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L.

Horizontal Speed
Measurements
Demonstrate
Dependence on
Subglacial
Drainage...

June 1, 1997

Horizontal Speed Measurements Demonstrate Dependence on
Subglacial Drainage System Configuration

by

Staci L. Ensminger

A Thesis

Presented to the Graduate and Research Committee

of Lehigh University

in Candidacy for the Degree of

Master of Science

in

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Date

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Abstract

The horizontal ice speed of the Matanuska Glacier, AK was measured for a three month period during the 1996 summer melt season using total station surveying equipment to monitor six stations positioned across the western portion of the glacier's terminus. The horizontal speed increased from ≈ 13 cm/day at the start of the meltseason, to ≈ 23 cm/day in late June and early July and decreased to ≈ 11 cm/day in late August. Superimposed on the seasonal trend are speed "spikes". Speed data are compared to input and output proxies to develop a conceptual model linking ice motion to the configuration of the subglacial drainage system. A continuous record of stream discharge was also collected from a stream sourced by the subglacial discharge vents. Ice speed and stream discharge have a hysteresis relationship which is thought to indicate water storage at the glacier's bed. Subglacial water storage is hypothesized to have occurred in late June and early July with increased water pressures due to large fluxes of seasonal meltwater. The water storage is conceptually modeled as occurring in the braided canals and cavities of a distributed configuration when pipe capacity is exceeded. Observations suggest that increased water pressure, due to storage at the bed, and the stage of drainage system evolution control the horizontal speed record.

INTRODUCTION

As a part of the ongoing studies of the subglacial drainage system at the Matanuska Glacier, AK, an ice motion study was conducted during the 1996 melt season. The purpose of this study was to conceptually model the link between ice motion the configuration of the subglacial drainage system. Variations of ice surface velocities have been shown to reflect changes in melt water storage within the subglacial drainage system, as well as changes in the system configuration itself (Iken, 1977; Iken, 1981; Iken et al., 1983; Iken and Bindshadler, 1986; Kamb, 1987; Iverson et al., 1995). Subglacial drainage systems are, in general, modeled as flow through conduits and tunnels or as distributed flow (Weertman, 1961; Röthlisberger, 1972). Distributed flow systems have been further modeled as having linked-cavity or braided canal configurations (Kamb, 1987; Walder and Fowler, 1994). The dominant subglacial drainage configuration(s) is important to the theories of the growth and accretion of basal ice. Terraces of frazil ice have been observed growing during the melt season at the terminus of the Matanuska Glacier. Processes similar to those known to produce ice terraces are hypothesized to act beneath the glacier to accrete ice to the base of the glacier and trap sediment, forming the basal ice facies (Lawson, 1979a; Strasser et al, 1996; Alley et al., in press). Ice accretion may take place in basal cavities opened during overpressurization of the water system (Iken et al., 1983; Alley et al., in

press). The accretion of discontinuous ice layers onto the sole of the glacier, or basal freeze-on, may also occur in low, broad canals (Strasser et al., 1996; Walder and Fowler, 1994). The depth of shallow, broad canals incised in subglacial till is a function of slope, grain size, and possibly discharge (Walder and Fowler, 1994). Debris entrainment, such as by freeze-on mechanisms, and debris transport are important in constraining many glaciological and glacial-geological problems (Alley et al., in press).

The stability or degradation of the subglacial drainage system throughout the year will affect how the system handles a large influx of melt water at the start of the melt season. Water pressure increases associated with rising water storage may result in accelerated sliding rates (Iken, 1981; Lawson, 1993) and possibly even "uplift" events (Iken and Bindschadler, 1986). The basal water pressure is determined by the water supply and the resistance of the subglacial drainage channels to flow (Lawson, 1993). Diurnal variations or large melt and rain events may increase the water supply faster than channels can enlarge, building up the water pressure. Basal water pressure is an important parameter in basal sliding as it counteracts the weight of the glacier by reducing the effective pressure ($=$ ice overburden pressure - water pressure). Increased basal water pressure may also reduce the shear strength of underlying permeable sediment, perhaps allowing it to

deform more rapidly under the shear stress of the ice and speeding ice motion (Paterson, 1994; Blake et al., 1994; Clark, 1995; Iverson et al., 1995).

Previous workers have concentrated on glaciers with small drainage basins that mostly overlie bedrock (most notably Iken, 1977; Iken et al., 1983). Early velocity studies established the existence of velocity variations on a glacier-wide scale (Meier, 1960), but it has been only recently that studies have begun to focus on variations occurring over much smaller scales (Harper et al., 1996). Ice motion studies at the Matanuska were initiated to search for localized velocity variations of a glacier that is underlain by till and that has a large drainage area. Questions concerning debris entrainment and transport by glaciers can best be answered by examining modern ice-water systems.

BACKGROUND

The Matanuska Glacier is a large valley glacier that is approximately 48 km long and reaches widths of 5 km at the terminal lobe. It flows north from the ice fields of the Chugach Mountains in south-central Alaska, into the upper Matanuska River valley (Figure 1). The Matanuska terminates about 135 km northeast of Anchorage (Lawson, 1979b; Arcone et al., 1995; Strasser et al., 1996). The glacier drains 647 km² of the highest area of the Chugach Mountains (Williams and Ferrans, 1961). Elevation decreases from 3500 m in the

accumulation zone to 500 m at the terminus. The terminus has been located within 4 km of its present position for the past 8,000 years (Williams and Ferrans, 1961). Most of the terminus is debris-covered, apparently stagnant ice.

The western portion of the terminus, however, has active ice which is flowing out of an overdeepening. The overdeepening pressurizes the subglacial water as it flows uphill and supercools it (Hooke and Pohjola, 1994; Lawson et al., 1996). Supercooled water has been shown to lead to ice nucleation and growth (Strasser et al., 1996). The current hypothesis is that the configuration of the Matanuska's subglacial drainage system is distributed flow through low, broad canals in the subglacial sediment such that basal freeze on is an important mechanism of debris entrainment at the terminus (Lawson et al., 1996).

METHODOLOGY

Target Stations

During mid- May, 1996, 6 stakes were placed in the western terminus region of the Matanuska Glacier, AK (Figure 1). Stake positions were measured daily or more often over the three month melt season. The stakes also served as a reference against which daily ablation measurements were made. The stakes were white PVC of 3.05 m length, stakes were drilled and were placed in hand-augered holes in

the ice initially 2.5 m to 3 m deep.

A daily record of ablation was obtained by measuring from the top of the stake down to the ice surface. A piece of plywood 1/2 in thick and 6 in by 6 in was used as a removable “foot” that fit around the stakes to average the ice surface for ablation readings. Ablation was measured to the nearest centimeter. The “foot” was also used for placement of the electronic distance measurement (EDM) reflecting prism during surveys. The stakes became prone to tilting as surface ablation removed the ice supporting them. To minimize the occurrence of tilting, the stakes were shortened and holes were redrilled. During mid- to late- July, when ablation was the fastest, stakes were cut every 3 to 4 days and holes were redrilled once a week. The lengths of stake shortening and depths drilled were recorded and accounted for in the survey analysis.

Surveying

The surveying station was located on the end moraine, just west of the terminus (Figure 2). Also located on the moraine were the fixed reference for turning angles and a target anchored into the moraine, or a “stationary target,” for determining survey errors. The fixed reference was a marked point on a large stable rock located due south of the survey station. The stationary target was an EDM reflecting prism located due north of the survey station. There was also a

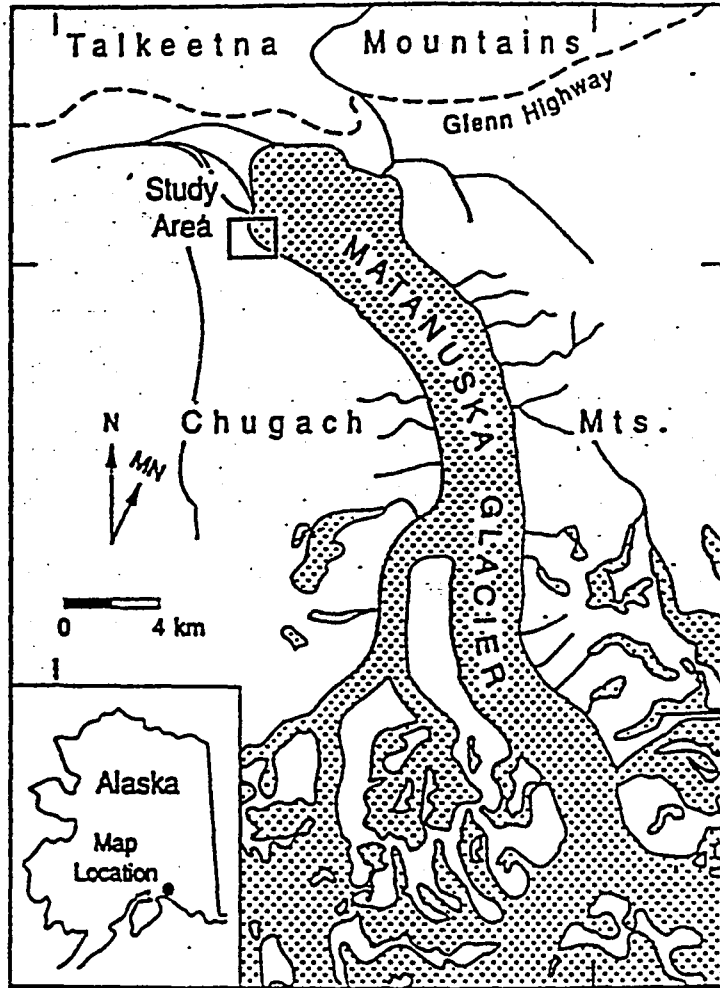


Figure 1. Location map of the Matanuska Glacier (Strasser et al., 1996)

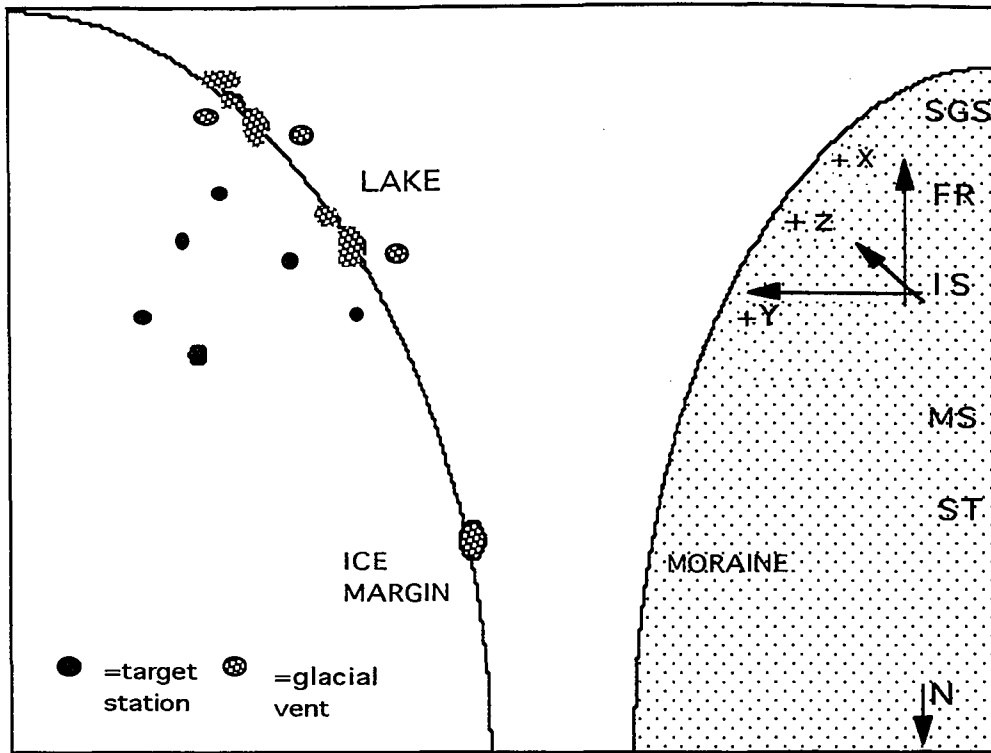


Figure 2. Configuration of survey. Instrument(IS), stream gauging station(SGS), fixed reference(FR), meteorological station(MS), and stationary target(ST) on moraine and target stations (black dots) on ice.

meteorological station in the vicinity of the stationary target on the moraine (Figure 2). The distance from the survey station to the stationary target was approximately the same as the distance from the survey station to the closest stake on the ice. Instrumentation for the survey was a total-station theodolite. Survey procedures began with leveling the instrument and then turning an angle from the fixed reference. Each survey consisted of measuring the distance to each of the six stakes and the stationary target.

