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Validation of the operational MSG-SEVIRI snow cover product over Austria

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Abstract

The objective of this study is to evaluate the mapping accuracy of the MSG-SEVIRI operational snow cover product over Austria. The SEVIRI instrument is on board of the geostationary Meteosat Second Generation (MSG) satellite. The snow cover product provides 32 images per day with a relatively low spatial resolution of 5 km over Austria. The mapping accuracy is examined at 178 stations with daily snow depth observations and compared with the daily MODIS combined (Terra + Aqua) snow cover product in the period April 2008–June 2012.

The results show that the 15 min temporal sampling allows a significant reduction of clouds in the snow cover product. The mean annual cloud coverage is less than 30 % in Austria, as compared to 52 % for the combined MODIS product. The mapping accuracy for cloud-free days is 89 % as compared to 94 % for MODIS. The largest mapping errors are found in regions with large topographical variability. The errors are noticeably larger at stations with elevations that differ much from those of the mean MSG-SEVIRI pixel elevations. The median of mapping accuracy for stations with absolute elevation difference less than 50 m and more than 500 m is 98.9 % and 78.2 %, respectively. A comparison between the MSG-SEVIRI and MODIS products indicates an 83 % overall agreement. The largest disagreements are found in alpine valleys and flatland areas in the spring and winter months, respectively.

1 Introduction

Monitoring and modeling of snow characteristics is important for many hydrological applications, including snowmelt runoff forecasting and water resources assessment using a range of techniques (e.g. Blöschl and Kirnbauer, 1991; Blöschl et al., 1991; Nester et al., 2012). The large spatial variability of snow cover, particularly in mountains, limits the use of ground based snow observations. Satellite imagery is thus an attractive alternative, as the resolution and availability does not depend much on the terrain characteristics (Parajka and Blöschl, 2008).

Recently, operational satellite products have become available that provide snow cover information at different spatial and temporal resolutions (Table 1). Table 1 indicates that most of the current products provide daily snow cover information at spatial resolutions ranging from 500 m to 5 km. The snow mapping accuracy with respect to ground snow observations for cloud free conditions varies between 69 % and 94 % in the winter seasons. The main limitation of existing optical platforms operating at daily time scale is cloud coverage, which significantly reduces the availability of snow cover information. There exist different approaches for cloud reduction including space-time filtering (e.g. Parajka and Blöschl, 2008; Gafurov and Bárdossy, 2009; Hall et al., 2010, among others), but clouds are real and the accuracy of such approaches decreases with their efficiency to reduce clouds.

An alternative to the space-time filtering of daily products is to merge satellite images obtained at higher temporal resolution. The new generation MSG-SEVIRI product provides snow cover information at 15 min temporal resolution for the whole Northern Hemisphere. The preliminary assessment of data from one snow season over Eastern Turkey (Surer and Akyurek, 2012) indicates that merging of 32 consecutive images per day enables a 37 % reduction of clouds in comparison to the MODIS daily product and improves the mapping of regional snow-cover extent over mountainous areas.

The main objective of this study is to assess the accuracy of the new MSG-SEVIRI snow cover product over Austria in the period 2008–2012. The spatial and temporal variability in mapping accuracy is examined for a large number of meteorological stations observing snow depth and evaluated against combined MODIS snow cover product. Austria is an ideal test bed for such an assessment, as it allows evaluating the mapping accuracy in different altitudinal zones ranging from the lowlands to the high Alpine environment.

2 MSG-SEVIRI snow cover product

The Spinning Enhanced Visible and Infrared Imager (SEVIRI) is an optical imaging radiometer mounted on board of the geostationary Meteosat Second Generation (MSG) satellite operated by EUMETSAT. MSG-SEVIRI provides continuous imaging of the Earth in 12 spectral channels with a repeat cycle of 15 min. The imaging spatial resolution is 3 km at sub-satellite point (Aminou, 2002) and degrades to 5 km over Europe.

The snow cover mapping is based on a multi-channel retrieval algorithm. It exploits the high reflectivity of snow in the visible spectrum and the low reflectivity at shorter wavelengths. The snow cover retrieval algorithm differs for flat and mountain regions. In flat regions, the algorithm utilizes the top-of-atmosphere radiance of 6 SEVIRI channels (0.6, 0.8, 1.6, 3.9, 10.8 and 12.0 µm) and brightness temperatures of three channels (3.9, 10.8, and 12.0 µm). The snow recognition is based on the snow cover classification (Siljamo and Hyvarinen, 2011). The cloud-snow discrimination for flatlands relies on the cloud mask (CMa) provided by the Nowcasting and Very Short Range Forecasting Project (NWCSAF, 2007). In this product clouds are classified only into two classes (cloud contaminated and cloud filled).

In the mountains, the snow recognition algorithm uses the snow index (SI) which relates 0.6 µm, and 1.6 µm SEVIRI channels. The cloud-snow discrimination is based on the CMa and cloud type (CT) product of the NWCSAF. The CT product has 15 different cloud types which allow more robust cloud recognition (Surer, 2008). Both algorithms use sun zenith angle for discarding the low illuminated areas, and land surface temperature values for covering all cold pixels below freezing point (Romanov et al., 2003). The main difference in the algorithms is the location of the samples collected for developing the thresholding method and the cloud-snow discrimination applied in the retrieval. A detailed description of the MSG-SEVIRI snow algorithm is presented in the Algorithm Theoretical Basis Document (HSAF, 2010).

The definition of the mountainous areas is based on the mean altitude and standard deviation of the slope within 5 km × 5 km pixels (Lahtinen et al., 2009). The area is defined to be mountainous if the mean altitude exceeds 1000 m or the mean altitude exceeds 700 m, and the standard deviation of the slope is greater than 2° or range in mean altitude exceeded 800 m and mean altitude exceeds 500 m.

Daily snow cover maps are derived from 32 images per day, blending data from 08:00–15:45 GMT. Snow cover is mapped when there are at least 4 hits of snow recognition in a day. The final snow cover product, which is merged at Finnish Meteorological Institute, has snow, land, cloud, water and unclassified classes. An example map for Europe is presented in Fig. 1.

