OPERATIONAL MONITORING OF ALPINE SNOW COVER WITHIN THE EUROPEAN COPERNICUS PROGRAMME

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ABSTRACT: The Copernicus Programme of the European Union is an operational Earth observation programme providing global, timely and easily accessible data and services for managing and protecting the environment and natural resources and for ensuring civil security. The dedicated space component of Copernicus comprises the Sentinel satellite constellation series, developed and operated by the European Space Agency (ESA). Cryosphere monitoring is among the main application fields of Copernicus. We developed, implemented and evaluated methods and processing lines for operational monitoring the area extent and melting state of snow based on data of the Sentinel-1, Sentinel -2 and Sentinel-3 satellite missions, each of which consists of a constellation of two identical satellites. We report on key features of the ensemble of snow products derived from medium and high resolution data of optical and radar sensors and show examples of the products over the Alpine area.

KEYWORDS: Snow extent, snow melt area, earth observation, Copernicus, Sentinel

1. INTRODUCTION

The Sentinel satellite constellation series represents the dedicated space component of the European Copernicus program, providing global, timely and easily accessible data for application domains in land, marine and atmosphere monitoring, emergency response, climate change, and security. The main mandate of the Copernicus space component is the support of operational services, but the improved observational capabilities and the long-term operational commitment of the Sentinel missions provide also unique and comprehensive observations on main components of the Earth System for a wide spectrum of research tasks (Malenovský et al., 2012).

Snow cover has a number of important physical properties that exert an influence on global and regional energy, water and carbon cycles. Seasonal snow is an important source for water in many regions. Snow may as well trigger avalanches, a major incidental hazard in steep mountain terrain. Changes in snow cover conditions can have serious economic and social impacts. Hence, regular monitoring of snow cover and its melting state is of high interest for climate monitoring, hydrology, water management, numerical weather prediction and avalanche warning services.

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The Sentinel-2 and Sentinel-3 missions are equipped with multi-spectral optical sensors, providing diverse spatial resolution and coverage. The Sentinel-3 sensors have spatial resolutions of 300 m and 500 m and cover swathes of 1270 km and 1420 km width, offering daily full coverage of mid latitudes with two satellites. The Sentinel-2 Multispectral Instrument (MSI) has high spatial resolution: 10 m (visible bands) and 20 m (near infrared bands). The constellation of two Sentinel-2 satellites provides full coverage of the Alps within 5 days.

The retrieval of snow extent by means of optical sensors exploits the characteristic spectral reflectance of snow relative to other media on the Earth's surface. Various algorithms have been developed for mapping binary and fractional snow extent. The fraction of snow cover is computed pixel-wise, based on multispectral signatures (Hall et al. 2006; Metsämäki et al., 2012; Salomonson and Appel, 2006; Riggs and Hall, 2015).

Whereas optical sensors are the main tools for monitoring the total snow extent, synthetic aperture radar (SAR) is used for mapping and monitoring the extent of snowmelt areas. C-band SAR data of the ERS-1, ERS-2, Envisat, and RADARSAT missions have been applied for mapping snowmelt area for scientific studies and for hydrological applications (Nagler et al. 2016; Nagler and Rott, 2000). Monitoring of snowmelt area has been identified as an important application also for Sentinel-1 (Malenovský et al., 2012).

2. METHODS

We developed and implemented an algorithm using multi-spectral VIS, SWIR and TIR bands of the Sentinel-3 Sea Land Surface Temperature Radiometer (SLSTR) for cloud screening and snow detection. The algorithm is based on the Normalized Snow Difference Index (NDSI) using reflectance at Visible and Shortwave Infrared bands to detect the presence of snow and calculate fractional snow extent at pixel-scale. The algorithm was tested and validated over the Alps using high resolution snow maps from coincidently acquired high resolution optical satellite data of Landsat-8 and Sentinel-2. A limitation for use of snow extent products from optical data is the susceptibility to cloud cover.