Atmospheric corrections were applied during data reduction following the field season, based on meteorological data collected with the survey data. Average calculated atmospheric corrections for the station furthest from the survey station was ± 3.5 mm. An unquantified amount of error may be associated with the properties of the air mass through which the survey was conducted. Most of the travel path of the theodolite's infrared beam was over moraine and debris flows, which should have the average characteristics of the air mass sampled by the met station. Part of the beam's travel path was over the glacier, however, and thermal gradients do exist near the ice surface. Because the beam did not have far to travel over the ice (generally much less than 30% of the beam's path), it is assumed here that these errors are small.

The survey data were reduced from a slope distance, vertical angle, and horizontal angle to *xyz* coordinates (Figure 3). The survey

station is at the origin of the coordinate system. The positive x-direction is from the survey station (IS) to the fixed reference (FR), which was chosen to be approximately normal to ice motion so that ice moves in the negative y-direction. The recorded ablation was added to the surveyed ice-surface elevation to provide an ablation-free ice motion record.

There were three operational errors that affected the distance and angle measurements. The first of these is the error associated with locating the EDM reflecting prism on the "foot" used to give a locally averaged ice surface. The second operational error is the error associated with leveling the reflecting prism so that it is directly over the desired point of the ice surface. The third is the operator error of sighting the target in the instrument cross-hairs.

Over the 96 days of surveying, the repeated measurements of the stationary target, after atmospheric corrections, yielded a range distance uncertainty of ± 0.2 cm (1 standard deviation). Horizontal angle and vertical angle uncertainties were determined to be ± 28 sec and ± 29 sec, respectively. At target station distances approximately equal to the distance from the survey station to the stationary target, a position error ellipse can be defined. The ellipse's long axis would be in the approximate across-glacier direction having a length of 5.0 cm (calculated as: $\text{Range} * \sin(\theta \pm 28'')$). The ellipse's short axis would

Map of Station Positions

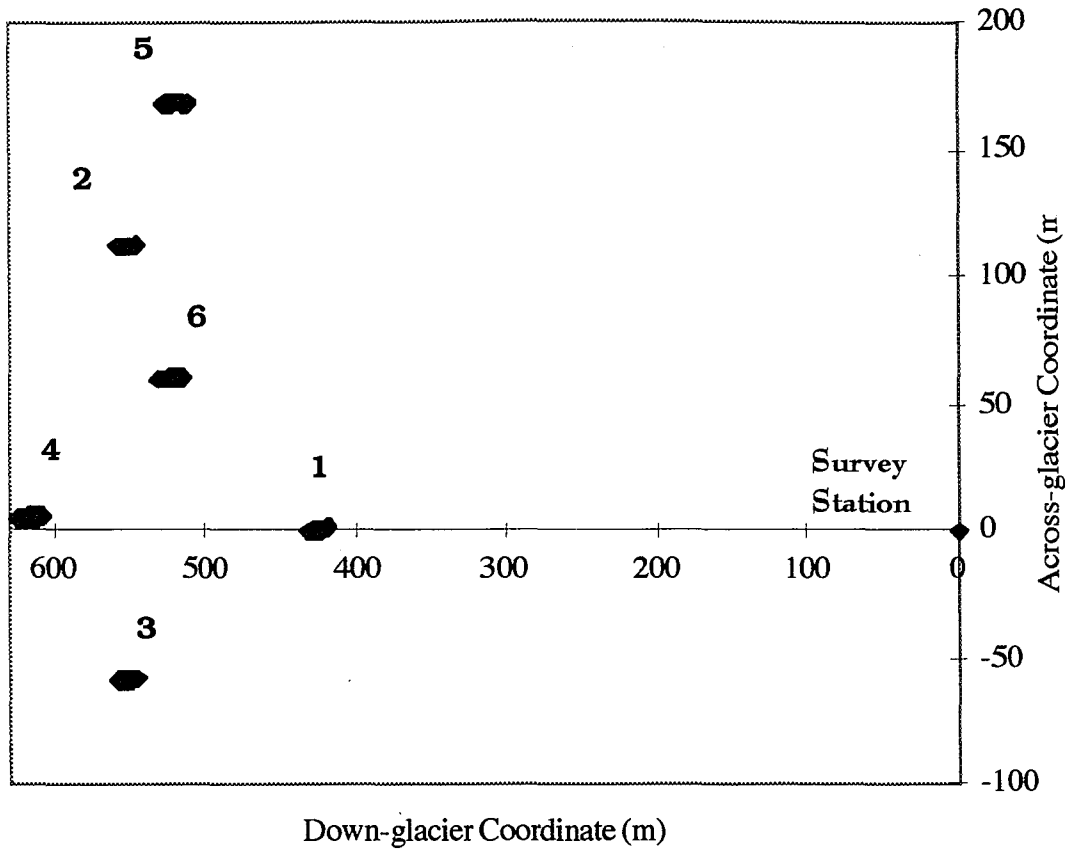


Figure 3. Map of study area in the western portion of the terminus. Survey station is located at the origin. All station positions throughout the melt season are shown for the six targets.

be in the down-glacier direction and of length 0.2 cm. The errors in the across- and elevation- coordinates would define a larger ellipse for the target furthest from the survey station.

Three schedules of surveying were followed to monitor events of high, low, and intermediate frequency. A short-term, or “high-intensity,” schedule consisted of measuring all six targets on the ice and the stationary target at fifteen minute intervals for periods of 6 to 8 hours at least once a week. For the high-intensity schedule, EDM reflecting prisms were placed into the PVC stakes, rather than being held by a rodperson. These data have not been completely processed yet, but preliminary examination of the data suggests that distances obtained with a 15 minute sampling interval differ by less than the location error ($\approx \pm 0.2$ cm). The purpose of the long-term schedule was to have a record of the low frequency seasonal trend. The long-term schedule consisted of a weekly measurement of all stations at a particular time on a particular day every week. This schedule was planned for in case numerous velocity or uplift “events” should have been frequent enough to obscure the seasonal signal.

An intermediate-term schedule consisted of station measurements at times of daily low and high glacial vent discharge. Daily low vent discharge was, as a summer average, approximately 10 am and daily high vent discharge was approximately 10 pm. A record of horizontal speed from the intermediate schedule is somewhat noisy,

so for clarity, only the data collected during the daily low discharge were used to construct a record of speed for discussion here. These data were selected for record construction because this scheduled time was adhered to the most rigorously.

Horizontal Speed Record Construction

Due to the good precision in the y-direction and large errors in the x- and z- directions, daily changes in the y- direction were used for the construction of the horizontal speed record. This required a fundamental assumption that the daily change in the down-glacier coordinate is approximately equal to the daily change in the range measured for each of the stations. Because each of the target stations was at approximately 90° to the fixed reference, the assumption was successfully tested for each station (Figure 4). Each station's daily position was mapped and an average direction of motion was determined (Figure 5, Appendix 1). The horizontal speed was determined for each station by:

$$s = (\Delta y / \Delta \text{time}) / \cos \Psi$$

where Ψ is the average angle the target station's motion made with the surveying station throughout the summer. The speed curves of the six target stations were stacked and a 7 point moving average was applied to the stacked record (Figure 6, Appendix 2). The uncertainty of the speed with this method of record construction is $\pm .33$ cm/d for an .

Station 2 Daily Change in Donw-glacier Coordinate and Range

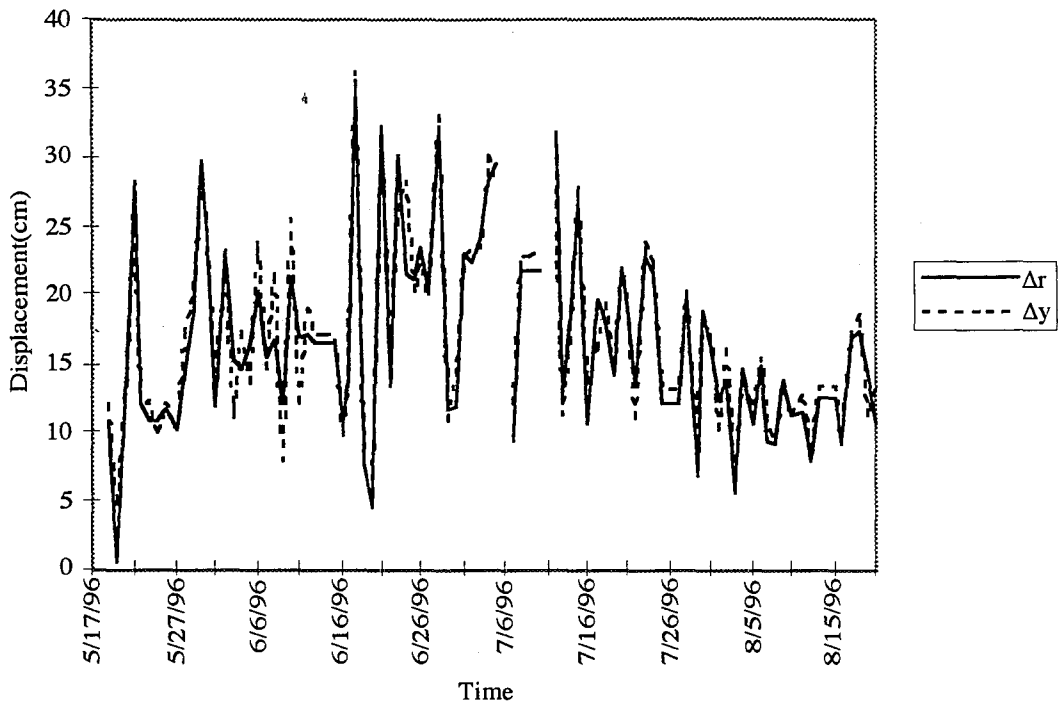


Figure 4. Daily change in range distance and down-glacier coordinate for one target station. Since the daily changes are approximately equal, the change in the down-glacier coordinate was used for speed calculations.

average speed of 16.7 cm/d. Conversely, for an average speed of 20.1 cm/d, as calculated as the magnitude of the sum of the squares of the *xyz* coordinates, the uncertainty is ± 8 cm/d. Large uncertainties in the *z*- direction prevent construction of an 'uplift' record. The general trend for all stations' elevations was increasing elevation over the course of the summer (Figure 7, Appendix 3).

SURVEY ANALYSIS

Horizontal Speed

The average speeds for all six station are very nearly the same so that there is not a recognizable spatial gradient (Figure 3). Because of this, target stations nearest the ice margin cannot be grouped together and described as faster than the stations further up-ice, nor is the converse true. The stations cannot be classified by local topographic expressions either, although topography did influence the direction of motion. For instance, the station with the greatest average speed (ranked 1) was situated on the nose of a local topographic ridge. The station with the slowest average speed was also located on a topographic ridge, which was located adjacent to the ridge of station 1. The same is true when stations located in topographic troughs are compared. A comparison of flow lines does not yield an obvious trend either.

