A GPS STUDY ON STORGLACIÄREN, SWEDISH LAPLAND

ELEANOR HARESIGN

UNIVERSITY OF ST. ANDREWS

Introduction

Tarfala Research Station is situated at the Tarfala Valley of the Kebnekaise massif in Swedish Lapland, at 67°55'N, 18°36'E. The course was organised by Dr. John Moore of the University of Lapland, and funded by a European Union grant – Glacio EuroLab. The course covered aspects of both glacier safety and practical techniques and methodologies. The weather conditions experienced were a good reminder of the need to have an adaptable fieldwork plan, as the weather may often determine the schedule of the work undertaken.

Project aims

During the course, several field techniques were learned, including the application of GPS to glaciology. The following report outlines our experience of using GPS, and some of the inferences of the data obtained, regarding glacier flow.

Storglaciären is a temperate valley glacier, feeding into the Tarfala valley. However, it has a complex thermal regime, with an internal warm base and a 30 – 40 m cold surface layer, which results in a 100 – 200 m wide cold based zone in the thin glacier snout (Holmlund *et al.*, 1996). Resistivity surveys and borehole deformation have demonstrated that much of the glacier is underlain by saturated deformable till (Hooke *et al*, 1988). Seasonal changes are known to operate, such that a distributed braided system becomes more efficient in the ablation season as linked conduits (Benn & Evans, 1998).

There is a long history of mass balance programs carried out, which started in 1945. It aims to evaluate how climate gradients through the Scandinavian mountain chain are coupled to the thermal and dynamic characteristics of glaciers and how changes in these gradients will affect the glacier (Holmlund & Jansson, 1999). Storglaciären was chosen because of its relative accessibility and simple geometry (Ahlmann, 1951).

In the late 19th century glaciers in northern Sweden began to expand, such that most glaciers reached positions close to their Holocene maximum at the beginning of the 20th century. A temperature maximum followed a dramatic recession in the 1930s, after which the climate was relatively stable. Accumulation increased rapidly in the 1980s, and during the 1990s most glaciers have grown thicker and some smaller glaciers are already advancing.

Different rates of glacier flow and flow direction relate to differences in a variety of factors, such as ice characteristics, basal sediments and bed topography i.e. a smoother, well lubricated base will create conditions of faster flow than rough bedrock where the ice is frozen to the base. It should be noted that surface flow velocities may differ from basal flow velocities. The bed topography, in particular, provides explanation for the observations discussed here.

Method

The developing use of GPS measurements in recent years, alongside the use of snow radar has improved the areal coverage of winter balance measurements. However, even without the selective availability implemented by the US Department of Defence, 20 m accuracy is inadequate for most applications of GPS. Methods have been developed to reduce such errors. If two receivers are used, then similar errors of similar magnitude will affect both receivers, resulting from error in the satellite clock, the satellite orbit, the ionosphere and the troposphere. If the exact location of one receiver is known, then errors for the other may be corrected. This is the differential mode. Differential GPS has a high degree of accuracy, which makes it very desirable. The receiver of known location is the 'base receiver' and the other is the 'rover receiver'. The range error calculated from the base receiver from each satellite is reported to the rover receiver. The rover can subtract the correction values from the corresponding satellites and computes its own position with much better accuracy. Depending on the distance between the base and rover receivers (the baseline), there will be some residual errors in the computed position of the rover that depend on its proximity to the base. The shorter the baseline, the less the error. As a rough guide, in the *x* and *y* direction accuracy is to within 1 mm, and in the *z* direction is to 3 mm.

A base station was established at Enquist Rock and used during the whole day of measuring. The roving Javad GPS (the antenna, receiver and batteries) was held at each stake for 3 minutes. The GPS was able to get signals from ~ 8 satellites most of the time, which is suitably sufficient in terms of location calculation accuracy. The continuous measurements taken during this period could then be averaged in the data processing. Four rows (of a potential seven) across the glacier were surveyed, each with six stakes. This stake net is on the lower part of the glacier, between ~1300-1400 m a.s.l. It was not possible to obtain the next row towards the terminus, as a zone of crevasses was reached, and the strength of the snow bridges was not known. The measurements from the receiver were later transferred to a computer, and ascribed to the WGS84 co-ordinates system.

