Annual mass balance estimates for Haut Glacier d′Arolla from 2000–2006 using a distributed mass balance model and DEM′s

Ruzica Dadic[1], Javier G. Corripio[2,1], Paolo Burlando[1]

[1] *Insitute of Environmental Engineering, ETH Zurich, 8093 Zürich, Switzerland*
E-mail: dadic@ifu.baug.ethz.ch
[2] *Tropical glaciology group, University of Innsbruck, 6020 Innsbruck, Austria*

ABSTRACT. In order to assess the impact of future climate scenarios on water availability in glaciated basins, we are implementing a combined field observation and distributed mass balance modeling approach. Accurate estimation of water stored within the snow and ice cover of these basins requires knowledge of the distributed snow and ice mass balance throughout the year. In this study, we are estimating the annual mass balance and runoff for Haut Glacier d′Arolla from 2000–2006. Haut Glacier d′Arolla is a small, temperate valley glacier in southwestern Switzerland. Our estimations are based on observed elevation changes from three digital elevation models (DEM′s), derived from aerial photographs in September 1999, 2005 and October 2006. An energy balance model, driven by meteorological variables from automatic weather stations (AWS) inside the catchment area, is run for the period 2005–2006. The model results are validated with direct mass balance and runoff measurements. From combined mass balance measurements, energy balance calculations and recorded runoff, we are estimating the contribution from icemelt to the runoff for this period to be around 25%, the contribution from snow around 60% and the contribution from rain 15%. It is therefore important for water resources management to understand the distribution of snow in an alpine catchment, as it seems to be the not only the controlling factor for the shape of the hydrograph, and therefore also for the availability of water throughout the season, but also for the total availability of water.

INTRODUCTION

In the European Alps and in most other areas in the world, the retreat of glaciers is a widely observed fact. It is reflecting the climate change, which is best observable in the temperature rise. The sensitivity of a water resource system to a climate change is a function of several physical features and societal characteristics (IPCC, 2001). A major proportion of annual streamflow is formed by snowmelt in spring. The most important climate change effect in the affected regions is a change in the timing of stremflow through the year (Arnell, 1999). Alpine regions show highly seasonal hydrology as a result of either seasonal precipitation or dependence on snowmelt (IPCC, 2001). Valley glaciers represent storages of water over long timescales. Many rivers are supported by glacier melt, which maintains flow through summer season (IPCC: Impacts and Vulnerability, 2001). The impact on water resources when glaciers retreat is not only due to a smaller storage in the form of ice, but also in the overall decrease in altitude in a catchment area with shrinking glaciers, which means that a smaller proportion of precipitation will fall as snow, not only due to increasing temperatures, but also due to a lower terrain. This has implications for the timing of the streamflow in such regions, with a shift from spring snowmelt to summer runoff (Arnell, 1999).

In this paper, ice volume loss has been estimated using DEM's from different time periods. The estimated ice volume loss plus the estimated precipitation from measurements are in good agreement with runoff measurements. An energy balance model (SnowDEM) was run, with and without including a mass transport and deposition routine (MTD), for the period 2005–2006. Both model runs were overestimating the water availability in the basin throughout the year due to overestimated snow- and icemelt. However, the model run, where SnowDEM was coupled with MTD resulted closer to the measured runoff. That means, that the distribution of snow is not only important for the correct shape of the hydrograph and the water availability throughout the season, but also for the correct estimation of the runoff and the total water availability.

METHODS

The field area

Haut Glacier d'Arolla, a small temperate valley glacier in southwestern Switzerland, has been the subject of ongoing research in glacier mass and energy balance, hydrology, geochemistry and dynamics since the early 1990s (eg. Sharp and others (1993); Arnold and others (1996); Hubbard and others (1998); Brock and others (2000); Willis and others (2002); Strasser and others (2004); Pellicciotti and others (2005); Arnold (2005)). The catchment area is approximately 13 km^2, with a glaciated area of about 5.3 km^2 and an elevation range from 2500 to 3800 m asl (Figure 1). The largest glacier in the area, the north-facing Haut Glacier d'Arolla has an area of 4.4 km^2 and a length of about 4 km. The glacier has been retreating since the second half of the 20th century (Oerlemans and others, 1998). Over the last decade, the altitude of the equilibrium line has been well above 2800 m asl (Oerlemans and others, 1998), leading to a strong negative mass balance with about 2.5 to 3 ma^{-1} water equivalent of surface ablation across the lower tongue and more of 100 m of retreat since 1989 (Hubbard and others, 1998). These numbers have increased in the last six years of our measurements.

