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Snowmelt modelling using Radarsat data

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Abstract

A procedure for mapping wet snow is described which is based on change detection to compensate for backscattering variations due to topography. The method requires repeat pass SAR images as provided by Radarsat. As test area the basin Tuxbach / Zillertal in the Austrian Alps was selected. Based on Radarsat SAR Beam Mode S7 images (look angle about 40°) and ERS-2 SAR images (look angle of 19°) snow maps were generated. A comparison between Radarsat and Landsat TM snow maps show good agreement. The SAR derived snow maps were used as input for calculating daily runoff in the basin Tuxbach during the snow melt season 1998.

Introduction

Snow extent is a key parameter for snow melt runoff modelling and forecasting. For operational runoff forecasting the capability of SAR to provide regular repeat pass observations, irrespective of clouds, is a significant advantage. The capability for mapping melting snow has been demonstrated with the C-band SAR of the European Remote Sensing Satellite ERS-1 (Nagler, 1996; Rott and Nagler, 1994), and with the C-band and X-band channels of SIR-C/X-SAR (Floricioiu, 1997; Rott et al. 1996), and with various airborne SAR systems (Rott and Davis,1993). The capabilities of ERS SAR data for runoff modelling was demonstrated by Nagler and Rott (1997). These investigations were carried out in the test site Ötztal in the Austrian Alps south-west of Innsbruck. As contribution to the Adro Project 414 the application of the snow mapping algorithm developed by Nagler (1996) was tested with Radarsat data, acquired under a different look angle than ERS, over the basin Tuxbach / Zillertal, Austrian Alps. The Radarsat SAR derived snow maps were compared with snow maps derived from Landsat TM images and locally with oblique photos to assess the accuracy. In order to investigate the application of Radarsat snow maps for hydrology and water management, simulations of daily runoff were carried out in the basin Tuxbach / Zillertal.

SAR Based Snow Mapping Procedure

The algorithm for mapping wet snow in mountain areas applies change detection in order to eliminate the effects of topography on backscattering. The low backscattering coefficient $\sigma°$ of melting snow in comparison to reference images is the basis for the classification. Reference images are needed in the same imaging geometry (repeat pass) at dates when the site is free of snow or covered by dry snow (Nagler, 1996). Because of the low losses of the SAR signal in dry snow, the backscattering signal from the soil below the dry snowpack dominates in the X- to L-band range. On mountain slopes with rough surfaces the differences of σ° between winter with dry snow and summer are very small (Floricioiu, 1997; Nagler, 1996). Therefore reduced σ° in spring relatively to the reference images is a clear indication of snow melt. Over agricultural surfaces and wetlands other factors such as differences in surface roughness and wetness may also cause pronounced temporal changes of σ°. Misclassifications for these areas can be excluded by means of land cover maps, topographic information or time sequence analysis.

The main processing steps of the snow mapping procedure can be divided into three parts. The first part includes the generation of a geocoded ratio image using repeat pass images to map changes in backscattering. It includes coarse matching of the snow (slave) image in full resolution to the reference (master) image, multilooking, and speckle filtering. We found that the Frost Filter is well suited for the snow mapping procedure, the filter size depends on the previously applied level of multi-looking. The ratio of the backscattering coefficient of the snow image ($\sigma°_{ws}$) versus the backscattering coefficient of the reference image ($\sigma°_{ref}$) is calculated, and the ratio image is geocoded using a digital elevation model and orbit parameters (Nagler and Rott, 1997).

The second part of the procedure includes the generation of the binary snow map by thresholding the geocoded ratio image. For steep terrain it may be necessary to combine the geocoded ratio images of crossing orbits in order to reduce the loss of information due to layover, shadow and inappropriate incidence angles. This step is required for low look angle SAR such as Radarsat SAR Beam Mode S1 or ERS SAR, if a significant part of the image is affected by foreshortening and layover. In images with high look angles (e.g. Radarsat Beam Mode S7) layover regions are of less concern, therefore this processing step may be omitted. The following rules are applied for combining crossing passes:

1. Exclude all pixels in layover and shadow regions and with local incidence angles $\theta<17°$ and $\theta>78°$; these pixels are included in the residual layover/shadow mask.
2. If a pixel is within the accepted range of incidence angles both in the image of the ascending and of the descending orbit, the pixel from the pass with the higher incidence angle is selected.