Displacement of the stakes from a previous measured position may be used to calculate the magnitude and direction of the surface ice movement. In this instance, measurements were compared with similar data collected from the same stakes by J. Hedfors (July 17, 2000).

The horizontal displacement of the stakes can be found by taking the difference in latitude and longitude of each point between July 17, 2000 and April 5, 2001. It was first necessary to convert the grid reference into northings and eastings in meters, using a Transverse Mercator Calculator (http://www.dmap.co.uk/ll2tm.htm), which can only convert to accuracies of 1 m. The resultant velocities calculated from this data are therefore only given to the nearest meter. The vertical displacement in meters was also considered, although the exact accuracy is unknown. Inaccuracies may arise as a result of changes of the stake position within the ice surface, although all the stakes are plugged at the lower end with a wooden plug to prevent them from pressure melting at the bottom (Holmkund & Jansson, 1999). The time period calculated for is 262 days.

Results

Displacement

- Stake displacement is plotted in metres as northings and eastings (see Figure 1) from the converted data (see Table 1).
- Displacement is generally greatest down the centre line of the glacier (see Figure 2), except that in rows 2 and 3 (2, in particular) there is a low in the central positions. In row 2, there is also a high amount of displacement near the SW margin.
- North side vectors are directed slightly towards margin. The south side ones are directed, if anything, into the glacier, except for one stake near the SW side in row 2. This is the same stake that exhibits the particular high amount of displacement. This is in agreement with the report of Schneeberger *et al* (September 2000 GlacioLab course), as well as the observation that those vectors at the side ten to be smaller.
- The displacement measured by Schneeberger *et al* was taken over the late ablation period, whereas that discussed here relates to the late ablation plus winter accumulation period. It is therefore interesting that I have obtained an average velocity of 11-12 m a^{-1}, compared to their values of 16.5-20.1 m a^{-1}. This is as would be expected, as the value here incorporates most of the winter accumulation season.

Change in stake altitude

- The change in elevation of stakes (measured at the top) is ~ 1.5-2.6 m higher than 2000.
- The elevation change is consistently greater at the sides across all four rows of stake (see Figure 3), as well as being more similar in the magnitude of change than those in the middle. In general, there is greater height change in the rows nearer the terminus.
- The greatest range in stake height change is in row 3. Where there is a large drop in the stake height change at stake 4, there is also a marked increase in the horizontal displacement.
- Comparison of stake altitude changes to Schneeberger *et al* is not possible, as this data was not included in their study.

Discussion

The ice displacement patterns are fairly standard for a temperate valley glacier. The displacement (velocity) is reduced at the margins by the effect of lateral drag. A high value for surface velocity at Storglaciären is expected, and has been attributed to high meltwater inputs and high basal water pressures by Hooke *et al* (1989), and the values calculated match well in comparison to other values previously obtained e.g. Iverson *et al* (1995) quoted a surface velocity of 14 m a^{-1}, with a significant contribution coming from subsole deformation. The values found by Schneeberger *et al* ranged from 16.4 – 20.1 m a^{-1}.

Unlike some glaciers that exhibit seasonal changes in velocity, the velocity increase maximum at Storglaciären moves up-glacier (Willis *et al*, 1995), close to the terminus (Brozowski & Hooke, 1981). The middle ablation zone velocity increase was found to occur before the upper ablation zone velocity increase (Hooke *et al*, 1983). It is very unlikely that this dataset would show up such seasonal changes, given it is averaged over a nine-month period, and therefore the high velocity value cannot be attributed to this explanation.

There are several plausible explanations for the observations seen in height change, which are outlined and discussed, below:

