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A satellite-based information system for glacier monitoring and modeling

H. Rott[1,2], T. Nagler[1], P. Malcher[1] & F. Müller[1]
[1]ENVEO, Environmental Earth Observation IT GmbH, Innsbruck, Austria
[2]Institut für Meteorologie und Geophysik, Universität Innsbruck, Austria,
Helmut.Rott@uibk.ac.at

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ABSTRACT: Earth observation satellites provide an excellent data base for compiling and updating glacier inventories and for retrieving input data for models of glacier mass balance and ice dynamics. We developed a glacier information system that uses optical and imaging radar (SAR) data for glacier monitoring and research. The capabilities for retrieving satellite products for glacier observations are summarized, including glacier area, topography, surface velocity, snow and ice facies, and albedo. Examples are presented on use of satellite products for modeling glacier mass balance and runoff, and for mapping ice velocities on glaciers in the Austrian Alps and in Norway. The software system facilitates the utilization of satellite data for retrieving up-to-date glacier-information.

1 INTRODUCTION

Glaciers are sensitive indicators of climate change and an important component of the hydrological cycle. A driver for glacier studies in many mountain regions is the concern about decreasing water supplies due to accelerating glacier retreat. Another incentive for glacier observations is climate research, aimed at understanding feedbacks between climate parameters and the cryosphere, at reconstructing past climate conditions and at studying future climate scenarios.

Because of accelerating retreat of glaciers world wide, conventional methods are too costly for providing comprehensive up-to-date information on glacier extent and characteristics. Earth observation (EO) satellites are able to fill this information gap, being used for compiling and updating glacier inventories and for retrieving data for process models. To this end we developed a glacier information system that uses optical and imaging radar data for glacier monitoring and research. The system is based largely on in-house software developments. It consists of modules for retrieving digital maps of key glacier parameters and includes process models for simulating and forecasting glacier mass balance and runoff. In this paper an overview on the glacier observation system is presented and a few application examples are shown. The information system has been used for glacier studies in the Alps, Norway, Svalbard, Iceland, Patagonia, and the Antarctic Peninsula.

2 OVERVIEW ON RETRIEVAL OF GLACIER PARAMETERS FROM SATELLITE DATA

Figure 1 summarizes the main features of the glacier information system of ENVEO. Optical imagery and synthetic aperture radar (SAR) satellite data are used as input. Multispectral high resolution optical images, acquired e.g. by Landsat Thematic Mapper, SPOT HRV, and ASTER, are the preferred data source for mapping glacier areas. SAR is also useful for updating glacier boundaries, in particular on glacier where rapid changes occur, such as calving or surging glaciers. Optical satellite imagery is the main source for the GLIMS (*Global Land Ice Measurements from Space*) project that is designed to map and monitor the glaciers of the world with standardized methods (Raup *et al.* 2007). We contribute to GLIMS by glacier monitoring in the Austrian Alps.

Surface topography is a key glacier parameter, but up-to-date topographic maps from airborne sensors are available only for a very small percentage of the global glacier area. Therefore satellite data are important. For latitudes of 60°N to 56°S topographic data are available from the Shuttle Radar Topography Mission (SRTM) C-band SAR, acquired in the year 2000. The absolute and relative vertical accuracies (90% linear error) are ±16 m and ±6 m, respectively, at a 90 m grid (Rodriguez *et al.* 2005). Differential repeat pass SAR interferometry (D-InSAR) is also a useful source for digital elevation models (DEMs) (Joughin *et al.* 1996). However, the rapid decorrelation over snow and ice limits the application mainly to short repeat pass data.