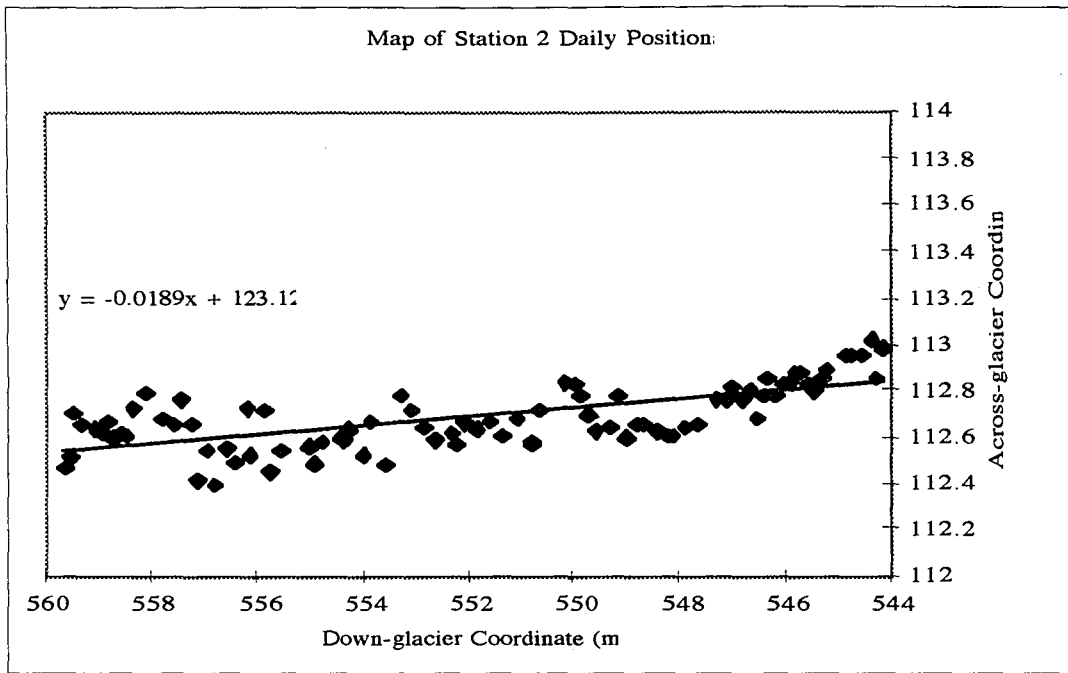


Figure 5. Map of one station's daily positions. Best fit line and its angle are given to illustrate method of development of the speed record. Target is getting successively closer to the moraine with decreasing y values.

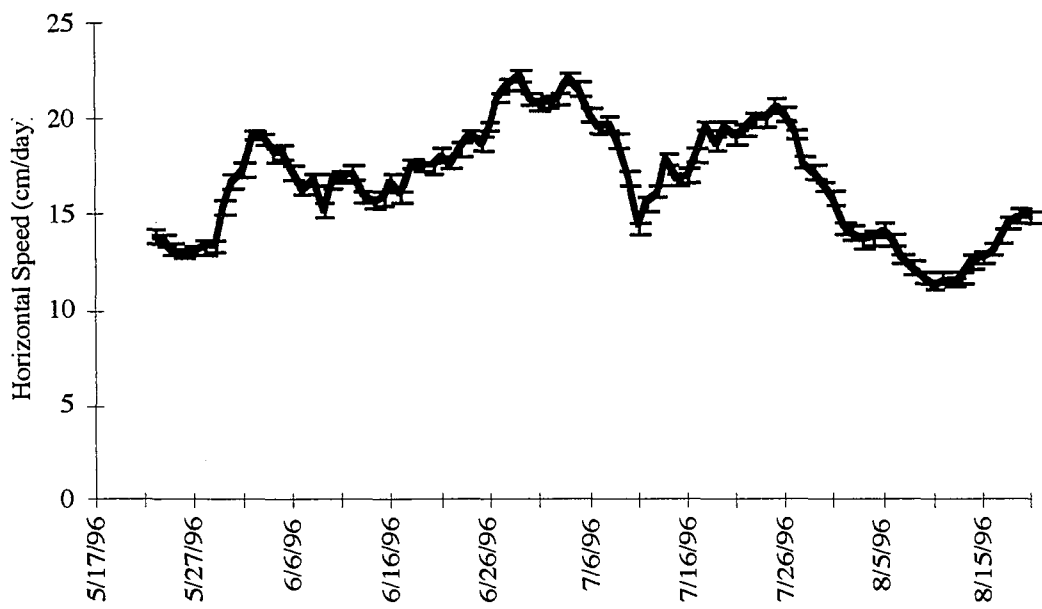


Figure 6. Ice speed record stacked from 6 stations with a 7 point moving average applied to smooth the curve. Error bars are ± 0.33 cm/d.

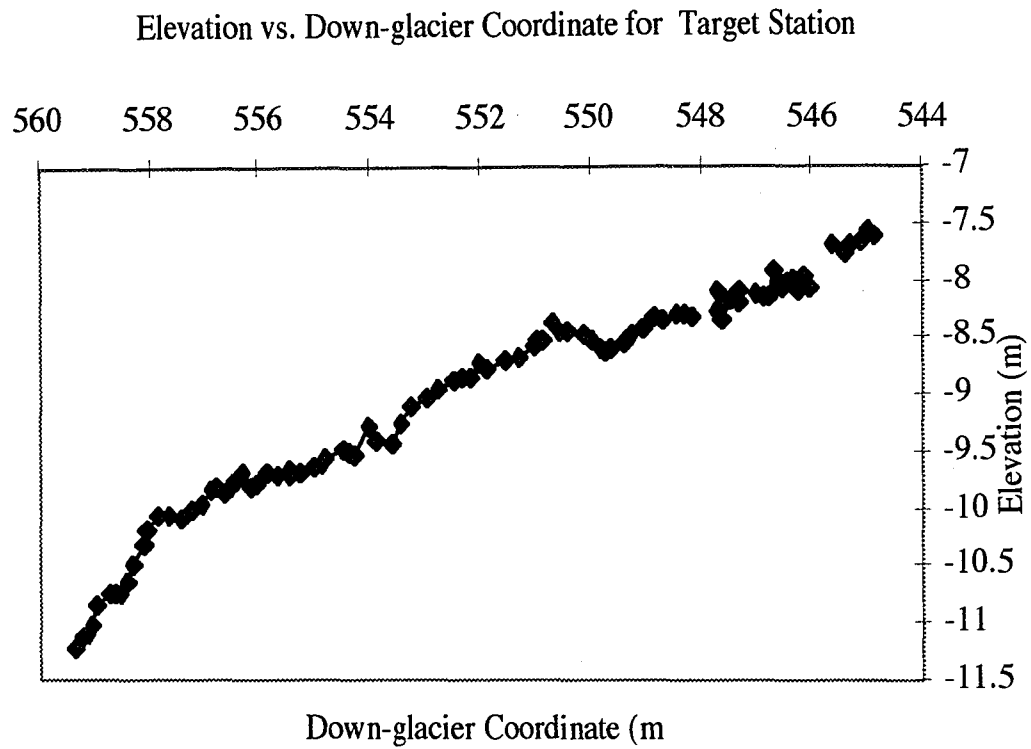


Figure 7. Map of one station's daily positions in the yz plane throughout the summer. Target is getting successively closer to the moraine with decreasing y values.

Subglacial Drainage Inputs

The stacked and smoothed record of horizontal speed has a seasonal trend with maximum speeds in late June and early July (Figure 8). There are three distinct peaks, with short-termed peaks or “spikes” superimposed. The first peak occurred early in June as air temperatures and incoming radiation were increasing. The second peak has two spikes on it. The earlier spike, on June 24, is well correlated to precipitation events, all of which were preceded by increased air temperatures and peak seasonal incoming radiation. Note that a large precipitation event on June 14, accompanied by cool air temperatures, did not generate the same results in the speed as the smaller rain events accompanied by warmer temperatures. The same is especially true for the large rain event of August 5 through 7. The speed spike on July 4 correlates to preceding rain events and concurrent warming temperatures. The air temperature data show significance at the 95 % confidence level to the speed data.

Subglacial Drainage Outputs

The output parameters include a glacial vent pressure record, stacked from two vents in the same local subglacial drainage system, and a stream discharge record collected from a stream fed almost entirely by glacially discharged waters (Figure 9). The stream discharge correlates well with the speed record only early in the summer and late

in the summer. The two major peaks of the discharge are similar in character to the corresponding speed peaks, but the first discharge peak lags behind the respective speed peak by 2 to 5 days, depending on which speed "spike" is considered the peak. The glacial vent pressure correlates to either the speed or the discharge curves at different times. For example, the vent pressure reaches a relative maximum at the same time as the speed reaches a maximum on June 26. Similarly, the pressure correlates to a discharge maximum on July 8. The nature of the vent pressure record may only be reflecting local drainage system conditions, or it may be indicating that the system is too complex to make simple generalizations. Other glacial vent data include the sediment concentration of subglacially discharged water. The vent sediment concentration significantly correlates to the stream discharge at the 95% confidence level (Figure 10).

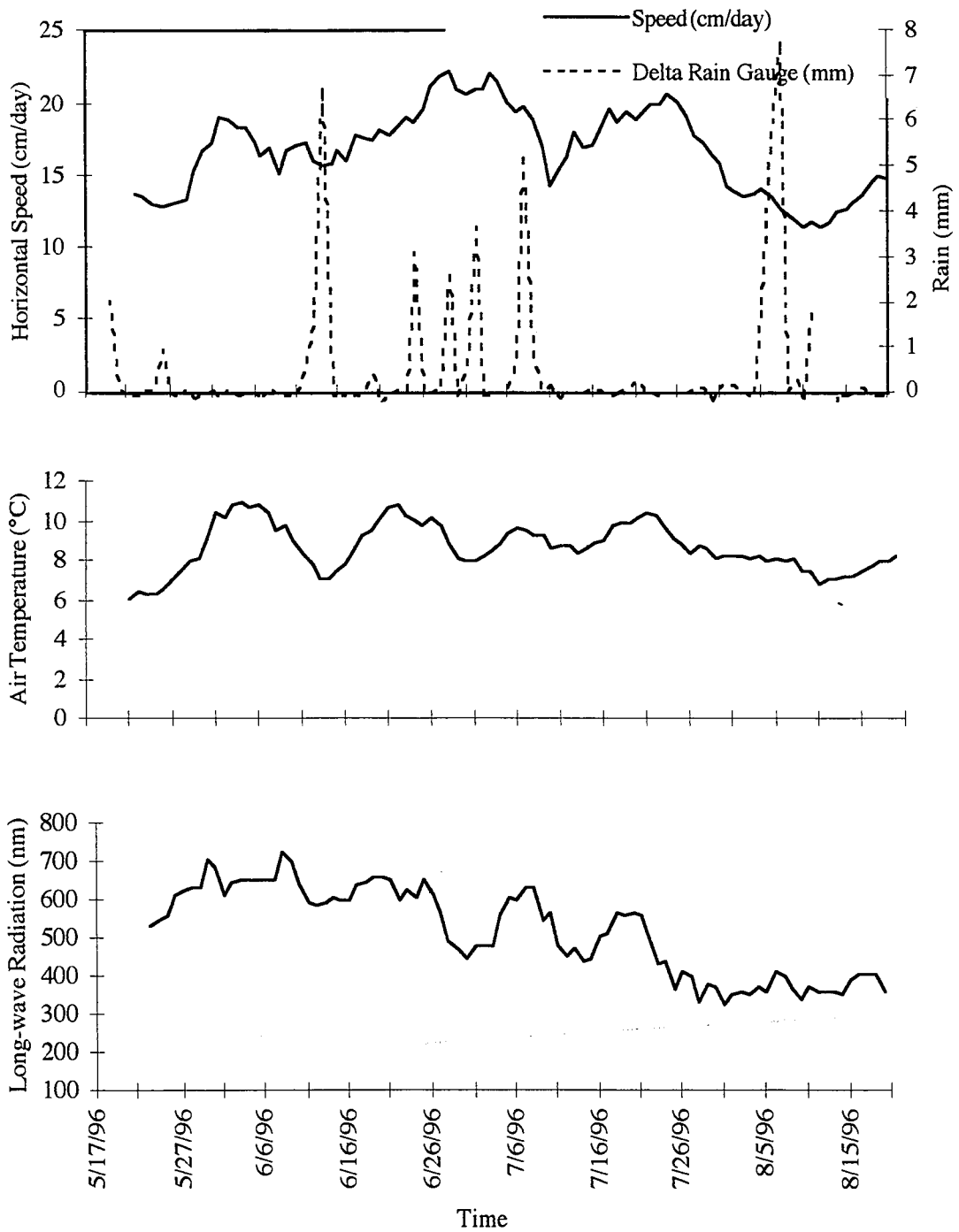


Figure 8. Glacier speed and input proxies. Horizontal ice speed and rain events, air temperature, and incoming radiation from top to bottom.

