The measurement of ice velocity , mass balance and thinning-rate on Johnsons Glacier , Livingston Island, South Shetland Islands, Antarctica

Mesures de velocitat del gel, balanç de massa i taxa d'aprimament a la glacera de Johnsons, Illa de Livingston, Shetland del Sud, Antàrtida

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ABSTRACT

A network of twenty stakes was set up on Johnsons Glacier in order to determine its dynamics. During the austral summers from 1994-95 to 1997-98, we estimated surface velocities, mass balances and ice thickness variations. Horizontal velocity increased downstream from 1 m a^{-1} near the ice divides to 40 m a^{-1} near the ice terminus. The accumulation zone showed low accumulation rates (maximum of 0,6 m a^{-1} (ice)), whereas in the lower part of the glacier, ablation rates were 4,3 m a^{-1} (ice). Over the 3-year study period, both in the accumulation and ablation zones, we detected a reduction in the ice surface level ranging from 2 to 10 m from the annual vertical velocities and ice-thinning data, the mass balance was obtained and compared with the mass balance field values, resulting in similar estimates. Flux values were calculated using cross-section data and horizontal velocities, and compared with the results obtained by means of mass balance and ice thinning data using the continuity equation. The two methods gave similar results.

Keywords: Ice velocity. Mass balance. Thinning-rate. Continuity equation. Livingston Island.

RESUM

Amb l'objectiu d'estudiar el funcionament de la Glacera de Johnsons, s'han instal·lat vint estaques a la seva superfície. Durant els estius australs compresos entre els anys 1994-95 i 1997-98, s'ha mesurat la velocitat superficial, el balanç de massa i la variació del gruix de gel. La velocitat horitzontal augmenta aigües avall amb valors entre 1 m a^{-1} a la divisòria d'aigües fins 40 m a^{-1} aprop del penya-segat terminal. La zona d'acumulació presenta taxes d'acumulació baixes, amb màxims de 0,6 m a^{-1} (gel), mentres que a la part baixa de la glacera, la taxa d'ablació és de 4,3 m a^{-1} (gel). Durant el període d'estudi i tant a la zona d'acumulació com a la d'ablació, s'ha detectat una reducció del nivell de la superfície del gel que oscil·la entre els 2 i els 10 m. A partir de les dades de velocitat vertical i taxa d'a-

primament, s'ha obtingut el balanç de massa i s'ha contrastat amb les dades obtingudes al camp per aquest mateix paràmetre, resultant en un bon ajust. S'han estimat valors de flux a partir de considerar la secció del canal i velocitats horitzontals. La comparació d'aquests valors amb els obtinguts mitjançant l'equació de continuitat, que considera el balanç de massa i la taxa d'aprimament, dóna resultats similars.

Paraules clau: Velocitat del gel. Balanç de massa. Taxa d'aprimament. Equació de continuïtat. Illa de Livingston.

INTRODUCTION

Livingston Island is an irregular shaped island reaching a maximum length of 70 km (Fig. 1). Approximately 90% of its area is covered by an ice cap. Airborne radio-echo sounding measurements performed in the eastern part of the ice cap during the 70s showed thicknesses ranging from 200 to 400 m (pers. com., Vaughan, 1990). The glaciers draining the ice cap terminate in ice cliffs reaching heights of 50 m.

With the aim of monitoring the dynamics of the Livingston Island ice cap, the Departament de Geodinàmica i Geofísica of the Universitat de Barcelona carried out yearly surveys, in the austral summers from 1994-95 to 1997-98, on Johnsons Glacier. Basic glaciological data were obtained, including surface velocities, accumulation and ablation rates, ice-thinning rates and meteorological data.

