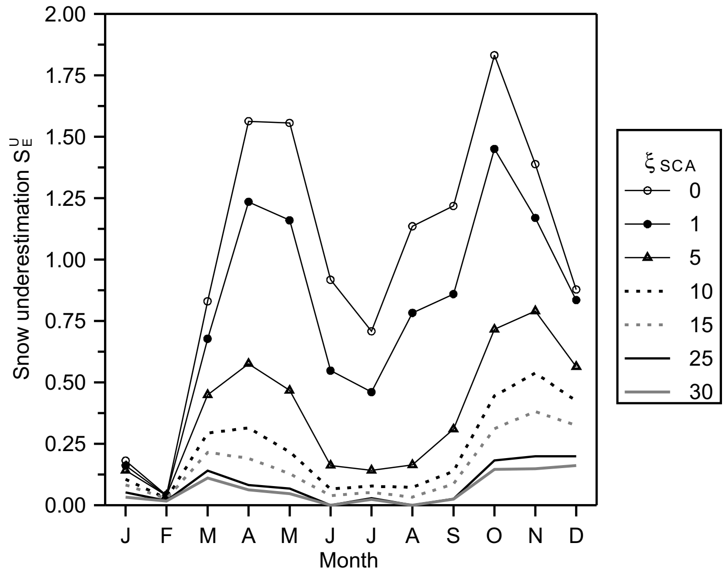

Figure 6 Seasonal distribution of the snow underestimation errors (S_E^U) estimated for different snow cover area thresholds ξ_{SCA} based on the combined MODIS (CM) snow product. Median over 148 catchments in the calibration period. Snow simulations are obtained by single-objective calibration to measured runoff only.

Table 4 Statistical evaluation of the S_E^O snow overestimation errors (%) estimated for different ξ_{SWE} thresholds and different MODIS snow cover products (see Table 2)

ξ_{SWE} (mm)	Terra	Aqua	CM	SF	1D	3D	5D	7D
0	1.0/2.5	1.8/3.1	1.5/2.7	1.6/2.9	1.5/2.7	1.5/2.6	1.6/2.5	1.6/2.6
0.1	0.9/2.5	1.5/3.2	1.3/2.7	1.3/3.0	1.2/2.6	1.2/2.5	1.4/2.4	1.5/2.3
0.5	0.7/2.6	1.4/3.1	1.1/2.7	1.1/3.0	1.0/2.6	1.1/2.5	1.2/2.4	1.3/2.3
1	0.7/2.6	1.3/3.1	1.0/2.7	1.1/3.0	0.9/2.6	1.0/2.5	1.1/2.5	1.2/2.3
5	0.5/2.5	1.2/3.1	0.7/2.7	0.9/3.0	0.6/2.6	0.7/2.5	0.8/2.5	0.8/2.4
10	0.5/2.4	1.0/3.0	0.6/2.5	0.8/2.9	0.6/2.5	0.6/2.4	0.6/2.4	0.7/2.4

The first value in the table is the median, the second value is the percentile difference (P75% − P25%) over 148 catchments in the calibration period. Snow simulations are obtained by single-objective calibration to measured runoff only.

Table 5 Statistical evaluation of the S_E^U snow underestimation errors (%) estimated for different ξ_{SCA} thresholds and different MODIS snow cover products (see Table 2)

ξ_{SCA} (%)	Terra	Aqua	CM	SF	1D	3D	5D	7D
0	13.7/9.8	10.9/9.3	14.2/10.7	15.5/11.7	16.8/12.7	18.7/13.3	19.1/13.1	19.3/12.9
1	10.3/5.7	7.4/5.5	10.1/6.4	11.8/7.3	11.6/7.2	12.9/8.1	13.2/8.5	13.3/8.4
5	6.7/5.0	4.1/3.9	5.3/4.5	6.2/4.8	5.9/4.8	6.5/5.5	6.6/5.8	6.6/6.1
10	4.8/4.8	2.6/3.1	3.5/4.1	4.0/4.3	3.9/4.4	4.0/4.8	4.0/4.6	3.9/4.7
15	3.7/4.4	1.9/2.7	2.4/3.3	2.9/3.6	2.7/3.7	2.8/4.0	2.9/4.1	2.9/4.2
20	2.9/4.1	1.4/2.2	1.9/2.7	2.1/3.0	2.0/3.2	2.2/3.4	2.2/3.4	2.2/3.4
25	2.3/3.7	1.0/1.8	1.4/2.4	1.7/2.4	1.4/2.6	1.7/3.0	1.7/3.1	1.7/3.1
30	1.8/3.4	0.8/1.6	1.1/2.2	1.3/2.2	1.2/2.3	1.3/2.7	1.3/2.9	1.4/2.9

The first value is the median, the second value is the percentile difference (P75% − P25%) over 148 catchments in the calibration period. Snow simulations are obtained by single-objective calibration to measured runoff only.

$\xi_{SWE} = 0$. It was considered an advantage to chose the thresholds in a way that the errors are unbiased, i.e., S_E^O and S_E^U are similar. Thresholds of $\xi_{SCA} = 25\%$ and $\xi_{SWE} = 0$ were hence selected in the remainder of this paper.

Model performance — calibration to runoff alone

The efficiency of the hydrologic model to simulate runoff and snow is evaluated in Table 6. The assessment of model performance represents a typical modelling concept where

Table 6 Statistical evaluation of the runoff model efficiencies (M_E, M_E^{log}), runoff volume error (V_E) and the snow model errors (S_D^O and S_D^U) obtained by single-objective calibration to measured runoff only

	Calibration period 2003–2005	Verification period 1987–1997
M_E	0.83/0.11	0.67/0.18
M_E^{log}	0.85/0.10	0.75/0.24
V_E (%)	−1.0/3.0	−4.0/11.0
S_D^O	7.3/6.9	7.1/10.0
S_D^U	4.5/4.5	4.7/4.8

The first value is the median, the second the percentile difference (P75% − P25%) over 148 catchments.

only runoff data are available for hydrologic model calibration. The runoff and snow model efficiencies are summarized over 148 catchments separately for the calibration and verification periods. The medians of the calibration runoff efficiencies M_E and M_E^{log} are 0.83 and 0.85, respectively, which indicates a good overall agreement between observed and simulated runoff. (See Merz and Blöschl, 2004 for an assessment of what is considered a ''good'' model performance.) The median runoff volume error (V_E) is −1.0%, which indicates that the calibration is essentially unbiased. The snow model performance evaluated against interpolated snow depth data shows that the median of the snow overestimation errors (S_D^O) is higher than the median of the snow underestimation error (S_D^U) (7.3 and 4.5, respectively).

