Glacier Mass Balance Changes and Meltwater Discharge (selected papers from sessions at the IAHS Assembly in Foz do Iguaçu, Brazil, 2005). IAHS Publ. 318, 2007.

Deriving glacier mass balance from accumulation area ratio on Storglaciären, Sweden

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Abstract Glacier net mass balance, b_n, tends to correlate well with accumulation area ratio (AAR). A method that substitutes the long term b_n – AAR relationship by the transient relationship, derived from repeated measurements during one ablation season, is tested on Storglaciären, a well-investigated glacier in Sweden. We use the 1946–2004 long term record, transient mass balance measurements in 2004, and results from a distributed energy-balance mass-balance model. The long term and transient relationships are in good agreement for negative and slightly positive mass balances corresponding to AAR of roughly 0.2 to 0.6, but progressively deviate from each other with increasing net balances and larger AARs. The modelling indicates that the deviation becomes smaller as winter mass balance increases. It is concluded that the transient $b_{n,t}$ – AAR_t relationship should: (a) be established during a highly negative mass balance year, and (b) exclude any data from the earlier part of the melt season. Deriving the relationship from mass balance modelling may provide a powerful alternative, circumventing the need for a highly negative mass balance year for the transient measurements.

Key words accumulation area ratio; glacier mass balance; Storglaciären; Sweden

INTRODUCTION

Monitoring glacier mass balance is important for understanding and predicting the response of glaciers to climate change and resulting impacts on sea level change, watershed hydrology, and glacier-related hazards. However, direct measurements are scarce (Dyurgerov, 2002) since traditional mass balance measurements are highly time- and labour-consuming, and glaciers tend to be located in remote areas. Hence, there is a need for alternative less expensive but accurate methods. Dyurgerov (1996) proposed a method that derives glacier mass balance from the accumulation area ratio (AAR) or the equilibrium line altitude (ELA). AAR is defined as the ratio of accumulation area at the end of the melt season and total glacier area. The purpose of this study is to test this method on Storglaciären, a well-investigated valley glacier in Sweden, where continuous mass balance measurements have been conducted since 1945/1946 (Holmlund *et al.*, 2005). Elaborating on previous studies that use direct measurements of mass balance, we also investigate the method based on results from distributed energy-balance mass balance modelling.

DYUGEROV´S METHOD

The method proposed by Dyurgerov (1996) is based on the generally observed close relationship between annual area-averaged net mass balances, b_n, and ELA or AAR for glaciers with a distinct winter accumulation and summer ablation season. While such a relationship can be established from long term field measurements, Dyurgerov (1996) proposes that this relationship can be obtained from repeated mass balance measurements during only one summer. From these measurements so-called “transient” (current) area-averaged mass balances, $b_{n,t}$, can be computed and related to concurrent transient values of AAR and ELA (here referred to as AAR_t and ELA_t, respectively). Hence, the method assumes that the relationship between transient (current) values of mass balance ($b_{n,t}$) and ELA_t/AAR_t in the course of one season is identical to the relationship between b_n and ELA/AAR at the end of the mass balance year over many years. Once the relationship has been established b_n can be computed from the ELA or AAR obtained, e.g. from remote sensing, thus greatly facilitating mass balance determination. The method has been tested on a number of glaciers, mostly in Asia (e.g. Dyurgerov *et al.*, 1996; Kamniansky & Pertziger, 1996). Since Storglaciären’s equilibrium line is very irregular (deviating strongly from the course of contour lines) we focus on the relationship between b_n and AAR instead of ELA. On Storglaciären, the accumulation area generally coincides with the area above the snowline.

FIELD MEASUREMENTS AND DATA

Storglaciären holds a continuous mass balance record starting in 1945/1946 (Holmlund *et al.*, 2005), and thus is an ideal site for this study. The glacier’s surface area has remained roughly constant at ~3.2 km^2 during the last three decades, and ranges in elevation from 1140 to 1730 m a.s.l. (Fig. 1). Winter mass balance is obtained from roughly 300 probings on a 100 × 100 m grid, while summer mass balance is derived from about 50–90 ablation stakes spread across the glacier. In 2004, detailed mass balance measurements were performed on nine occasions during the melt season in