DISCUSSION

Field Observations

Field observations at the ice margin are drawn upon here to help conceptually model, or draw inferences about, the configuration of the subglacial drainage system. Throughout the melt season, the subglacial vent discharge data provide “boundaries” to data interpretation. A very generalized summary of the subglacial vent characteristics can be made. For the first few weeks of the study period, there were few vents fountaining along the margin. There were 3 large vents proximal to the study area which were 2 to 3 m in diameter. These large vents sometimes fountained to approximately 1 m in height. Associated with the large vents were approximately 5 much smaller vents. The small vents had orifices of the size of a quarter at the beginning of the melt season, but by mid-summer vents had grown to nearly 1 m wide and in many areas, had merged with several other vents. As the smaller vents grew in size and in number through the summer, the larger vents quit fountaining as high as they had and instead upwelled

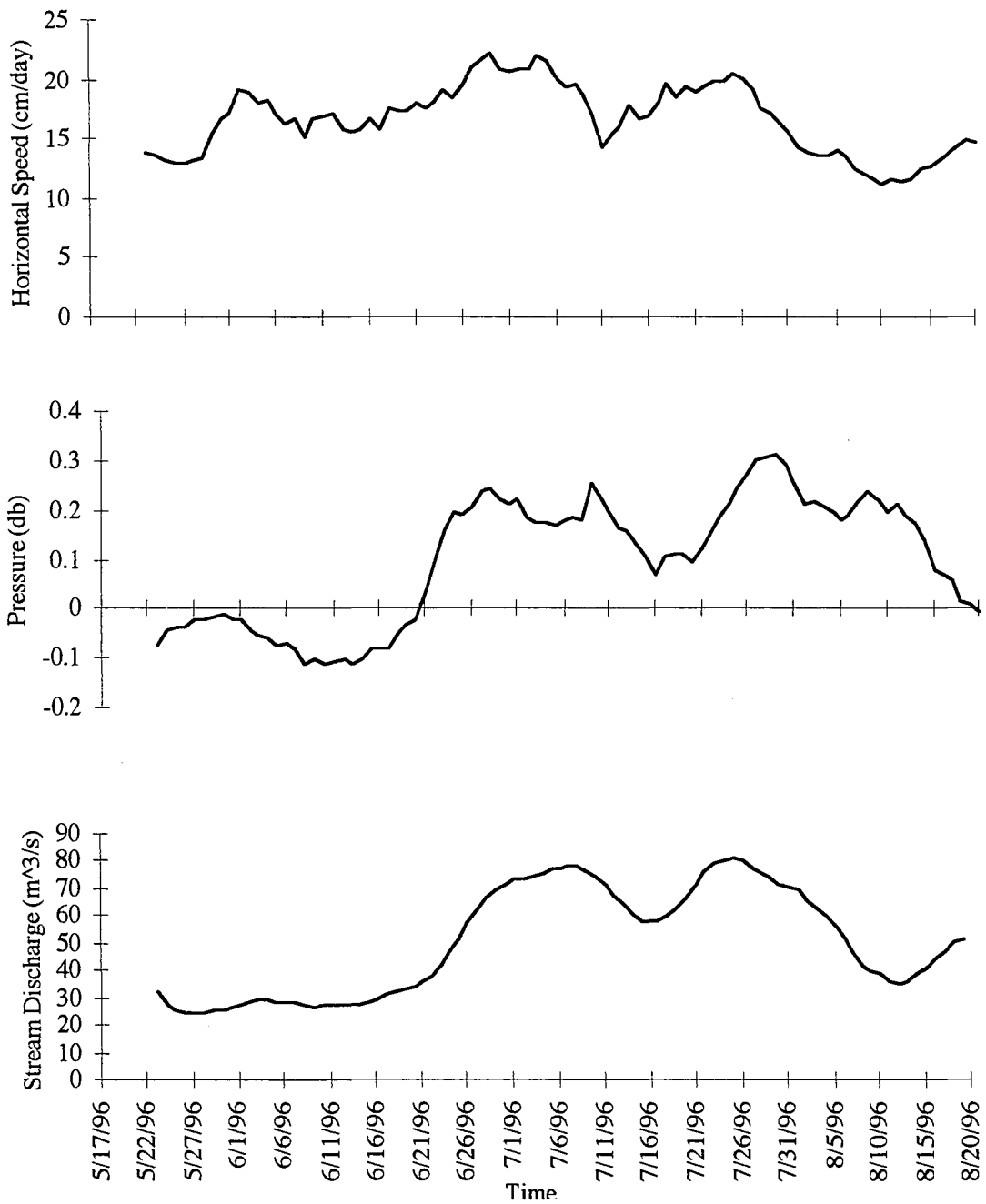


Figure 9. Glacier speed and outputs. Horizontal ice speed, glacial discharge vent pressure, and stream discharge from top to bottom.

Stream Discharge and Glacial Vent Sediment Concentration

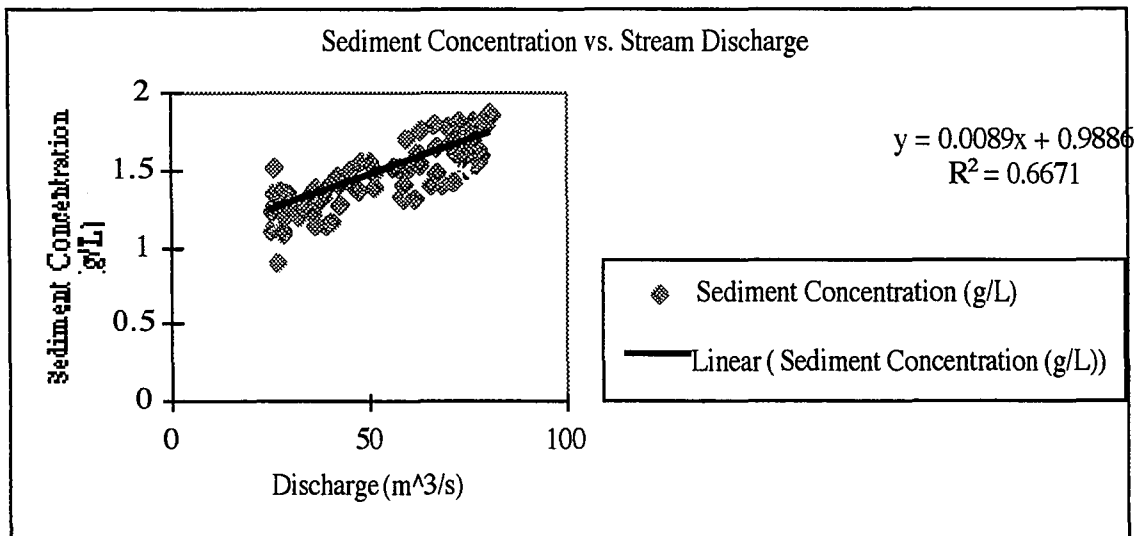
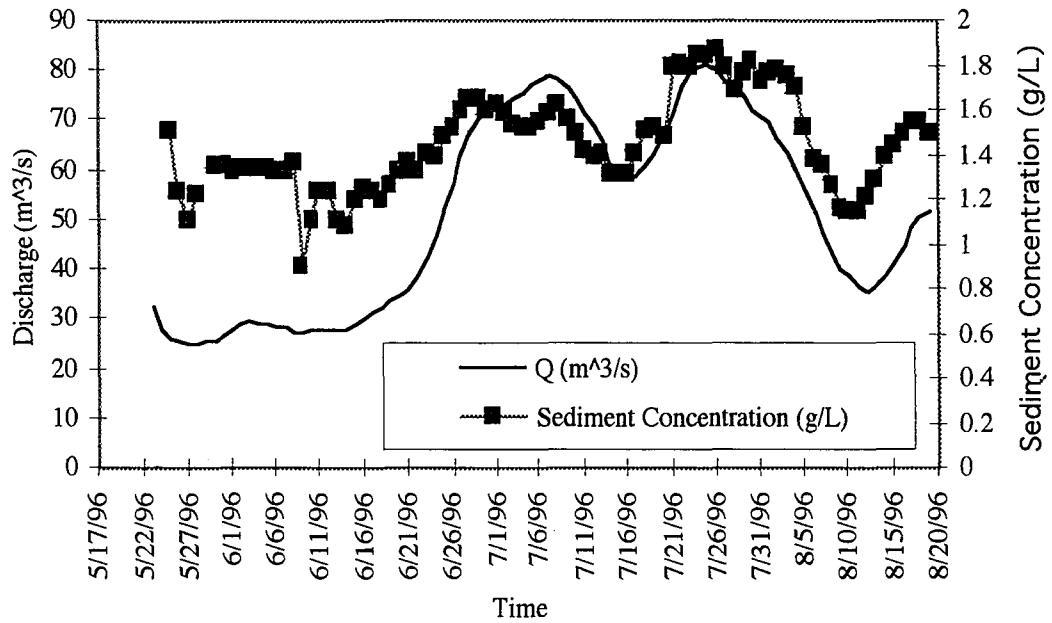


Figure 10. Relationships between glacial vent discharge versus stream sediment concentration.

gently. One feature common to all of the fountaining vents was the growth of frazil ice, which, in many localities grew into large terraces. Frazil ice growth was common even during periods of warm summer air temperatures.

Additionally, the area \approx 10 to 15 m to the south and \approx 20 m to the east of station 5 became fractured in late July. Occasionally, when standing at station 5, one could hear and feel the ice "pop." Very small upwellings of dirty water were also observed within the fractures. Station 5 was located at the base of an ice fall.

Conceptual Model of Link

A number of assumptions have been made to develop the conceptual model linking ice motion to the subglacial drainage system. The first of these is that speed is approximately equal to water storage at the bed of the glacier. It is also assumed that the drainage system consists of pipes that have a capacity so that water goes into storage when inputs exceed that capacity (and vice versa). Water storage takes place in canals and cavities so that the sum of the canals and cavities approximates the speed. Finally, it is assumed that the pipes grow with high water pressure so that on Figure 11, an increasing trend implies input exceeded pipe capacity and a decreasing trend implies the inputs were less than pipe capacity.

