MODELLING MASS BALANCE OF GLACIERS USING SATELLITE DATA

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ABSTRACT

A spatially detailed glacier mass balance model was developed that calculates daily accumulation and ablation in dependence of surface elevation. Meteorological input is obtained from stations or numerical analysis. Satellite data are used for model setup and continuous model runs. Glacier boundaries are mapped from optical and SAR images, and topography can be obtained from SAR interferometry. During diagnostic runs the temporal dynamics of the snow and ice zones, derived from satellite image time series, enables updating the mass fluxes at the glacier surface. For this task we use Envisat ASAR and on large glacier also MODIS images. Examples of mass balance modelling are shown for glaciers in Scandinavia, the Alps and Patagonia, revealing significant differences in mass balance properties.

1. INTRODUCTION

A key parameter for climate research and glacier hydrology is the glacier mass balance which is governed by synoptic scale meteorological processes. Variations in glacier extent represent the delayed, time-filtered response to mass balance changes. There is significant interest in mass balance studies of glaciers, on one hand for climate research, on the other hand for hydrology and water management. The headwaters of many rivers in Asia, the Americas, and Europe come from glacier covered mountain regions, being important water resources in particular during the dry season. In many regions the retreat of glaciers causes significant concern on the future abundance of this resource.

Glacier mass balance has been determined traditionally by the glaciological method, using labour-intensive point measurements of ablation and accumulation distributed over a glacier. Long time series of mass balance measurements are available only on few glaciers world-wide. Because the mass balance of glaciers may vary significantly not only from region to region, but also within a region from one glacier to another, there is significant need for additional mass balance data. A range of models with different degrees of complexity is available that calculate the surface mass balance of glaciers from meteorological or climate data [3]. Temperature index models represent a good compromise in terms of complexity [4]. However, a key problem of such models is the calibration of model parameters relating meteorological data to accumulation and ablation on the glacier. In order to mitigate this problem, we developed a model concept that combines the temperature index approach with satellite observations to improve the definition of model parameters. The original version of our model uses the end-of-summer snow line as tuning factor to adjust accumulation. The model was extended within the EC project INTEGRAL, adding a module that uses time series of satellite data to iteratively adjust the accumulation in dependence of elevation.

The model has been applied for mass balance studies in various climate regions. In this paper we report on applications in Scandinavia, the Alps, and the Southern Patagonia Icefield.

2. THE MASS BALANCE MODEL GMB-RS

A semi-distributed concept is applied by the glacier mass balance model GMB-RS, based on software developments and experience in snowmelt runoff modelling and forecasting at ENVEO for Alpine basins [9] [10]. Continuous time series of meteorological data are used to calculate snow accumulation and melting of snow and ice in time steps of one day for sub-units of a glacier. As sub-units we use discrete elevation zones, usually in steps of 100 m. Earth Observation (EO) data are obtained discontinuously and provide information on temporal retreat of the snowline on a glacier during the ablation period. These data are used to iteratively improve the estimate of accumulation and ablation obtained at first from meteorological input data only. Model output includes ablation, accumulation, and runoff on a daily basis for each glacier elevation zone.

Fig. 1 illustrates the basic concept of GMB-RS. EO satellite data are used for model set-up, as well as for the continuous model runs calculating surface mass balance in daily steps. Glacier boundaries are mapped in high resolution optical satellite images. Glacier surface topography can be retrieved by means of SAR interferometry, or obtained from other sources. The Shuttle Radar Topography Mission (SRTM) is a very useful basis for digital elevation data at latitudes between 60 degrees north and 56 degrees south. We use SRTM data for glacier model set-up on the Patagonia Icefield, where no other reliable topographic data are available.

Another useful data base for glacier topography is interferometry of the ERS-1/ERS-2 tandem mission. For estimating mass balance of calving glaciers, data on ice velocity at the front and ice thickness are needed to calculate the ice export due to calving. Also for this task interferometric SAR data are very useful [11].