A typical simulation of the hydrologic model and the comparison of the model outputs with the observed runoff and MODIS snow cover are presented in Figs. 7 and 8. Fig. 7 compares the SCA estimates obtained from the combined MODIS product with the model snow simulations for three elevation zones of the Kindthal–Mürz catchment (Fig. 2). The lowest elevation zone (A, left panel) represents fairly good agreement between the MODIS data and the model snow estimates. The model simulates a shallow snow pack, which starts in the middle of December and quickly melts in February and again in the middle of March. The middle elevation zone (B, centre panel) is an example of model underestimation of the snow cover. The simulated snow pack starts in December and disappears on 4th April while the MODIS data suggest that snow covers the elevation zone till the end of April. Much more snow is simulated in the highest elevation zone (C, right panel). This is an example when the hydrologic model likely overestimates the MODIS observations. However during the snowmelt season, clouds prevailed, so very little SCA estimates are available from MODIS. Fig. 8 shows the agreement between simulated and observed hydrographs for Miklauzhof–Vellach catchment. The runoff model efficiency for Miklauzhof is the same as the median of M_E evaluated over the 148 catchments ($M_E = 0.83$). Visual comparison between simulation and observation indicates that the runoff model efficiency of 0.83 represents fairly well simulated runoff. About half of the selected 148 catchments are simulated better than this, the rest is simulated poorer than this.

The evaluation of model performance in the verification period (Table 6) indicates that the median of runoff model efficiency is somewhat smaller than that of the calibration period as would be expected. M_E and M_E^{log} are 0.67 and 0.75, respectively. The median runoff volume error (V_E) is somewhat more different from zero (−4%), indicating a somewhat larger bias. More importantly, the percentile difference (P75% − P25%) for the V_E increased from 3% to 11% as one moves from calibration to verification, indicating larger scatter of V_E values over the 148 catchments. This is because, for some of the catchments, the volume balance is poor. This may be due to both long range climate variability and data errors. An increase of scatter was also observed for the snow model efficiency S_D^O and S_D^U which increases from 6.9 (S_D^O) and 4.5 (S_D^U) in the calibration period to 10.0 (S_D^O) and 4.8 (S_D^U) in the verification period, respectively. The median of S_D^O errors slightly decreased to 7.1, while the median of S_D^U errors increased to 4.7 within the verification period. Interestingly, the median of snow model efficiencies

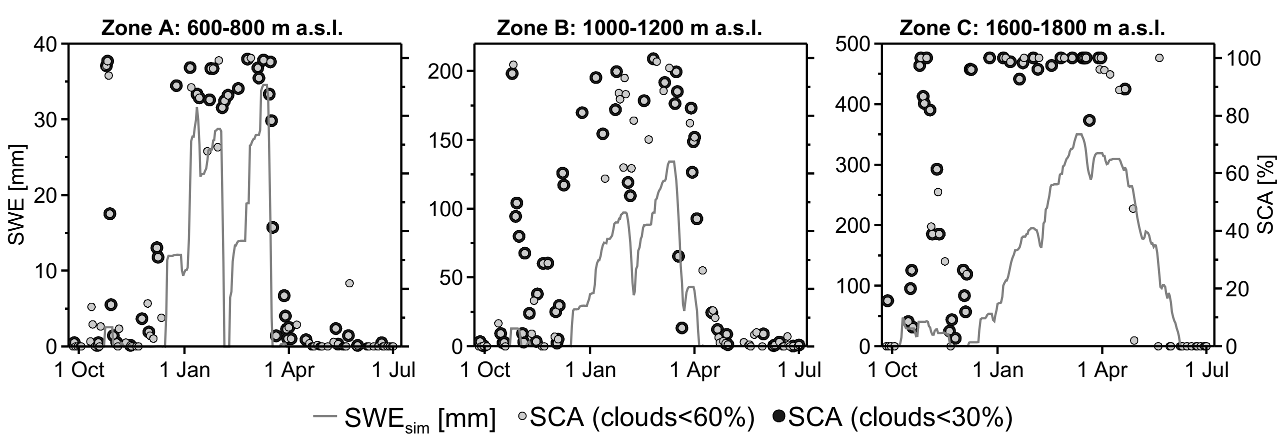

Figure 7 The triplet of panels compares the MODIS snow cover area (SCA) with the simulated snow water equivalent (SWE) in three elevation zones of the Kindthal-Mürz catchment (Fig. 2) during the snowmelt season 2003–2004. The SCA was estimated from the combined MODIS product, using two cloud thresholds: 30% (larger symbols) and 60% (smaller grey symbols). This is an example for which the snow model efficiency corresponds to the median over the 148 catchments.

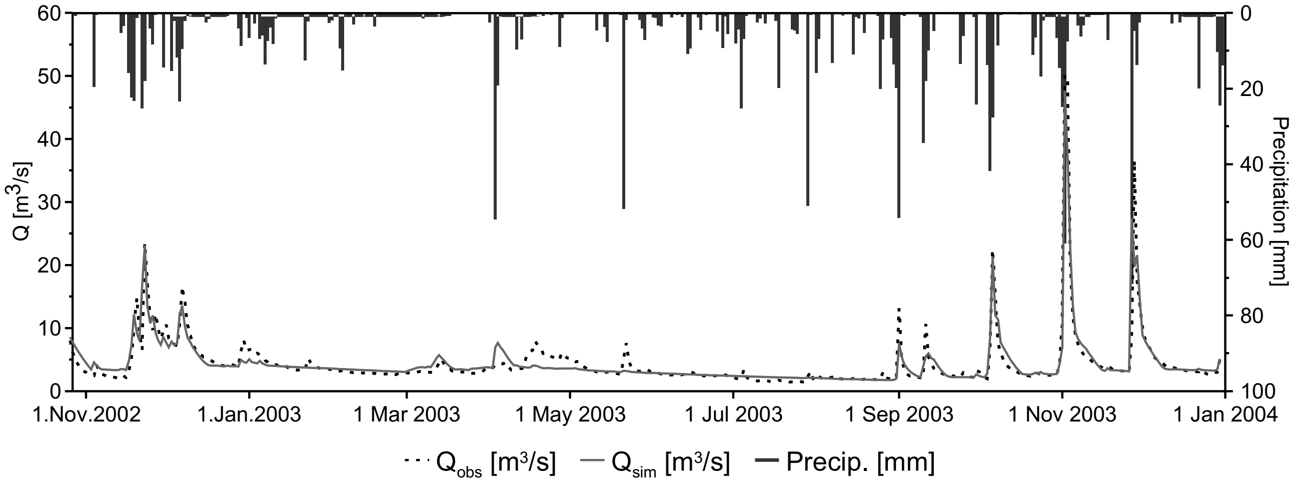

Figure 8 Simulated (Q_{sim}) and observed (Q_{obs}) runoff for the Miklauzhof—Vellach catchment (Fig. 2). Calibration to runoff alone. This is an example for which the runoff model efficiency corresponds to the median over the 148 catchments.