Early in this survey, the glacier's horizontal speed rapidly

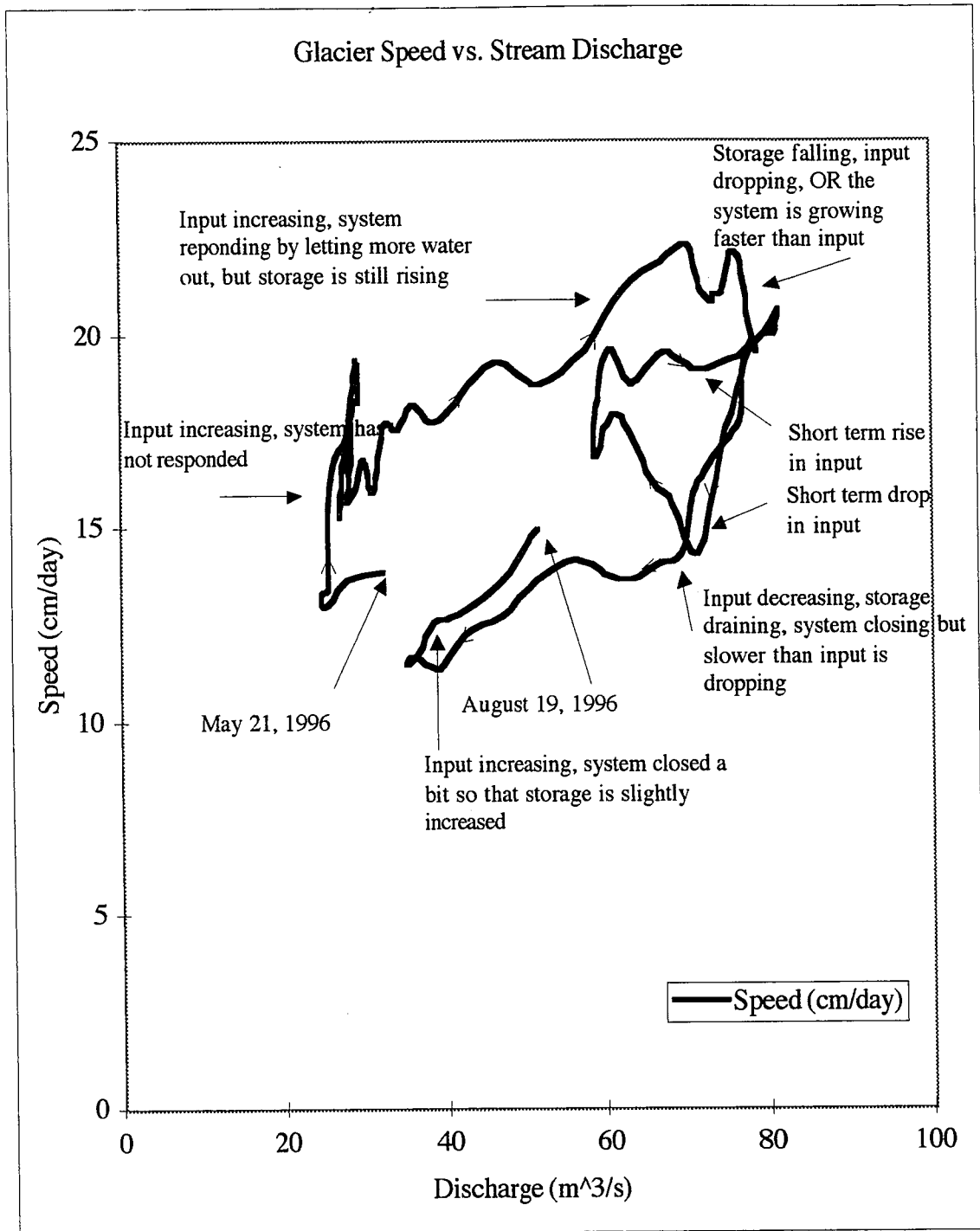


Figure 11. Hysteresis loop of glacier speed versus stream discharge with inferences about the subglacial drainage system.

increased with almost no change in discharge, suggesting that the subglacial drainage system had not responded to the influx of water with melt season onset. Discharge lagging behind the speed hints that water was being stored at the glacier's sole until the drainage system could accommodate the influx. By mid-June, the system had begun to respond to the increased inputs by allowing more water to drain while still retaining some water in storage at the bed. Also, the sediment concentration data indicates that the subglacial system may have been growing by removing till at the bed of the glacier.

Early in July, the water storage fell and input dropped, or else the system was growing faster than input entered the system. A smaller loop was defined over a period of approximately 20 days (Figure 11). The horizontal speed decreased to a relative minimum on July 11 and increased to a relative maximum on July 25. The outputs did not reach minima until July 16 (approximately a five day lag). Outputs, especially the stream discharge, increased at rates faster than the speed increased. The stream discharge peaked on July 25 as well, but the sediment concentration did not reach a maximum until July 28. The sediment concentration peak was the summer maximum. The characteristics of the three sides of the small loop (as per following the small arrows) suggest that the system capacity was unchanged by the change of inputs. Following peak speed and peak outputs, all parameters (ins and outs) decreased to minima between August 11 to

13. The weather was very autumn-like over this two week period so that water storage was possibly draining and the system began closing, but at a slower rate than the input decreased. A warm, sunny event on August 14 increased inputs into the drainage system. Because the system had closed somewhat, storage rose and therefore the speed increased.

CONCLUSIONS

An areal speed gradient of this small-scale study is not apparent in the data. The ice motion survey recorded the ice flowing out of the overdeepening. The drainage system was pressurized, as supported by the presence of fountaining and upwelling discharge, frazil ice terraces, and fractures that may have formed due to the high subglacial water pressures. Output parameter increases lagged behind increases of the ice speed, suggesting that there was water storage at the glacier's bed until the drainage system was able to accommodate the large fluxes of seasonal melt water. The speed peaked in late June and early July, which is when the melt water inputs, or at least the melt water input proxies, were the greatest. The subglacial drainage system configuration is conceptually modeled as pipes with braided canals in till and cavities throughout the melt season. The data do not directly support the current hypothesis of a braided system configuration, but the data does fit the model reasonably well. The configuration of the subglacial

drainage system at the Matanuska Glacier did control the effective pressure and therefore, the horizontal sliding speed. The dominant subglacial drainage configuration(s) is important to the theories of the growth and accretion of basal ice and it is important when considering debris entrainment and transport models of ancient systems.

REFERENCES

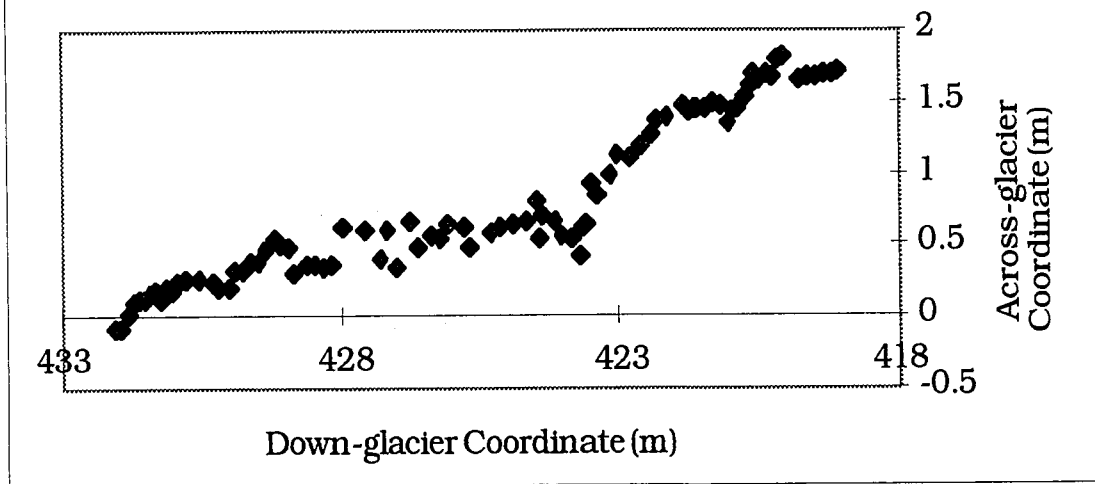
- Alley, R. B., K. M. Cuffey, E. B. Evenson, D. E. Lawson, and J. C. Strasser. In press. Glacial debris transport: physical constraints. *Quaternary Science Review*.
- Arcone, S. A., D. E. Lawson, and A. J. Delaney. 1995. Short-pulse radar wavelet recovery and resolution of dielectric contrasts within englacial and basal ice of Matanuska Glacier, Alaska, U. S. A. *Journal of Glaciology*, 41: 68-86.
- Blake, E. W., U. H. Fischer and G. K. C. Clarke. 1994. Direct measurement of sliding at the glacier bed. *Journal of Glaciology*, 40: 595-599.
- Harper, J. T., N. F. Humphrey, W. T. Pfeiffer, and B. C. Welch. 1996. Short wavelength variations in the horizontal velocity field of a valley glacier in Colbeck, S. C. (Ed) *Glaciers, ice sheets and volcanoes: A tribute to Mark F. Meier*. USA Cold Regions Research Engineering Laboratory, 96- 27.
- Hooke, R. L. And V. A. Pohjola. 1994. Hydrology of a segment of a glacier situated in an overdeepening, Storglaciären, Sweden. *Journal of Glaciology*, 40: 140-148.

- Iken, A. 1977. Variations of surface velocities of some alpine glaciers measured at intervals of a few hours. Comparison with arctic glaciers. *Zeitschrift für Gletscherkunde und Glazialgeologie*, 13: 23-35.
- Iken, A. 1981. The effect of the subglacial water pressure on the sliding velocity of a glacier in an idealized numerical model. *Journal of Glaciology*, 27: 407- 421.
- Iken, A., H. Röthlisberger, A. Flotron, and W. Haeberli. 1983. The Uplift of Unteraargletscher at the beginning of the melt season. A consequence of water storage at the bed? *Journal of Glaciology*, 29: 28- 47.
- Iken, A. and R. A. Bindchadler. 1986. Combined measurements of subglacial water pressure and surface velocity of the Findelngletscher, Switzerland. Conclusions about drainage system and sliding mechanism. *Journal of Glaciology*, 32:101-119.
- Iverson, N. R., B. Hanson, R. L. Hooke, and P. Jansson. 1995. Flow mechanism of glaciers on soft beds. *Science*, 267: 80- 81.
- Kamb, B. 1987. Glacier surge mechanism based on linked- cavity configuration of the basal water conduit system. *Journal of Geophysical Research*, 92(B9): 9083- 9100.
- Lawson, D. E. 1979a. Characteristics and origins of the debris and ice, Matanuska Glacier, Alaska. *Journal of Glaciology*, 23: 437-438.

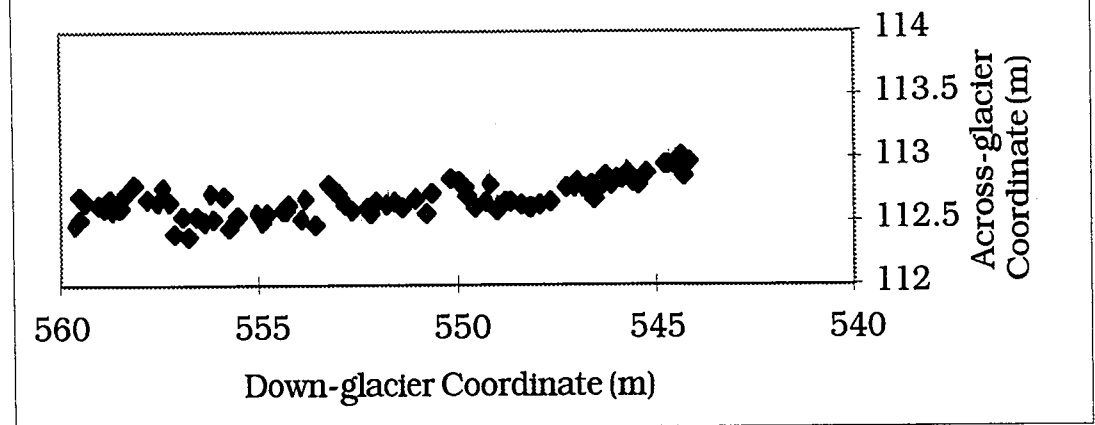
- Lawson, D. E. 1979b. Sedimentological analysis of the western terminus region of the Matanuska Glacier, Alaska. *CRREL Report* 79- 9.
- Lawson, D. E. 1993. Glaciohydrologic and glaciohydraulic effects on runoff and sediment yield in glacierized basins. *CRREL Monograph* 93- 2.
- Meier, M. F. 1960. Mode of flow of Saskatchewan Glacier, Alberta Canada. U. S. Geological Survey Professional Paper 351, 70 p.
- Paterson, W. S. B. 1994. *The Physics of Glaciers*. New York: Pergamon Press, 480 p.
- Röthlisberger, H. 1972. Water pressure in intra- and subglacial channels. *Journal of Glaciology*, 11: 177- 203.
- Strasser, J. C., D.E. Lawson, G. J. Larson, E. B. Evenson and R. B. Alley. 1996. Preliminary results of tritium analyses in basal ice, Matanuska Glacier, Alaska, USA: evidence for subglacial ice accretion. *Annals of Glaciology*, 22: 126-133.
- Walder, J. S. and A. Fowler. 1994. Channelized subglacial drainage over a deformable bed. *Journal of Glaciology*, 40: 3- 15.
- Weertman, J. 1961. Mechanism for the formation of inner moraines found near the edge of cold ice caps and ice sheets *in*, Goldthwait, R.P. (ed.) *Glacial Deposits*. Stroudsburg, PA: Dowden, Hutchinson and Ross, Inc., 208- 221.