- Holmlund *et al* (1996) have observed that, from the later half of the 1980s to the present, there has been ice thickening, supposed to have been caused by an increase in precipitation, and that the glacier grew 4 m thicker between 1989 and 1994. It is possible that this is continuing, especially given that the current mass balance of the glacier is positive.
- Following up the idea of a cold based marginal zone, it is possible that, whilst the glacier as a whole is not thickening, an increased input of accumulation is causing a kinematic wave, resulting in local ice bulging near the snout, due to the resistance to forward motion provided by the frozen marginal base.
- There is a period of known uplift on Storglaciären, which occurs in July-August and the glacier surface then declines steadily for the rest of the year. This would suggest that the uplift seen in the GPS data cannot be attributed to seasonal uplift, as a decrease in height would have been observed. Nor can it relate to diurnal changes that might have happened to have been recorded, as these only happen during the summer period (Hooke *et al*, 1989).
- Hooke *et al* (1989) stated that seasonal uplift is not attributed to subglacial cavitation, but instead is due to increase in vertical straining within the ice due to variations in longitudinal stress gradient. Hence, if it is known that vertical straining occurs, then there is a small possibility that the uplift may relate to bulging out of season, perhaps triggered by a large increase in mass input from further up-glacier.
- It is quite certain that there is a bedrock ridge (a riegel, Hooke, 1991) which, according to the bedrock map of (Schneeberger *et al*, report September 2000, p.16) would imply that the row of stakes nearest the terminus is just up-glacier, and therefore approaching it. This would also explain the differences in stake height change, i.e. more at the lateral margins, because the riegel is less pronounced in the center. The cross section of the glacier at row 3, in particular would indicate that there is not much change in

bedrock topography at that point. Thicker ice and, hence, lower effective basal pressure would encourage the relatively abrupt increase in displacement (and therefore ice velocity) in that area.

Conclusions

The study demonstrates the simplicity of using GPS in the field for glacier velocity surveys. However, it has also highlighted the problems that can arise from having inadequate means by which to process the data., resulting in the introduction of large errors to the final data. Bearing this in mind, the values obtained for velocity range from 11-12 m a^{-1}, which agrees well with other observations. The altitude changes range from 1.55–2.60 m, and are most likely to relate to the progression of the ice surface towards a bedrock riegel or, secondarily, to unseasonal uplift in conjunction with a basally frozen terminus causing bulging behind the terminus.

It is well known that changes in glacier front position result predominantly from ice flow, mass balance, and bed morphology. It would have been interesting to have measured stake position at the glacier front margin. This could have been compared with the glacier margin position from previous years, to compare if terminus position change corresponds with our calculated annual rate. This was analysed by Kaczmarska (from the course in September 2000) for Isfallsglaciären, where it was observed that part of the front retreats while the rest slightly advances, although the amounts were considered insignificant. At Storglaciären, I would expect that the whole front would be advancing. However, if the margin was static, it would support the idea of ice bulging towards the terminus.

What is most evident is that, as is the case for most glaciological studies, one field method is inadequate in order to make any meaningful inferences from the data it provides, as the quantity of factors influencing one aspect of glacier behavior are numerous.