Table 7 Statistical evaluation of the snow overestimation (S_E^O) and underestimation (S_E^U) errors in the calibration period for different MODIS snow cover products (see Table 1)

	Terra	Aqua	CM	SF	1D	3D	5D	7D
S_E^O	1.0/2.5	1.8/3.1	1.5/2.7	1.6/2.9	1.5/2.7	1.5/2.6	1.6/2.5	1.6/2.6
S_E^U	2.3/3.7	1.0/1.8	1.4/2.4	1.7/2.4	1.4/2.6	1.7/3.0	1.7/3.1	1.7/3.1
N (%)	38.7	35.7	45.5	50.5	62.9	80.0	87.7	90.8

The first value is the median, the second the percentile difference (P75%-P25%) of the snow model efficiency over 148 catchments. The *N* represent the relative frequency of days available for the evaluation of the snow model performance in the calibration period. Single-objective calibration to measured runoff only.

does not change much between the calibration period to the verification period.

The validation of hydrologic model simulations using different MODIS snow cover products is summarized in Table 7. This variant has only been calibrated to runoff, so MODIS data have not been used in the calibration process. The results indicate that the snow model underestimation errors with respect to Terra are larger than the overestimation errors, but the converse is true for the case of Aqua. Interestingly, the comparison of the snow performance for the combined and filtered snow cover products shows over- and underestimation errors of similar magnitudes. This indicates that the combined and filtered products provide an appealing alternative for snow simulation assessment, which may be of interest because of the significant reduction of clouds and hence increased availability of snow cover information.

A more detailed assessment of snow model performance in individual basins indicated that similar medians of the snow over- and underestimation errors obtained by the combined and filtered MODIS snow products (Table 7) does not necessarily imply that the S_E^O and S_E^U errors are similar in the majority of individual catchments. Fig. 9 analyses the relationship between the S_E^O and S_E^U snow errors over the 148 catchments in terms of the S_E^O error scaled by the total error. The frequency distribution of the scaled overestimation error is bimodal which indicates that for the majority of catchments only one type of snow error dominates. This suggests that for the integration of the MODIS snow cover

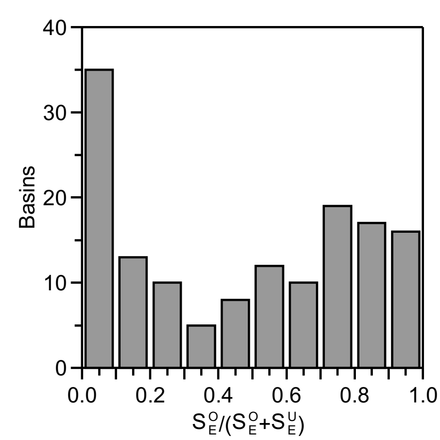

Figure 9 Frequency distribution of snow overestimation error (S_E^O) scaled by the total error of the 148 basins. The bimodal shape of the distribution indicates that, for the majority of catchments, one type of snow error dominates. The S_E efficiencies compare the hydrologic model simulations with the combined (CM) MODIS snow cover product in the calibration period.

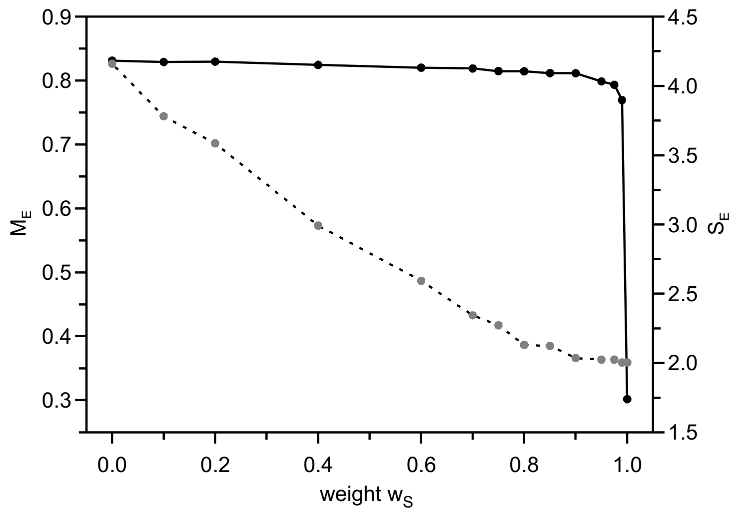

Figure 10 Sensitivity of the runoff model efficiency M_E (solid line) and snow cover error $S_E = S_E^O + S_E^U$ (dashed line) to the weight w_s (Eq. (9)). The S_E efficiencies compare the hydrologic model simulations with the combined (CM) MODIS snow cover product. Median over 148 catchments in the calibration period.

data into hydrological modelling an individual assessment of both types of snow errors will be necessary.

Model performance — calibration to both runoff and MODIS snow cover

The integration of MODIS snow data into the hydrologic model calibration involves a runoff component and a snow cover component that are weighted by w_s (Eq. (9)). The limiting cases are $w_s = 1$ where only the snow component is used in the objective function, and $w_s = 0$ where only the runoff component is used. To obtain some understanding of the effects of w_s on the model errors, a sensitivity analysis was performed as shown in Fig. 10. The runoff model efficiency (M_E, solid line) changes very little for almost the entire range of w_s. Only as w_s exceeds 0.90, M_E begins to drop as very little information on the runoff data is used in the calibration. The converse pattern is exhibited by the snow model error, S_E which is the sum of the over and underestimation errors. The snow model error (S_E, dashed line) changes very little for w_S between 0.9 and 1.0. When the weight $w_s$drops below 0.9, S_E begins to increase as very little information on the MODIS snow cover data is used in the calibration. There is only a small range of w_s (between 0.9 and 0.975) where both the runoff efficiency is large and the snow model error is small.

