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Tarfala Research Station Annual Report 1999–2000 and 2000–2001

Per Klingbjer (Ed.)

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and Quaternary Geology
Stockholm University

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Annual Report 1999–2000
and 2000–2001

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Cover figure. Drilling site at Tarfalaryggen in april 2000. (Photo: Per Holmlund)
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Introduction

Introduction

The years 2000 and 2001 have been characterised by scientific and funding success and major changes. Three PhD-thesises and one fil. lic. have successfully been defended in glaciology at Stockholm University. New research programmes on ice dynamics and hydrology have been initialised and the monitoring programme has been expanded now to include up to 100 m boreholes in bedrock for temperature measurements. A new programme for student eductaion at high school level was initialised in 2001 funded by the Swedish Research Council (VR).

In 2000 a major grant was approved for Tarfala Research Station by the Knut and Alice Wallenberg Foundation for an expansion and restoration of the station. The construction work began in July 2001 and is planned to be finished in May 2002. In 2001 the CIRC programme was closed down in its previous shape. A small number of employees were funded until the end of 2001, which became the final date for the CIRC programme. The basic ideas and some of the infrastructure will be integrated in the new Environmental and Space College in Kiruna wich is planned to be in operation by the autumn of 2002.

There is also a dark side of the two years passed. For a long time we have luckily been spared from accidents but this period reminded us about the hard side of the Subarctic alpine nature. In August 2000 a Swedish Army helicopter, which at the time was based at Tarfala on a rescue mission, crashed on the mountain Kaskasapakte in sight from the station and all three crew members were killed. In the spring 2001 a scientist in our group was badly hurt in his hand while ice drilling at Salajekna. In August the same year a member of a mountaineering course, staying at the station, was killed in a crevasse on Kebnepakteglaciären. All these events have been carefully examined and the wisdom we earned will help us to minimise future incidents.

In September 2001 our new lecture hall was inaugurated by representatives from the university, the Wallenberg Foundation, the Swedish Science Foundation and Kiruna municipal. We are now well prepared to face future challenges in science and education at Tarfala Research Station.

Stockholm, April 2002

Prof. Per Holmlund
Director, Tarfala Research Station

Per Klingbjer
Editor

Tarfala Research Station

Founded 1946

Location

The station is located in the Tarfala Valley, 67°55’N 18°36’E, at 1130 m a.s.l. in the Kebnekaise massif, Swedish Lappland. The valley is surrounded by glaciers and 2000 m peaks. Tarfala can be reached by foot (25 km hike) or by helicopter from the nearest village, Nikkaluokta. Public transportation is available to Nikkaluokta.

Environment

Arctic alpine environment. The tree line (birch) is at ~700 m a.s.l. in the area. Several glaciers in the valley terminate below 1200 m a.s.l. Mean annual temperature is –4°C, resulting in widespread permafrost conditions.

Availability

The station is open during the summer season: June – September. Summer bookings must be made before May 1. Restricted availability during winter, contact the station director for details.

Monitoring programme

The research at Tarfala Research Station has two components, one basic monitoring programme and one externally funded project part. The basic monitoring programme is also dependent on external funding, but costs are integrated with costs for the maintenance of the research station.
The montitoring program includes:

- The mass balance of Storglaciären and four other glaciers
- Changes in front positions of 20 Swedish glaciers
- Weather data from Tarfala Research Station and four other mountain sites
- Hydrology in Tarfala valley
- Ground temperatures from Tarfala

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Mass balance of Storglaciären 1999/2000

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Summary

The determination of the mass balance of Storglaciären was based on extensive fieldwork performed during spring and summer 2000 by the Tarfala Research Station personnel.

The mass balance of Storglaciären was computed with a sequence of m-files (i.e. small MatLab programs). Due to the high number of measurements, the imposed boundary conditions do not influence significantly the final result.

The winter balance was surveyed between May 1 and May 9, 2000. Snow depth was determined at 259 points in a 100*100 meter grid network by manual probing. During the same period, snow density was measured in 2 pits at stake positions 20 and 29 (figure 1). The conversion of snow depth, d_{snow}, into water equivalent values, $d_{w.eq.}$, was done by determining an empirical relationship between the two. Data from the density pits were plotted as cumulative water equivalent vs. cumulative snow depth and the logarithmic regression model was choosed and adopted. The snow depths recorded by probing was then converted using this relationship. Accumulation in areas with no probings were extrapolated. Interpolation method used for the winter balance was cubic spline.The total accumulation during the winter 1999/2000 was 1.62 m w. eq. (figure 2 and 3, table 1, appendix 1).

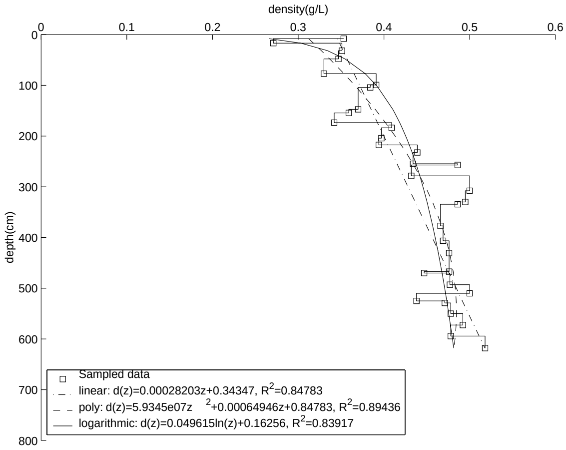


Figure 1. Snow density at stake 20 and 29 in May 2000. Curves corespond to linear, polynomials and logarithmic fits.