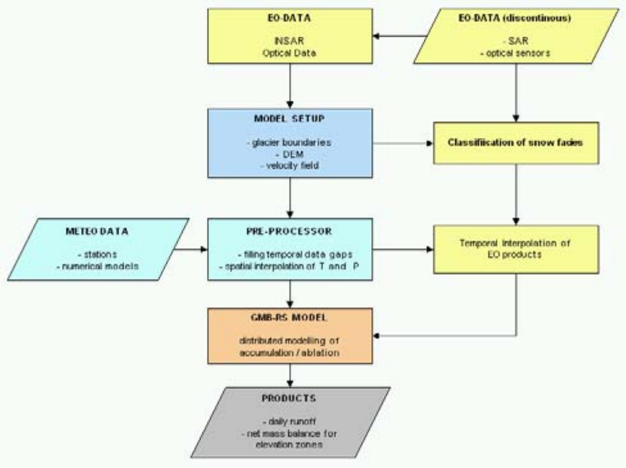

Figure 1. Basic concept of GMB-RS, based on meteorological data and EO satellite data.

For calculating snow and ice melt with GMB-RS, a temperature index is used which is a simple parameter for the energy available for melt. The amount of snow or ice melted during a time period is set equal to the sum of positive air temperatures T^+ (°C) over this period, times a factor of proportionality, the positive degree-day factor, DDF. The factor is different for snow and ice, and varies also with the saturation of the snowpack and with the surface albedo. DDF can be calibrated accurately by means of ablation measurements in the field. However, as the use of mass balance models is primarily aimed at glaciers without field observations, DDF has to be estimated from observations on other glaciers in the region or from published data [4].

The model calculates the net balance B_n [m^3] in dependence of elevation of the glacier surface. For elevation zone *i* the net balance during time step *t* is

$$B_{n,i}(t) = C_{sn,i} DDF_{sn,i}(t) T_i^+(t) A_{sn,i}(t) + \\ + C_{ice,i} DDF_{ice,i}(t) T_i^+(t) A_{ice,i}(t) + f_p(T) C_{p,i} P_i(t) \qquad (1)$$

The index *sn* refers to the snow surfaces in the elevation zone, and *ice* to the ice surfaces. T^+ is the daily mean air temperature above a threshold close to 0 °C (degree days) at the hypsometric mean height of the zone. A is the area of snow or ice, respectively, and C_{sn} and C_{ice} are correction factors accounting for losses (e.g. evaporation). On glaciers these factors are close to 1. *P* is the precipitation, and the factor f_p decides if P falls as rain or snow. For calculating snowfall we use a transition with varying percentage of solid and liquid precipitation for mean daily temperatures between –1°C and +2°C. The coefficient C_p accounts for the percentage of precipitation that is stored in the snow or firn.

3. SATELLITE DATA INPUT FOR MASS BALANCE MODELLING

Whereas EO satellite data for model set-up are needed at annual or multi-year time intervals, information on ice and snow area extent on the glacier is required for the model in daily time steps. Usually SAR and optical satellite images, which can be used for mapping snow and ice areas, are obtained at irregular time intervals. Therefore a data assimilation scheme is applied to estimate the retreat of the snow line or the accumulation of fresh snow, based on daily values of temperature and precipitation. An interpolation scheme, accounting for spatial and altitude gradients, is applied to extrapolate the meteorological data from the stations to the glacier surface and calculate initial snow accumulation and depletion in daily time steps [10].

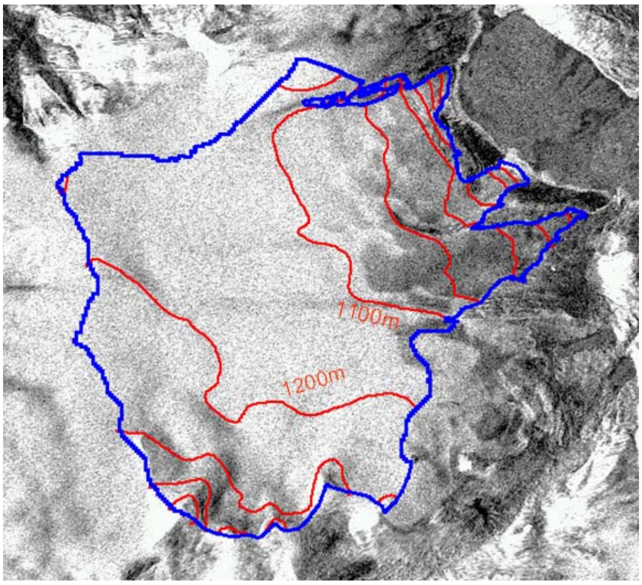

Figure 2. Section of geocoded ERS SAR image (28 & 29 March 1996). Blue - boundary of Storglombreen, Svartisen, Norway. Red – 100 m elevation contour lines.