Johnsons Glacier is a temperate glacier (Furdada et al., this volume) draining that part of the ice cap which lies near the Hurd Peninsula (southern part of Livingston Island). Its basin covers an area of approximately 5 km^2 in which two main fluxes of different slope and length converge on a 50-m-high calving ice cliff, extending 500 m along the coast (Fig. 2). The Dorotea line is 2,150 m long

with a mean slope gradient of approximately 6º; the Johnsons line is 980 m long with a mean gradient of approximately 10º. Dorotea and Johnsons divides are at elevations of 330 and 270 m respectively. The drastically different orientation of the flow lines relative to the prevailing NE wind direction (Vilaplana and Pallàs, 1993) gives rise to large differences in the accumulation of blowing snow, which is significantly greater on the Johnsons line. Ice thickness estimates of about 100 m have been obtained from preliminary seismic results (Benjumea et al., 1998) on the Dorotea profile (Fig. 3).

Previous glaciological studies on Livingston Island were carried out on the Rotch Dome during the period 1971-74. Those studies included horizontal velocity measurements, mass balance and equilibrium line altitude (ELA) determinations (Curl and Brink, 1974; Orheim and Govorukha, 1982). Vilaplana and Pallàs (1993) studied the snow distribution at Johnsons Glacier with the aim of determining the ELA. Other studies at Johnsons Glacier (Furdada et al., this volume) obtained mean net accumulations and ELA location for a 28-year period by using the maximum ^{137}Cs concentrations from the 1965 thermonuclear tests (Pourchet et al., 1997). Cartographic studies of Livingston Island showed a surface reduction of 4% between 1956 and 1991 (Calvet and Corbera, 1993) and no
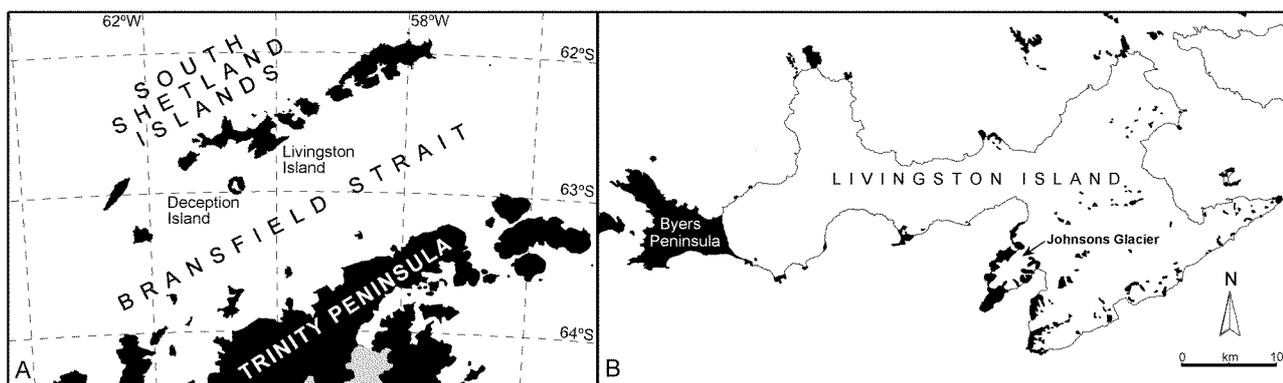

Figure 1. Regional setting of the study area. (a) South Shetland Islands. (b) Location of Johnsons Glacier at Livingston Island.

Figura 1. Context regional de l'àrea d'estudi. (a) Shetland del Sud. (b) Ubicació de la Glacera de Johnsons a l'Illa de Livingston.
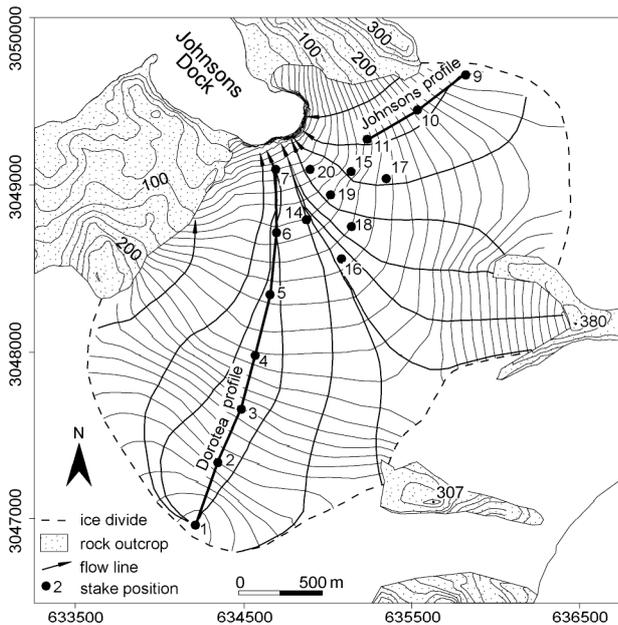
Figure 2. Map of Johnsons Glacier showing the Dorotea and Johnsons profiles.