3 Study area and snow cover data

This paper evaluates the accuracy of snow cover images over Austria. Austria is located in the temperate climate zone, where the Alps act as a dominant barrier between continental climate in the north and the meridional circulation from the Adriatic Sea in the south. Elevations range from 115 m in the flatlands to more than 3700 m in the mountains (Fig. 2). Mean annual precipitation varies between 400 mm in the eastern flatlands and almost 3000 mm in the western part of the Alps. The mountainous parts of Austria are covered by snow for several months in a year (Parajka and Blöschl, 2006), while the flatlands are characterized by warm and dry summers and cold winters without significant snowfall. Land use is mainly agricultural in the lowlands and forest in the medium elevation ranges. Alpine vegetation and rocks prevail in the highest catchments.

Snow cover data used for MSG-SEVIRI evaluation includes ground snow depth measurements at 178 meteorological stations (Fig. 2) and daily MODIS satellite snow cover images from April 2008–June 2012. The snow depth readings are taken from permanent staff gauges and represent point measurements performed daily at 7.00 a.m. with 1 cm reading precision (Parajka and Blöschl, 2006). Table 2 summarizes the number of stations in different elevation zones and indicates that most of the stations are located in elevation zones between 500 m and 1000 m. In the mountains, the stations tend to be located at lower elevations, typically in the valleys, which suggest a slight bias of the validation statistics towards lower elevations.

The satellite snow cover images have been acquired by the MODIS instrument mounted on Terra and Aqua satellites of the NASA Earth Observation System. The daily Terra (MOD10A1, V005) and Aqua (MYD10A1, V005) snow products are available through the Distributed Active Archive Center located at the National Snow and Ice Data Center (NSIDC, http://www.nsidc.org). The spatial resolution of the products is 500 m. For the validation, the snow cover product obtained from the Terra satellite and a combined product of the Terra and Aqua satellites are used. The two products are combined to reduce cloud coverage in the mountains (Parajka and Blöschl, 2008). In the combined product, the pixels classified as clouds in the Terra images are updated by the Aqua pixel value of the same location if the Aqua pixel is snow or land. This approach combines satellite observations on the same day, shifted by several hours.

4 Methodology of MSG-SEVIRI evaluation over Austria

Evaluation of the MSG-SEVIRI snow cover accuracy is performed in two steps. In the first step, the accuracy of MSG-SEVIRI is evaluated at meteorological stations by using daily snow depth observations. Snow depth observations at the stations are considered as ground truth for each MSG-SEVIRI pixel that is closest to each station. The ground is considered as snow covered if the snow depth measurement exceeds 1 cm. In the second step, MSG-SEVIRI images are compared with daily MODIS snow cover maps. In this case, the frequency of MODIS snow, no snow and cloud classes is estimated and compared within each MSG-SEVIRI pixel.

The snow cover mapping accuracy with respect to snow depth observations is quantified by three variants of the accuracy index: k_A, k_M and k_C. The overall accuracy index k_A is estimated at each meteorological station and compares the sum of all correctly classified days with the presence of snow and no snow to the number of all cloud-free days at each meteorological station (station-days) in the selected period. The seasonal

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accuracy index k_M is defined in a similar way, but relates the sum of all correctly classified station-days (snow-snow, no snow-no snow) at different meteorological stations to the number of all cloud-free station-days at those stations in a particular month. The k_M index is estimated separately for all stations located in the mountain and flatland areas as defined by the MSG-SEVIRI mountain mask (Fig. 2), respectively. The all-days accuracy index k_C relates the correctly classified station-days to the total number of station-days in the selected period, including days with cloud cover. It is also estimated for each month and two groups of stations (mountain and flatland).

Additionally to the three accuracy indices, two types of mapping errors are quantified with respect to the ground snow depth observations: the MSG-SEVIRI misclassification of land as snow termed here the MSG-SEVIRI overestimation error (k_O) and the misclassification of snow as land termed the MSG-SEVIRI underestimation error (k_U). Both types of errors relate the sum of misclassified station-days to the total number of station-days in each particular month and mask region.

The agreement between MSG-SEVIRI and MODIS snow cover products is quantified by the index of overall m_A and seasonal agreement m_M. These indices are defined in a similar way as the k_A and k_M, but instead of using snow depth observations at meteorological stations, the aggregated frequencies of MODIS snow, land and cloud classes within each MSG-SEVIRI pixel are used. The comparison is performed at the coarser spatial resolution of the MSG-SEVIRI and for those MSG-SEVIRI pixel-days where the relative frequency of MODIS pixels classified as clouds is less than 60 %. Our test simulations (not shown here) indicate that the results are insensitive to the selection of this threshold between 40 and 70 %. In the m_A and m_M evaluation, the ground is considered as snow covered if the frequency of MODIS snow pixels within the MSG-SEVIRI pixel is at least 50 % of the sum of MODIS pixels classified as snow and land. The presence of no snow (land class) is considered in the same way, i.e. the frequency of MODIS pixels classified as land is larger than the sum of snow and land pixels.

5 Results

5.1 Validation of MSG-SEVIRI against ground snow depth measurements

The snow cover accuracy (k_A) of MSG-SEVIRI estimated for cloud-free days at the meteorological stations is presented in Fig. 3 and summarized in Table 3. The k_A varies between 51.3 % at the Villacher Alpe (2140 m a.s.l.) in the Eastern Alps (Carinthia) and almost 100 % in Gross-Enzersdorf (154 m a.s.l.) near Vienna. Table 3 indicates that the MSG-SEVIRI accuracy is larger in the flatland than in the mountain regions, i.e. the median of k_A is 98.8 % and 84.3 % in the flatland and mountain regions, respectively. Figure 4 shows a clear decrease of snow mapping accuracy with increasing elevation of the meteorological stations. The results indicate that this tendency is caused mainly by increasing sub-grid topographical variability in the mountains. Meteorological stations are often situated at different elevations than the mean elevation of MSG-SEVIRI pixels, which causes biases between station and satellite snow cover observations. As is indicated in the left panel of Fig. 4, the mapping accuracy is larger for stations with smaller elevation difference. For example, the median of k_A for stations with absolute elevation difference less than 50 m and more than 500 m is 98.9 % and 78.2 %, respectively. For the station with the largest mapping errors (Villacher Alpe) the elevation difference is larger than 960 m. The stations located significantly below or above the pixel mean may have noticeably different snow cover observations (right panel of Fig. 4). The snow cover observations at meteorological stations in Austria show a clear linear relationship (R^2 = 88 %) between snow cover duration and the altitude, indicating an increase of snow cover duration by 2.8 %/100 m (not shown here). An elevation difference of 500 m can therefore be easily transferred in about 14 % difference in snow cover duration and thus different snow cover mapping accuracy. Interestingly, the MSG-SEVIRI mapping accuracy is larger than 90 % for two stations situated above 2000 m a.s.l. (Ischgl-Idalpe and Pitztaler Gletscher), but located approximately at the mean elevation of the MSG-SEVIRI pixel. This finding indicates the importance of the spatial resolution and sub-grid topographical variability for the assimilation of satellite snow cover images in operational hydrological applications.