In the following the processing of satellite data and application in GMB-RS is explained with the example of Storglombreen, a glacier of the Western Svartisen ice cap in Norway (66.6° N, 14.0° E). Storglombreen covers an area of 62 km^2, extends over altitudes from 520 m to 1580 m a.s.l., and drains into the lake Storglomvatn [5]. As evident in the geocoded ERS SAR image (Fig. 2), the elevations between 1000 m and 1300 m include the main parts (80 %) of the glacier area. The bright areas on the glacier surface in this winter SAR image correspond to the accumulation area where frozen firn is an efficient volume scattering medium [7]. Glacier ice surfaces, covered by fine grained winter snow, show lower backscattering coefficients. The boundary between strongly reflecting frozen firn and ice surfaces in winter SAR images represents the average equilibrium line over several years, which is useful for a first estimate of glacier mass balance [7], [6].

For obtaining good time series of snow line retreat on the glaciers during the melting period, we optionally use both SAR and optical satellite images. The classification of snow and ice areas on glaciers with C-and X-band SAR data is based on multi temporal backscatter ratios [7], [8]. Melting snow areas are detected due to low backscatter relative to the winter images. Over glacier ice the seasonal changes of backscatter are much smaller.

For glaciers of the size of Storglombreen medium resolution optical imaging sensors, such as MODIS or MERIS, are very useful for monitoring snow line retreat, because of the frequent repeat coverage. We used data of the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra satellite because it has a channel in the short-wave infrared (SWIR). For classification of snow versus ice and firn (snow from previous years) we use the Normalized Difference Snow Index (NDSI) [2], based on differences in reflectivity between visible and SWIR. In addition, an albedo threshold in the near infrared band is used.

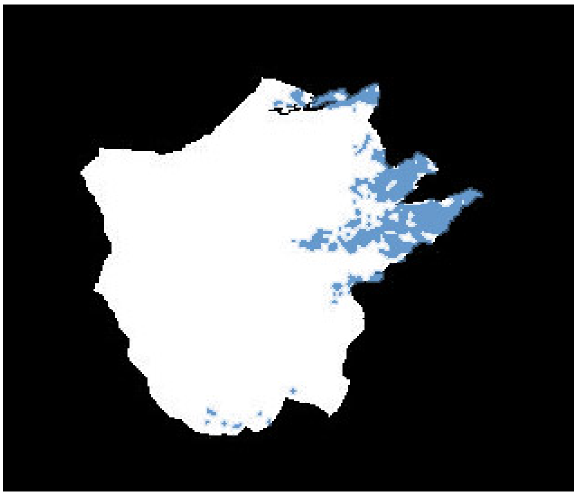

Figure 3. Map of snow(white) and ice (blue) areas on Storglombreen, from ASAR WS image of 12 June 2006.

Figures 3 and 4 show maps of snow and ice areas on Storglombreen derived from MODIS and ASAR Wide Swath (WS) images. The images are from the ablation season, when ice was exposed on the lower glacier termini. The ASAR images show usually slightly less snow extent. In this example it may be partly attributed to the later date in the ablation period: However, SAR images show a general trend for underestimating snow extent compared to optical images, in particular in areas of patchy snow cover [7], [8].

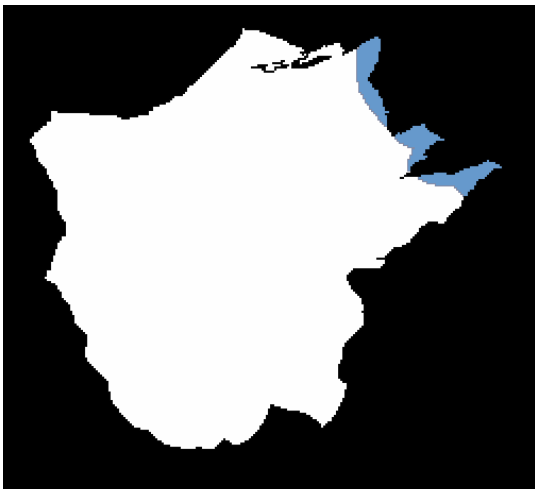

Figure 4. Map of snow(white) and ice (blue) areas on Storglombreen, from MODIS image of 6 June 2006.