Binary snow maps are generated by thresholding the ratio image. A pixel is classified as wet snow when the condition $\sigma°_{ws} / \sigma°_{ref} < TR$ is valid. Based on signature studies (Nagler, 1996) and on field observations a threshold of TR = -3 dB was determined for alpine regions.

The third part includes post processing steps, which are required to generate snow maps (dry snow and wet snow) as input to hydrological models. We included corrections for agricultural fields and for dry snow areas at higher elevations. For basins in a different environment the post processing steps have to be modified:

- Agricultural areas are located mainly in the lower areas of the alpine basins, and become snow free earlier in spring than the mountain slopes. These areas are flagged out and are assumed to be snow free after the snowline retreated to higher elevations.
- In mountainous regions melting is strongly influenced by topography. In general snow melt starts at lower altitudes while the snow remains dry at higher elevations. We defined the decision rule that surfaces above the upper boundary of wet snow areas are covered by dry snow and use archived snow maps to exclude snow free areas at higher elevations such as mountain ridges.

For generation of snow maps we developed a software package in C and Fortran. It is linked with the commercially available software system EASI/PACE of PCI Inc. So for we used it to process Radarsat SGF and ERS PRI products but it can be easily modified for other sensors. For automatic processing a shell script has been developed which handles the operation of the programs in the required order and aids in the selection of input parameters. It is especially designed for generating time series of snow maps for operational application with a minimum of user interaction. The automatic generation of a snow map for an area of 45 x 50 km^2 takes about 30 minutes on a SUN Ultra 2 and requires about 500 MB disk space.

The Investigation Area

Figure 1 shows a Landsat-5 Thematic Mapper image of the drainage basin Tuxbach (130 km^2) in the Zillertaler Alpen, located north of the main ridge of the Eastern Alps of Austria. The basin extends from the runoff station Persal at an elevation of 880 m to the peak Olperer at 3476 m. The area is characterized by steep topography. Less than 2 % of the area are affected by minor slopes of less the 6°, 77% have slopes between 16° and 40°. A digital elevation model (DEM) with grid spacing of 25 m is available. It is used for geocoding of the SAR data and of the data from optical imagers and for delineating the basin boundaries. We carried out a classification of the main land cover types based on multitemporal Landsat TM data. 72 % of the basin are covered by low vegetation, which is made up by alpine meadows and dwarf shrubs at higher elevations, and by cultivated meadows in the valleys. Coniferous forests cover about 11% of the basin, the timberline is at 2100 m. At high elevations bare soil, rock and moraines are dominating, covering 14 % of the total basin, 3 % are covered by glaciers.

SAR data analysis

Due to the steep topography the basin Tuxbach offers the possibility to investigate effects of SAR imaging geometry and to select the most appropriate look angle for snow mapping. We analyzed Radarsat SAR images acquired at standard beam