Along-track optical stereo, as provided by ASTER and SPOT-5, is also a good basis for topographic data. The ASTER DEMs reveal similar accuracy as the SRTM product in

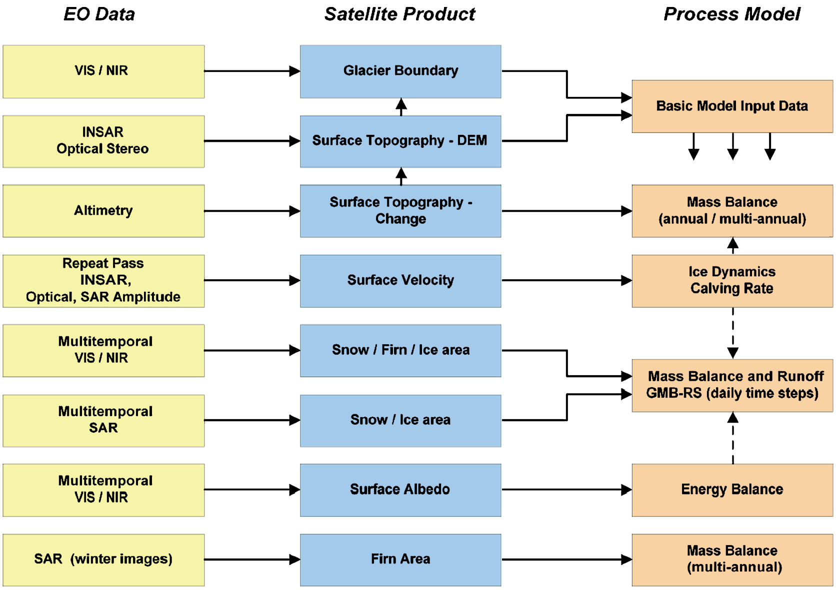

Figure 1. Overview on main features of ENVEO's glacier information system.

areas of sufficient contrast (Kääb 2005), but the accuracy deteriorates over snow fields. Satellite based altimetry, revealing very high elevation accuracy, has the drawback of measuring only along the sub-satellite track, with footprints of 70 m for laser altimeter (ICESat) and a few kilometers for radar altimeters. Regarding imaging instruments, high accuracy can be expected with the new PRISM (Panchromatic Remote-sensing Instrument for Stereo Mapping) on ALOS and the upcoming TanDEM-X mission of DLR with two satellites for single pass interferometry (Moreira *et al.* 2004).

For ice velocity mapping D-InSAR is very accurate but suffers from rapid decorrelation. Therefore most D-InSAR applications over temperate glaciers are based on ERS-Tandem data (one day repeat), available during 1995–2000, or on 3-day repeat pass data of the ERS-1 Ice Phase in winter 1992 and 1994. A limited repeat pass SAR data set over glaciers was also acquired by the Shuttle Radar Mission (SIR-C/X-SAR) in 1994, e.g over the Patagonia Icefields (Rott *et al.*, 1998). Ice velocities can also be mapped by image correlation of repeat pass SAR amplitude images (e.g. Rott *et al.* 2007a,b) and of optical images (Kääb 2005), but only in zones of distinct surfaces features.

Temporal changes of snow and ice areas are useful input for glacier mass balance modeling. In case of optical images, the discrimination is based on albedo differences (Rott and Markl, 1989), and for C- and X-band SAR data on temporal change of backscattering (Nagler 1996, Nagler & Rott 2000). For separating ice and melting snow in summer, the backscattering ratio of summer to winter images is applied. In winter images the accumulation areas can be detected due to high reflectivity of the refrozen firn, but the boundary between firn and ice areas is an average over a few years because the SAR signal integrates over several meters (Nagler 1996, Floricioiu & Rott 2001). A useful parameter for energy balance studies and for estimating ablation in mass balance models is the surface albedo. Our software tool for retrieving albedo maps from optical satellite imagery applies the radiative transfer model 6S for atmospheric correction (Vermote *et al.* 1997).

Because satellites provide spatially detailed information, the data are very useful for input to distributed or semi-distributed process models. In the next section examples for modeling glacier mass balance and runoff are shown. Another important application of satellite products are InSAR velocity maps used in ice dynamic models, providing new insights into rheological and hydraulic properties of glaciers (e.g. Magnússon *et al.* 2007).