As input for the mass balance model the daily percentage of snow and ice area in each elevation zone of the glacier is needed, because snow and ice have different DDFs. On the other hand, we use the snow depletion curves also to iteratively improve the snow accumulation in dependence of elevation on the glacier. Fig. 5 shows snow depletion curves for 5 elevation zones on Storglombreen in summer 2002. 22 satellite images were available between May and end of September. This was a year with rather negative mass balance. The snow line shifted across the glacier plateau during summer.

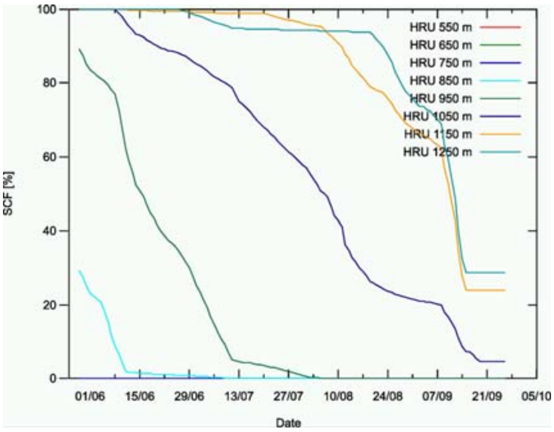

Figure 5. Snow depletion curves for 5 elevation zones of Storglombreen in summer 2002.

Snow accumulation on the glacier, extrapolated from precipitation measurements at meteorological stations, often far way from the glacier and at low elevation, is a main error source for mass balance modelling. Therefore we developed a procedure using time series of snow and ice area extent from satellite data to iteratively adjust the snow accumulation in each elevation zone. Because the snow depth is not uniformly distributed, it is necessary to define a relation between snow cover fraction (SCF) and snow mass (mean snow water equivalent, SWE) in each elevation zone. Within the iterative GMB-RS procedure the precipitation factor for each elevation zone is optimized by minimizing the absolute error between the SWE determined at first by spatial extrapolation from the station and the mean SWE based on EO derived SCF. An example for improving mass balance calculation with this method is shown below.

4. MASS BALANCE MODELLING FOR STORGLOMBREEN

As example for iterative improvement of the modelled mass balance we show results for the year 1 October 2001 to 30 September 2002. In Fig. 6 the results for direct forward modelling are shown, where precipitation on the glacier is extrapolated from the station Glomfjord (15 km north of the glacier, 39 m a.s.l.) using pre-scribed precipitation gradients. The modelled mass balance gradient shows reasonable agreement with the field observations. Major differences in absolute mass are evident between 1000 m and 1200 m where the accumulation is underestimated. Above 1200 m the mass balance is overestimated, because snow drift due to wind is taken into account. However, for the total glacier mass balance these zones are less relevant because they cover a small area.

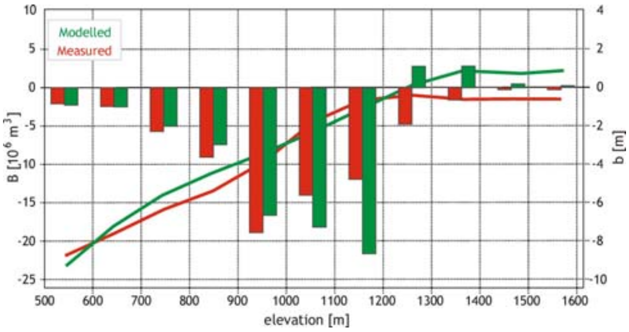

Figure 6. Modelled specific [m w.e.] and absolute [10^6 m^3 w.e.] net mass balance for 100 m elevation zones of Storglombreen 2001/02, compared with mass balance from field observations .