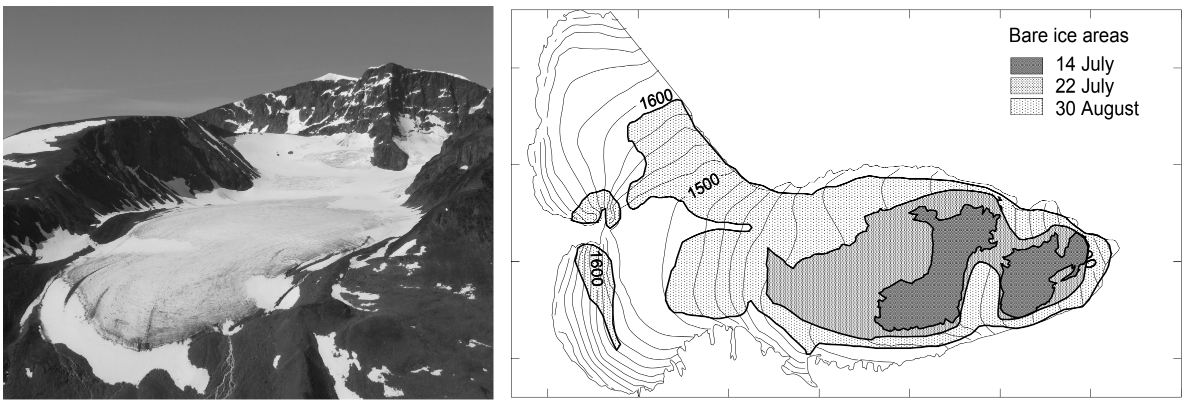

Fig. 1 Photograph taken on 29 July 2004 (left) and map of Storglaciären (right) showing the typically irregular pattern of snowline retreat. Bare ice areas as mapped on three of nine occasions on Storglaciären in 2004. Elevation contours with 20 m spacing. Tick mark spacing corresponds to 500 m horizontal distance.

order to establish the transient $b_{n,t} - \mathrm{AAR}_t$ relationship. A network of 88 ablation stakes was available for computation of the summer mass balance. Meltwater equivalent was computed considering changes in snow density during the season based on snow pit measurements and previous studies (Schytt, 1973). Concurrent with each mass balance measurement, the snow line retreat was mapped using a handheld GPS. From these data, AAR_t values were computed and compared to those obtained from the mass balance integrations. Since deviations between both data sets were negligible the latter values were used in further analysis. The mass balance (in water equivalent, w.e.) in 2004 was slightly negative (–0.19 m year^{-1}) and similar to the long term (1945/1946–2003/2004) average of –0.24 m year^{-1} (Kootstra, 2005).

MASS BALANCE MODELLING

In addition to the transient $b_{n,t} - \mathrm{AAR}_t$ relationship derived from the 2004 measurements, we investigate the relationship based on results from mass balance modelling. This has the advantage that the relationship can be obtained for the entire range of possible AAR values (0–1) by sufficiently manipulating the climate forcing to remove the winter snow cover by the end of the melt season. In contrast, the actual AAR recorded at the end of the season in 2004 only reached a minimum of 0.38. The mass balance model is based on a distributed surface energy balance model (Hock & Holmgren, 2005) coupled to a multi-layer snow model (Reijmer & Hock, 2007). Shortwave incoming and longwave radiation are computed considering the effects of slope, aspect and surrounding topography. Ice albedo is assumed constant in time while snow albedo is generated internally according to Zuo & Oerlemans (1996) and Oerlemans & Knap (1998). The turbulent fluxes are computed by the bulk aerodynamic approach correcting for atmospheric stability following Munro (1990) and using the non-linear stability functions by Beljaars & Holtslag (1991). The multi-layer snow model is a modified version of the model presented by Greuell & Konzelmann (1994) and Bougamont *et al.* (2005). It determines surface temperature, melt and runoff by calculating vertical profiles of temperature, density and water content down to 30 m below the surface taking the processes of melt, refreezing, meltwater percolation, slush formation and densification into account.

Computations are performed on a 30-m resolution grid and driven by hourly air temperature, humidity, wind speed, precipitation, shortwave incoming and reflected radiation, and longwave incoming and outgoing radiation. The model was run for the melt season 1999 when a detailed automatic weather station was operated on Storglaciären from 9 May to 2 September, providing the necessary input data to the model for an entire melt season (Hock *et al.*, 2000). Modelled mass balances, snow line retreat and snow temperatures generally agreed well with observations (Reijmer & Hock, 2006). The model was initialized with the measured winter mass balance (1.34 m w.e.). From the model run, transient mass balances and corresponding AAR values were extracted for every couple of days during the simulation period for which climate data were available. The mass balance in 1998/1999 was –0.21 m year^{-1} (AAR = 0.39), and thus similar to the one in 2003/2004 (–0.19 m year^{-1}, AAR = 0.38).