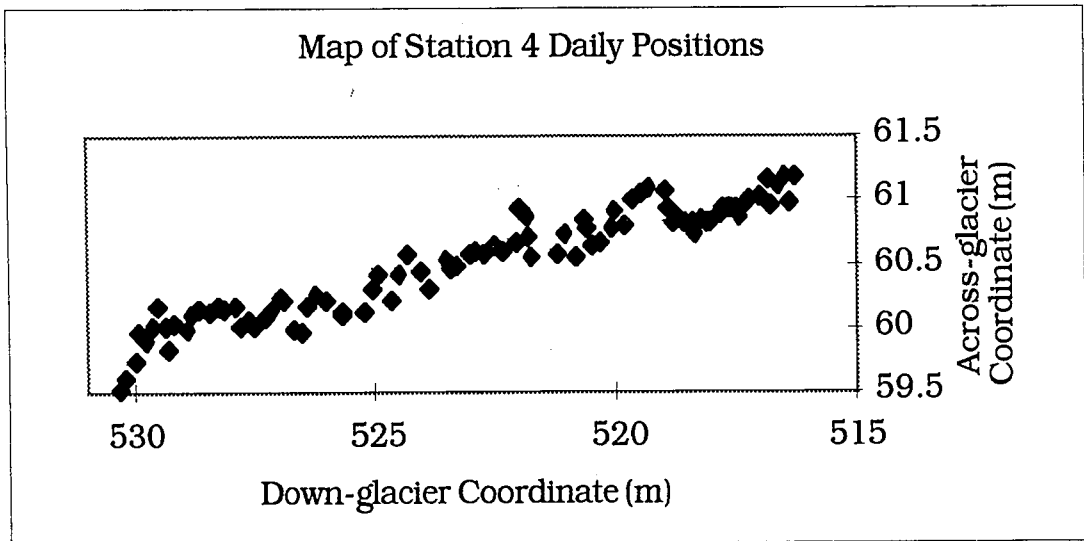
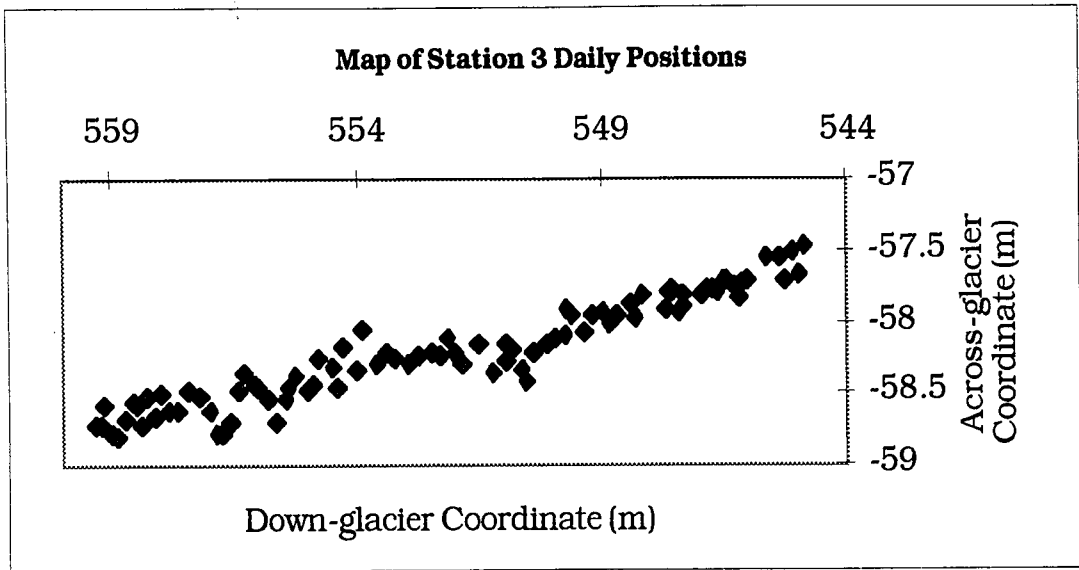
Appendix I: Maps of Station Daily Positions

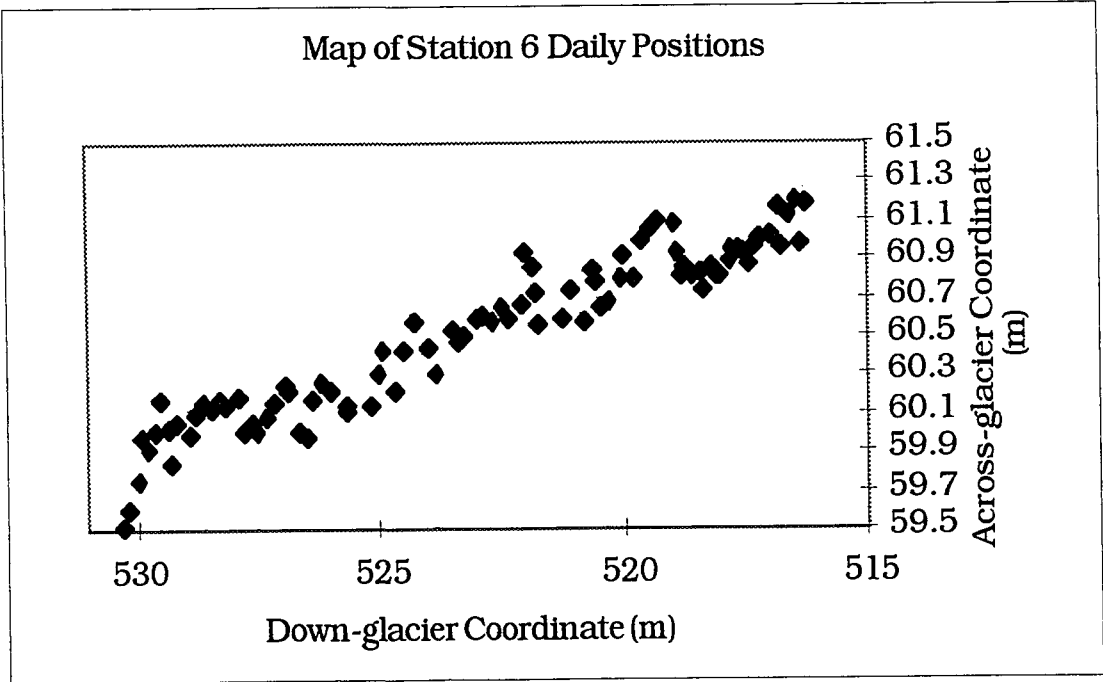
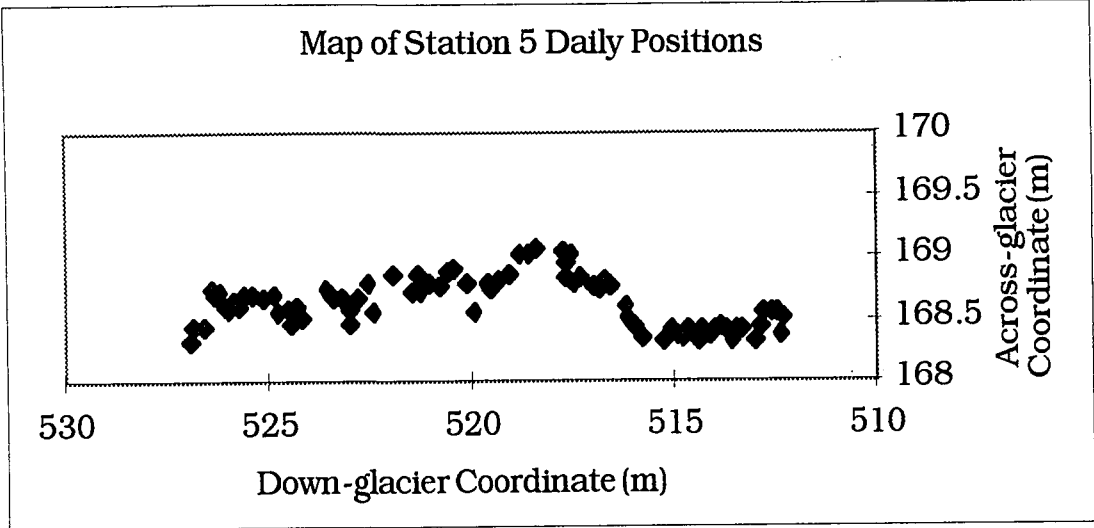
Map of Station 1 Daily Positions