Acknowledgements

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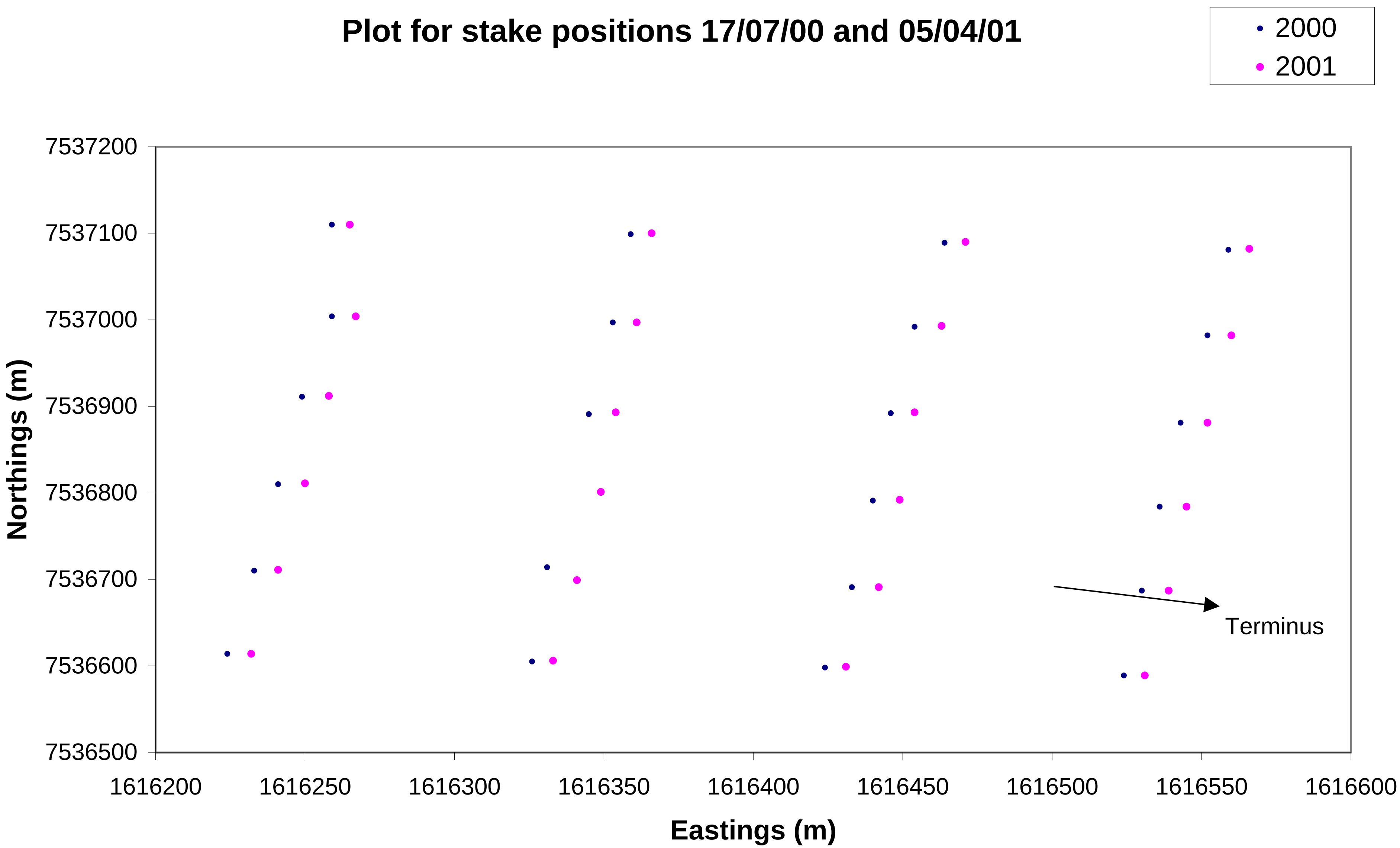