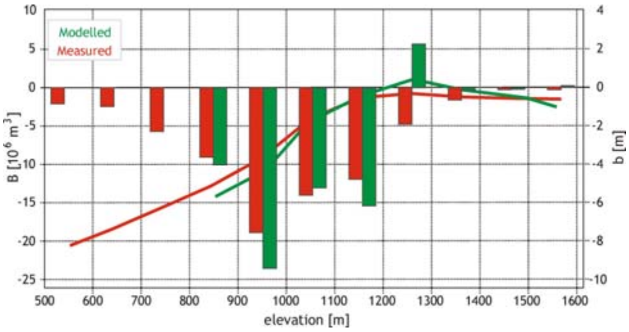

Figure 7. As Fig. 6, with iterative retrieval of accumulation, based on satellite data time series.

Fig. 7 shows the modelling results for the iterative approach, using satellite images to adjust accumulation. A linear relation between mean SWE and SCF was assumed for each elevation zone, with 400 mm SWE when ice started to melt out. Compared to the previous estimate, precipitation was increased by 10 % between 1000 m and 1200 m, so that the mass balance fits quite well. Also in the top zones the modelled mass balance agrees better with the observations. Below 800 m the iterative procedure could not be applied, because the first image became available only after ice melt had started.

5. MASS BALANCE MODELLING IN THE AUSTRIAN ALPS

GMB-RS has at first been developed and tested for glaciers in the Alps. Here we show an example for the glacier Hintereisferner (Ötztal Alps, Austria) where field measurements for model validation are available. In 1999 the glacier covered an area of 8.22 km^2 and extended from 2450 m to 3700 m in altitude. Data of the climate station Vent (1900 m a.s.l.) were extrapolated to the glacier. The mass balance of the glacier has been negative since the late 1980s. The example shown is from the balance year 1 October 1998 to 30 September 1999.

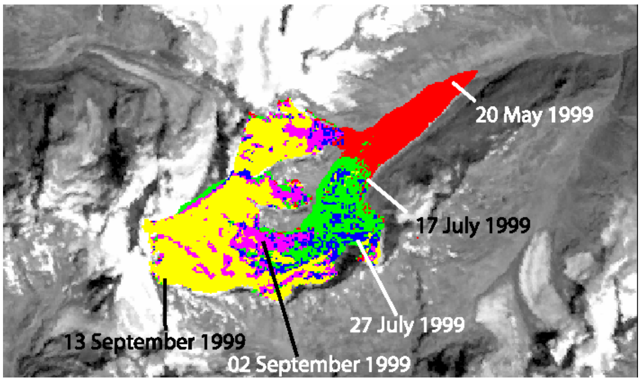

Figure 8. Retreat of snow area on Hintereisferner during the ablation period 1999, from satellite data. ERS SAR: 20 May (fully snow covered), 29 July, 2 September. SPOT: 17 July, Landsat 7 ETM+: 13 September.

Fig. 8 shows the retreat of the snow area on the glacier, mapped in ERS SAR and optical imagery. In the SAR image of 20 May 1999 the glacier was still completely snow covered. In the next image (SPOT), from 17 July 1999, the snow line was at 2800 m elevation. As for Storglombreen, the SAR snow area is more patchy than the snow area retrieved from optical data.

The modelled and measured mass balances agree quite well (Fig. 9). The modelled specific net balance is –839 mm w.e./a and the observed balance –861 mm w.e./a. Major deviations are evident in the top elevation zones which cover only a small area. In these zones with steep surface slopes the accumulation is overestimated by the model. The mass balance gradient, about 1 m w.e. per 100 m elevation, is about the same as on Storglombreen.