The seasonal frequencies of MSG-SEVIRI snow mapping accuracy (k_M) is presented in Fig. 5. The results show that, in the mountains, the k_M accuracy varies between 70–77 % in the winter and 92–97 % in the summer months. The flatland region has typically much shorter snow coverage, which most likely results in larger k_M accuracy between April and October, but larger mapping errors (k_M between 79 and 83 %) in the winter months. As compared to k_M obtained for the MODIS/Terra and MODIS/combined snow cover products, the MSG-SEVIRI mapping accuracy is 10–13 % lower in the mountains and 3–11 % in the flatland area in the winter months. However, the MSG-SEVIRI product contains significantly less pixels classified as clouds than MODIS, particularly in the mountains (Fig. 6, top panels). Here, the merging of 32 MSG-SEVIRI images per day reduces cloud coverage between 15 to 29 % in the period November–June as compared to MODIS-combined product. The cloud reduction is even about 7 % larger when compared to the MODIS-Terra product. In the period July–October, the cloud coverage of MSG-SEVIRI is similar to that of MODIS in the mountains. Interestingly, in the flatland areas a decrease in cloud coverage is observed only in the period April and September. In the winter months, MSG-SEVIRI indicates cloud coverage larger than 75 %, which is similar or even slightly larger than indicated by the MODIS products. This is probably caused by use of different cloud masking algorithms.

The reduction in clouds, particularly in the mountains, then translates into an improvement of all-days mapping accuracy k_C (Fig. 6, bottom panels). The k_C accuracy assumes clouds as a mapping error and it varies for MSG-SEVIRI between 26–31 % (mountains) and 9–25 % (flatland areas) in the winter and spring periods. In the mountains, this is about 3–14 % larger than the k_C obtained for the MODIS dataset. In the flatland areas, the large cloud coverage in winter does not enable an increase in k_C as compared to MODIS products. The evaluation of k_C clearly indicates the tradeoff between increased cloud reduction due to higher temporal sampling (32 images per

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day) and higher mapping error due to coarser spatial resolution (particularly in the mountains) of the MSG-SEVIRI snow product.

The seasonal frequency of MSG-SEVIRI mapping errors is summarized in Table 4. Table 4 compares the overestimation (k_O) and underestimation (k_U) errors of MSG-SEVIRI, MODIS-Terra and MODIS-combined datasets as observed at meteorological stations. The general distribution of MSG-SEVIRI errors shows a typical seasonal pattern of larger errors in winter and spring and smaller errors in summer. In comparison to MODIS products, the MSG-SEVIRI mapping errors are particularly larger during the snowmelt season in the mountains (4–9 %) and somewhat larger during the winter months in the flatlands (1–3 %). A detailed analysis of k_O and k_U errors (Fig. 7) indicates that the MSG-SEVIRI mapping errors are much larger at stations that are located at different elevations than the mean elevation of the closest MSG-SEVIRI pixel. The largest k_O, i.e. more than 25 % in April or 15 % in November, is estimated at stations that are located more than 500 m lower than the pixel mean. Similarly, the largest k_U errors are found at stations located more than 500 m above the pixel mean. The evaluation of MSG-SEVIRI mapping errors at stations that are located at approximately the same elevation (yellow triangles in Fig. 7) indicates that the MSG-SEVIRI tends to more frequently underestimate snow cover in winter than overestimating it. The largest k_O errors are less than 0.5 %, but k_U errors exceed 3 % in the winter months.

5.2 Comparison between MSG-SEVIRI and MODIS snow cover data

The overall agreement between the MSG-SEVIRI and MODIS-combined maps (m_A) is summarized in Table 5. The m_A vary between 57.3 % to 92.7 %, with a median of 82.5 %. The difference in medians between the flatland (82.9 %) and mountain (81.6 %) regions is not large. The spatial patterns indicate (Fig. 8) that m_A is between 80 % and 90 % in the flatland, with an exception in the hilly region at the border between Upper and Lower Austria (Waldviertel), where m_A is less than 75 %. In the mountains, the m_A variability tends to be larger. The m_A agreement is over 90 % in the high mountain locations, but smaller than 65 % in the Alpine valleys in western Austria. It is also less than 70 % in the south-eastern part of the (Lahtinen et al., 2009) mountain mask region (Styria). The relationship between m_A and altitude is plotted in Fig. 9. While in the flatlands, m_A tends to decrease with elevation, in the mountains there is a tendency of increasing m_A with altitude. The results show that the largest m_A variability in Austria is in the regions with altitudes between 700 and 1500 m.

The seasonal variability (m_M) in the agreement between MSG-SEVIRI and MODIS is presented in Fig. 10. In the flatland areas (red line), m_M is the largest in April and July and less than 70 % in the winter months. The m_M amplitude is smaller in the mountains (blue line), ranging from more than 85 % in May, June and August to 70 % in September. A more detailed evaluation of the spatio-temporal patterns of the agreement between MSG-SEVIRI and MODIS is presented in Figs. 11 and 12. Figure 11 compares the spatial patterns of the frequencies of three MSG-SEVIRI and MODIS mapping classes – clouds, snow, no snow. It is clear, that the agreement between the snow cover products is the largest for mapping the clouds, for mapping the land in the flatland and snow in the high alpine areas. These cases occur in more than 25 % of days in the selected period, in most of the MSG-SEVIRI pixels. The MSG-SEVIRI maps snow, while the MODIS combined product indicates clouds in 10–15 % of days in the Alps. Interestingly, in the flatland, there are only a few days when both MSG-SEVIRI and MODIS indicate snow. The spatial patterns of the disagreement between the products, i.e. MSG-SEVIRI maps no presence of snow (land), but MODIS indicates snow, show that most of the cases are in Upper Austria, Styria and the mountain valleys. An opposite case occurs quite frequently in the mountain valleys of western Austria, where MSG-SEVIRI and MODIS map snow and land in 10–15 % of days, respectively. Figure 12 shows that MSG-SEVIRI overestimates snow in comparison to MODIS (middle panels) mainly in the summer for both mountain and flatland areas. The bottom panel (Fig. 12) indicates that the opposite case, i.e. MSG-SEVIRI underestimates snow in the winter, is less frequent (up to 10 %). There is quite a large frequency of days where MSG-SEVIRI maps land or snow and MODIS indicates clouds. These cases occur in 24–31 % of the days of winter season in the mountains and around 20 % of days of

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each month in the flatlands. In the mountains, the reduction of clouds by MSG-SEVIRI is noticeable in the winter months, where MODIS indicates clouds, but MSG-SEVIRI maps snow in more than 15 % of the days.