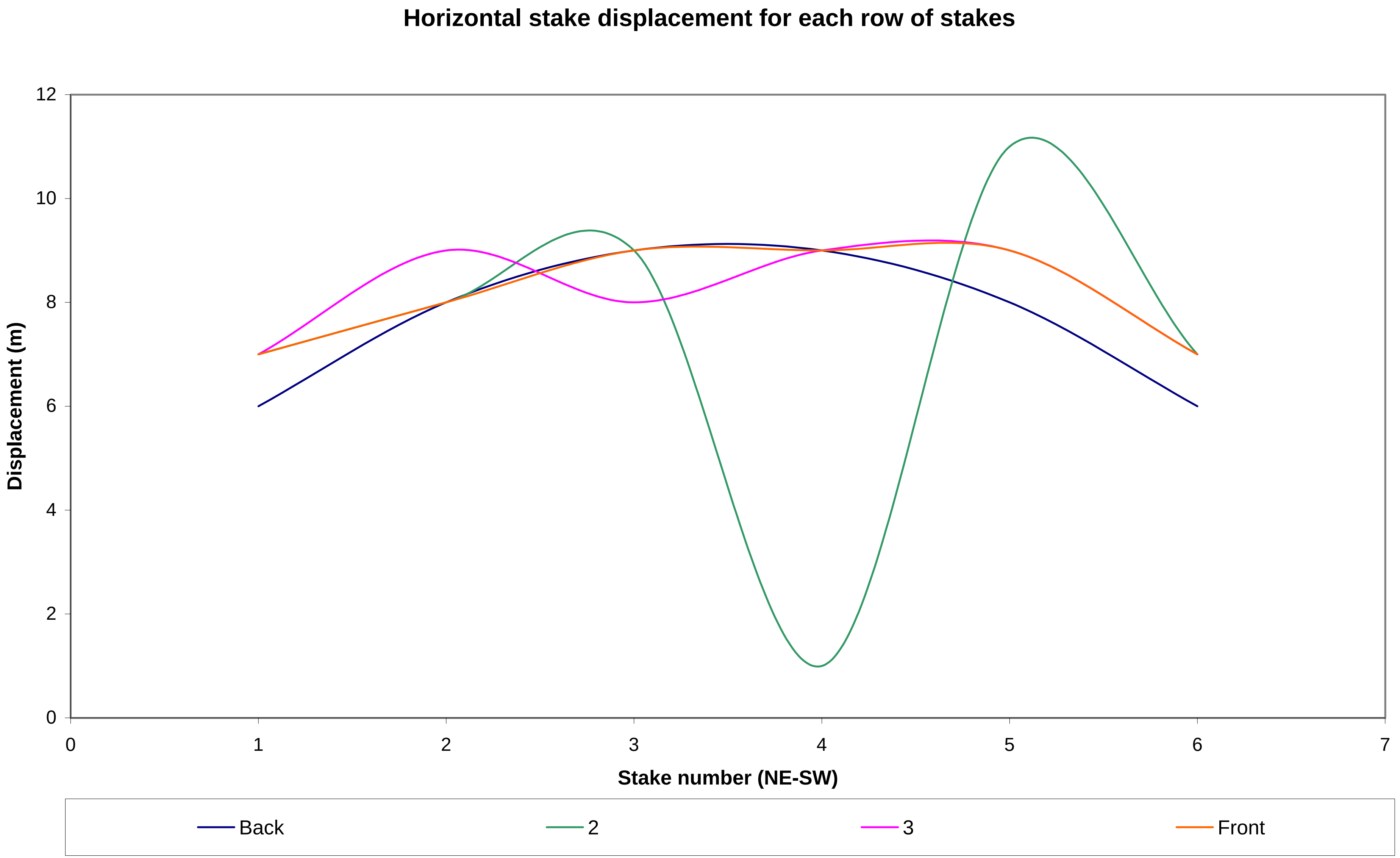
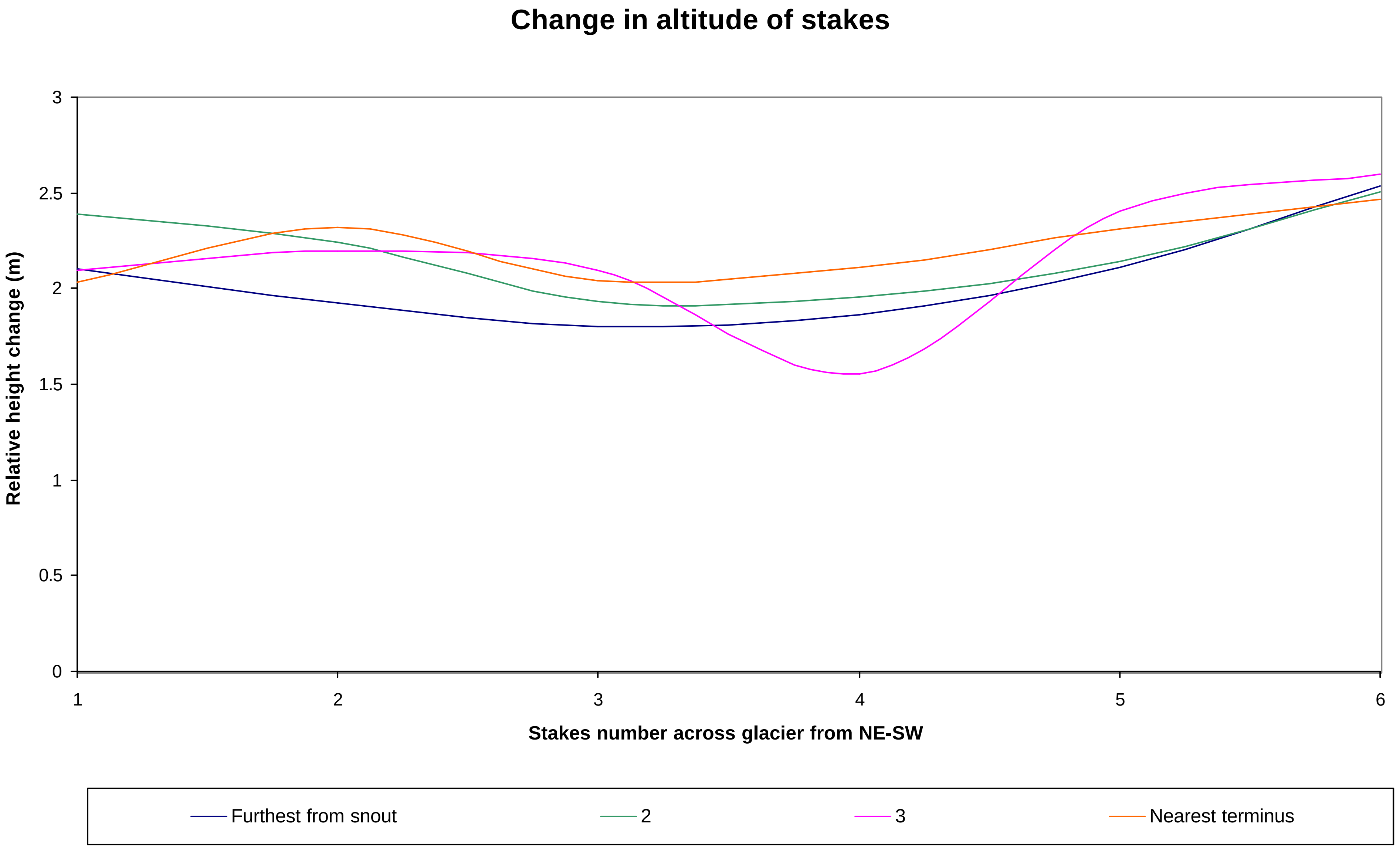