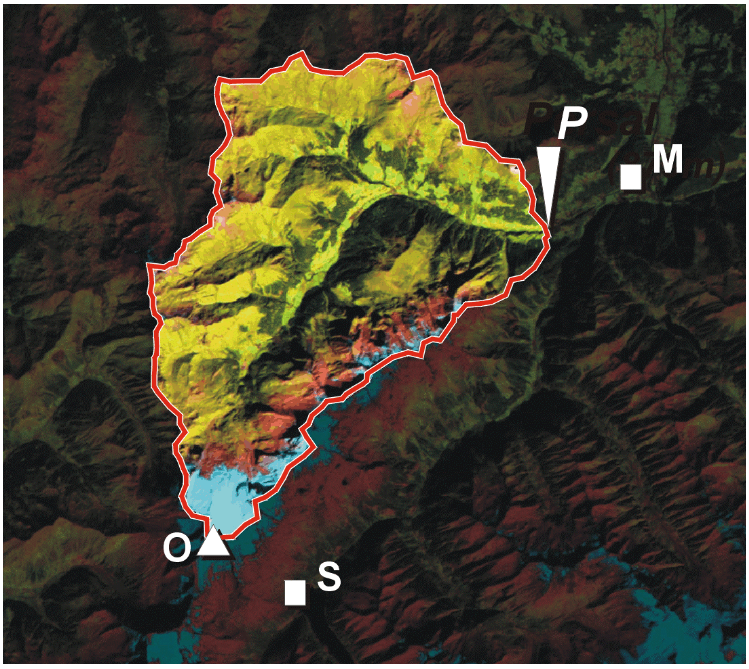


Figure 1: Landsat-5 Thematic Mapper (band 5/4/3) Image of the basin Tuxbach / Zillertal from 15 September 1997. The boundaries of the drainage basin are shown; runoff gauge Persal (P), the meteorological station Schlegeis (S) and Mayrhofen (M), the peak Olperer (O).

mode S7 (look angle 38 to 42 degrees) and ERS-2 images (look angle between 17 to 23 degrees), with a similar imaging geometry as Radarsat SAR S1 data. A Radarsat SAR S7 (SGF-Product) image and ERS-2 SAR (PRI-Product) image of the basin Tuxbach are shown in Figure 2, the corresponding geocoded images are shown in Figure 3. Due to the steep look angle foreshortening and layover are important in ERS images of mountainous terrain, while areas covered by radar shadow can be neglected. The fraction of the test basin Tuxbach affected by layover in the ascending and descending pass of ERS is 27.8 % and 34.9 % respectively, radar shadow covers less than 1 % of the basin. Outside of the layover and shadow regions about 4 % of the area are seen at very steep (lower than 17°) or at grazing (higher than 78°) local incidence angles. By combining ascending and descending passes the fraction of areas where no information can be extracted is reduced to 5 % of the basin. ERS SAR observes the basin Tuxbach from ascending and descending passes within 12 hours time difference. In other latitudes, where the time difference of crossover can be several days, the combination of images from crossing passes may be affected by change of snow extent due to melting. In Radarsat SAR S7 images the amount of layover and radar shadow in the basin Tuxbach is less than 1% of the area. About 7 % and 9% are imaged at inappropriate local incidence angles from the ascending and descending orbit, respectively. This means that in this terrain a Radarsat SAR S7 image of one pass is sufficient to get information of more than 90% of the basin.

SAR snow mapping in mountain regions

The selection of a suitable reference image, with snow free surfaces or dry snow cover, is crucial for snow mapping by means of change detection. In 1998 eight Radarsat SAR images in Mode S7 were acquired over the basin Tuxbach, four images during descending passes on 4 February, 17 April, 11 May, 4 June at 6:15 MET and four images during the ascending pass on 6 February, 19 April, 13 May, 6 June at 18:15 MET. The images acquired on 4 February (descending pass) and 6 February 1998 (ascending pass) were selected as reference. It should be noted that due to the comparatively warm and sunny weather on 6 February the snow surface was slightly wet at south facing slopes and lower elevations in the afternoon. In these areas the change detection algorithm does not work correctly and the melting snow is missed. In the morning image of 4 February the snow surface was completely dry, therefore this image is the more appropriate reference image.

Additionally, more than 20 ERS-2 images have been acquired over the test basin since 1996. To improve the representativity of the backscattering properties and to reduce the amount of speckle, an average reference image was derived as a mean of two repeat pass ERS images. We used the images from 18 November 1997 and 27 January 1998, when the air temperature was low and the snow pack was completely dry. For both ERS C-Band VV and Radarsat C-Band HH data we applied the same threshold of -3 dB to discriminate between wet snow covered and snow free areas.