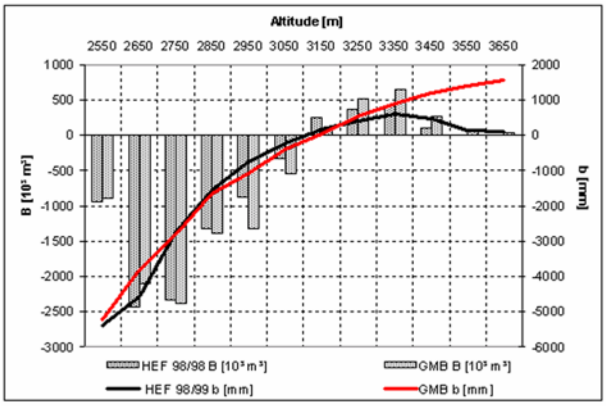

Figure 9. Mass balance of Hintereisferner, Austria, for 1998/99. Modelled (black), field measurements (red). Left: net balance per elevation zone (10^3 m^3 w.e.). Right specific net balance (mm w.e.)

6. MASS BALANCE MODELLING ON GLACIERS OF THE PATAGONIA ICEFIELD

The Southern Patagonia Icefield is the largest contiguous mid-latitude ice mass, covering about 13000 km^2 in area and extending for 350 km from 48.3° S to 51.5° S. It comprises several icefields and ice caps, at elevations between 1500 m and 2500 m that nourish large outlet glaciers. The western outlet glaciers calve into Pacific fjords and the eastern glaciers into the large Patagonian lakes. Because Patagonia is the main landmass in this southern latitude zone and is close to Antarctica, the icefield is of great interest for studies of climate change.

Here we presents results of mass balance modeling for two adjoining eastern outlet glaciers, Moreno glacier (MG) and Ameghino glacier (AG). MG covers 254 km^2 in area and flows over a length of about 30 km from the continental divide, with Cerro Pietrobelli (2950 m a.s.l.), down to Lago Argentino at 185 m. Glaciological field measurements were carried out on the glacier from 1995 to 2003 [11] [13] [14]. Whereas ice ablation was measured directly by means of ablation stakes, total net accumulation was determined from the mass transport through a transverse profile. The calving flux was determined using satellite-derived surface velocities and lake depth in front of the glacier. Moreno glacier is close to steady state, as the damming events in 2003/04 and 2005/06 have shown when after minor frontal advance the glacier dammed the southern arm of Lago Argentino for several months [12] [14].

Ameghino glacier, on the other hand, shows significant retreat since about 40 years [13] It calves into a pro-glacial lake that started to form in the late 1960s. On AG only few ablation stake measurements are available over a one year period, so that the mass balance estimate has to rely on model calculations. We carried out these calculations for Ameghino main glacier, covering an area of 53 km^2, as outlined in Fig. 10.

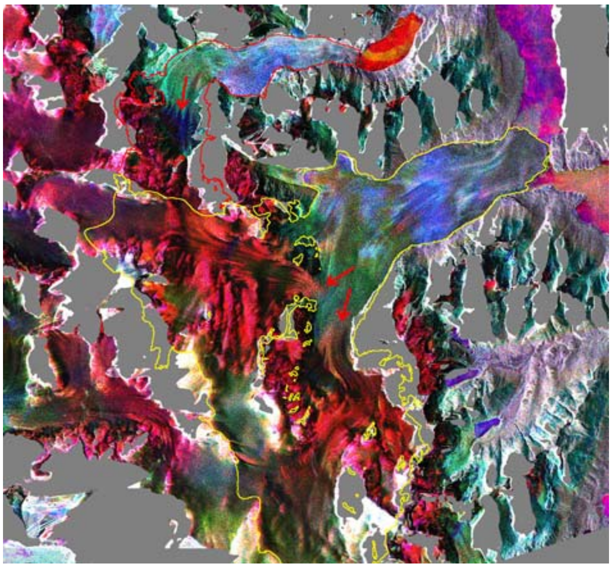

Figure 10. Section of geocoded ERS-2 SAR image, *ascending orbit, illumination from left. Blue – 12 October 1995. Green – 2 Feb. 1996. Red – 8 March 1996. Grey – mask of layover and foreshortening. Red line – boundary of Ameghino glacier. Yellow line – boundary of Moreno glacier. The red arrows point to snowline on 2 Feb 1996.*

For model set-up we used optical satellite imagery to map the glacier boundaries [1] and Envisat ASAR to update the frontal positions. DEM data are obtained from SRTM. Temperature data for input to the mass balance model are available from a meteorological station near the Moreno front for an 8 year field observation period. Precipitation was measured at a station of the National Park service for a shorter period. The extrapolation of precipitation to the upper glacier reaches is problematic due to strong gradients and orographic effects. The DDF values were calibrated with the field measurements of ablation. The modelled accumulation on MG was matched to conform with the net accumulation from field observations. On AG it was tuned to match the mean observed end of summer snowline of several years, determined in satellite imagery. An example is shown in Fig. 10.