3 APPLICATION OF SATELLITE DATA FOR MASS BALANCE MODELLING

We apply a semi-distributed concept for computing glacier mass balance with the model GMB-RS. Time series of meteorological data are used to calculate snow accumulation and melt of snow and ice for sub-units of a glacier (e.g. elevation zones). EO satellite data provide information on temporal retreat of the snowline during the ablation period. These data can be used to iteratively improve the estimate of accumulation and ablation obtained at first from meteorological data only. The model output includes daily ablation, accumulation, and runoff for each glacier zone.

EO data are used for model set-up and for model runs calculating surface mass balance in daily intervals (Figure 2). The set-up includes the definition of glacier boundaries, delineation of glacier zones, and retrieval of ice velocities. The latter is important for calving glaciers, to determine the calving flux from frontal velocity and ice thickness (Rott *et al*. 1998). For calculating snow and ice melt with GMB-RS, a temperature index is used, parameterising the energy available for melt (Hock 2003). With this approach the amount of snow or ice melted during a time period is set equal to the sum of positive air temperatures over this period, times a factor of proportionality, the degree-day factor, DDF. The factor is different for snow and ice, and varies with the saturation of the snowpack and the surface albedo.

The meteorological input data to the model may come from individual stations, re-analysis, or numerical meteorological forecast models (Nagler *et al.* 2007). For temperature and precipitation we developed a meteorological pre-processor that provides fully distributed fields in daily time steps. For input into GMB-RS the data are merged to match the glacier zones. Information on ice and snow extent on the glacier is required for the model in daily time steps. SAR and optical satellite images are usually obtained at longer time intervals. Therefore we developed a data assimilation scheme to estimate the daily retreat of the snow line or the accumulation of fresh snow, based on daily values of meteorological data (Nagler *et al.* 2007).

A main error source for mass balance modelling is snow accumulation, extrapolated from precipitation measurements at meteorological stations, often far away from a glacier and at low elevation, or from numerical models. In order to improve the estimate of the

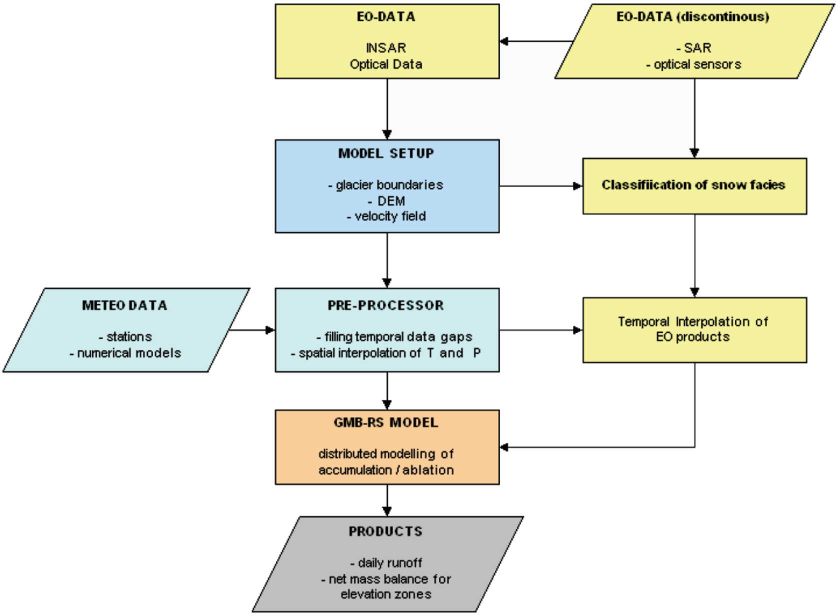

Figure 2. Work flow for glacier mass balance modeling using EO satellite data with GMB-RS.

snow accumulation in each elevation zone, we developed a procedure to iteratively adjust the modelled snowline to the snowline in satellite images by iteratively adjusting the accumulation.

3.1 *Example for modeling glacier mass balance and runoff in the Austrian Alps*

GMB-RS has been used for modeling mass balance and runoff for glaciers in the Zillertal and Ötztal mountain ranges of Austria. In Figures 3 and 4 we show examples for modeled mass balance and runoff for the glacier Vernagtferner, Ötztal, for the balance year 1998/99.