Figura 2. Mapa de la Glacera de Johnsons amb els perfils de Dorotea i de Johnsons.

significant variation for the period 1991-96 (authors unpublished data, 1998). Field observations support the hypothesis that there has been an ice thinning process from 1956 to 1998, reaching 15-20 m at some points (Calvet et al., 1998).

The main objective of this study is to obtain surface velocities, mass balance and ice thinning rates to describe aspects of glacier dynamics. We use basic glaciological re-

lations to test the validity of our estimates. Taking into account the general topographic configuration of Johnsons Glacier, we considered the Dorotea profile to be the most appropriate when discussing dynamic characteristics, though some references are made to the Johnsons profile.

FIELD OBSERVATIONS

Seventeen rigid stakes, 3,65 m long and 3 cm cross section, were set up in December 1994 and a further three stakes were added in December 1995. Two main flow lines were marked with stakes 1-8 (Dorotea) and 9-13 (Johnsons). Stakes 14-20 were placed near the area where the flow lines converge (Fig. 2). Stakes 8 and 13 were lost during 1995 due to calving, whereas the rest required almost annual replacement due to intense ablation or accumulation. Stake positioning was determined by an electronic theodolite (Geodolite 504), which has a distance precision of ± 5 mm + 5ppm and an angular precision of 3". We took a minimum of two measurements per summer from the reference points (Sofia, Refugio and Johnsons, Fig. 2) to obtain stake coordinates by means of trigonometric calculations. Z coordinates were obtained as part of the same theodolite survey and the sphericity error was corrected. The refraction error was not considered because of the small distances involved, so Z data is presented to the nearest centimetre.

Data related to mass balance (annual accumulation and ablation) were obtained for each of the rigid stakes. In order to avoid any problems derived from the stake replacement operation, 11 articulated stakes, composed of five 2-m long segments with a 3-cm cross-section connected with a chain, were placed near some of the rigid stakes mentioned above. Subsequently, we used accumu-
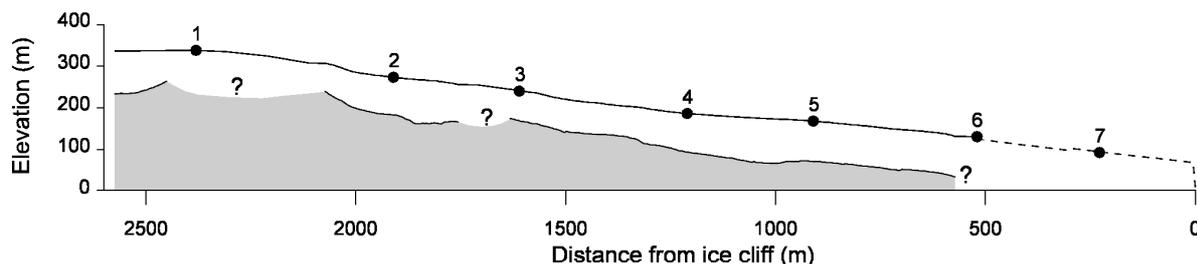

Figure 3. Bedrock and surface topography along the Dorotea profile based on preliminary seismic results. Discontinuities on bedrock representation correspond to segments where seismic reflections were poorly defined. Stake positions (1-8) are also plotted.