6 Discussion and conclusions

This study evaluates the snow cover mapping accuracy of the MSG-SEVIRI operational product. This product is based on blending 32 consecutive images per day, which is foreseen as an alternative to different filtering methods used for cloud reduction in optical remote sensing products. The limitation of the product is a coarser spatial resolution of about 5 km. Our results indicate that the blending of multiple observations during the day allows a significant cloud reduction in Austria. The mean annual cloud coverage of the MSG-SEVIRI product is less than 30 %, which is 23 % and 30 % lower than obtained by the MODIS-combined and MODIS-Terra snow cover products, respectively. Such cloud reduction is similar to that obtained by 1 day temporal filter performed on the MODIS-combined product (Parajka and Blöschl, 2008). The results are consistent with the preliminary MSG-SEVIRI assessment study (Surer and Akyurek, 2012), which indicates a 31–49 % of cloud reduction in mountainous parts of Turkey in winter season. Despite the coarser spatial resolution of MSG-SEVIRI, the overall mapping accuracy is large. The average accuracy for cloud-free days is 89 %, which is 5 % lower than obtained by the MODIS-combined product, but similar to that obtained by land-surface (JULES) model simulations driven by a regional climate model HadRM3-P (Parajka et al., 2010). The overall accuracy relates also well with the hit rate measure of Surer and Akyurek (2012) which is in between 68–81 % in winter. The accuracy with respect to all weather conditions (in all weather conditions assessments the pixels with clouds are considered as mapping errors) is, however, about 3–4 % larger than obtained by the MODIS product. The larger frequency of snow cover information, even for coarse resolution, indicates the potential of MSG-SEVIRI for operational assimilation into hydrologic models.

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The analysis of mapping errors indicates that MSG-SEVIRI tends to underestimate snow cover, particularly in flatland areas. Large errors are found also in the Alpine region characterized by large topographical and snow cover variability. The errors are noticeably larger at stations that are located at different elevations than the mean of the MSG-SEVIRI pixels. The differences in mapping accuracy clearly indicate the limits of using meteorological stations for validating coarse satellite products. In order to account for scaling relationships between point measurement and pixel size (Blöschl and Kirnbauer, 1992; Blöschl, 1999; Skøien et al., 2003) some studies used different thresholds for considering ground as snow covered. For example, Simic et al. (2004) examined the sensitivity of the mapping accuracy to the reference threshold of 1 and 3 cm and found that the difference is small, ranging approximately between −2 % and 4 %. In this study, a 1 cm threshold is used in order to be consistent and comparable with other studies performed in Austria. In the future, the sensitivity of results to this reference threshold should be investigated in more detail.

The comparison between MSG-SEVIRI and MODIS snow cover products shows a good overall agreement.

The snow retrieval algorithms for MSG-SEVIRI and MODIS snow products are more or less the same. The comparison between the normalized difference snow index (NDSI), used as the retrieval algorithm for MODIS product, and SI, used as the retrieval algorithm for MSG-SEVIRI product, shows a good relationship for several clear-sky MSG-SEVIRI images (Surer and Akyurek, 2012). The selected SI threshold value of 0.6 for the snow-cover area retrieval corresponds to 0.2 for NDSI value. For the MODIS products the NDSI value for 50 % snow-covered areas is taken as 0.4 (Dozier, 1989; Hall et al., 2002). The aim of selecting SI as 0.6 is to include the partial snow-covered areas in the retrieval of MSG-SEVIRI snow product. The differences are because of coarse spatial resolution of MSG-SEVIRI. The finding in this study indicates the importance of spatial resolution and sub-grid topographical variability for the use of satellite snow cover images in operational hydrological applications or climatological studies.

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Besides the importance of spatial resolution of snow products, a better temporal resolution helps to increase the cloud/snow discrimination, which is very important for the use of satellite snow products in further analysis. The new sensors and satellite missions to be used for hydrological, climatological studies can be designed according to an optimum spatial and temporal resolution.

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Table 1. Summary of some existing operational satellite snow cover products.

Snow cover product	Sensor	Available since	Spatial resolution	Temporal resolution	Mapping accuracy
NOHRSC/ NOAA/NESDIS (IMS)	NOAA/AVHRR + GOES GOES + SSM/I	1986 1998	1 km 4 km	Daily Daily, weekly	76 % (Klein and Barnett, 2003) 85 % (Romanov et al., 2000); < 20 %(Oct), ~ 60 % (Nov), ~ 95 %(Dec), ~ 70 % (Mar) (Brubaker et al., 2005)
MOD10A1,MYD10A1, MOD10A2,MYD10A2, MOD10C1,MYD10C1, MOD10CM,MYD10CM	MODIS-Terra/Aqua	2000/2002	500 m – 0.05°	Daily, 8-day, monthly	~ 94 % (see e.g. Hall and Riggs, 2007 or summary in Parajka and Blöschl, 2012)
HSAF (Eumetsat)	MSG-SEVIRI	2008	5 km	Daily	80 % compared to IMS (Siljamo, and Hyvärinen, 2011); 69–81 % in winter months (Surer and Akyurek, 2012)

Table 2. Number of meteorological stations in different elevation zones.

Elevation zone (m a.s.l.)	0–500	500–1000	1000–1500	1500–2000	2000–2500	2500–3109
Number of stations	59	78	29	6	4	2

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Table 3. Overall accuracy k_A (%) of the MSG-SEVIRI snow cover product for cloud-free days at the meteorological stations. Stations in flatland and mountains are stratified according to the mountain mask used for the MSG-SEVIRI product (Fig. 2).