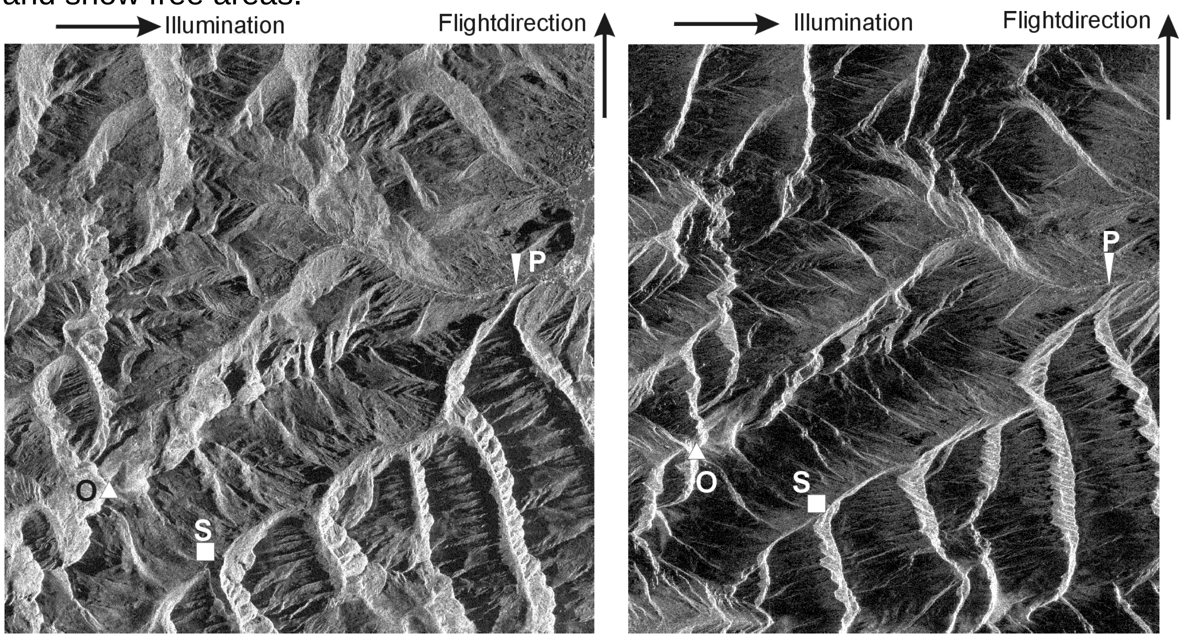
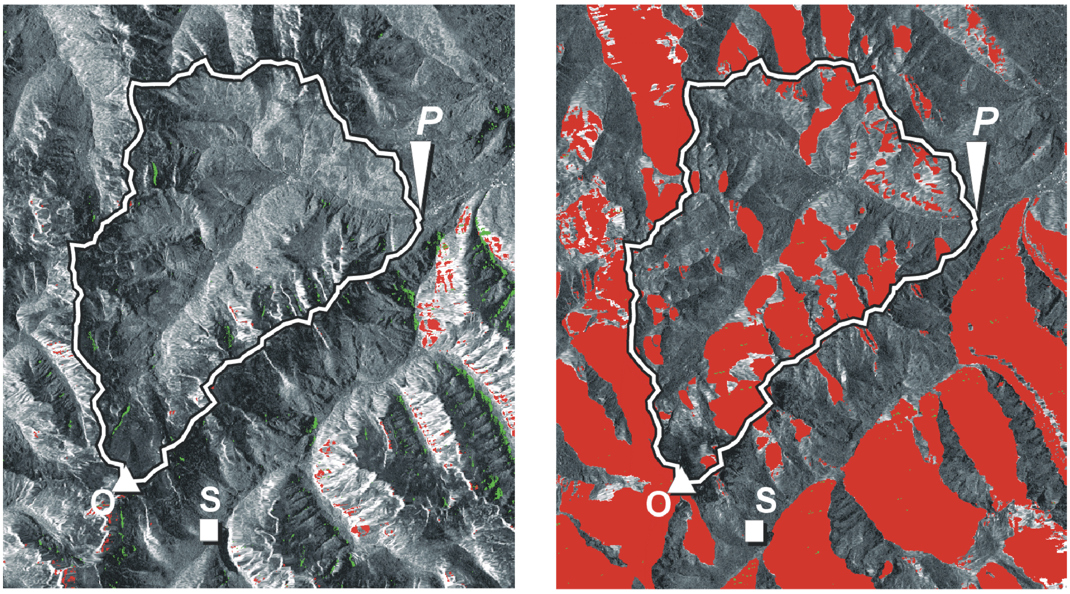


Figure 2: Ascending Radarsat SAR Beam Mode S7 SGF image, 13 May 1998, and ascending ERS-2 SAR PRI image, 6 July 1998, of the basin Tuxbach. Summit of Olperer (O), runoff gauge Persal (P), meteorological station Schlegeis (S).