In 1999 the glacier covered an area of 8.86 km^2 and extended from 2600 m to 3600 m in altitude. Data of the climate station Vent (1890 m a.s.l.) were used as input for the model. The accumulation was adjusted according to the retreat of the snowline observed in several satellite images (Landsat TM and ERS SAR) during summer. For 1998/99 the model slightly overestimates the mass deficit; the difference is within the expected accuracy of the model.The runoff data cannot be directly compared, because the runoff gauge collects water from an area that was 30% (2.6 km^2) larger than the glacier in 1999 (Escher-Vetter 2005). The comparison between the measured and modeled values shows the same trend and variability. The model reproduces the beginning of the snowmelt in late May and during the main ablation period well. The highest peaks of measured runoff in summer are caused by intensive glacier melt combined with convective rainfall.

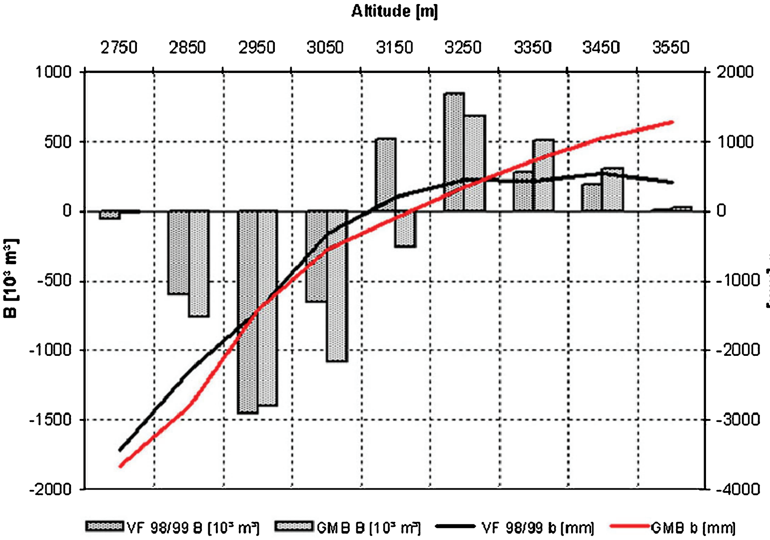

Figure 3. Mass balance of Vernagtferner, Austria, 1998/99. Modeled (red), field measurements (black).

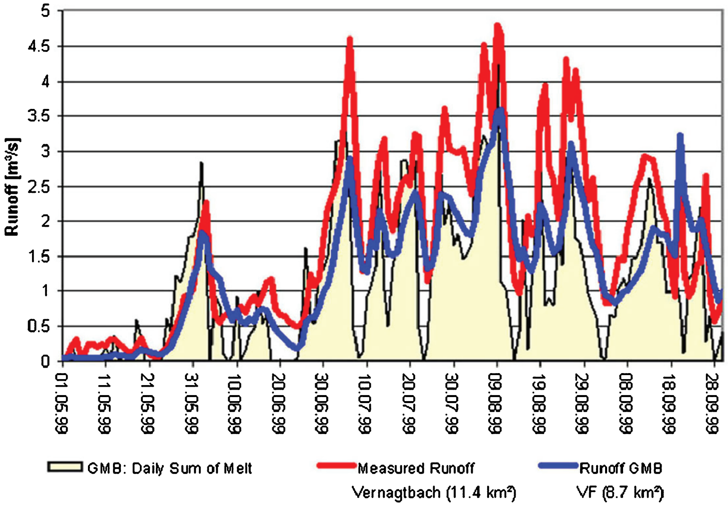

Figure 4. Daily runoff, 1 May to 30 September 1999, measured at the gauging station Vernagtbach (drainage area 11.4 km^2), red line, compared to simulated runoff for Vernagtferner (8.8 km^2), blue line.