Along with the sensitivity of model efficiencies, we investigated the similarity between model parameters obtained by the traditional single-objective and the multiple-objective calibration approach using different weights w_s. The similarity was measured by the coefficient of determination (R^2) between the corresponding parameters obtained by the two approaches in the 148 catchments, analysing each model parameter separately (Fig. 11). The case $w_s = 0$ represents the single-objective variant as the objective function consists of the runoff component alone, so R i^2 should be unity. As the weight w_s of the multiple-objective function increases the snow components gets more weight, so the parameters differ increasingly more from those of the single-objective variant and R^2 tends to decrease. The results in Fig. 11 indicate that the most different parameters (smallest R^2) within the range of interest (w_S greater than 0.85) are the threshold melt temperature (T_M) and the degree-day factor (DDF), which are part of the snow routine of the hydrologic model. Not surprisingly, these two parameters are most affected when a snow constraint is introduced into the model calibration. Generally, very different parameter values are found for the very fast storage coefficient (K_0) of the runoff routine, which gives R^2 below 0.3. On the other hand, the most similar model parameters are the fast and slow storage coefficients K_1 and K_2 and the percolation rate coefficient C_P. There is a range, ($w_S = 0.1$—0.9) where R^2 of the runoff parameters (Fig. 11 bottom) is large at a plateau, but the R^2 for the snow and soil model parameters (Fig. 11 top) decreases. Interestingly, the two extreme cases, calibration against runoff alone and calibration against snow cover alone, resulted in completely different model parameters, i.e., $R^2 = 0$. This suggests that the runoff data and the snow data contain independent and hence complementary information.

Based on these sensitivity tests, the combination of weights, and $w_S = 0.90$, was selected as a representative trade-off between the runoff and snow objectives. The weight of $w_S = 0.90$ was used in the remainder of this paper for the evaluation of multiple-objective calibration using different MODIS snow cover data.

A statistical evaluation of the runoff and snow model efficiencies for cases where different MODIS snow cover products were applied in the multiple-objective calibration is presented in Table 8. The efficiency, when using different MODIS snow cover products, is remarkably similar. The median over the 148 catchments is always 0.81, which is slightly less than that for the traditional, single-objective calibration (0.83, Table 6). The snow errors in the calibration period of the multiple-objective calibration are smaller than in

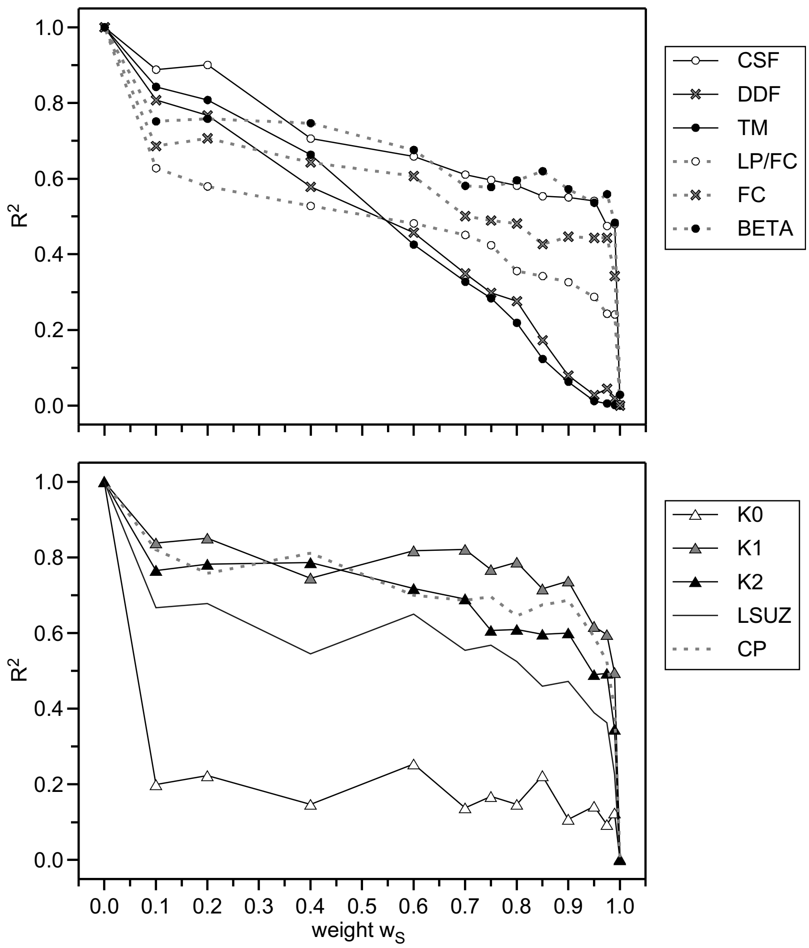

Figure 11 Correlation between the model parameters (Table 3) estimated by calibrating the model to runoff alone and by calibrating the model to both runoff and CM MODIS snow cover, using different weights w_S in the compound objective function (Eq. (9), same discrete w_s values as in Fig. 10).

Table 8 Statistical evaluation of runoff model efficiency (M_E) and the snow overestimation (S_E^O) and underestimation (S_E^U) errors in the calibration period for different MODIS snow cover products (see Table 2)

	Terra	Aqua	CM	SF	1D	3D	5D	7D
M_E	0.81/0.12	0.81/0.12	0.81/0.12	0.81/0.12	0.81/0.12	0.81/0.12	0.81/0.12	0.81/0.12
M_E^{log}	0.84/0.09	0.84/0.09	0.84/0.09	0.84/0.09	0.84/0.09	0.84/0.09	0.84/0.09	0.84/0.09
V_E (%)	−1.1/4.8	−0.7/4.8	−0.8/5.4	−1.2/5.0	−1.0/5.2	−1.0/5.3	−1.1/5.1	−0.9/5.2
S_E^O	1.0/1.0	0.9/0.8	0.9/0.9	1.1/1.0	1.1/0.8	1.3/1.0	1.4/1.2	1.5/1.3
S_E^U	1.4/1.0	0.8/0.7	1.1/0.9	1.2/1.1	1.1/1.1	1.1/0.9	1.1/0.9	1.1/0.8
S_D^O	4.2/4.2	2.7/3.0	3.5/3.8	4.1/4.5	4.2/3.9	4.9/5.0	5.4/5.2	5.8/5.2
S_D^U	3.0/2.4	4.1/2.8	3.5/2.6	3.7/2.6	3.6/2.4	3.5/2.8	3.6/2.9	3.6/2.5s