Meteorological and glaciological measurements

The meteorological measurements in the catchment area are made at one permanent AWS in the proglacial area at 2500 m asl, approximately 1 km distance from the glacier snout (T1), and one permanent AWS in the non glaciated part of the upper basin at 3000 m asl, approximately 0.5 km from the glacier margin (T2). Both of these stations are outside the glacier boundary layer, but while the lower station (T1) is influenced by katabatic winds and therefore recording colder temperatures than it would in absence of a glacier, the upper station (T2) is recording rather high temperatures, being located at a spot, where air can get trapped and warms up more than in the rest of the catchment area. Both stations measure shortwave incoming and outgoing radiation, longwave incoming and outgoing radiation, air temperature and relative humidity, wind speed and wind direction and precipitation. Snow height is only measured by T2. Another station (AWS glacier) is located on the glacier at about 2800 m asl, and is used for validation of the model. Figure 1 shows the location of the automatic weather station and ablation/accumulation stakes. AWS glacier is similarly equipped as T1 and T2, lacking the precipitation gauge.

Hourly discharge has been recorded for more than thirty years at about 1 km from the present glacier snout (100 m from T1) by the hydroelectric company Grand Dixence using a pressure transducer in an artificial channel of known dimensions. The accuracy is given with 10%.

Direct measurements of snow depth distribution over the glacier were carried out in may 2005 and 2006. These surveys also include measurements of snow density in snowpits. The snow depth distribution is measured with a graduated metal pole. The snow density is measured by snow sampling in a snowpit with a small cylinder, which is weighted using a spring balance. A set of 16 ablation/accumulation stakes is been monitored continuously since may 2005.

Two DEM's used for this study were derived from areal pictures taken in September 1999 and 2005 by the Glacier and Permafrost working group from the Laboratory of Hydraulics, Hydrology and Glaciology at ETH Zürich, using digital photogrammetry. The horizontal resolution of the DEM's is 10 m and 25 m. respectively. The absolute accuracy in the horizontal as well as in vertical direction is 0.6–0.7 m. The elevation changes on the glaciated area in the catchment have been estimated from the difference between these two digital elevation models with an accuracy of about ±1 m. Another DEM was generated in November 2006 using airborne laser scanning with a higher resolution (Vallet, 2002) but has been gridded to a resolution of 10 m to mach the existing DEM's.

Mass Balance Modeling

We use the energy balance model SnowDEM, coupled with a gravitational mass transport of snow and deposition routine (MTD) to model the mass balance. Not included in the present version of the model is mass transport caused by wind distribution. SnowDEM (Snow Distributed Energy balance Model) is a distributed, multilayered snow energy balance model that takes full account of topographic influences and simulates following fluxes:

incoming and outgoing shortwave radiation (direct, diffuse and reflected)

incoming and outgoing longwave radiation (atmospheric thermal radiation and emitted radiation from surrounding slopes)