3.2 *Example for glacier mass balance modeling and glacier flow on Svartisen*

The mass balance model GMB-RS was successfully tested also in northern regions. Here we show an example from Svartisen, Norway (66.6° N, 14.0° E) where mass balance and ice dynamic modelling was carried out within the EC FP6 project INTEGRAL. D-InSAR with one-day repeat pass SAR data was applied to retrieve the surface velocity. Figure 5 shows the magnitude and the velocity vectors superimposed to a SAR image in 3D view. For estimating the three components of the velocity vector ascending (18–19 March 1996) and descending (1–2 April 1996) InSAR pairs were combined and surface parallel motion was assumed. On the central plateau the ice velocities are very small, and the ice flow accelerates significantly on the steep outlet glaciers.

Figure 6 shows an example for mass balance modeling on the glacier Storglombreen which covers an area of 62 km^2 and extends over altitudes from 520 m to 1580 m a.s.l. The glacier drains into the lake Storglomvatn (Figure 5). Between 1000 m and 1300 m the surface inclination is small. This zone covers about 80 % of the glacier area and is crucial for the mass balance. Accumulation on the glacier is estimated from precipitation data at the station Glomfjord, about 15 km to the north, on the coast. In this example the accumulation was iteratively improved by matching the modeled snow line with the snowline mapped in 22 MODIS satellite images from May to September 2002. Compared to the first guess, precipitation is increased by 10 % in the main part of the accumulation area, so that the observed and modelled mass balances fit quite well.

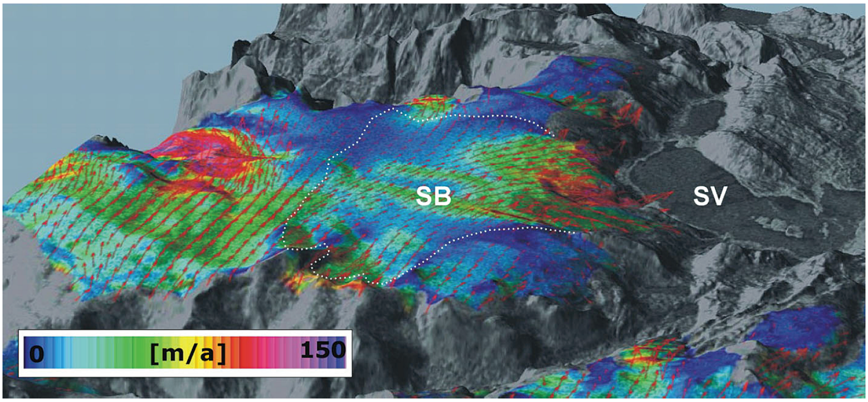

Figure 5. Surface velocity (color coded) on Western Svartisen Ice Cap, Norway, derived from ERS-1/ERS-2 Tandem SAR data (SB-Storglombreen, SV-Storglomvatn).

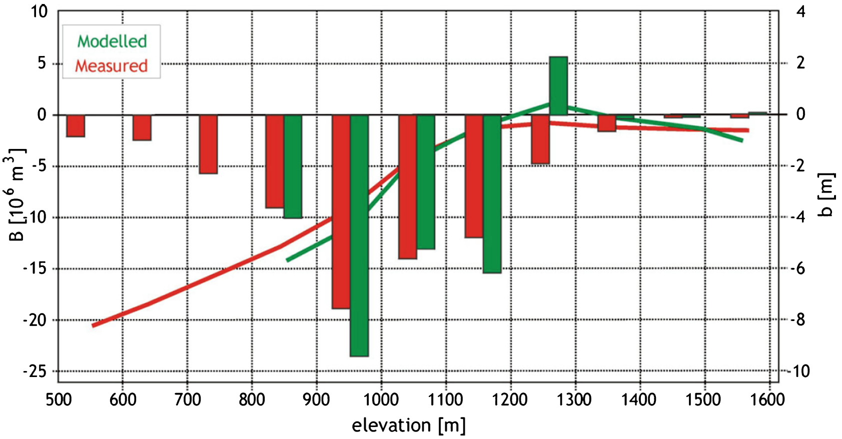

Figure 6. Modeled (green) specific [m w.e.] and absolute [10^6 m^3 w.e.] net mass balance for 100 m elevation zones of Storglombreen (Svartisen) 2001/02, compared with mass balance from field observations (red).

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