The first value is the median, the second the percentile difference (P75% − P25%) of the snow model efficiency over 148 catchments. Multiple-objective model calibration (w_S = 0.9, Eq. (9)).

the single-objective calibration which, however, is not surprising as MODIS snow data have been used in the multiple-objective calibration. The median snow SE_O and SE_U errors range between 0.9 and 1.5% for all MODIS products, as compared to a range of 1.0–2.3% in the case of single objective-calibration. More importantly, the percentile differences are much smaller in the case of multiple-objective calibration (around 1% as compared to around 3% in single-objective calibration). This means that the snow simulations based on multiple-objective calibration are slightly more accurate than the single-objective counterparts and much more consistent across the study area. Analyses of the errors (not shown here) indicate that the snow model performance tends to increase with catchment area while there

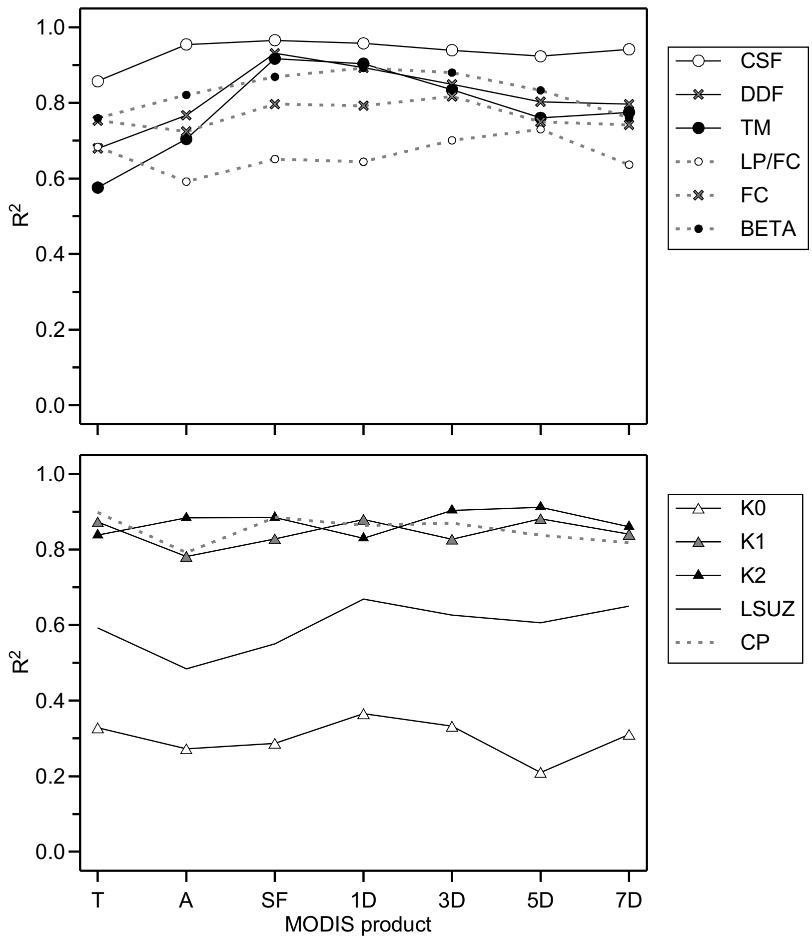

Figure 12 Correlation between the model parameters (Table 3) estimated by calibrating the model to the combined (CM) MODIS snow product and by calibrating the model to the other MODIS snow products (see Table 2).

are no apparent relationships with mean catchment elevation, slope and dominant aspect.

The consistency of the calibrated model parameter obtained by using different MODIS products in the multiple-objective calibration is evaluated in Fig. 12. The consistency is expressed by the coefficient of determination (R^2) between each parameter obtained by the combined (CM) MODIS product and the corresponding parameter obtained by other MODIS products. Fig. 12 indicates that there is not much difference between the products. The spatial filter gives slightly more consistent parameters than the other products. This is likely because the differences between the combined (CM) and spatially filtered (SF) MODIS products are small. Overall, the most similar parameters to CM are the snow correction factor (CSF). The least consistent parameters are the very fast runoff storage K_0 and the runoff storage state LS_{UZ} parameters. These are also the parameters that cannot be identified well in the multiple objective calibration procedure (see Parajka et al., 2007, results for MULTI). The other model parameters yielded R^2 greater than 0.6, which indicates better consistency than obtained in the comparison between the single-objective and the multiple-objective calibration.

Validation of the multiple-objective calibration is performed in an independent verification period 1987–1997. Table 9 summarises the model efficiencies obtained by multiple-objective calibration approaches that utilize different MODIS snow cover products in the parameter optimisation. Use of the combined (CM) MODIS images yields the largest value of the median of M_E runoff efficiency over the 148 catchments but the other products only give slightly smaller medians. The median runoff volume error V_E is in the range from −5.5% to −7.2%, which indicates a small underestimation of runoff in the verification period for all products. The median of the snow overestimation errors S_D^O ranges from 4.9% (Aqua) to 6.7% (7D). The snow underestimation errors S_D^U are somewhat smaller ranging from 3.4% (Terra) to 4.5% (Aqua). Interestingly the S_D^U errors for the calibration variants that are based on the combined and filtered MODIS products are within the range of efficiencies based on variants that utilize the original Terra and Aqua images.

The multiple-objective approach outperforms the single-objective calibration method in the majority of catchments in terms of the ME runoff efficiency and practically in almost all catchments in terms of the snow model efficiencies. The median of the ME runoff efficiency is 0.70 for the multiple-objective (based on the combined CM MODIS product) and 0.67 for the single-objective approach, which is a small improvement in absolute terms but statistically significant at the 1% level. The most noticeable differences between

Table 9 Statistical evaluation of the runoff model efficiencies (M_E, M_E^{log}), runoff volume error (V_E) and the snow model errors (S_D^O and S_D^U) in the verification period (1987—1997) for different MODIS snow cover products (see Table 2)

	Terra	Aqua	CM	SF	1D	3D	5D	7D
M_E	0.69/0.14	0.70/0.15	0.70/0.14	0.69/0.13	0.69/0.14	0.69/0.13	0.69/0.13	0.68/0.13
M_E^{log}	0.74/0.20	0.74/0.20	0.74/0.19	0.73/0.19	0.74/0.20	0.73/0.19	0.74/0.19	0.74/0.19
V_E (%)	−7.2/0.14	−6.1/0.14	−6.1/0.12	−5.5/0.12	−6.7/0.13	−6.4/0.14	−6.5/0.13	−6.1/0.13
S_D^O	6.3/7.5	4.9/5.3	5.6/6.3	6.1/7.2	6.2/6.7	6.3/7.5	6.6/7.9	6.7/7.8
S_D^U	3.4/3.5	4.5/4.0	4.1/3.7	4.1/3.7	4.2/3.7	4.2/3.6	4.2/3.7	4.0/3.7

The first value is the median, the second the percentile difference (P75% − P25%) over 148 catchments. Multiple-objective calibration approach (w_S = 0.9, Eq. (9)).