Complementary to the fractional snow extent, derived from Sentinel-3 SLSTR and Sentinel-2 MSI, we utilize Sentinel-1 SAR data to map the extent of melting snow areas. The Copernicus Sentinel-1 mission, comprising two identical satellites (S1A and S1B), is equipped with a C-Band SAR sensor. For snowmelt area classification a change detection method is applied, using multitemporal SAR data acquired in Interferometric Wide swath (IW) mode, the basic operation mode of Sentinel-1 over land surfaces covering a swath of 250 km width at 5 m x 20 m nominal ground resolution (Nagler at al., 2016). As first processing step multi-channel speckle filters are applied to the precisely co-registered snow image and to reference images acquired under snow-free conditions. In a next step the ratio of backscatter intensity of the SAR image with melting snow versus the reference images is calculated. Terrain corrected geocoding and segmentation is performed for the ratio image, using precise orbit data and a DEM. Post-processing employs a land cover map in order to exclude water surfaces and dense forests. The Sentinel-1 snow melt extent products are posted at 20 m pixel spacing matching the resolution of the Sentinel-2 snow products.

For melting snow in mountain areas and on open land performance tests show good agreement between snow extent derived from SAR and from high resolution optical sensors of Sentinel-2 and Landsat-8. In lowlands ambiguities may arise from temporal changes in backscatter related to soil moisture and agricultural activities. Dense forest cover is a major obstacle for snow detection by SAR. Therefore, areas with dense forest cover are masked out. In high mountain areas main differences between SAR and optical images are observed in patchy snow areas close to the snow line which may not be observable by SAR due to the dominance of backscatter from rough, snow-free surfaces. Based on the results of round-robin tests with different versions of the change-detection algorithm, we use for the retrieval of snowmelt area a weighted combination of VV- and VH-polarized backscatter data (Nagler et al., 2016).

3. EXAMPLES FOR SNOW EXTENT PRODUCTS

Figure 1 shows a section of the fractional snow extent map derived from Sentinel-3 SLSTR data of 22 April 2018, covering the Eastern Alps. The product is generated and made available on a daily basis. For various applications, such as climate monitoring and research, the daily data are merged to obtain weekly maps of snow extent. Main application fields for the daily medium-resolution snow product are hydrology, water management, and meteorological modelling and forecasting.

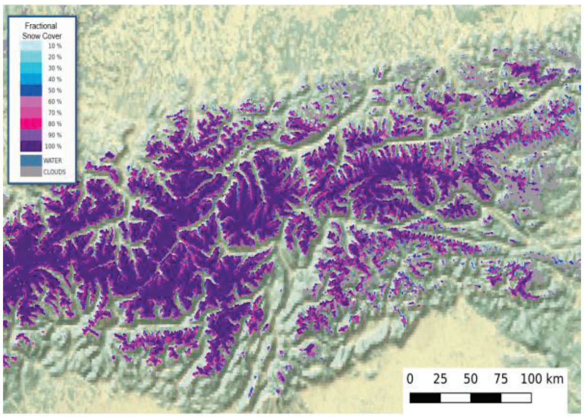

Figure 1: Map of Fractional Snow Extent from Sentinel-3 SLSTR data of the Eastern Alps, 500 m pixel spacing, 22 April 2018.

For various local- to regional-scale applications high resolution snow maps are required. Figure 2 shows a small section of a map on fractional snow extent on 27 May 2018 covering a site in the Kaunertal region near the main ridge of the Austrian Alps. A single Sentinel-2 scene with 290 km swath width covers a substantial part of the Alps as shown in the inset of Figure 2a. The combined duty cycle and coverage of the Sentinel-2 A&B satellites enables basically complete coverage of the Alps in 5-day intervals. Cloudiness is a major obstacle for achieving this sequence.