Figura 3. Topografia del substrat i de la superfície del gel al llarg del perfil Dorotea, segons resultats preliminars de la prospecció sísmica. Les discontinuïtats en la línia del susbrat corresponen a segments on les reflexions sísmiques no van ser prou resolutives. S'hi representa també la posició de les estaques.
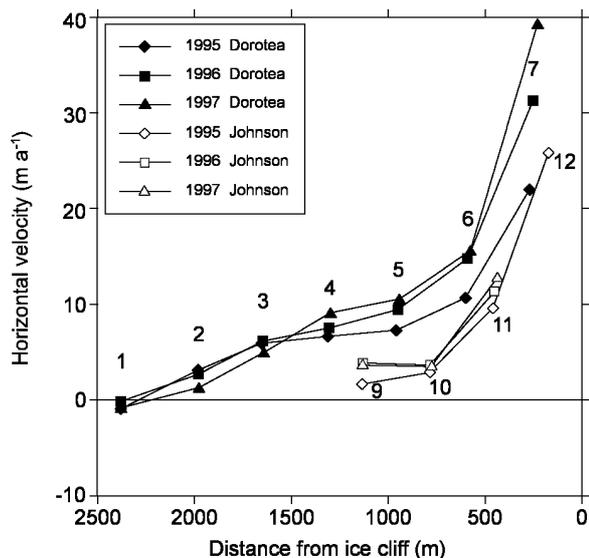
Figure 4. Annual horizontal velocities for the period 1995-97 on the Dorotea and Johnsons profiles.

Figura 4. Velocitats horitzontals anuals pel període 1995-97 als perfils Dorotea i Johnsons.

lation and ablation data derived from both rigid and articulated stakes.

To detect possible fluctuations in the ice surface level, Z coordinates were measured at the original stake positions (December 1994) in January 1998. This process involved re-establishing X, Y coordinates by using the tracking mode from the theodolite and obtaining the new Z coordinate for the point. The Z coordinates thus obtained are accurate to the nearest decimetre. In the ablation zone, we estimated ice surface level by subtracting the remaining snow-layer thickness from the Z coordinates cited above. Where measurements of the exact snow layer thickness were not available, we used the maximum value observed during the current season. In this way, ice thinning rates are always minimum estimates of the real value. To calculate ice thinning rates in the accumulation zone, we used topographic data from the glacier surface.

RESULTS AND DISCUSSION

Horizontal v elocities

Annual horizontal velocities increased downstream (spatial variation), with minimum values of about 1 m a^{-1}

near the ice divides and maximum values of 40 m a^{-1} near the ice terminus (Fig. 4).

In the Dorotea profile, stakes 2 to 7 flowed towards the NNE, whereas stake 1 flowed in a WSW direction. Although surface topography indicated that stake 1 was situated at the highest part of a dome, the seismic data revealed a possible topographic high in the bedrock between stakes 1 and 2, indicating that stake 1 possibly did not belong to the Dorotea flow line (Fig. 3). Stake 3 showed relatively high horizontal velocities presumably because it lay on relatively thin ice corresponding to the zone just over a threshold in the bedrock (Fig. 3).

Differences in horizontal velocity gradients between the Johnsons profile and the Dorotea profile are assumed to be a consequence of different slopes.

The horizontal velocities on the Johnsons and the lower part of the Dorotea profiles (stakes 4 to 7) showed interannual increments (temporal variation). These were higher than those suggested solely by the variations in the distance from the ice cliff (spatial variation). The increments were of the same magnitude at all the stakes. Thus a general cause, such as increasing sliding rates between years, seems to constitute an adequate explanation. According to this general tendency, the highest acceleration
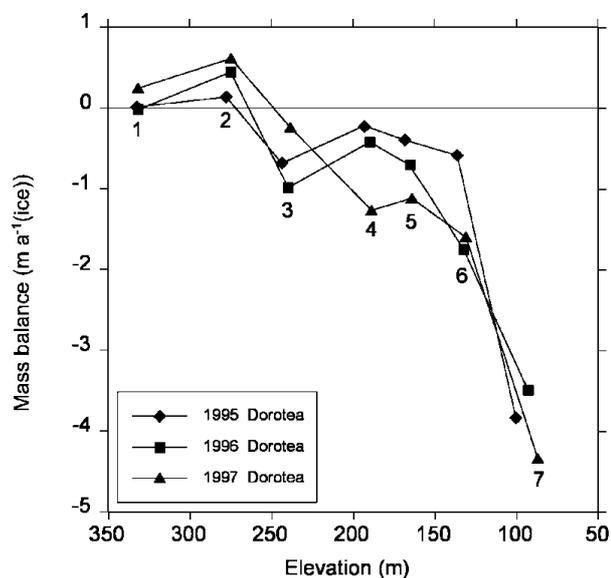