Map of Station 2 Daily Positions

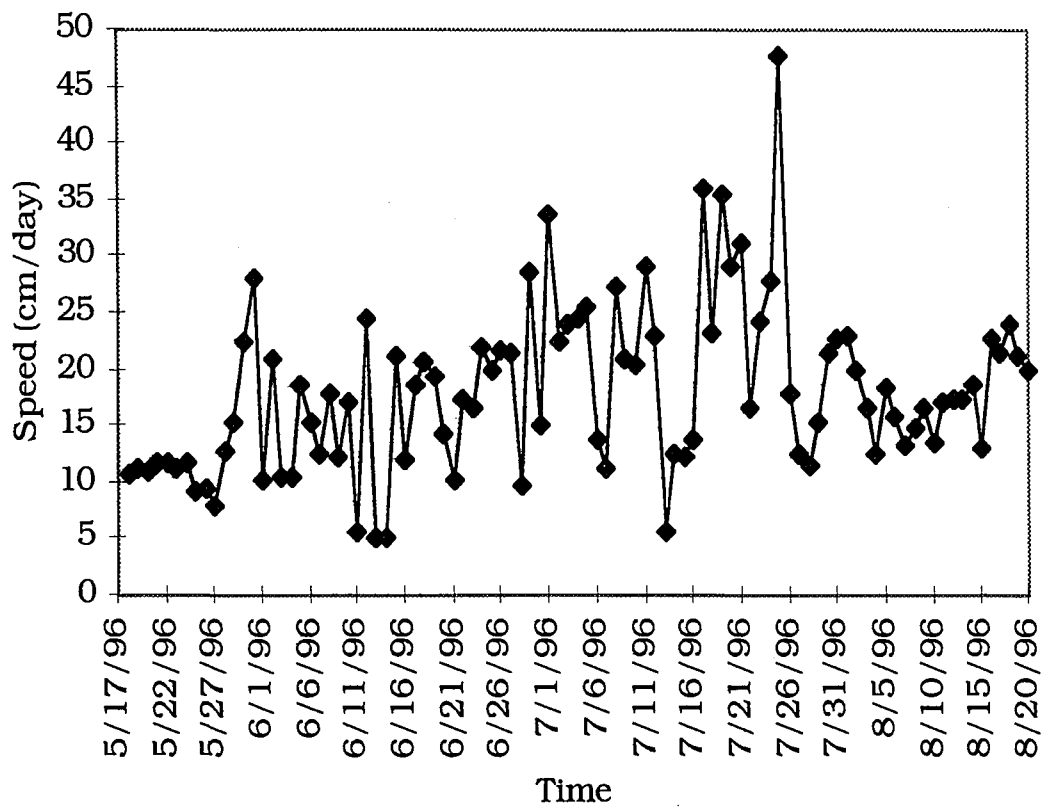




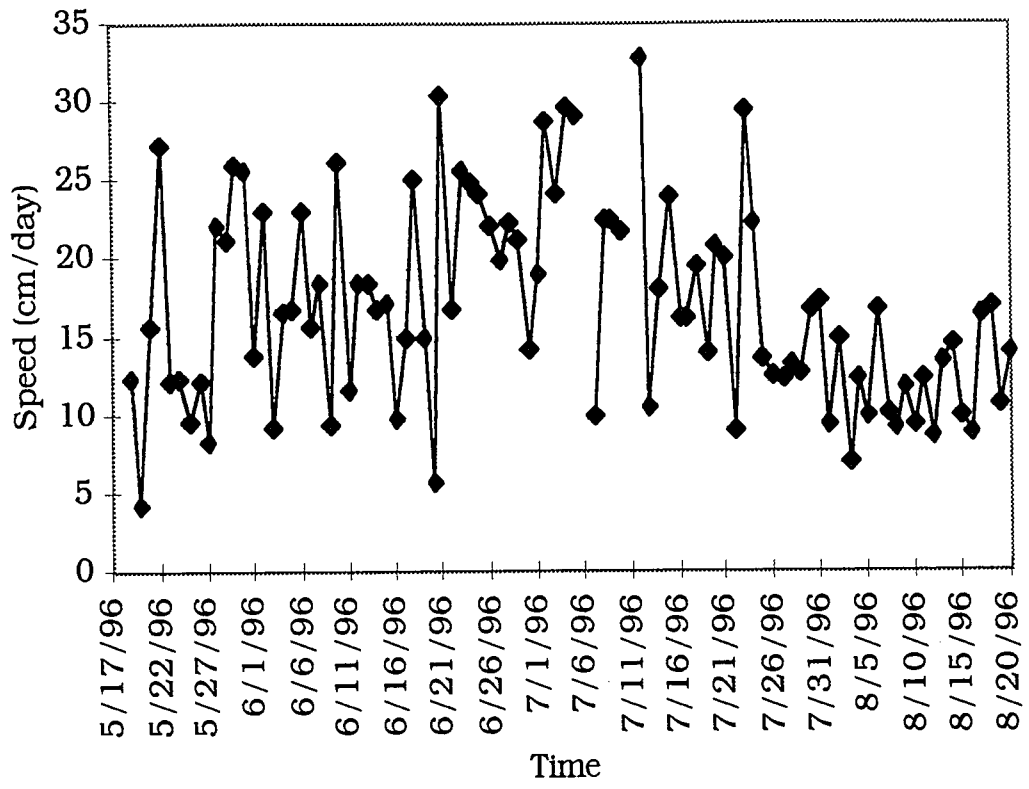


Appendix II: Target Station Ice Speeds

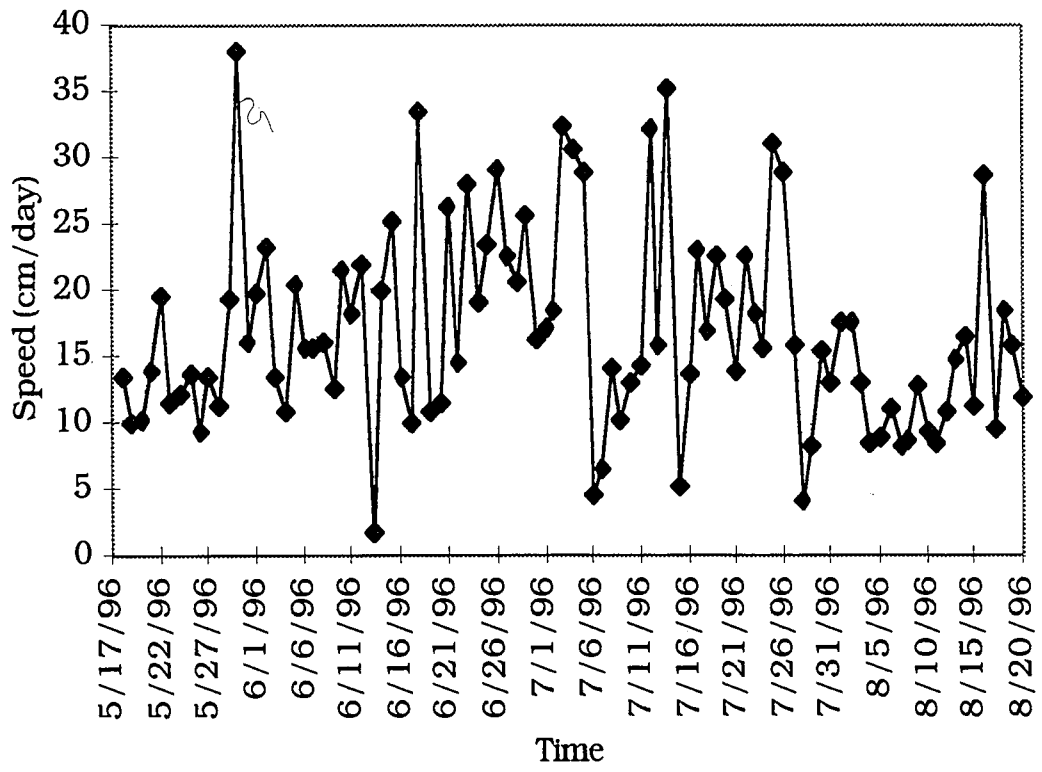
Station 1 Horizontal Speed



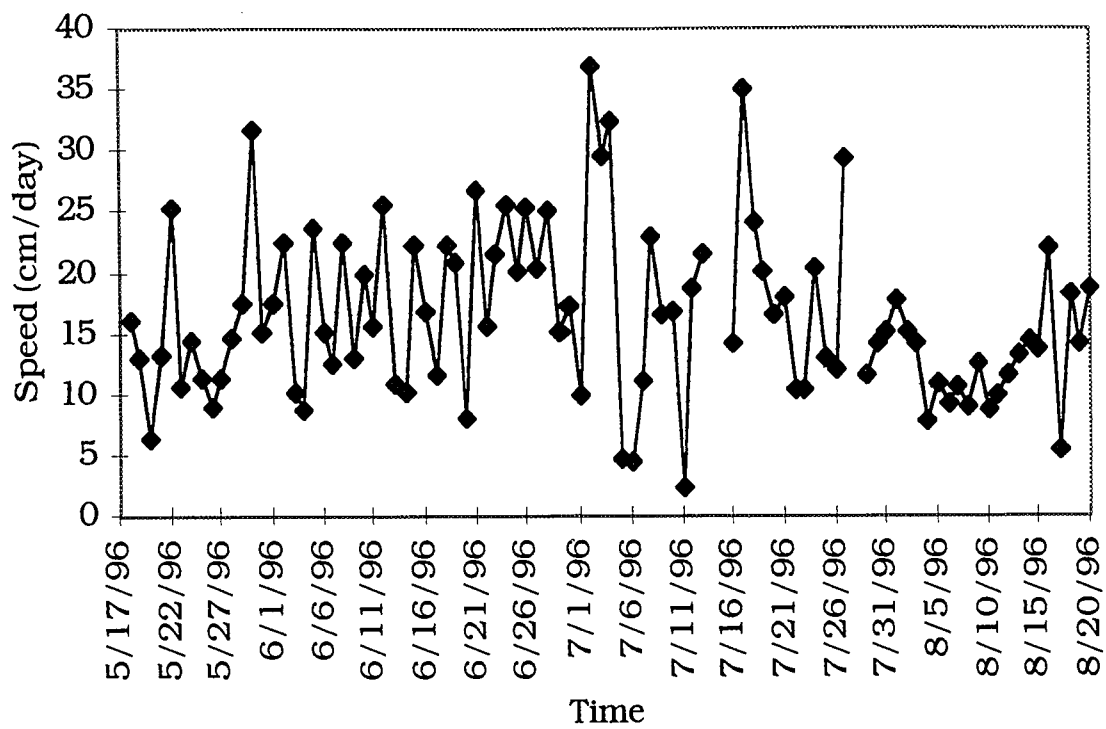
Station 2 Horizontal Speed



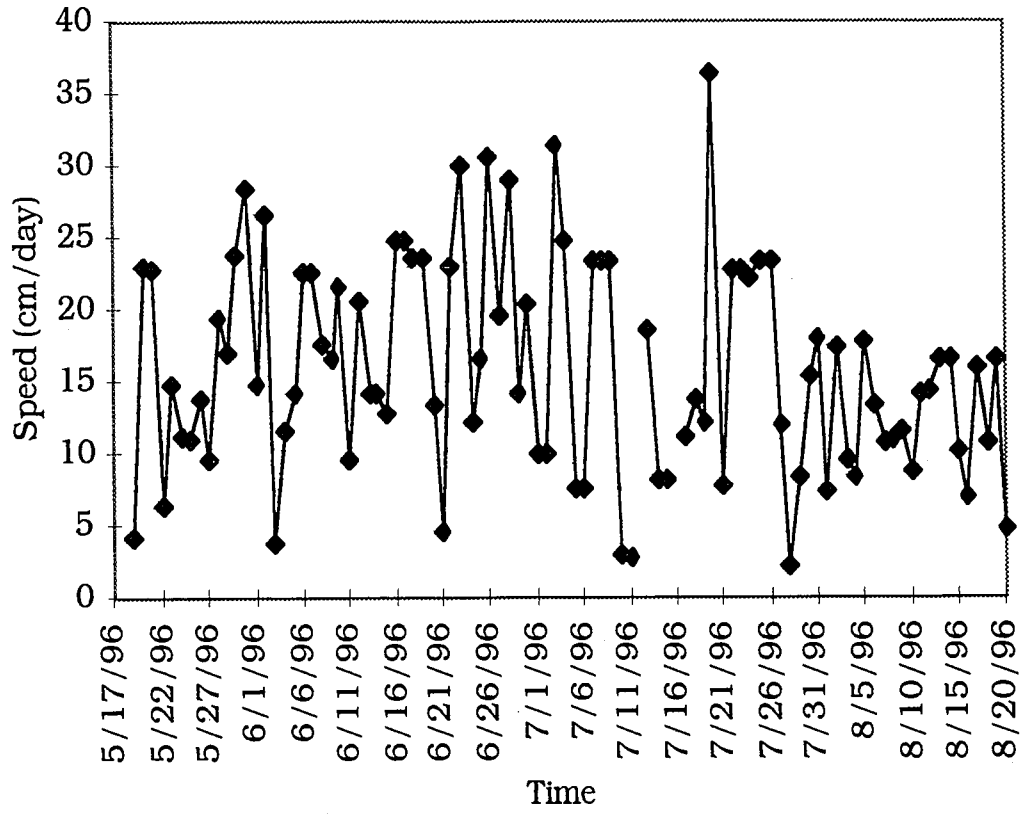
Station 3 Horizontal Speed



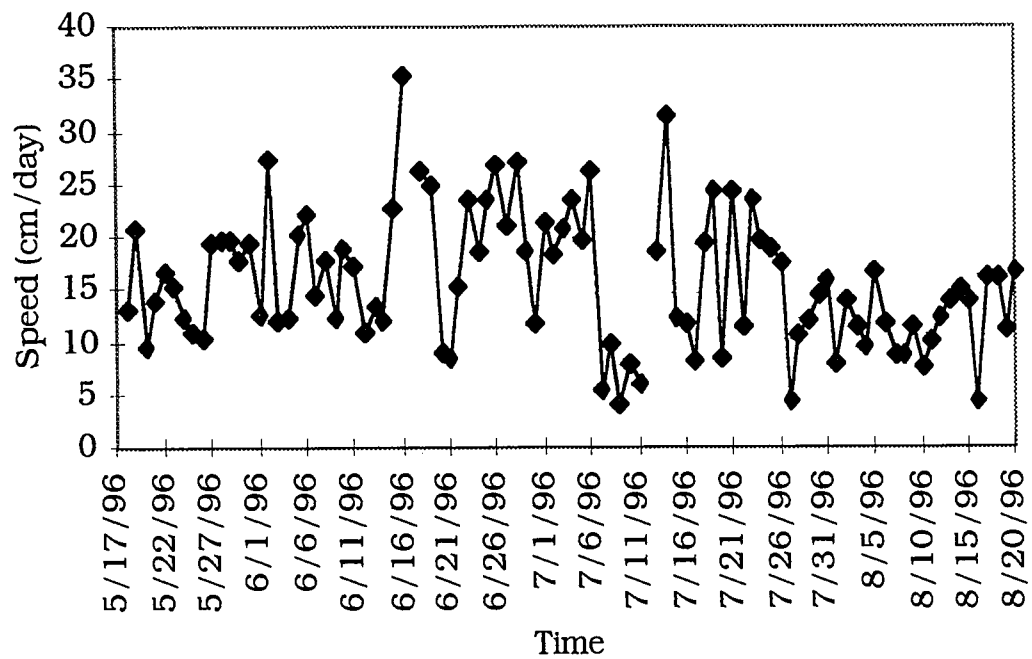
Station 4 Horizontal Speeds



Station 5 Horizontal Speed

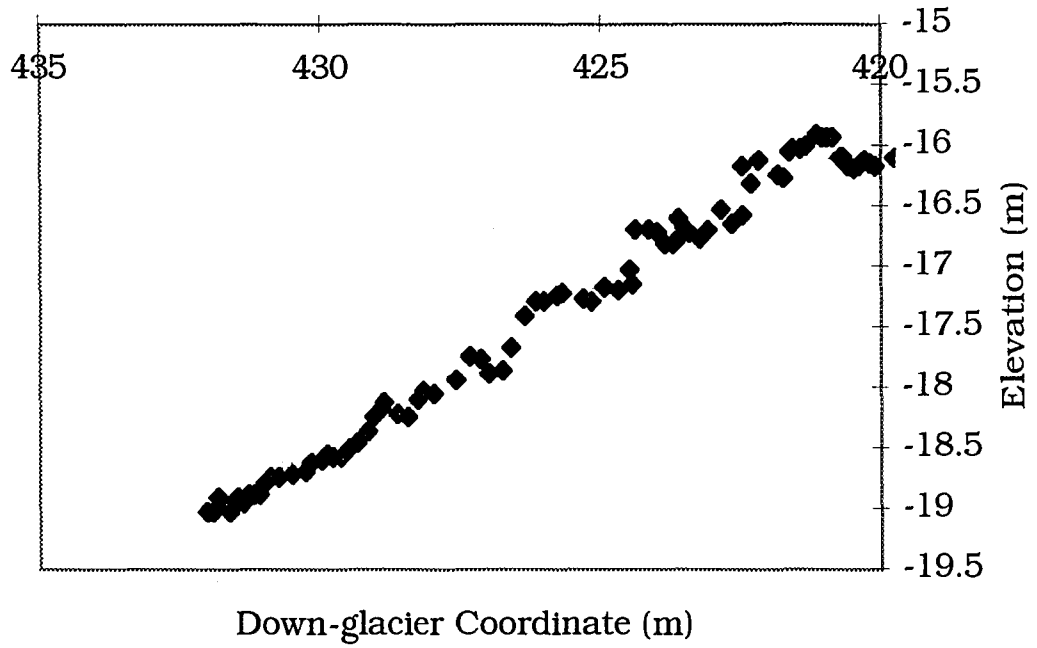


Station 6 Horizontal Speed

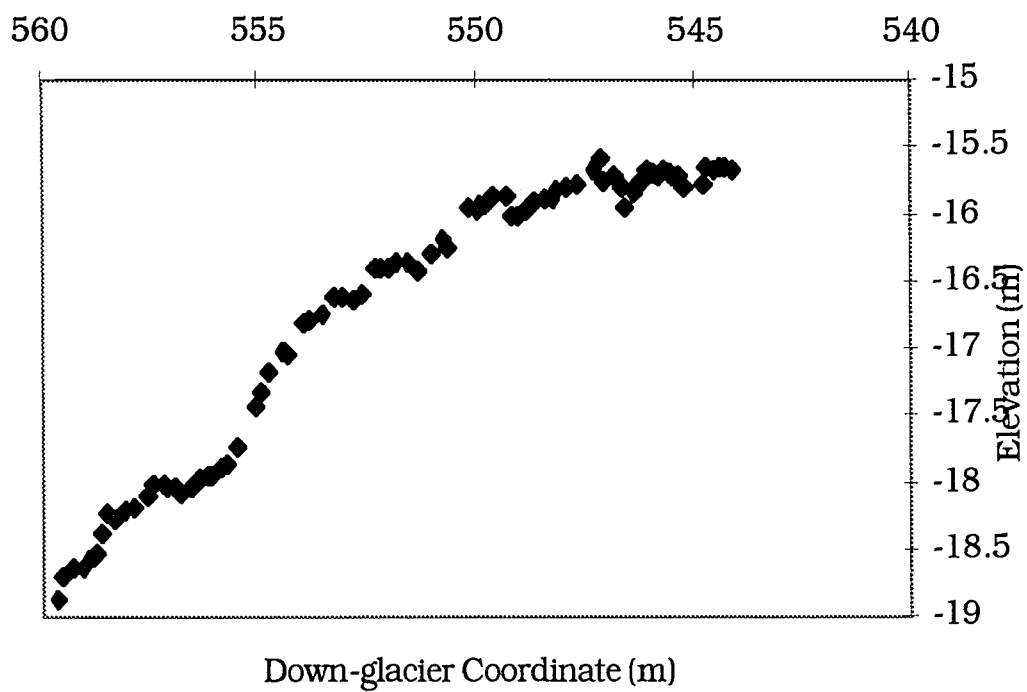


Appendix III: Station Elevations

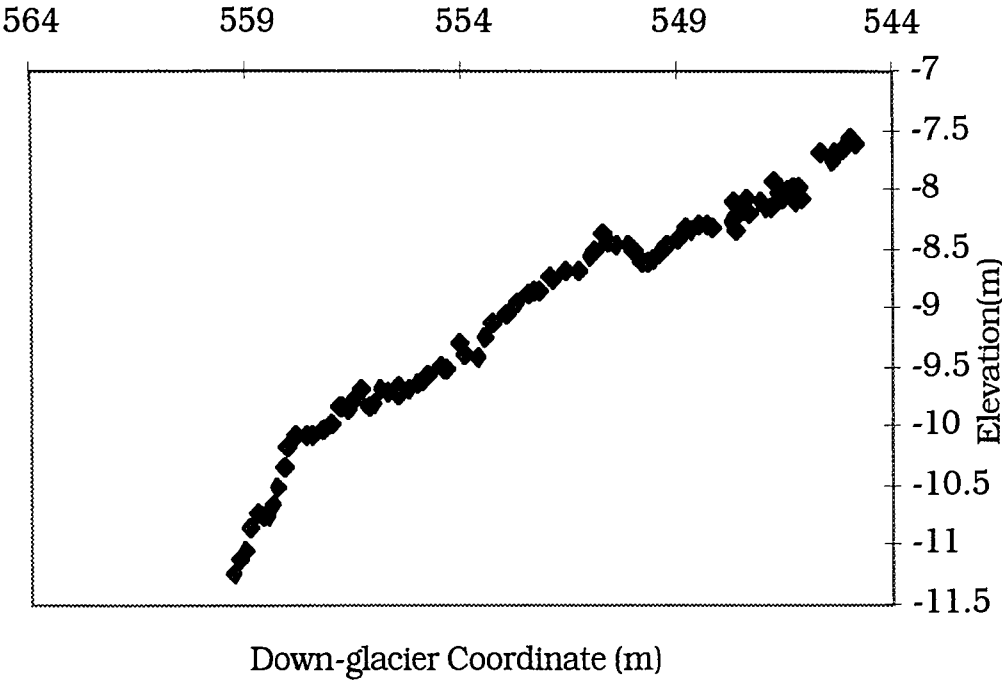
Station 1 Daily Elevations



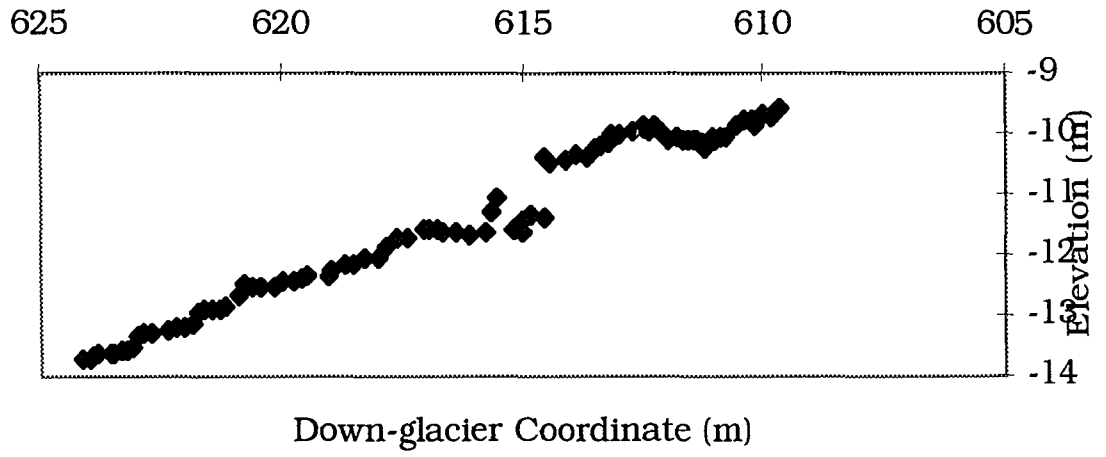