During the snowmelt period SAR based maps of melting snow extent, available from Sentinel-1 in 3-day intervals, are able to bridge gaps in the time sequence of Sentinel-2 snow maps. Figure 2c shows Sentinel-1 based extent of snowmelt area superposed to a map of Sentinel-2 fractional snow extent of the same day. The two products, based on rather different signals, show good overall agreement of snow extent in this case with wet snow. Some differences in snow detection are evident in zones of patchy snow where SAR underestimates the snow extent due to the strong signal from snow-free surfaces.

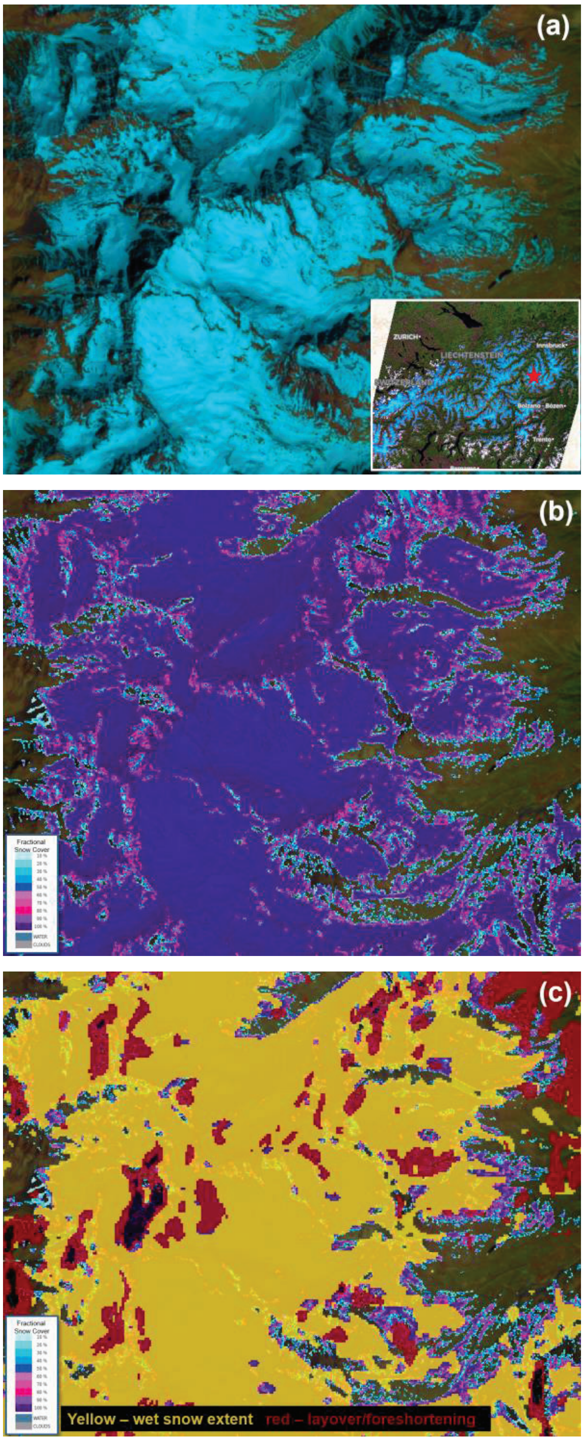

Figure 2: (a) Section of a multispectral Sentinel-2 MSI Scene from 27 May 2018, 20 m pixel spacing. The inset shows the area coverage of a full MSI scene. (b) Map of fractional snow extent. (c) Melt extent observed by Sentinel-1 SAR, overlaid on the Sentinel-2 snow map.

Figure 3 shows a time series of maps on snow-melt area covering a section of the Eastern Alps over Tyrol during the main melting period from 17 April to 29 May 2018, derived from Sentinel-1 SAR images of descending orbits. The pixel size is 40 m. Because of strong compression of the SAR signals on steep slopes facing towards the radar these slopes (affected by layover and foreshortening) are masked out. These slopes can be surveyed with SAR images of opposite view direction (ascending orbits). Gaps in the SAR snow maps, related to dry snow at high elevation, are filled with snow extent derived from optical imagery in order to obtain maps of total snow extent. The time series, showing maps of snowmelt area in regular time intervals, demonstrates the great potential of Sentinel-1 SAR for operational snowmelt monitoring.