Figure 5. Annual mass balance for the period 1995-97 on the Dorotea profile.

Figura 5. Balanç de massa anual pel període 1995-97 al perfil Dorotea.

occurred in 1996 when increments in horizontal velocity of almost 50% were detected at the lower stakes.

By contrast, stakes 2 and 3 in the Dorotea profile showed a marked reduction in horizontal velocity, which could be related to different ice dynamics upstream and downstream of a threshold between stakes 3 and 4.

Mass balance

The accumulation zone was confined to the upper part of the Dorotea profile (Fig. 5). Contrary to expectations, accumulation at stake 1, at the top of the profile, was lower than that at stake 2. Field observations suggest that the divide area is exposed to eolian erosion which reduces the amount of accumulated snow around stake 1 (Vilaplana and Pallàs, 1993). The accumulation rates obtained at stake 1 for the period 1995-97 agree with the mean net accumulation determined for the period 1965-93 by ^{137}Cs concentrations (Furdada et al., this volume) at the same place.

Interannual variation of mass balance on the Dorotea profile for the 1995-97 period, showed increasingly positive values in the accumulation zone and increasingly negative values in the ablation zone, possibly due to increasing summer temperatures and increasing winter precipitation.

Figure 7. Annual mean vertical velocities with and without the influence of the annual mean ice thinning for the period 1995-97. The negative of annual mean mass balance for the same period is included for comparison.

Figura 7. Mitjana anual de les velocitats verticals amb i sense la contribució de la mitjana anual de l'aprimament, pel període 1995-97. Per facilitar la comparació, s'hi inclou la corba, en negatiu, de la mitjana anual del balanç de massa pel mateix període.

In relation to ELA location, studies during the period 1971-74 (Orheim and Govorukha, 1982) suggested an ELA of about 150 m at Rotch Dome, situated in the eastern part of Livingston Island, and having a similar physiography to that of Johnsons Glacier. Studies on the snow distribution on Johnsons Glacier during 1992-93 located the ELA at 235 m (Vilaplana and Pallàs, 1993). Furdada et al., (this volume) found a mean value for the ELA of 200 m in the Dorotea profile for the period 1965-1993. The mass balance data we present here for the Dorotea profile during the period 1995-97 located the ELA at 250 m. Thus, recent ELA determinations together with previous observations seem to indicate a rising trend in the ELA between 1965 and 1997.