Radarsat SAR - S7 SGF Product ERS-2 AMI SAR - PRI Product

Figure 3: Geocoded Radarsat SAR Mode S7 image, 13 May 1998, (left) and ERS-2 SAR image, 6 July1998, (right). Layover regions (red), radar shadow (green).

The SAR based snow classifications were locally verified by oblique photos taken during field campaigns on the day of the image acquisition and by comparison with snow maps from other sources. Figure 4 compares the snow extent on 11 May 1998 derived from Radarsat Mode S7 SGF data (descending pass) and the snow map from Landsat-5 TM data of 13 May 1998. In order to avoid misclassification of dry snow, at higher elevations the snow extent of the SAR image from 4 June 1998 was used under the assumption that it was the same as the snow extent on 11 May. The Landsat-5 TM snow classification was based on the ratio of the planetary albedo R_{pl} in TM band 3 and 5 corrected for the local illumination angle (Rott, 1994). A threshold of $R_{pl}(TM3) / R_{pl}(TM5) = 4.3$ was used to classify pixels which are fully snow covered (Rott and Markl, 1989).

The general patterns of the snow maps from SAR and Landsat TM agree well. Looking in more detail, the Landsat TM snow map is less noisy. In dense forests snow can usually not be detected by means of remote sensing data, but at this date the snow line was higher than the timberline. The pixel by pixel comparison between Landsat TM and SAR classification of snow free and snow covered areas has an overall agreement of 82.8 % (Table 1). However, it should be noted that this comparison is affected by inaccuracies in the geocoding of Landsat TM and SAR images due to errors in the satellite orbits and in the DEM. In the test basin the co-registration accuracy of the images of the two sensors, derived for a few natural ground control points at various elevations, shows differences up to 4 pixels. On 11 May 1998 the total snow extent derived from Radarsat SAR is 46.4 km^2, the snow extent from Landsat-5 TM data, 13 May 1998, is 44.4 km^2, which corresponds to a retreat of the snow coverage of 2 km^2 within 2 days. This agrees well with field observations, because significant snow melt was observed in these two days due to warm temperatures. The main differences are found near the snow line, where the snow cover is broken. In such areas SAR tends to underestimate the snow extent in comparison to Landsat TM, which confirms our conclusions from previous intercomparisons (Nagler, 1996, Nagler and Rott, 1998). For hydrological applications the total snow area and the fraction of snow cover in the various elevation zones is of main relevance. These quantities compare very well between the two sensors.