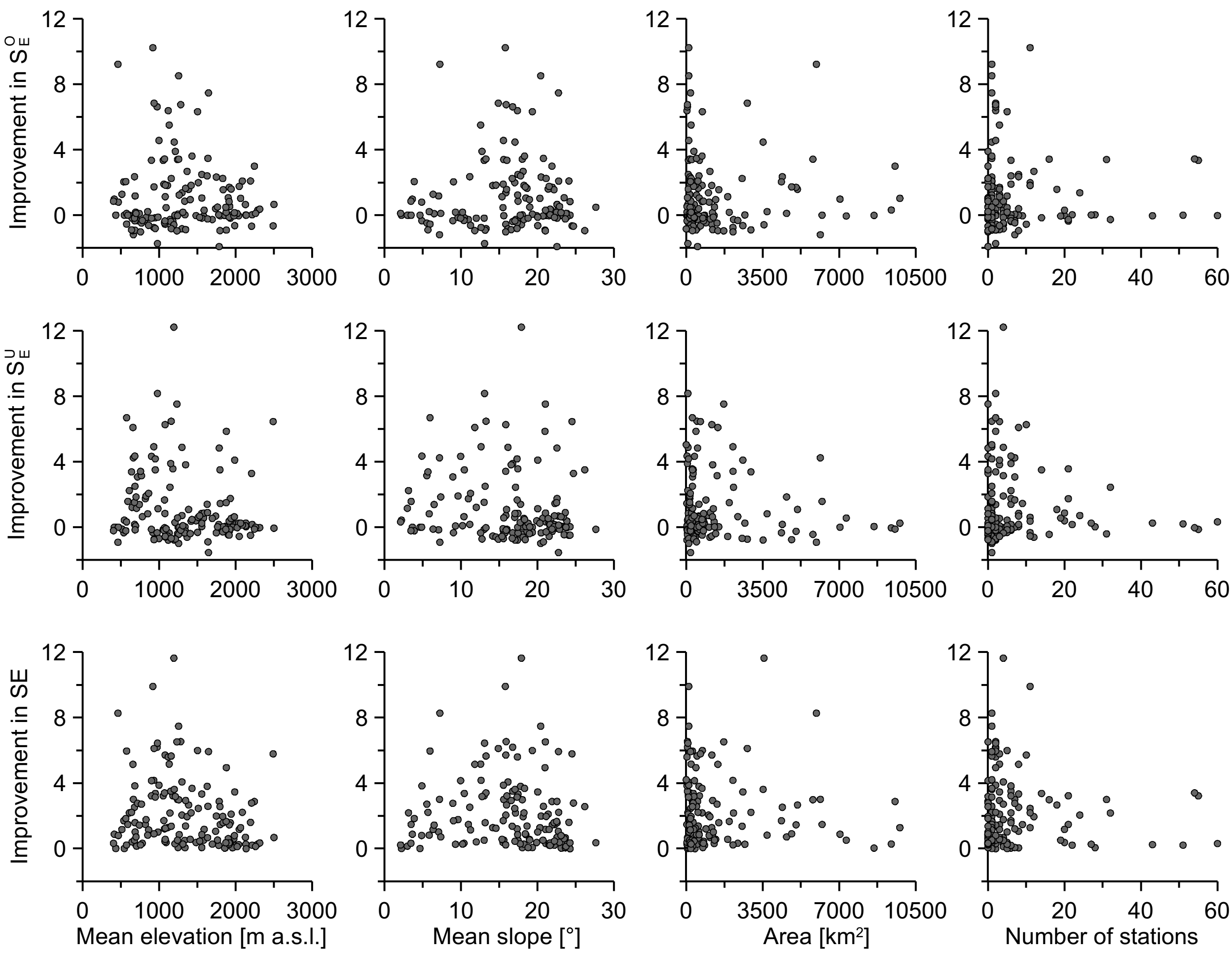

Figure 13 Improvement in the snow overestimation (S_E^O), underestimation (S_E^U) and overall snow simulation performance (SE) with respect to the mean catchment elevation, mean slope, catchment area and the number of climate stations in a catchment. The improvement in performance is defined as the difference between the snow model errors obtained by the single-objective and multiple-objective calibration in the calibration period 2003—2005. The multiple-objective approach is represented by the calibration variant based on the combined MODIS product (CM).

the multiple-objective and single-objective snow model performance are the decrease in the snow overestimation errors and the reduction in the regional variability of snow model efficiencies exhibited by the decrease in percentile differences (from 10% to 6.3% for CM). This indicates that constraining the model parameter estimation to runoff and MODIS snow cover provides in general more robust parameter sets than parameter optimisation based on the runoff data only. The regional distribution of the runoff M_E efficiency shows very similar spatial patterns for both calibration concepts. The most noticeable differences are the snow cover efficiencies (the S_O^E and S_U^E errors), where the multiple-objective approach resulted in significantly improved snow model performance in comparison with the