Three additional model experiments were conducted. The model was also run, shifting measured temperature uniformly by +2 and +4 K, in order to generate more negative mass balances and lower AARs, and to investigate the effect of the melting "history" on the results. The perturbations reduced the AAR to 0.24 and 0.09, respectively, by the end of the simulation period. Finally, the winter mass balance was increased uniformly by 1 m w.e. in order to analyse the effect of winter balance on the $b_{n,t}$ – AAR_t relationship. For this run, temperature was shifted by +6 K to generate AARs that span the entire range of possible AAR values. It is emphasized that increasing both winter balance and temperature in the same run is not necessarily a realistic scenario, but it suffices for our purpose to investigate the effect of winter balance on the $b_{n,t}$ – AAR_t relationship. Without a temperature increase AAR would change only a little throughout the season.

RESULTS AND DISCUSSION

Figure 2(a) shows the relationship between net balance and AAR for both the 59-year record of Storglaciären and the transient values obtained from repeated mass balance measurements for the melt season 2004. As found on other glaciers (e.g. Dyurgerov *et al.*, 1996; Kamniansky & Pertziger, 1996) there is a strong linear relationship between these quantities for the long term data set (r^2 = 0.88). However, in contrast to the underlying assumption of the method, the $b_{n,t}$ – AAR_t relationship for the transient data set of the year 2004 strongly deviates from the long term b_n – AAR relationship. Using

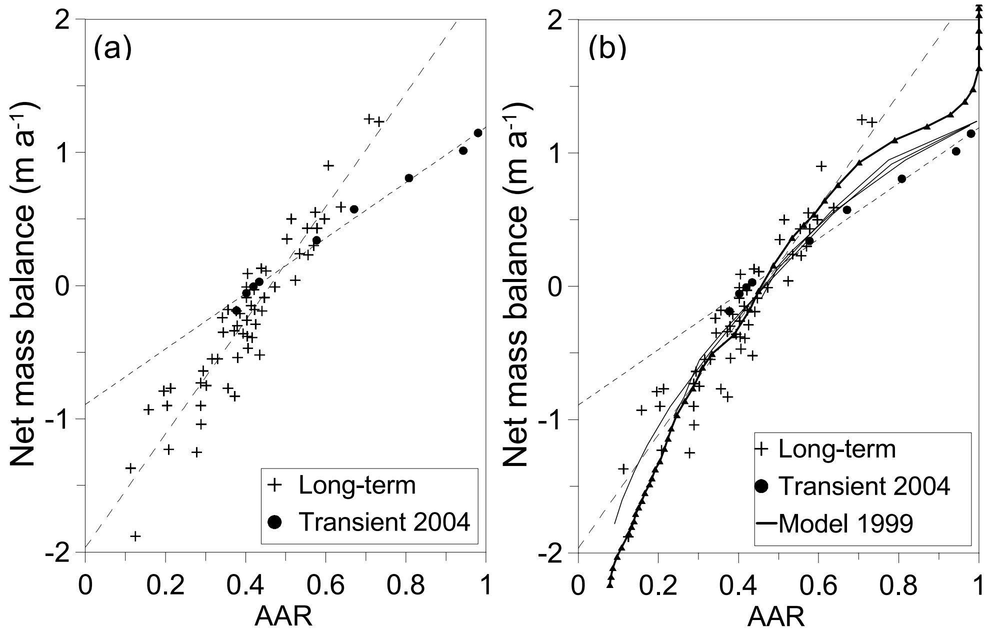

Fig. 2 Net mass balance *vs* accumulation area ratio (AAR) for: (a) the long term mass balance data of Storglaciären (1945/1946–2003/2004) and the transient data of 2004, and (b) including the results from four model runs (forced with measured temperatures, and temperatures shifted by 2 and 4 K (thin lines). Thick line (with triangles marking every second day) refers to model run with temperature shifted by 6 K in addition to increasing the measured winter balance by 1 m w.e.. The dashed lines are the linear regression lines for the long term (y = 4.26 × –1.97; r^2 = 0.88) and the transient data set (y = 2.08 × –0.89; r^2 = 0.99).

the $b_{n,t}$ – AAR$_t$ relationship to estimate the net mass balance leads on average to an overestimation of 0.2 m ranging from up to 0.52 m underestimation to up to 0.83 m overestimation for individual years. In comparison, b_n is underestimated and overestimated by up to 0.37 m and 0.46 m, respectively, with no difference for the mean, when the long term b_n – AAR relationship is used. Sensitivity analysis was performed to investigate whether this discrepancy between the long term b_n – AAR and the transient $b_{n,t}$ – AAR$_t$ relationship could be explained by uncertainties in the mass balance computations. Mass balances were computed using different assumptions on snow and firn densities as well as different methods of interpolating the point measurements across the glacier. Results indicated that the discrepancy could not be explained by uncertainties in the mass balance computations. Statistical tests indicate that the difference in slope between both regression lines is significant at 95% confidence interval.