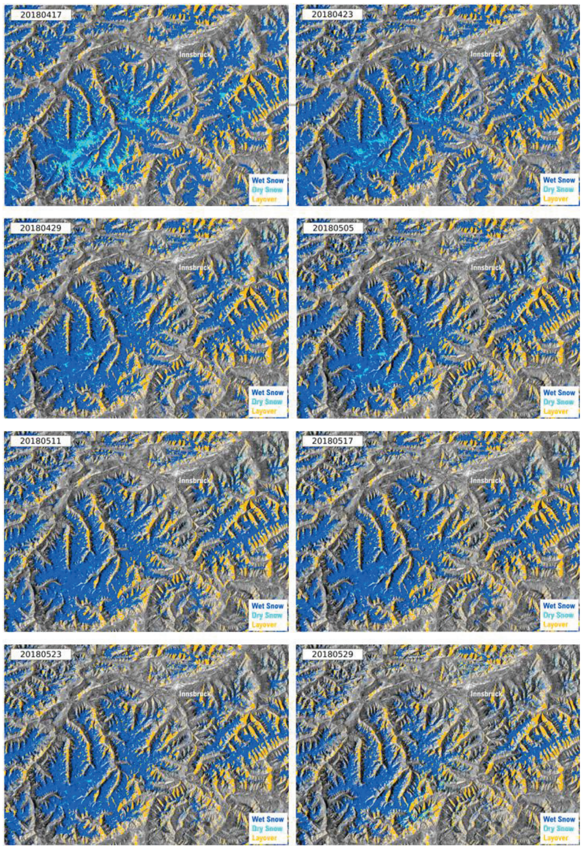

Figure 3: Time series (6-day interval) of snow melt area (blue) from Sentinel-1 SAR data, 17 April to 29 May 2018. Cyan: extent of dry snow on 17 and 23 April, from optical satellite data Yellow: areas affected by radar layover and foreshortening.

4. EXPLORING CAPABILITIES OF SENTINEL FOR AVALANCHE DEBRIS MAPPING

High resolution optical sensors and SAR offer the possibility to detect and map avalanche deposits based on changes of reflectivity, respectively radar backscatter, compared to undisturbed snow. Inventories of avalanche deposition zones are of interest for supporting avalanche warning and research activities. We show a case study on detecting avalanche debris deposited by powder snow avalanches during a critical avalanche hazard situation along the main Alpine ridge of Tyrol, triggered by heavy snowfall and strong winds between 20 and 22 January 2018.