Plot for stake positions 17/07/00 and 05/04/01
2000
2001
7537200
7537100
7537000
7536900
7536800
7536700
7536600
7536500
Northings (m)
1616200
1616250
1616300
1616350
1616400
1616450
1616500
1616550
1616600
Eastings (m)
Terminus



Horizontal stake displacement for each row of stakes
Displacement (m)
12
10
8
6
4
2
0
0
1
2
3
4
5
6
7
Stake number (NE-SW)
Back
2
3
Front


Change in altitude of stakes
Relative height change (m)
3
2.5
2
1.5
1
0.5
0
1
2
3
4
5
6
Stakes number across glacier from NE-SW
Furthest from snout
2
3
Nearest terminus

Easting 00	Easting 01	diff	Northing 00	Northing 01	diff	(x,y) moved^2 (m)	Stakes NE-SW	9 months s moved inc. height (m)	estimated velocity m/a	av vel per row m/a	total av vel m/a
1616259	1616265	6	7537110	7537110	0	36	2.11	6.4	9	11	11
1616259	1616267	8	7537004	7537004	0	64	1.93	8.2	11		
1616249	1616258	9	7536911	7536912	1	82	1.80	9.2	13		
1616241	1616250	9	7536810	7536811	1	82	1.87	9.2	13		
1616233	1616241	8	7536710	7536711	1	65	2.11	8.3	12		
1616224	1616232	6	7536614	7536614	0	36	2.54	6.5	9		
1616359	1616366	7	7537099	7537100	1	50	2.39	7.5	10	11	
1616353	1616361	8	7536997	7536997	0	64	2.25	8.3	12		
1616345	1616354	9	7536891	7536893	2	83	1.93	9.3	13		
1616349	1616349	0	7536800	7536801	1	1	1.95	2.2	3		
1616331	1616341	10	7536714	7536699	15	115	2.15	10.9	15		
1616326	1616333	7	7536605	7536606	1	50	2.50	7.5	10		
1616464	1616471	7	7537089	7537090	1	50	2.39	7.5	10	12	
1616454	1616463	9	7536992	7536993	1	82	2.25	9.3	13		
1616446	1616454	8	7536892	7536893	1	65	1.93	8.3	12		
1616440	1616449	9	7536791	7536792	1	82	1.95	9.3	13		
1616433	1616442	9	7536691	7536691	0	81	2.15	9.3	13		
1616424	1616431	7	7536598	7536599	1	50	2.50	7.5	10		
1616559	1616566	7	7537081	7537082	1	50	2.09	7.4	10	12	
1616552	1616560	8	7536982	7536982	0	64	2.19	8.3	12		
1616543	1616552	9	7536881	7536881	0	81	2.09	9.2	13		
1616536	1616545	9	7536784	7536784	0	81	1.55	9.1	13		
1616530	1616539	9	7536687	7536687	0	81	2.41	9.3	13		
1616524	1616531	7	7536589	7536589	0	49	2.60	7.5	10		

Horizontal displacement	inc height
6	6
8	8
9	9
9	9
8	8
6	7
7	8
8	8
9	9
1	2
11	11
7	8
7	8
9	9
8	8
9	9
9	9
7	8
7	7
8	8
9	9
9	9
9	9
7	8