Statistics	All stations	Stations in mountains	Stations in flatland
Count	178	97	81
Minimum k_A	51.3	51.3	78.9
25 % percentile k_A	82.6	78.2	93.9
50 % percentile k_A	89.3	84.3	98.8
75 % percentile k_A	98.7	88.4	99.4
Maximum k_A	99.9	94.4	99.9

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Table 4. Seasonal frequency of overestimation (k_O) and underestimation (k_U) mapping errors (%) estimated for the MSG-SEVIRI, MODIS-Terra and MODIS-combined snow cover products in the period April 2008–June 2012. The mapping errors are estimated at 97 and 81 meteorological stations in the mountain (Mnt) and flatland (Flat) areas, respectively (the largest mapping error for each product and mask area is marked by bold print).

Season	MSG-SEVIRI overest. k_O (Mnt/Flat)	MSG-SEVIRI underst. k_U (Mnt/Flat)	MODIS-Terra overest. k_O (Mnt/Flat)	MODIS-Terra underest. k_U (Mnt/Flat)	MODIS-comb. overest. k_O (Mnt/Flat)	MODIS-comb. underest. k_U (Mnt/Flat)
Jan	4.6/0.4	6.3/2.4	1.0/**1.0**	**1.8/0.8**	1.4/1.6	**2.2/1.2**
Feb	4.3/0.4	**6.8/2.6**	0.7/0.7	1.5/0.6	1.1/1.2	1.8/0.8
Mar	6.1/0.3	5.7/1.1	1.1/0.3	1.3/0.4	1.5/0.7	1.7/0.6
Apr	**8.8**/0.1	2.5/0.2	0.8/0.1	0.7/0.2	1.4/0.5	1.0/0.2
May	5.5/0.2	1.1/0.0	0.3/0.1	0.3/0.0	0.7/0.2	0.3/0.0
Jun	2.2/0.1	0.4/0.0	0.1/0.0	0.1/0.0	0.3/0.2	0.1/0.0
Jul	1.3/0.2	0.2/0.0	0.1/0.0	0.1/0.0	0.3/0.2	0.1/0.0
Aug	0.9/0.2	0.4/0.0	0.1/0.0	0.1/0.0	0.3/0.1	0.2/0.0
Sep	1.0/0.1	0.3/0.0	0.3/0.0	0.1/0.0	1.0/0.3	0.1/0.0
Oct	4.0/0.2	1.1/0.0	**1.2**/0.2	0.3/0.0	2.4/1.2	0.4/0.0
Nov	6.1/0.2	7.9/0.4	1.1/0.4	0.5/0.2	**2.4/2.0**	0.7/0.3
Dec	5.1/**0.5**	4.6/1.5	0.9/0.7	1.6/0.5	1.4/1.6	2.0/0.6

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Table 5. Overall agreement m_A (%) between MSG-SEVIRI and MODIS-combined snow cover products for MSG-SEVIRI pixels with less than 60 % MODIS cloud coverage. The agreement m_A accuracy is evaluated for all MSG-SEVIRI pixels, flatland and mountain mask areas in Austria.

Statistics	All pixels	Pixels in mountains	Pixels in flatland
Count	2635	1403	1232
Minimum m_A	57.3	57.3	64.4
25 % percentilem k_A	78.4	77.4	81.1
50 % percentile m_A	82.5	81.6	82.9
75 % percentile m_A	84.3	85.2	84.1
Maximum m_A	92.7	92.7	86.0

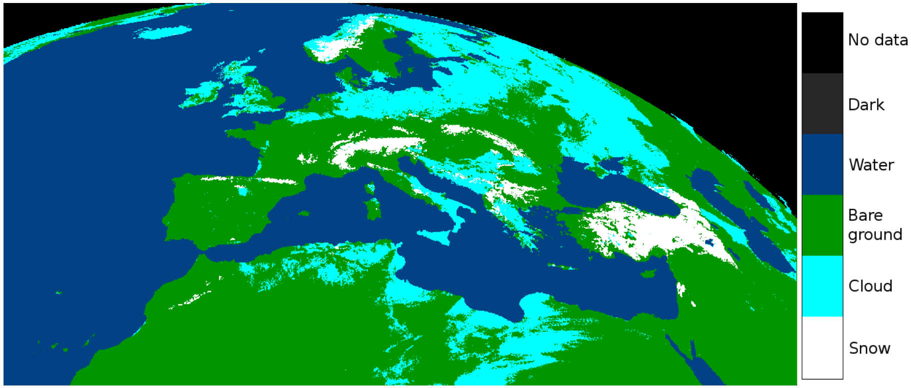

Fig. 1. Example of a MSG-SEVIRI snow cover map for 21 February 2012.

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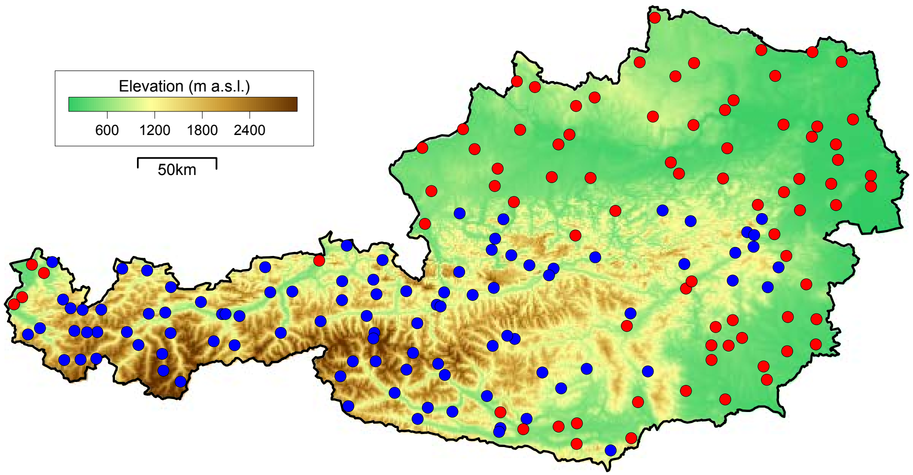

Fig. 2. Topography of Austria and location of 178 stations with daily snow depth measurements in the period April 2008–June 2012. Red and blue colors represent meteorological stations located in the flatland and (81 stations) and mountain (97 stations) regions according to the MSG-SEVIRI mountain mask, respectively.