We further investigate if a significant difference in slope between the annual and transient relationship (Fig. 2) is a coincidence for the year 2004, or to be expected for the entire record by adopting the following approach. For each year of the long term record the maximum slope, $\alpha_{t,max}$, of the transient $b_{n,t}$ – AAR$_t$ linear regression line can be approximated by:

$$\alpha_{t,\max} = \frac{b_w - b_n}{1 - AAR} \tag{1}$$

where b_w and b_n are winter and net mass balance, respectively. Figure 3 illustrates schematically that α computed thus provides the maximum slope $\alpha_{t,max}$ for each year's transient relationship (provided that the glacier is entirely snow-covered at the beginning of the melt season, which is the case on Storglaciären). Unless snow-cover on at least part of the glacier immediately melts off exposing bare ice, the actual transient slope, α_t will be lower, because AAR remains 1 for an initial period of melting until the first ice is exposed at the surface. $\alpha_{t,max}$ was computed for each year of the 59-year mass balance record and compared to the slope of the long term b_n – AAR regression line (The years 1960 and 1963 had to be excluded due to lack of reported AARs). Mean maximum slope, $\alpha_{t,max}$, of the transient $b_{n,t}$ – AAR$_t$ relationship (equation 1) is

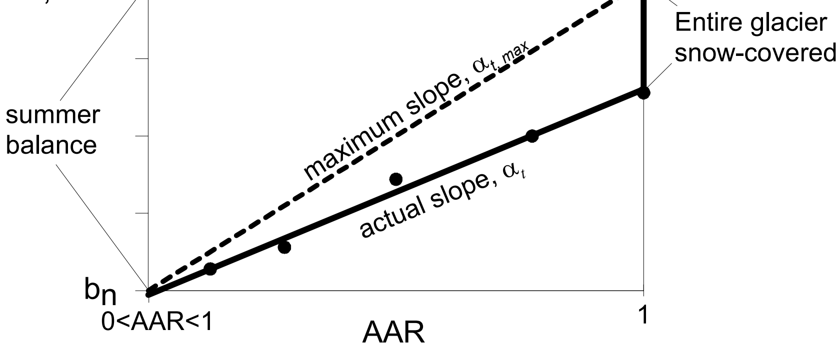

Fig. 3 Schematic sketch illustrating that the maximum possible slope, $\alpha_{t,\ max}$, for each year's transient $b_{n,t}$ – AAR$_t$ relationship derived from the winter (b_w) and net balance (b_n) exceeds the actual slope, α_t, since the glacier will remain entirely snow-covered for an initial period before bare ice is first exposed and the AAR drops below 1.

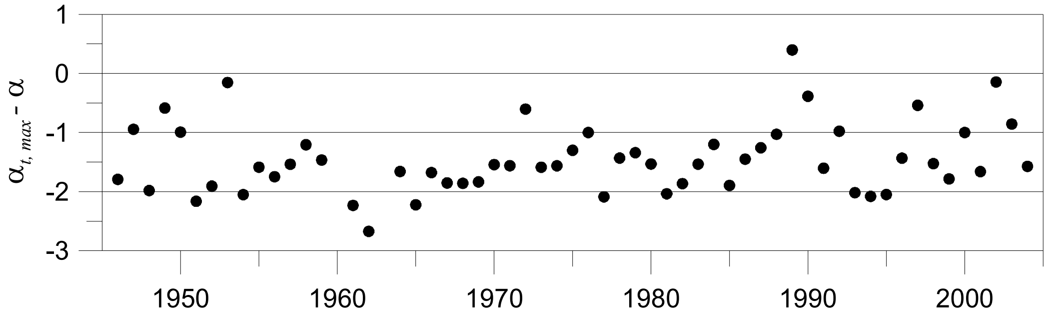

Fig. 4 Maximum slope, $\alpha_{t,\ max}$, obtained for each year from equation (1) minus the slope, α, derived from the b_n – AAR regression line based on the long term mass balance record of Storglaciären. The mean difference is -1.46. Mean $\alpha_{t,\ max}$ and α are 2.80 and 4.26, respectively.