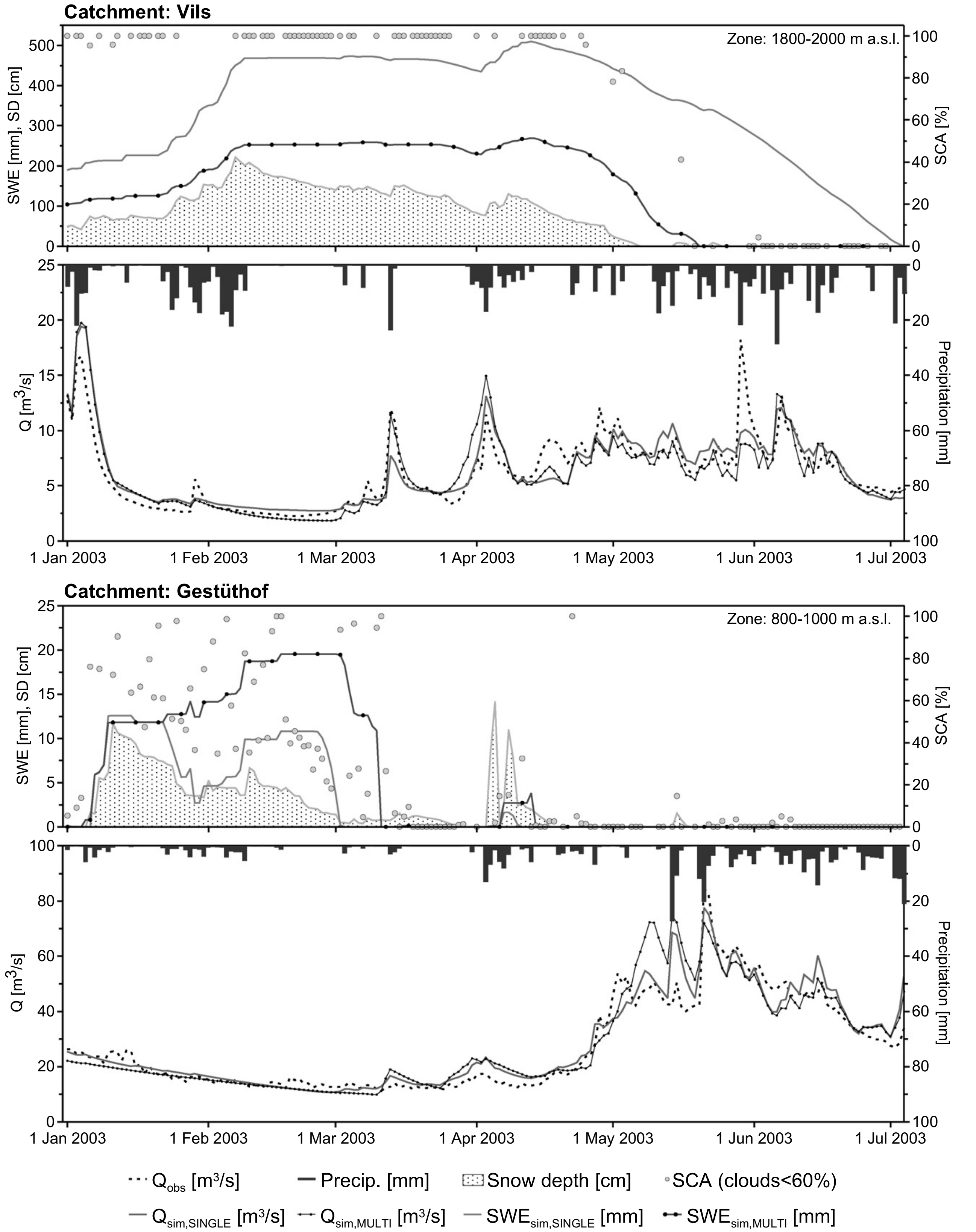

Figure 14 Comparison of the measured runoff and observed MODIS snow cover data with the model simulations based on the traditional (to runoff only) and the multiple-objective calibration approaches. Top panels show an example for Vils catchment, bottom panels show the simulations for Gestüthof catchment.

traditional single-objective approach. Comparison of S_O^E and S_U^E obtained by the single-objective approach shows that the S_O^E errors dominate in catchments located in the central alpine part of Austria, while in most of the northern prealpine catchments the S_U^E errors are somewhat larger than the S_O^E errors.

It is now interesting to understand in which situations the added value of using MODIS data is largest. Assessment of the significance of selected factors and indices that may favour the use of MODIS snow data for hydrologic model calibration is evaluated in Fig. 13 in more detail. This figure shows the improvement in snow model performance with respect to selected catchment descriptors (mean catchment elevation, slope and catchment area) and with respect to the number of climate stations available in each catchment. The improvement in snow model performance is defined as the difference between snow errors obtained by the single-objective calibration and multiple-objective calibration in the calibration period. A negative improvement implies that the model performs poorer when calibrated to MODIS data. The top, middle and bottom panels show the improvement in snow overestimation (S_O^E), underestimation (S_U^E) and overall snow performance (SE), respectively. The results indicate that the topographic characteristics are not related to the added information of MODIS snow cover data in model calibration. Interestingly, the area of the catchment and the number of climate stations in a catchment provide an indicator of the added value. In small catchments with insufficient climate observations the MODIS data are particularly useful in hydrological modelling. In these catchments MODIS data may significantly improve the snow model performance. Clearly, if in a catchment only a few ground based observations exist, the remote sensing data become relatively more important.

An example of the benefits of the multiple-objective calibration is presented in Fig. 14. The top panels show a significant reduction of snow overestimation error in a particular elevation zone of the Vils catchment (201111) and its effect on the simulated runoff. Interestingly, there is more than 200 mm difference in maximum zone SWE accumulation, but the overall runoff model efficiency remains the same as obtained by the traditional single-objective approach. The bottom panels exhibits the reduction of snow underestimation errors in Gestüthof catchment (211086). In comparison to simulations based on single-objective model parameters, the parameters from multiple-objective calibration resulted in better agreement between the SWE simulation and the SCA derived from MODIS data. However the differences in absolute values of the SWE are small and only slightly affect the runoff model simulations. Both examples indicate that the compensation effects of both the hydrologic model parameters and the combination of simulations for different elevation zones result in the same overall runoff model efficiency, however the runoff simulation for individual events may differ.

Discussion and conclusions

The objective of this study was to test the potential of MODIS snow cover images for validation and calibration of a conceptual hydrologic model. The cornerstone of the investigation was based on an indirect comparison of snow water equivalent (SWE) modelled by a hydrologic model in different elevation zones and a snow cover area (SCA) estimated using different MODIS snow cover products. The main implications of such indirect comparison are related to the application of different thresholds necessary for the validation of snow model performance. Sensitivity analyses indicated that the snow model efficiency is sensitive to the choice of the threshold of snow covered area (ξ_{SCA}) used in estimating the snow underestimation errors and the cloud cover threshold (ξ_C) used in deciding whether a MODIS image can be used for model analysis. The analysis of the seasonal distribution of snow underestimation errors indicated that the MODIS misclassification errors, especially in the summer months, may significantly affect the magnitude of the snow model efficiency and hence a value of $\xi_{SCA} = 25\%$ was deemed appropriate for robust snow underestimation error assessment. The selection of the cloud threshold ξ_C affects how much information is applied to the evaluation of snow model performance and how representative is the MODIS snow cover area. In previous studies, different cloud thresholds were utilized. E.g. Udnaes et al. (2007) estimated and integrated snow cover data into hydrological modeling only when clouds obscured less than 30% of the catchment. Andreadis and Lettenmaier (2006) used a 20% cloud threshold to decide whether to assimilate the MODIS observation into the macroscale hydrologic model. On the other hand, Rodell and Houser (2004) assumed that 6% is the minimum visibility for which a MODIS observation is useful, which translates into a 94% cloud threshold. In this study, we have found that a 60% cloud threshold is a reasonable compromise between snow data availability and SCA robustness.