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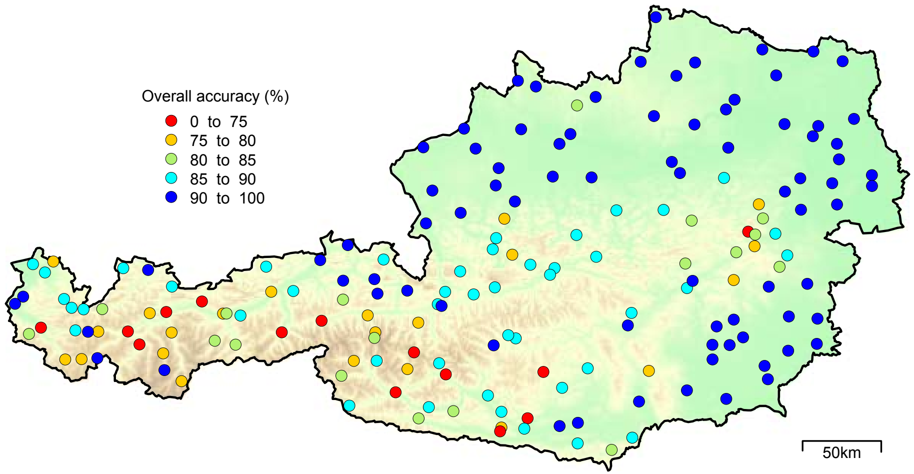

Fig. 3. MSG-SEVIRI snow product overall accuracy k_A (%) at 178 meteorological stations in the period April 2008–June 2012.

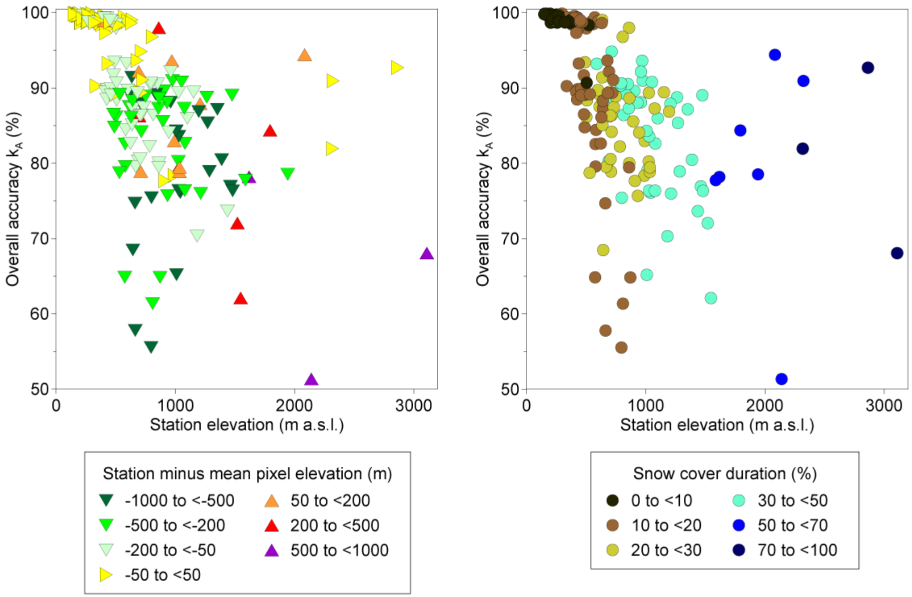

Fig. 4. Relationship between MSG-SEVIRI snow mapping accuracy (k_A) and elevation of the meteorological stations. Color of the triangles in the left panel indicates the difference between elevation of the meteorological stations and mean elevation of the respective MSG-SEVIRI pixels (as derived from a 25 m digital elevation model). Color of the symbols in the right panel shows relative snow cover duration observed at the meteorological stations in the period April 2008–June 2012.

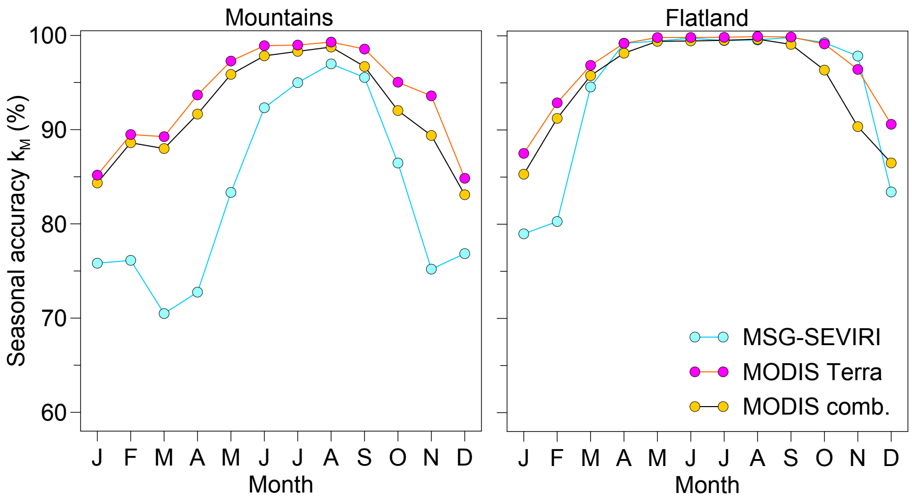

Fig. 5. Seasonal frequency of snow mapping accuracy k_M for the MSG-SEVIRI, MODIS-Terra and MODIS-combined products estimated for cloud-free days in the period April 2008–June 2012. Left and right panels show the results for meteorological stations in the mountain (97 stations) and flatland (81 stations) regions, respectively.