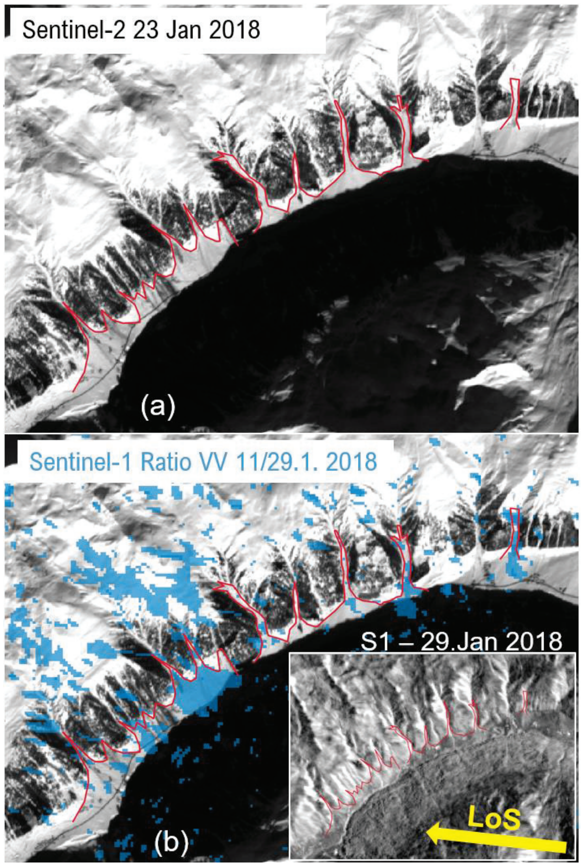

Figure 4: Sentinel-2 MSI images of Langtauferer Tal (South Tyrol), acquired on 23 January 2018 a few days after major avalanche events: (a) Red lines – estimated outlines of avalanche debris zones. based on Sentinel-2 surface reflectance; (b) Blue – areas with a change of backscatter ratio ≥+3dB, derived from Sentinel-1 SAR images of 29 vs. 11 January 2018. Inset: SAR image; LoS – radar line-of-sight direction.

Figure 4 shows features in Sentinel-2 optical and Sentinel-1 SAR images that are indicating the presence of avalanche debris. The optical image (Figure 4a) was acquired 2 to 3 days after avalanche release. The avalanche deposit zones show reduced surface reflectance versus undisturbed snow. This is confirmed by comparison with oblique aerial photography. The detected deposit areas are located on south-facing slopes, offering suitable illumination conditions.

Figure 4b shows a mask of backscatter change ≥+3 dB based on the ratio of Sentinel-1 SAR backscatter coefficients after and before the avalanche release (backscatter ratio 29 vs. 11 January 2018). The mask is superposed onto the Sentinel-2 image. Parts of the avalanche debris areas are corresponding to areas of increased backscatter ratio, very likely caused by larger surface roughness and coarser volume structure of the deposited snow masses. Increased backscatter is also evident in parts of the avalanche release areas. This is probably related to the increased backscatter of a frozen melt crust. Positive air temperatures in 2000 m a.s.l. after 22 January and solar irradiance caused melting of the top snow layer on south-facing slopes during the day. During the Sentinel-1 descending orbit overflight (about 6h UTC) the snow pack was frozen.

The SAR image (inset in Figure 4b) shows the direction of radar illumination, in this case an oblique angle versus the slope. The illumination angle is of particular importance for the sensitivity in detecting surface roughness change.

The case study shows that the feasibility for detecting avalanche deposits depends on properties and extent of the avalanche debris and on the orientation of the slope versus the illuminating source. In the case of optical imagery the detection is limited to cloud clear conditions and solar illuminated slopes.

5. CONCLUSIONS

Consolidated and validated methods and products for operational monitoring seasonal snow extent and snow conditions using Sentinel 1, 2 and 3 satellites are available. The constellation of Sentinel-3 A&B is able to provide daily full coverage of the Alps and other mountain regions, an excellent basis for observing the high temporal and spatial variability of snow cover. The Sentinel-3 snow maps have the potential for supporting daily updates of baseline snow products at regional to continental scale.

Sentinel-2 A&B satellites provide high resolution regional maps of total snow extent with repeat observation capability of a few days. Complementary to optical snow maps, Sentinel-1 SAR delivers maps of snowmelt area. The Sentinel-1 A&B missions provide repeat observations over the Alps in 3-day time intervals. The synergy of optical and SAR is the basis for generation of an advanced snow product of extent and melting state, which addresses specific needs of hydrology, water management, numerical weather prediction and land surface process modelling.

The case study on mapping of avalanche debris zones shows the feasibility for using Sentinel-1 SAR backscatter and Sentinel-2 reflectivity data to map the location and extent of avalanche deposits. However, suitable orientation of the slope versus the illuminating source is critical, and ambiguities may arise in case of changes in snow metamorphic state affecting reflectivity.

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