The integration of MODIS snow cover data into a hydrologic model was tested in a calibration mode, where the hydrologic model calibration was constrained using runoff and MODIS snow cover data. Evaluation of the runoff and snow model efficiencies demonstrated that the multiple-objective calibration framework enables a robust estimation of hydrologic model parameters (model calibration). The runoff performance obtained in the calibration period was similar or only slightly poorer then obtained by calibration to runoff only (single-objective model calibration). However, the snow model efficiency was improved. This finding is important especially for change assessment studies where model calibrated to runoff only may not adequately represent the internal variables, e.g. snow accumulation and melt in climate warming scenarios. Comparable results were presented by Udnaes et al. (2007) who found that (p. 26): ''...Calibration against SCA in addition to runoff improved the simulated SCA considerably.''. The runoff model efficiencies (M_E) estimated in their study for 10 Norwegian catchments ranged from 0.76 to 0.94 (with a median 0.85) for calibration to runoff only and from 0.73 to 0.94 (with a median 0.83) for the calibration that utilized runoff and MODIS SCA data. This fits well to the statistical evaluation over 148 catchments performed in this study, which give median M_E of 0.83 and 0.81 for these two calibration cases.

A detailed evaluation of the factors that influence the added value of the MODIS data indicates that they are particularly useful to improve the snow model performance in small catchments with no or only a few ground based observations. These results and more general analyses of snow simulations suggest that data availability is the major factor that controls the snow model performance. The magnitude of the improvement is also likely related to the quality of the MODIS data. Although, overall, the MODIS data can be considered rather accurate (see Parajka and Blöschl, 2006, 2008) it is clear that with increased spatial and temporal resolution of the satellite sensors and more accurate snow cover classification the added value in hydrologic simulations would also increase.

The statistical assessment of runoff and snow efficiencies in an independent verification period showed that MODIS snow cover data also slightly improve the runoff model performance in the verification period. The median runoff model efficiency increases from 0.67 to 0.70 if MODIS data are used for calibration as compared to the case where no MODIS data are used. These results demonstrate that large samples of catchments enable a more robust examination of the effects of snow cover data on runoff model performance than was possible in previous studies. For example, the study of Udnaes et al. (2007) reported a slight decrease in runoff model performance when snow cover data were applied in model calibration, however these results are based only on 10 catchments and a shorter verification period.

The snow model performance in the verification period was assessed against the snow cover area calculated from the interpolation of ground based snow depth measurements. The results show that the snow overestimation (S_D^O) and underestimation (S_D^U) errors are smaller for the multiple objective calibration approach and have a similar magnitude as the errors obtained in the shorter calibration period. Interestingly, the S_D^O and S_D^U errors (assessed against snow depth) are much larger than the S_E^O and S_E^U errors (assessed against MODIS snow cover) in the calibration period. Fig. 15 provides a more detailed assessment of the seasonal distribution of S_D^O and S_D^U and their comparison to S_E^O and S_E^U. It is clear that both types of snow errors have similar seasonal trends, however, in the transition periods (onset of snow accumulation and late snow melt season) is the difference between hydrologic model simulations and snow depth interpolation larger than that between hydrologic model simulation and the MODIS data. The differences are large, in particular for the simulations in the high elevation zones, where only a limited number of ground snow depth observations are available and the spatial snow variability may be larger than in lower elevations. This is likely because the error measure will be significantly affected by the accuracy of the snow depth interpolation which is less than perfect in alpine terrain where few snow depth stations exist. In our future research, we plan to evaluate in more detail the spatial consistency of the snow cover estimated by the snow depth interpolation and MODIS snow cover products.

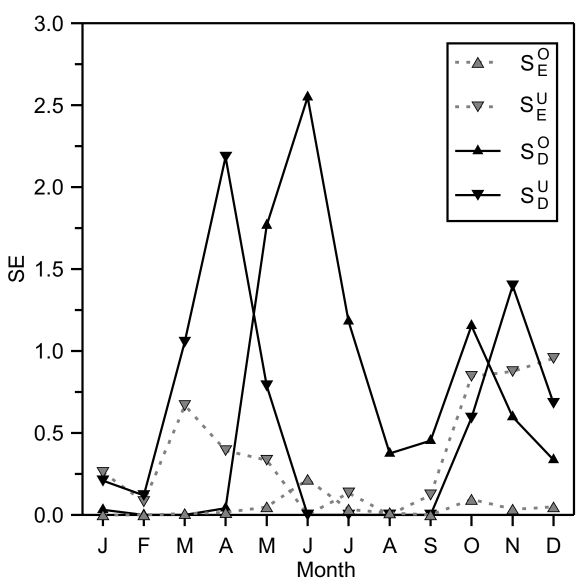

Figure 15 Seasonal distribution of the snow over- and underestimation errors (S_E^O, S_E^U) of the hydrological model evaluated against the combined MODIS snow product, and the snow over- and underestimation errors (S_D^O, S_D^U) of the hydrological model evaluated against the ground snow depth data. Median over 148 catchments in the calibration period (2003—2005). Snow simulations are obtained by single-objective calibration to measured runoff only.

Evaluation of the model performance against different MODIS snow products shows that the combination and filtering of the Aqua and Terra images does not significantly affect the runoff and snow model efficiencies. The assessment of the runoff and snow model efficiencies complements the trade-off evaluation presented in Parajka and Blöschl (2008) where the cloud coverage reduction is compared to the decrease in mapping accuracy. The results of this study indicate that the combined and filtered MODIS products provide a snow cover data source which is a useful alternative to ground snow depth data, especially in regions with sparse observations. In this study we used the MODIS dataset for the assessment of the snow model performance in a simulation mode. Another possible application of the MODIS data is to assimilate them into the snow state variable of a hydrologic model in a real time mode, which will be evaluated in a future study.

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