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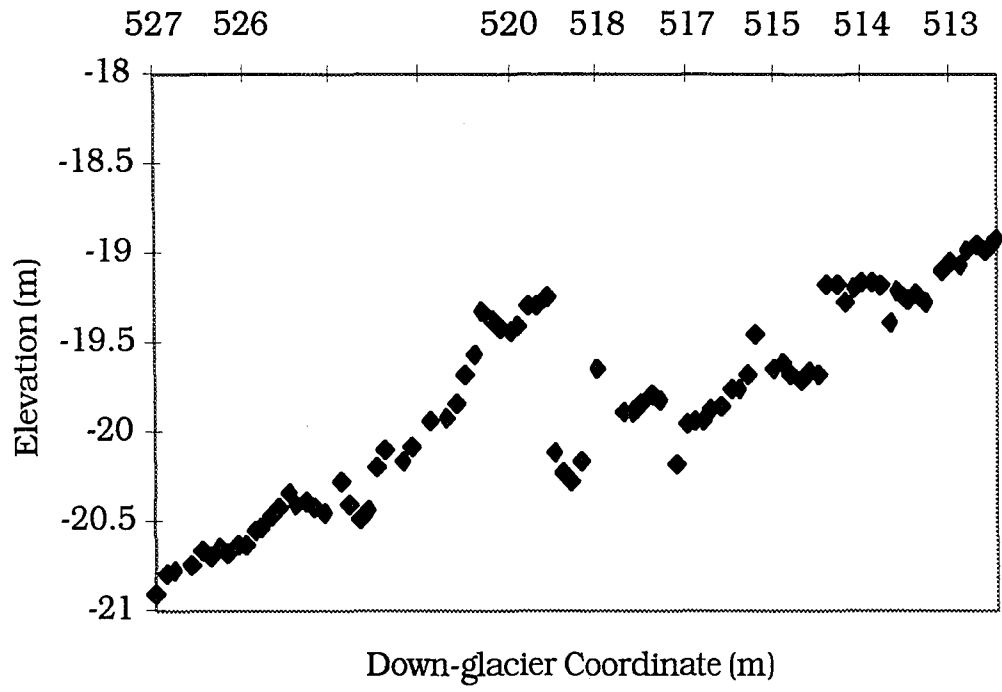
Station 3 Daily Elevations



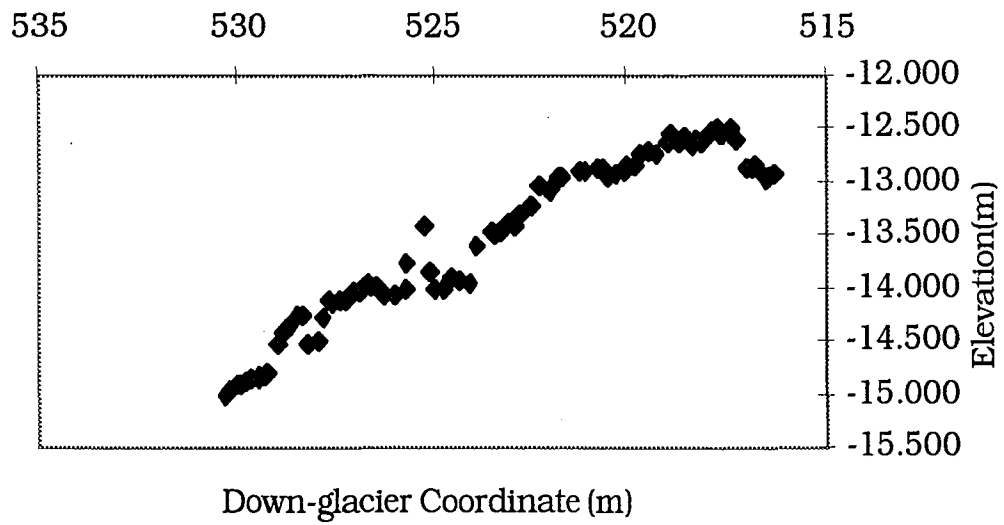
Station 4 Daily Elevations



Station 5 Daily Elevations



Station 6 Daily Elevations



Curriculum Vitae

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Presentations: "Horizontal Speed Measurements Demonstrate Dependence on Subglacial Drainage System Configuration," presented at North Central GSA, May 1997.

Selected Academic

Honors: Kravitz Fellowship, Lehigh University, 1995-96.

Haworth Award, University of Kansas, 1995.

Tarr Award, University of Kansas, 1995.

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**END
OF
TITLE**