snow surface and subsurface temperature

latent and sensible turbulent heat interchange with the atmosphere

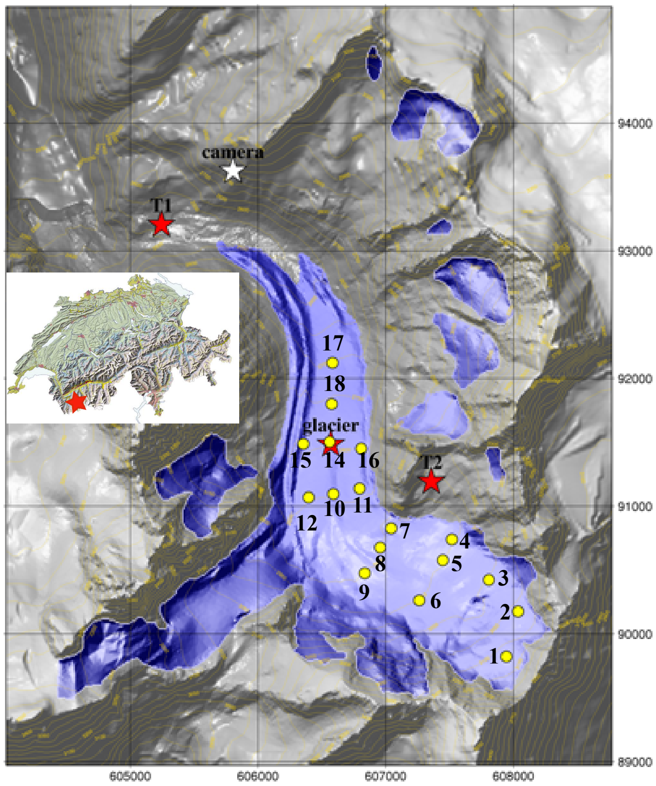

Fig. 1. Digital map of the Haut glacier d'Arolla basin. In blue indicated is the glaciated area (5.3 km^s), red stars show the locations of three automatic weather stations, white is the location of an automatic camera and yellow circles show the locations of accumulation/ablation stakes. The total area of the catchment is 13 km^2 and the elevation range is from 2500–3800 m asl. The inset shows a map of Switzerland with the indication of the Haut Glacier d'Arolla.

The model is slightly modified from that described in Corripio (2002), which can be summarised in the following equation expressing the net energy flux at the surface, Q:

$$IG(1-\alpha) + L\downarrow + L\uparrow + H + L_vE + Q_s + Q_M = Q \qquad (1)$$

where IG is global shortwave radiation, α is albedo $L\downarrow$ is downward flux of longwave radiation, $L\uparrow$ is upward flux of longwave radiation, H and L_vE are sensible and latent heat fluxes, Q_s is internal heat flux within the snow pack, and Q_M is available heat for melting.

Table 1. Different components contributing to runoff. Yearly average for the periods 1999–2005 and 2005-2006.

Period	1999–2005	2005–2006
Water generation (10^6 m^3)	(yearly average)	
Runoff	25	30
Icemelt	6	10
Precipitation	15	16
specific net balance (m)	-1.25	-2.0

Coupled with SnowDEM is a mass-conserving algorithm to parametrize gravitational mass transport and deposition (MTD) using digital elevation models (Gruber, 2007).

The model is run for the period between Sepember 2005 and October 2006, corresponding to the date of the DEM generation, so that it can be compared to ice volume loss, which is estimated using difference in elevation. First model run (MR1), was run without the MTD routine. A second model run (MR2) was coupled with MTD and the routine was run every time step at which precipitation was not zero. The model was run using input data from T1. T1 was chosen over T2, because it better represents the climate of a glaciated catchment. The lapse rates used for the model were estimated from NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/ (datasource: Kalnay and others (1996)).

RESULTS

Contribution from ice volume loss to runoff: 1999–2005

The estimated loss of ice volume, derived from elevation changes in the DEM's, is approximately 40 ±5 million m^3 for the six years between 1999 and 2005 (Figure 2). Maximum ice thickness loss is at the decaying tongue with 35 m. This part of the tongue is downwaisting ice, which is decoupled from the dynamical active part of the glacier. The specific net balance for this period is -7.5 ±1 m (of ice). This results in yearly values of an average yearly loss of ice volume of 6.6 million m^3 and an average yearly specific net balance of -1.25 m (Table 1).

The measured runoff for the same period is 150 million m^3 of water, whereas water generation from ice melt, derived from the volume loss, is 36 million m^3 ±5 million m^3. Thus, the ice melt roughly contributes about 25% to the annual runoff in the catchment area. The other 75% are either from snow melt or from rain. This is consistent with our precipitation measurements, which result in a total measured precipitation in 92 million m^3 of generated water equivalent. The measured precipitation can be underestimated up to 50% because of undercatching in the precipitation gauge during snowfall because of wind. These values result in 25 million m^3 of yearly runoff, 6 million m^3 of yearly water generation due to icemelt and 15 million m^3 yearly water generation due to precipitation (Table 1).