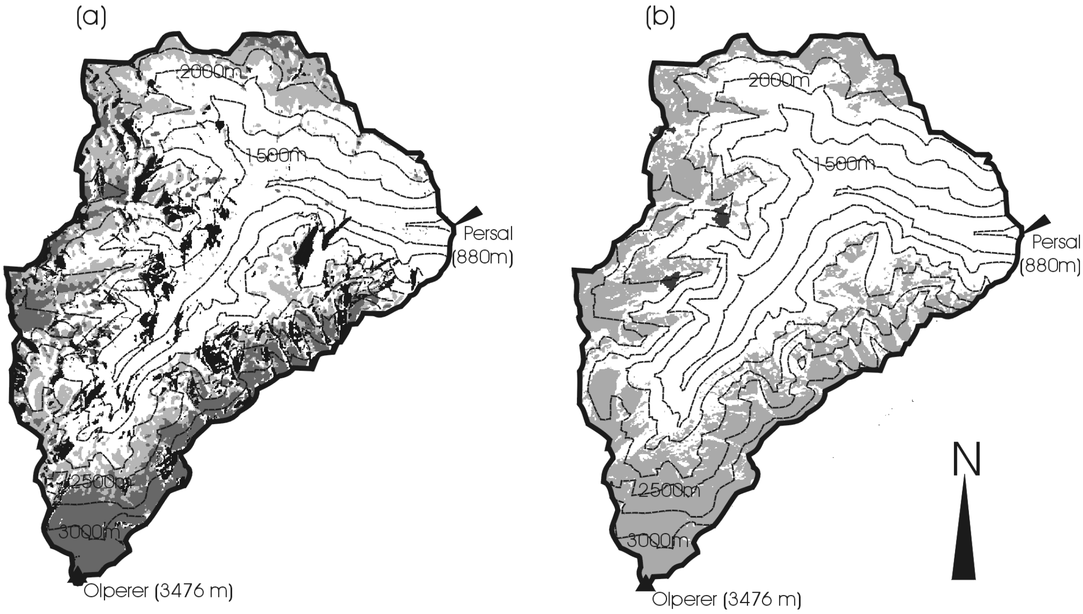


Figure 4: Snow map from (a) Radarsat SAR data beam mode S7; light grey: change of snow extent between 11 May 1998 and 4 June 1998, dark grey: snow extent on 4 June 1998; and (b) from Landsat-5 TM data 13 May 1998; light grey: snow; black: no information (clouds in Landsat TM image; SAR: layover, radar shadow, and local incidence angles <17° and >78°); white: snow free areas.

Table 1:
Confusion matrix derived from Landsat-5 TM, 13 May 1998, and Radarsat SAR S7 snow map from 11 May 1998 for the basin Tuxbach/Zillertal.

	Radarsat - 11May98	
Landsat TM 13May98	*Snow covered*	*Snow free*
Snow covered	76.4 %	23.6 %
Snow free	13.7 %	86.3 %
Snow covered area:	Overall Agreement: Radarsat, 11 May98 Landsat TM, 13 May98	82.8 % 46.4 km^2 44.4 km^2

Runoff Simulation

The daily stream flow in the basin was calculated using the Snowmelt Runoff Model (SRM) of Martinec and Rango (Rango, 1995). For hydrological modeling the test basin was divided into 7 elevation zones (zone boundaries at: 880, 1300, 1700, 2100, 2400, 2700, 3000, 3480 m), for which daily values of precipitation, temperature and fraction of snow covered area are required as model input. The runoff parameters for model calibration were determined from historical runoff data. Daily values of precipitation and temperature were measured at Schlegeis (1800 m) and Mayrhofen (670 m), which are located near the boundary of the basin (Figure 1). The values of the snow covered area are interpolated from the SAR based snow maps using the cumulative degree day model (Rott et al., 1998). Because fresh snow, falling during the main melting period, disappears within a few days, it does not make any significant contribution to the runoff. Therefore we used only images which were not affected by fresh snow falls. Figure 5 shows the time series of the three variables used in the runoff simulation. These variables are calculated separately for each elevation zone.