Ice thinning

The ice-surface level decreased during the period 1995-97 all over the glacier (Fig. 6); this variation intensified sharply near the front. The ice thinning value at stake 1 could not be obtained due to problems during data collection. No annual ice thinning rates were avail-
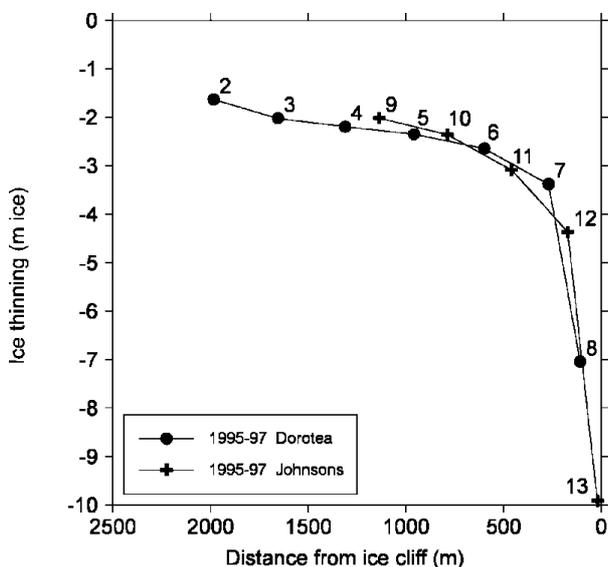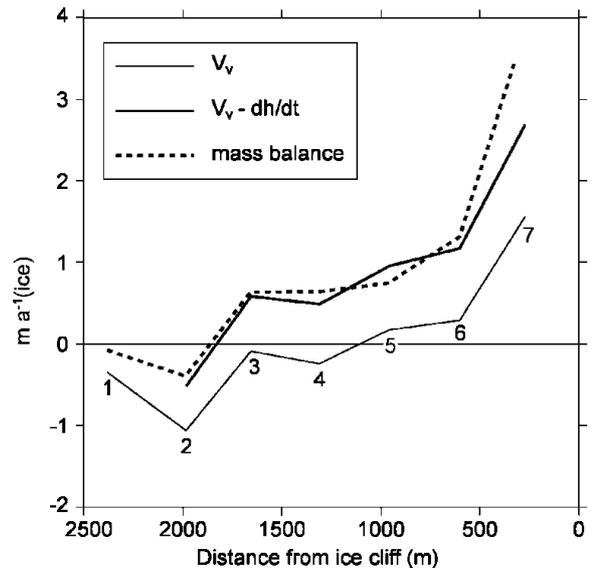
Figure 6. Total ice thinning for the period 1995-97 on the Dorotea and Johnsons profiles.

Figura 6. Aprimament total experimentat durant el període 1995-97 als perfils Dorotea i Johnsons.

able. However, annual surface velocity data showed large vertical component during 1996 and no accumulation irregularity was detected for that period. Thus, most of the thinning is likely to have occurred during 1996.

These data agree with recent findings based on former field observations and aerial photographs, which show a clear ice cap thinning from 1956 onwards (Calvet and Corbera, 1993; Calvet et al., 1998). In some cases, this thickness decrease is greater than 15 m.

Vertical velocities

Annual vertical velocities were calculated by subtracting downward motion due to down slope movement of the stake from the vertical component of the displacement vector (Fig. 7, curve marked V_v). The slope value was obtained from two topographic measurements, one at the stake and one at 20 to 30 m upstream along the flow line.

In steady-state conditions, the vertical velocities obtained were equal in magnitude but opposite in sign to the mass balance (Fig. 7, curve marked mass balance). Hence, to obtain mass balance estimates under non steady-state conditions, the ice surface level fall must first be subtracted (Fig. 7, curve marked V_v-dh/dt).

The increasing differences observed between the curves marked as mass balance and V_v-dh/dt towards the lower parts of the profile are due to errors in the mass balance values that arise when non-monitored ablation occurs after a stake falls.

Approximation to the Dorotea profile flow

In order to verify the field data collected, flux values were calculated using two different methods.

The flux through the cross section at stake i was calculated for each stake in the Dorotea profile,

$$Q_i = h_i * w_i * V_{hi} = S_i * V_{hi} \qquad \text{equation 1}$$

where Q_i is the annual ice flux through the cross section corresponding to stake i; h_i is the ice thickness derived from the seismic data under stake i (Fig. 3); wi is the width of the particular flow basin at stake i estimated from a topographic map; and V_{hi} is the annual mean horizontal velocity for stake i. Surface velocities were con-

sidered as being representative of the total flux cross section.

On the other hand, the discrete continuity equation gives the differences in flux between two cross sections using mass balance and ice thickness variation parameters,

$$Q_i - Q_{i-1} = A_i * (b_i - dh_i/dt) \qquad \text{equation 2a}$$

where Q_i and Q_{i-1} are the annual ice fluxes through the cross sections corresponding to stake i and stake i-1, respectively; A_i is the basin area between stake i and stake i-1; bi is the annual mean net balance for the period 1995-97 at stake i and dhi/dt is the annual mean ice thickness variation for the period 1995-97.