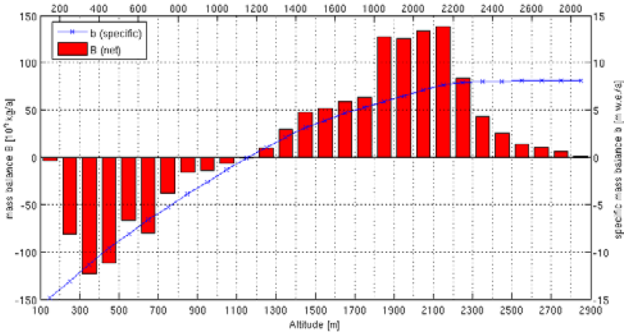

Figure 11. Modelled specific [m w.e.] and absolute [10^9 kg/100 m elev.) annual surface mass balance for Moreno glacier.

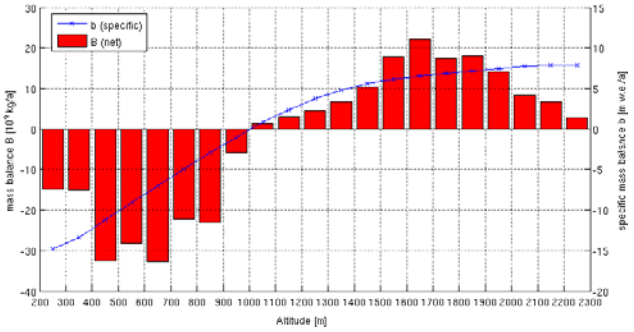

Figure 12. As Fig. 11, for Ameghino main glacier.

Figs. 11 and 12 show the surface mass balance for both glaciers for a typical year of the observation period. The calving fluxes are not included. For MG the calving flux amounts to 37% of net accumulation and 66% of net ablation [14]. On AG the calving front is narrow and the lake is less deep. Therefore the calving flux amounts only to 15% of net accumulation and 11% of net ablation.

The modelled mass balance for MG of + 0.26 m w.e./a agrees with the mean value of the observation period, corresponding approximately to a balanced glacier state within the range of uncertainty. For AG the modelling results reveal a clearly negative mass balance of –1.15 m w.e./a which agrees with the observed retreat. These differences are also reflected in the Accumulation Area Ratio (AAR) estimated from satellite data which is 0.71 for MG and 0.43 for AG. On the other hand, the estimated Equilibrium Line Altitude (ELA) is 1160 m a.s.l at MG and 1005 m a.s.l at AG. For obtaining the lower ELA at AG with the model, higher precipitation rates are needed. The increased precipitation is not able to compensate for the high ablation losses. The differences between both glaciers can be understood by the area altitude distributions, causing AG to be more sensitive to climate change, as evident from the absolute balance numbers in Figs. 11 and 12. On AG the elevation zone between 800 m and 1000 m covers a large percentage of glacier area, whereas on MG the mean elevation is higher and the main parts of the accumulation area are located well above the equilibrium line.

7. CONCLUSION

The synergy of climate data and satellite data is a very useful basis for modelling glacier mass balance. Satellite data of surface topography and ice velocity enable determining boundary conditions for the model. Satellite time series of snow and ice areas on glaciers improve the accumulation estimate which is a main factor of uncertainty if inferred from meteorological station data or models. The model GMB-RS has been applied successfully in different climate zones, as the examples show. It can also be used for simulating effects of climate change on glacier mass balance [1], as well as for modelling and forecasting glacier runoff in daily steps.

ACKNOWLEDGEMENTS

This work was supported in part by EC, FP6 project INTEGRAL (SST3-CT-2003-502845). Svartisen field data were kindly provided by M. Jackson (NVE). The satellite images were made available by ESA for projects ERS AO3.108 (VECTRA) and Envisat AOE-308.

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