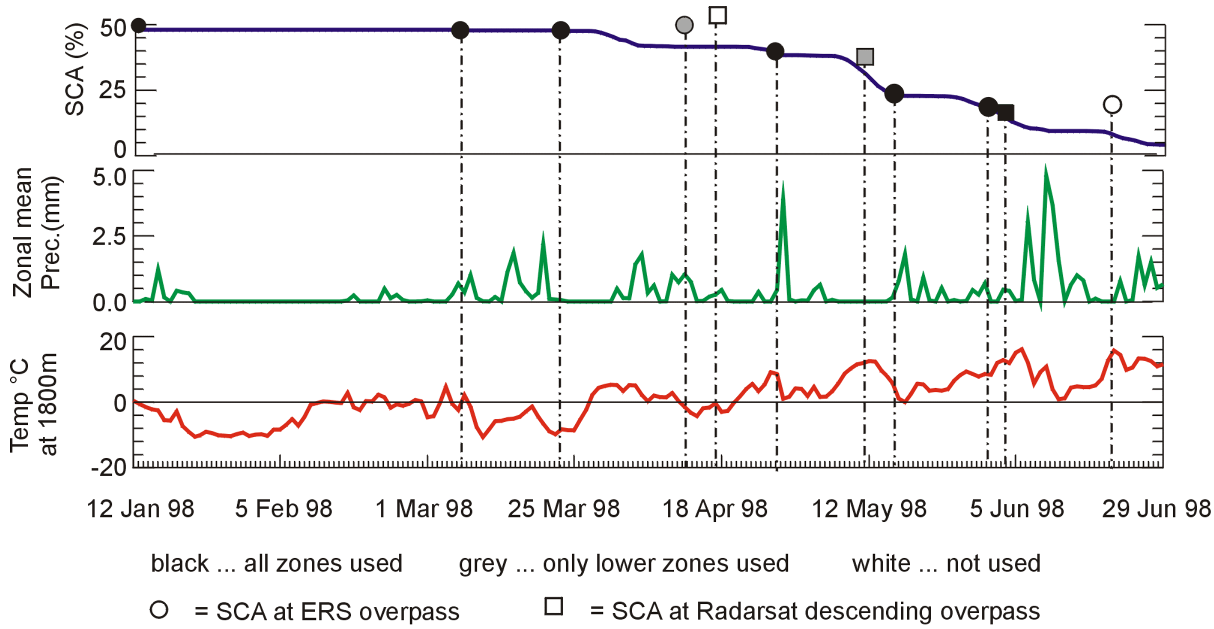


Figure 5: Daily values of the snow covered area (SCA) in the basin Tuxbach / Zillertal derived from ERS-2 and Radarsat SAR data, the mean zonal precipitation and the typical temperature at 1800 m based on daily measurements at the stations Schlegeis and Mayrhofen.

The runoff calculations for the basin Tuxbach were carried out for the period 1 January 1998 to 30 June 1998 (Figure 6). Until mid May the simulated runoff and the measured runoff agree comparatively well. The first melt peak in the simulation is somewhat overestimated due to a delay of snow melt runoff until the snow pack is saturated. Once the snow pack is saturated the correspondence between measured and calculated runoff is better. Differences between simulated and measured discharge are mainly observed in periods with high rainfall in June (Figure 5), which points out that the measurements of the precipitation gauges at Schlegeis and Mayrhofen poorly represent the precipitation in the basin. Over the whole period the Nash Sutcliffe coefficient of determination between simulated and measured runoff is R^2=0.75, the volumetric difference is -5.69 %.

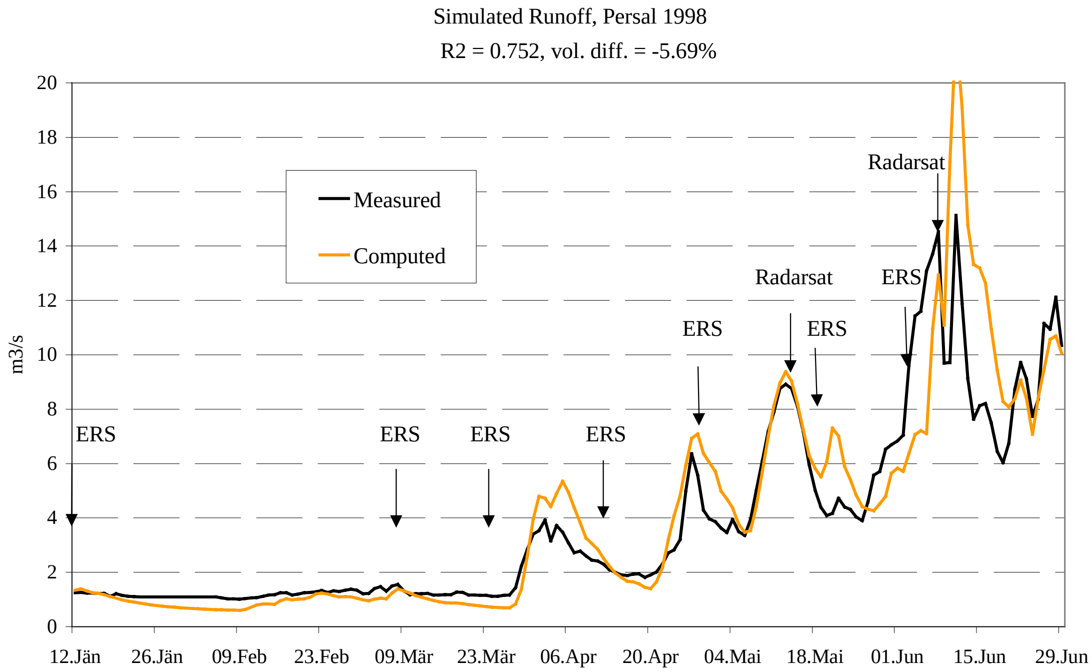


Figure 6: Measured and simulated runoff for the basin Tuxbach in spring 1998. The arrows indicate the acquisition of SAR images used for the model calculation.