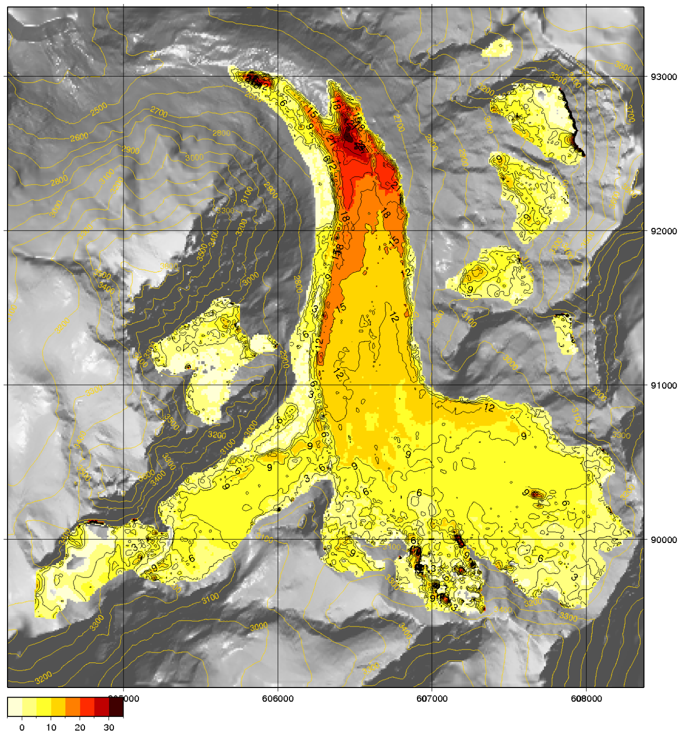

Fig. 2. Difference (m) in elevation (1999–2005) in the glaciated area of the Haut Glacier d'Arolla catchment area in color. The accuracy is about 1 m in. Maximum ice loss is observed at the tongue with 34 m and average ice loss over the glaciated area is 7.5 m. The background is a shaded image of the 1999 DEM.

Ice velocities

In order to be able to fully interpret the spacial variation visible in Figure 2, ice dynamics should be considered. We do not address this topic here, but measurements show that the ice flow is rather slow. Measurements of ice velocities in August 2005 made by Mair, D.W.F. (personal communication) show highest velocities in the upper part of the glacier with a maximum of 11 ma^{-1}. The annual velocities are a bit slower with a maximum of 10 ma^{-1}.

Contribution from ice volume loss to runoff: 2005–2006

The estimated loss of ice volume, derived from elevation changes in DEM's from 2005 and 2006, is approximately 11 million m^3, with very similar ice ablation distribution like in the period from 1999–2005 (Figure 2). The specific net balance is -2 m (of ice).

The measured runoff for the period 2005–2006 is 30 million m^3, the water generation from icemelt about 10 million m^3 and the estimated precipitation 16 million m^3 (Table 1). For comparison: the measured runoff in the remarkably hot year 2003 was also 30 million m^3.

Model results from SnowDEM: 2005–2006

SnowDEM was run for the period between September 2005 and October 2006 using input data from the station T1. In the first model run (MR1), MTD was not coupled to SnowDEM, while the algorithm was included in the second model run (MR2), being executed each timestep where precipitation was not zero. T1 was chosen over T2, because it seems to better represents the climate of a glaciated catchment, which is colder than a non-glaciated catchment would be.

Both model runs overestimate the water contribution in the

Table 2. Model results for MR1 and MR2, showing the different components of the contribution to runoff in the 2005–2006 season.

Model run Water generation (10^6 m^3)	MR1	MR2
Runoff	47	41
Icemelt	16	14
Precipitation	31	27
specific net balance (m)	-3.0	-2.6

basin due to icemelt and precipitation (Table 2). The difference in MR1 and MR2 of the modeled precipitation lies in the distribution of snow, because they have the same amount of rain/snow in the basin. The difference in icemelt is caused by longer lasting snow in regions where avalanches occur, and ice is therefore exposed later. The resulting specific net balance for MR1 and MR2 is -3.0 my^{-1}, -2.6my^{-1} respectively.

The modeled amount of SWE at the end of the winter is underestimated by both models, although MR2 (MTD included) is performing better. Table 3 shows the comparison between measured and modeled (MR2) SWE at day 144, where SWE is underestimated up to 30% of the measured values. Figure 3 shows the ablation/accumulation measurement from the AWS located on the glacier against model results from MR2 at the same location. While ablation is modeled quite good, the model is underestimating snowfall (day 210 and later).

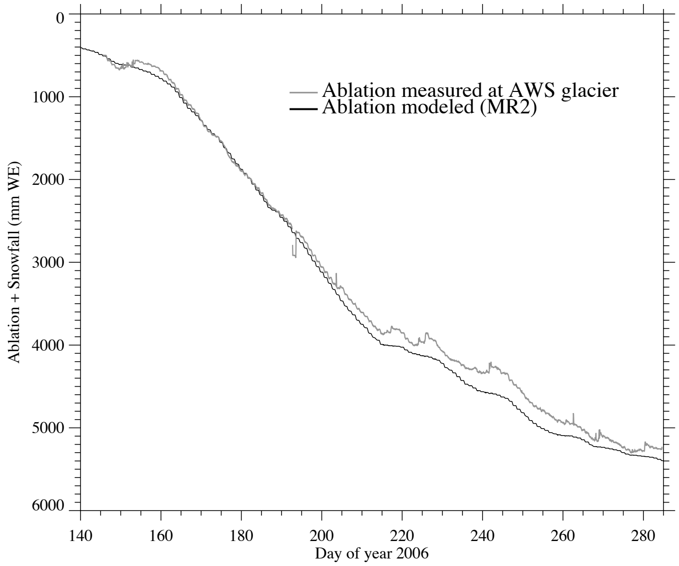

Fig. 3. Measured ablation (grey line) against modeled ablation (black line) from the model run including the gravitational mass transport and deposition routine (MTD). The model is understimating snowfalls, which are good distinguishable in the automatic measurement at the AWS located on the glacier from day 210 on.