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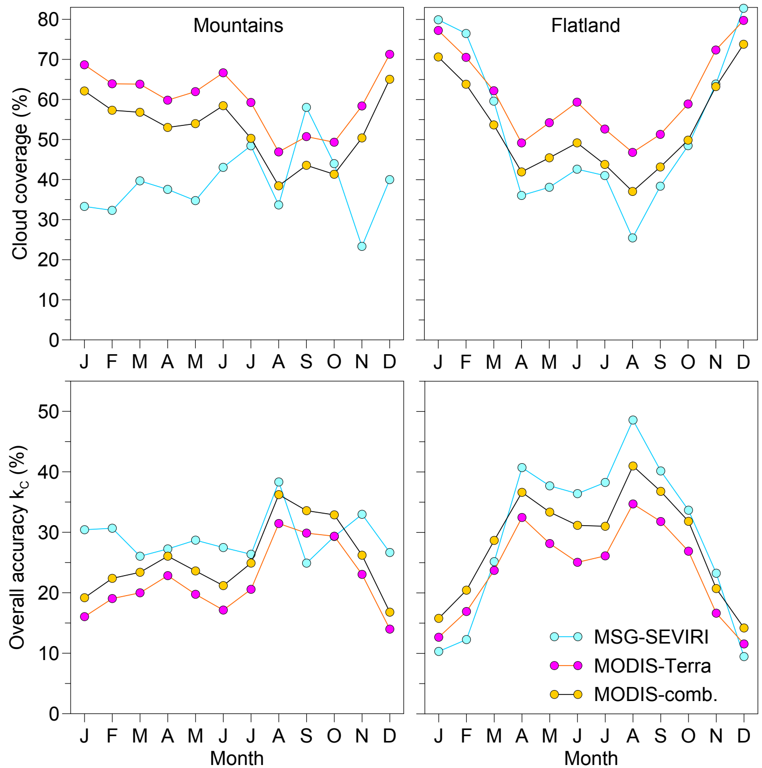

Fig. 6. Seasonal frequency of the clouds (top panels) and snow mapping accuracy k_C for the MSG-SEVIRI, MODIS-Terra and MODIS-combined products estimated for all days in the period April 2008–June 2012. Left and right panels show the results for meteorological stations in the mountain (97 stations) and flatland (81 stations) regions, respectively.

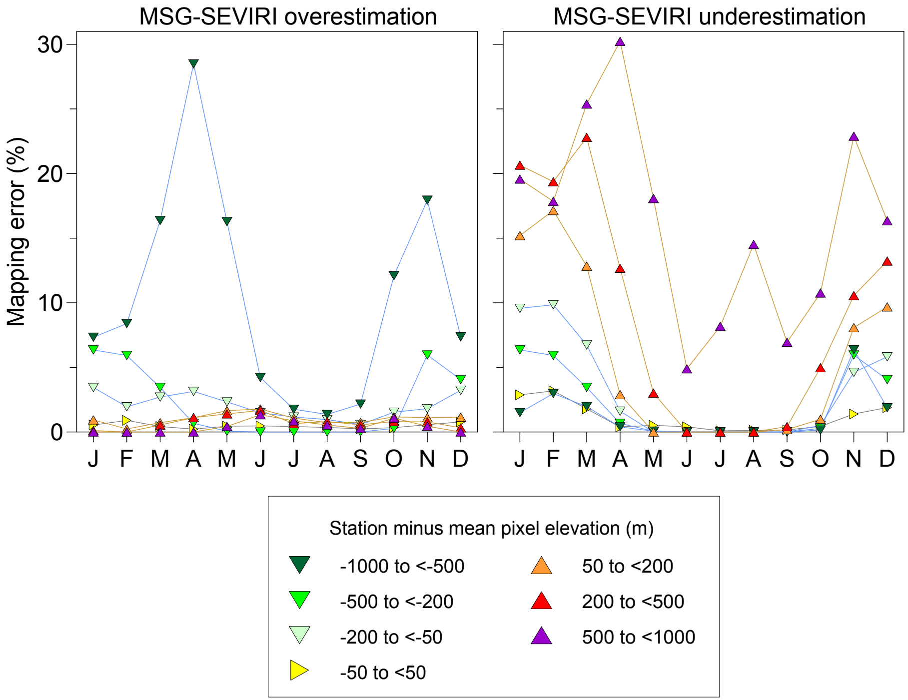

Fig. 7. Seasonal frequency of MSG-SEVIRI overestimation (k_O, left panel) and underestimation (k_U, right panel) errors summarized for stations with different elevation difference between meteorological station and respective MSG-SEVIRI pixel mean. The elevation difference is estimated as station elevation minus mean pixel elevation (as derived from a 25 m digital elevation model).

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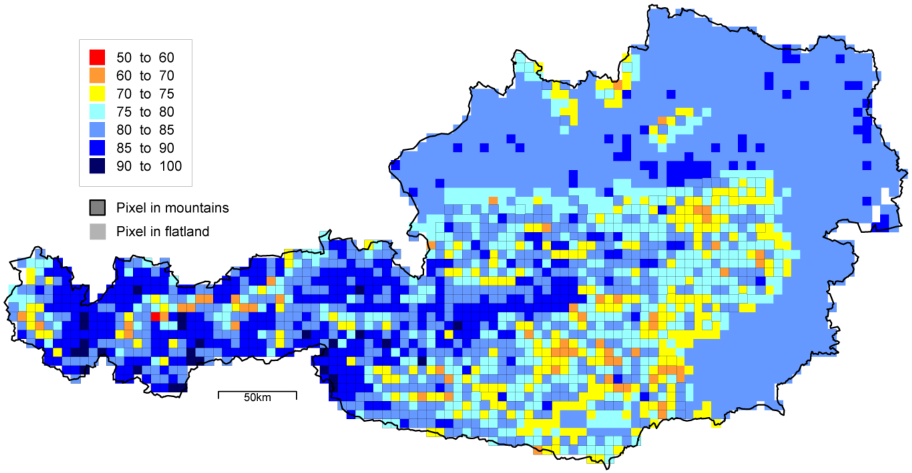

Fig. 8. Overall accuracy k_A of MSG-SEVIRI with respect to the MODIS-combined product in the period April 2008–June 2012. k_A is estimated for the MSG-SEVIRI pixels where MODIS cloud coverage is less than 60 %. Pixels with black outline indicate the MSG-SEVIRI mountain mask.