Summary and Conclusions

An automatic snow mapping algorithm, based on change detection, was used to generate maps of melting snow from SAR data of the mountain basin Tuxbach in the Eastern Alps. Radarsat SAR Beam Mode S7 data, with a typical look angle of 40°, and ERS-2 SAR data, with mean look angle of 19°, were used. Because of the comparatively high look angle, geocoded Radarsat SAR Mode S7 images (ascending or descending) provides useful information on more than 90 % of the basin Tuxbach, whereas for ERS SAR only about 65% to 70% of the area can be classified. This makes the combination of crossing passes necessary to generate a single snow map, whereas the use of a single Radarsat SAR S7 image is sufficient. To discriminate between wet snow and snow free areas we applied the same threshold of -3 dB on the ratio image for Radarsat C-Band HH and ERS-2 C-Band VV data. The Radarsat SAR snow map from 11 May 1998 agrees well with the Landsat TM snow classification from 13 May 1998. Based on the SAR derived snow maps simulations of the daily runoff were carried out for the basin Tuxbach in 1998. Simulation and measurements agree well during the melting period, confirming the usefulness of SAR derived snow maps for calculation of daily runoff.

Acknowledgements

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References

Floricioiu D.M., 1997: Polarimetric Signatures and Classification of Alpine Terrain by Means of SIR-C/ X-SAR. PhD Thesis, Univ. Innsbruck, p. 184.

Nagler T.,1996: Methods and Analysis of Synthetic Aperture Radar Data from ERS-1 and X-SAR for Snow and Glacier Applications, PhD Thesis, Univ. Innsbruck, p. 183.

Nagler T. and H. Rott,1997: The application of ERS-1 SAR for snowmelt runoff modelling. Proc. IAHS Symposium S3, Rabat, IAHS. Publ. no. 242.

Nagler T. and H. Rott,1998: SAR Tools for snow melt modelling in the project HydAlp, Proc. of IGARSS'98, Seattle 6-10 Jul 98, pp 1521-1523.

Rango A., 1995: The Snowmelt Runoff Model. in Ed: V. P. Singh: Computer Models of Watershed Hydrology, Water Resources Publications, p 1130.

Rott H. and G. Markl, 1989: Improved Snow and Glacier Monitoring by the Landsat Thematic Mapper. Proc. of Workshop on "Earthnet Pilot Project on Landsat Thematic Mapper Appications", ESA SP1102. pp.3-12.

Rott H. and B. Davis, 1993: Multifrequency and polarimetric SAR observations on alpine glaciers. Annals of Glaciology, 17, pp.98-104.

Rott H., 1994: "Thematic studies in Alpine areas by means of polarimetric SAR and optical imagery". Adv. Space Res. 14(3), 217-226.

Rott H. and T. Nagler, 1994: Capabilities of ERS-1 SAR for Snow and Glacier Monitoring in Alpine Areas, Proc. 2nd ERS-1 Symp. ESA SP-361, pp. 965-970.

Rott, T. Nagler, and D.M. Floricioiu: Snow and Glacier Parameters derived from Single Channel and Multiparameter SAR. Proc. of Int. Symp. on Retrieval of Bio- and Geophysical Parameters from SAR Data for Land Applications. CNES, Toulouse, Oct. 1995, pp. 479-488.

Rott H., N. Batlogg, and T. Nagler, 1998: Modellierung des Abflusses aus hochalpinen Einzugsgebieten unter Verwendung von Satellitendaten. Österr. Zeitschrift Vermess. und Geoinform., in press.