Table 3. Model results for MR2 at day 122, compared to measured snow depths at day 144. The model is underestimating the SWE in all but one stake up to 30%. See Figure 1 for the location of the measurements.

Stake number (altitude m asl)	SWE measured (mm)	SWE modeled (mm)	meas - mod (mm SWE)
1 (3135)	>1000	2000	?
2 (3085)	>1000	1200	?
3 (3050)	1000	1200	-200
4 (2956)	850	840	10
5 (2956)	800	610	190
6 (2958)	1000	990	10
7(2902)	850	530	320
8 (2900)	850	480	370
9 (2902)	900	750	150
10 (2838)	750	680	70
11 (2836)	800	500	330
12 (2854)	750	550	200
13 (2758)	300	310	-10
14(2799)	500	380	120
15 (2792)	550	410	140
16 (2774)	650	360	290
18 (2752)	300	300	0

DISCUSSION AND CONCLUSIONS

Ice volume loss has been estimated using DEM's from different time periods. The maximum ice thickness loss during a 6 years period (1999–2005) was 7.5 m at the decaying tongue. The specific net balance over the whole glaciated are is -1.25 my^{-1} between 1999 and 2005, and -2 my^{-1} for the year 2005–2006. The estimated ice volume loss plus the estimated precipitation from measurements are in good agreement with runoff measurements.

A energy balance model including a gravitational mass transport and deposition routine (MTD) was run for the period 2005–2006. MTD was in the first model run (MR1), while it was fully coupled in the second model run (MR2). Both model runs are overestimating the contribution from ice melt to the runoff around 5 million m^3. The contribution of runoff coming from precipitation is also overestimated. The latter could be because caused because our model does not include a snowdrift routine. (Mernild and others, 2006) show that approximately 12% of the precipitation can be returned to the atmosphere by sublimation of drifting snow. However, including the MTD routine in MR2 shows better results than MR1. The avalanching routine brings snow down from the steep walls to the glacier and keeps the glacier longer snow covered. Furthermore, having the snow removed from the steep slopes, the snow covered surface becomes smaller, which leads to less melt. Overall, the MR2 results are closer to the estimated ice volume loss from DEM's, but still overestimating the total amount of water up to 11 million m^3, which is about 30% of the total runoff.

The difference in modeled and measured mass balance (estimated from DEM's) is caused mainly by differences in the winter balance. Figure 3 shows that the ablation at the location of AWS glacier is in good agreement with the measurement, while snowfall (day 210 and later) is underestimated in the model. The underestimated snowfall leads to a lower albedo, which leads to an overestimation of melt. Table 3 shows that the SWE is underestimated in MR2 up to 30%. This causes an early exposure of ice, which can also be a reason, why our model runs are overestimating icemelt. Because ice is exposed too early, the melt season for ice is longer, which enhances icemelt due to the lower albedo of ice. The overall snowfall is rather overestimated, but it is not distributed correctly, as we did not include any redistribution by wind, which would deposit snow in the flat glaciated area.

Our results lead to the conclusion, that the distribution of snow is not only important for the correct shape of the hydrograph and the water availability throughout the season, but also for the correct estimation of precipitation, runoff and the total water availability. It is therefore highly important to include other processes in mass balance models, that are able to correctly distribute snow within a catchment. some of these processes are distribution of snow due to wind, sublimation of drifting snow and the precipitation distribution due to topographical obstacles in steep terrain.

ACKNOWLEDGMENTS

The authors are very grateful to T. Blunschi, H. Bösch, M. Funk, M.G. Haas, P. Jenni, T. Keller, F. Pellicciotti, P. Perona, S. Rimkus, K. Schroff, C. Senn, R. Weber, T. Wyder and many more people who are still supporting us during fieldwork fieldwork. The project is carried out under the Swiss National Science Foundation Grant No. 200021105586.

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