From a flux value calculated for a given stake, it is possible to obtain the flux corresponding to the stake immediately upstream using equation 2ª:

$$Q_{i-1} = Qi - Ai * (bi - dhi/dt) \qquad \text{equation 2b}$$

Then, starting with the flux value calculated at the lowest stake by equation 1, we used equation 2b to esti-
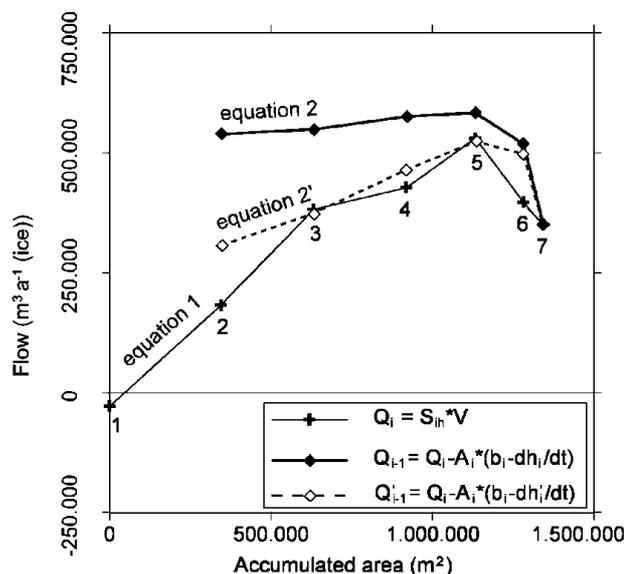

Figure 8. Annual flux values for the Dorotea profile obtained from equations 1 and 2. Equation 2' considers an ice thinning increase of up to 30 %.

Figura 8. Valors anuals de flux al perfil Dorotea, obtinguts a partir de les equacions 1 i 2. L'equació 2'considera un augment en l'aprimament del gel de fins el 30%.

mate flux values corresponding to the stakes upstream along the flow line.

Since it is unclear whether the motion at stake 1 is attributable to the Dorotea flow line, we used equation 1 assigning a negative value to the velocity calculated at this stake. For the same reason, it was not possible to calculate the flux value at stake 1 by applying equation 2b.

We obtained different values using the two equations described above. However, a common maximum was found at stake 5, suggesting a similar overall tendency (Fig. 8).

If steady state conditions were present, maximum flux values would be located near the equilibrium line (in our study, between stakes 2 and 3). But the ice thinning process detected on Johnsons Glacier produced a displacement of the flux maximum downstream along the flow line to stake 5.

Amongst the possible causes of the differences observed between the two curves (Fig. 8, curves marked "equation 1" and "equation 2"), we consider ice thinning to be the most likely. This assertion is based on the fact that the ice thinning data used in equation 2b are minimum estimates of the real values. In fact, we observed a good fit between the two curves (Fig. 8, curves marked "equation 1" and "equation 2") when we increased the assumed ice thinning by 30 %. This confirms that minimum ice thinning estimates are indeed lower than the real values.

CONCLUSIONS

The results presented in our study correspond to data collected over three years. In spite of this short time series, we observed clear tendencies that fit the general pattern of ice cap reduction detected on Livingston Island since 1956 (Calvet and Corbera, 1993; Calvet et al., 1998). The main findings indicating this are:

1) Horizontal velocities at the lower part of the glacier increase at similar rates. Incremental sliding rates are thought to lie behind this observation.

2) Temporal variation in mass balance data: increasingly positive values in the accumulation zone and increasingly negative values in the ablation zone.

3) ELA values obtained by different methods over the last 28 years allow us to confirm an ELA rise of about 100 m.

4) Direct measurements of ice thinning during 1995-97 indicate a fall of about 2 m, increasing to 10 m near the ice terminus.

5) Differences between V_v and mass balance data are explained by an ice thinning process.

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