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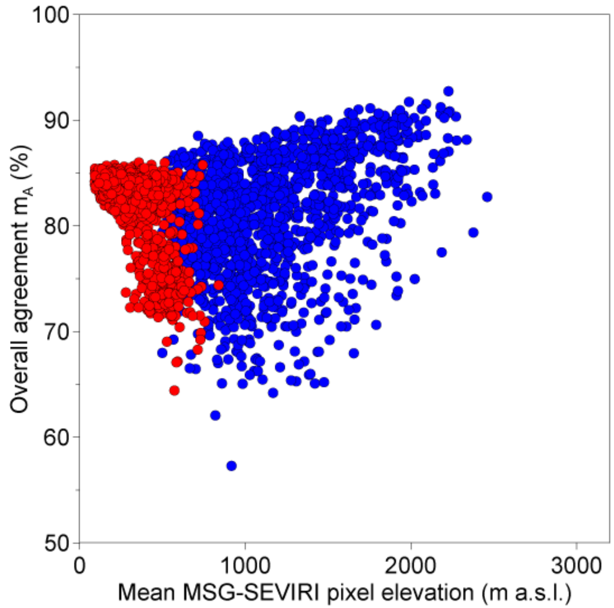

Fig. 9. Relationship between mean MSG-SEVIRI pixel elevation and the overall agreement (m_A) between the MSG-SEVIRI and MODIS-combined products. Red and blue points represent MSG-SEVIRI pixels in the flatland and mountain mask areas, respectively.

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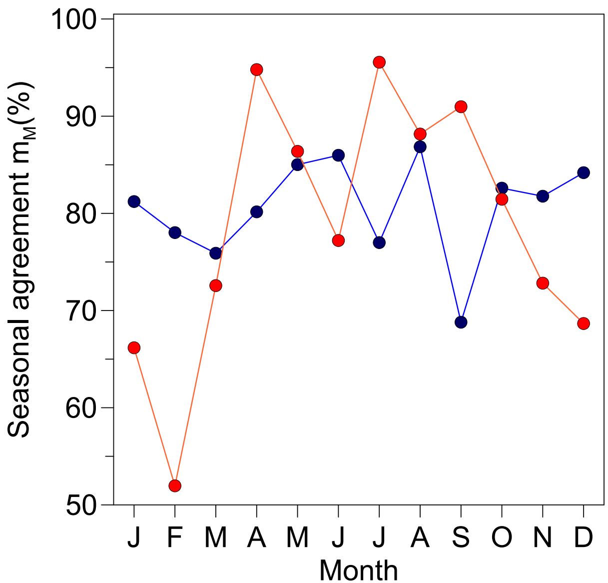

Fig. 10. Seasonal agreement m_M between the MSG-SEVIRI and MODIS-combined products for MODIS cloud-free pixels in the period April 2008–June 2012. Red and blue lines represent mountain and flatland areas, respectively.

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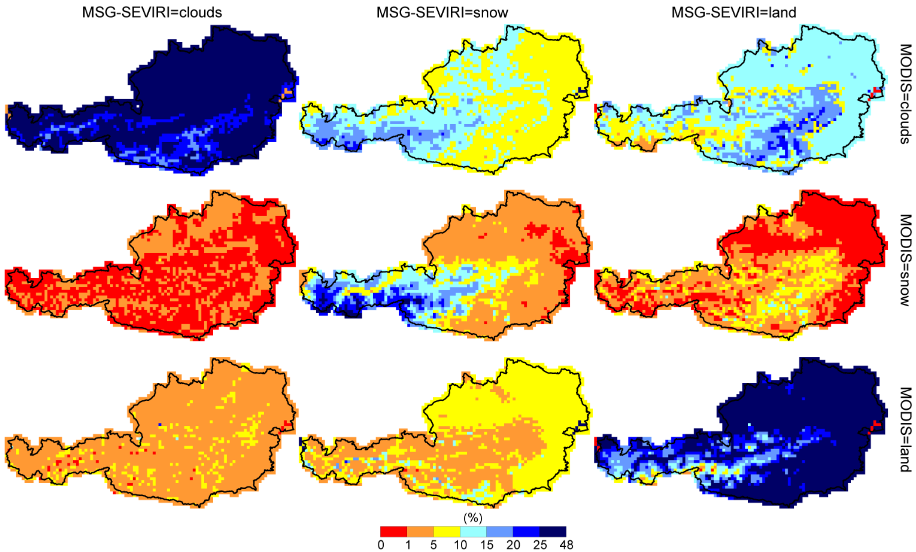

Fig. 11. Relative frequency of days with agreement and disagreement between the MSG-SEVIRI and MODIS-combined snow cover products in the period April 2008–June 2012.

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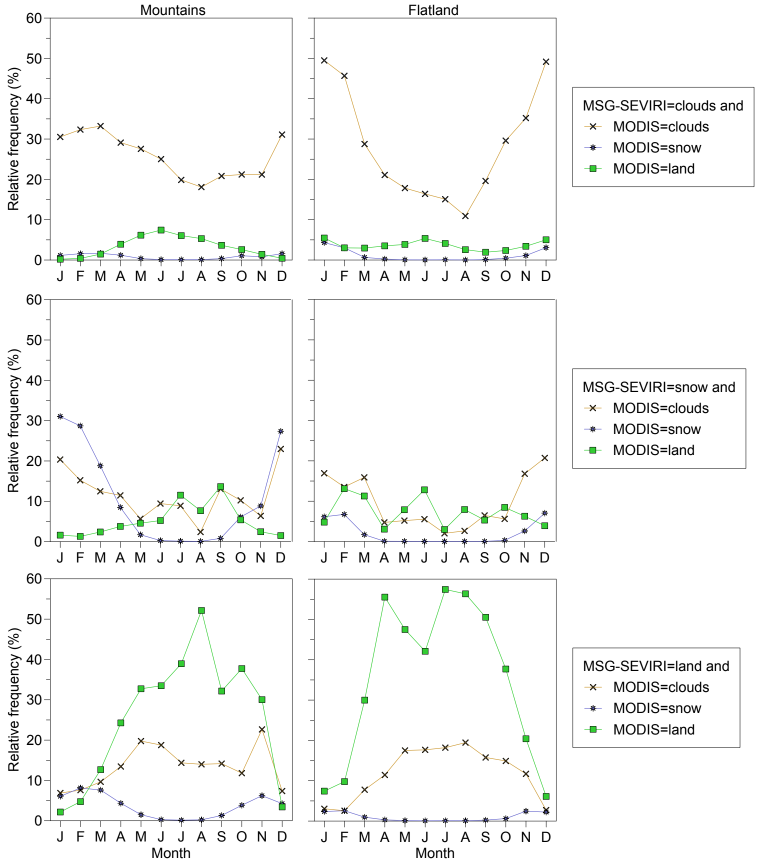

Fig. 12. Mean seasonal frequency of days with agreement and disagreement between the MSG-SEVIRI and MODIS-combined snow cover products in each month of the period April 2008–June 2012.