2.80 ± 0.59, which is considerably lower than the slope α = 4.26 (Fig. 2) of the long term b_n – AAR regression line. Figure 4 shows that the maximum slope, $\alpha_{t,max}$, obtained by equation (1) for all but one year is lower than the slope, α, obtained from the long term b_n – AAR regression line. This indicates that the long term b_n – AAR and transient $b_{n,t}$ – AAR_t relationships generally differ from each other, and the different relationships obtained for t 2004 are not a coincidence. Figure 3 also illustrates that the method is only effective when AAR has dropped below 1. There is no correlation between b_n and AAR for both the long term and transient case, as long as the glacier is entirely snow-covered. The method also becomes insensitive in highly negative mass balance years with continued ablation after the AAR has reached 0.

Figure 2(b) shows the results from the mass balance modelling. All relationships derived from both data and modelling results largely coincide for AARs varying roughly between 0.2 and 0.6, but relationships progressively deviate from each other outside this range, in particular with increasing AAR. For overlapping ranges the results for the three model runs that were initialized with measured winter mass balance also largely coincide for large AARs. This indicates that the relationship is independent of the climate forcing applied. The +4 K and +6 K model runs span almost the entire range of possible AAR values and suggest a logarithmic $b_{n,t}$ – AAR_t relationship which is roughly linear for AARs varying between 0.2 and 0.6. The modelled transient $b_{n,t}$ – AAR_t relationships based on measured winter mass balance agree well with the one derived from the measurements, hence deviating from the long term b_n – AAR relationship for more positive mass balances and associated high AARs. However, results from the model run initialized with +1 m winter mass balance coincides more closely with the regression line for the long term relationship. This indicates that for large AARs the transient $b_{n,t}$ – AAR_t relationship depends on winter mass balance. With increasing winter balance the transient $b_{n,t}$ – AAR_t relationship tends to approach the long term b_n – AAR relationship.

A discrepancy between long term b_n – AAR and transient $b_{n,t}$ – AAR_t relationships has been found typical for all experiments run in the Tien Shan and the Pamir glaciers (Dyurgerov, 1996; Kamniansky & Pertziger, 1996). Long term mass balance data covers the climate conditions over about 50 years since the middle of the previous century. Due to relatively warm conditions during this period and associated general glacier retreat, observations including very high end-season AAR values are scarce. On

Storglaciären, AAR exceeded 0.7 only twice in the almost 60 year data record, and consequently the b_n – AAR relationship beyond this range is unknown. However, uncertainties in the b_n – AAR relationship for higher AARs are of decreasing practical importance in the light of generally predicted further glacier retreat.

CONCLUSIONS

Measurements and modelling results show that the b_n – AAR relationships derived from long term and transient values within one summer closely agree over the range of AARs roughly from 0.2 to 0.6. However, they progressively deviate from each other as AAR increases above 0.6, but modelling suggests that this deviation becomes less as winter mass balance increases. Hence, the transient relationship should preferably be established during a year of strongly above average winter balance, but also highly negative net mass balance to include lower AAR values. It is obvious that such conditions rarely occur. Nevertheless, our results suggest that a transient $b_{n,t}$ – AAR_t relationship intended to be used for long term mass balance determination can be acceptably established from transient measurements, irrespective of winter mass balance. However, it is essential that the net mass balance is highly negative and early season data are excluded. Due to acceleration of glacier wastage observed on a global scale, mass balances are likely to become more negative, accompanied by decreasing AARs, thus facilitating establishment of the $b_{n,t}$ – AAR_t relationship from transient measurements during only one year. The relationship, thus obtained, can then be used to substitute the long term b_n – AAR relationship. Once calibrated, this approach provides a powerful method for widely monitoring glacier contribution to regional and global water cycles and sea level rise, especially in the light of increasing availability of remote sensing products.

Our study indicates that use of mass balance modelling based on weather station data may provide an efficient alternative to transient field measurements since the $b_{n,t}$ – AAR_t relationship can be established for the full range of AAR values irrespective of annual mass balance. Further studies including more mass balance years and other glaciers are desirable to ascertain results.

Acknowledgements RH is a Royal Swedish Academy of Science Research Fellow supported by a grant from the Knut Wallenberg Foundation. Gratitude is expressed to the staff at Tarfala Research Station, especially Mart Nyman, who greatly assisted in collecting the transient mass balance measurements in 2004 and providing the mass balance record. Mark Dyurgerov is gratefully acknowledged for fruitful discussions and valuable comments on the manuscript. An anonymous reviewer, Bryn Hubbard and editor Jean-Emmanuel Sicart are acknowledged for their comments.

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