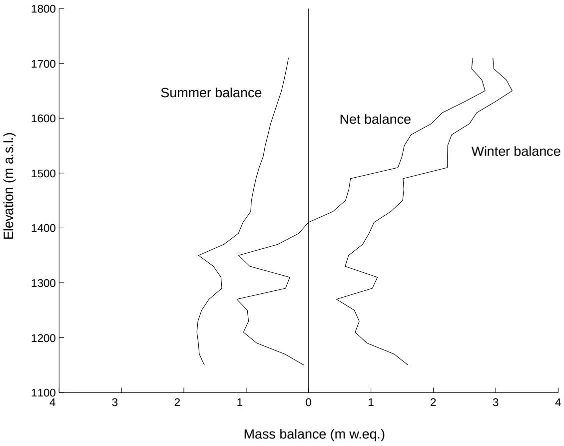
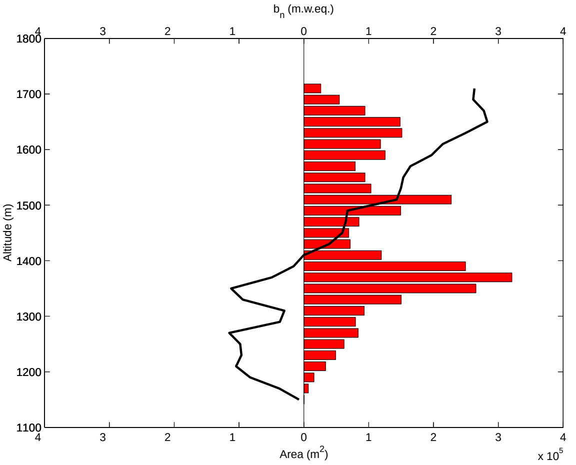


Figure 2. Winter, summer and net balance as a function of altitude for Storglaciären 1999/2000.



Figur 3. Net balance and area distribution (%) as a function of altitude for Storglaciären 1999/2000.

During the winter some stakes were lost due to accumulation. During the spring, several new ablation stakes were established to improve on the existing ablation stake net. In September 2000 a total of 85 stakes were available for determining the summer balance of the glacier. Ablation in areas with no stakes were extrapolated. The integration method used for the summer balance was cubic spline. The summer balance of 2000 was -1.04 m w. eq. (figure 2 and 3, table 1, appendix 1).

The winter and summer balance values yield a net balance volume of 1801*10^3 m^3, equivalent to 0.58 m w. eq., on Storglaciären for the 1999/2000 mass balance year (figure 2 and 3, table 1, appendix 1).

Acknowledgements

The authors traineeship at the Tarfala Research Station was funded by the Ecole Normale Superieure de Lyon, France.

Table 1. Mass balance of Storglaciären 1999/2000.

Elevation	Area	Winter balance		Summer balance		Net balance	
m a.s.l.	m^2	m^3	m w.eq.	m^3	m w.eq.	m^3	m w.eq.
1140-1160	100	160	1.60	-167	-1.67	-7	-0.07
1160-1180	6900	9477	1.37	-12088	-1.75	-2611	-0.38
1180-1200	15600	14617	0.94	-27560	-1.77	-12942	-0.83
1200-1220	33500	24987	0.75	-59990	-1.79	-35003	-1.04
1220-1240	49100	39832	0.81	-87127	-1.77	-47295	-0.96
1240-1260	62100	45509	0.73	-106460	-1.71	-60950	-0.98
1260-1280	83700	37394	0.45	-133685	-1.60	-96291	-1.15
1280-1300	79700	81370	1.02	-110902	-1.39	-29532	-0.37
1300-1320	93100	102645	1.10	-130692	-1.40	-28046	-0.30
1320-1340	150100	87743	0.58	-228979	-1.53	-141236	-0.94
1340-1360	265500	170501	0.64	-468368	-1.76	-297867	-1.12
1360-1380	321000	277620	0.86	-436475	-1.36	-158854	-0.49
1380-1400	249400	241396	0.97	-280666	-1.13	-39270	-0.16
1400-1420	119600	125457	1.05	-125771	-1.05	-314	0.00
1420-1440	71400	94094	1.32	-66325	-0.93	27770	0.39
1440-1460	69200	104317	1.51	-63385	-0.92	40932	0.59
1460-1480	85000	129759	1.53	-74953	-0.88	54807	0.64
1480-1500	149400	226215	1.51	-125856	-0.84	100359	0.67
1500-1520	227400	505647	2.22	-180265	-0.79	325382	1.43
1520-1540	103500	230211	2.22	-75366	-0.73	154845	1.50
1540-1560	94300	210182	2.23	-65533	-0.69	144648	1.53
1560-1580	79200	181696	2.29	-51526	-0.65	130169	1.64
1580-1600	125400	323285	2.58	-76379	-0.61	246905	1.97
1600-1620	118200	318553	2.70	-65109	-0.55	253444	2.14
1620-1640	151300	452453	2.99	-74590	-0.49	377863	2.50
1640-1660	148500	484635	3.26	-64436	-0.43	420200	2.83
1660-1680	94300	298775	3.17	-36957	-0.39	261818	2.78
1680-1700	54800	162637	2.97	-19450	-0.35	143187	2.61
1700-1720	26200	77405	2.95	-8448	-0.32	68957	2.63
1140-1720	3127500	5058572	1.62	-3257508	-1.04	1801068	0.58

Mass balance of Storglaciären 2000/2001

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Summary

The determination of the mass balance of Storglaciären was based on extensive fieldwork performed during spring and summer 2001 by the Tarfala Research Station personnel.

Snow depth was measured between May 1 and 18, 2001 in a 100*100 meter grid network containing 304 probing sites (Appendix 1). During the same period snow density was measured in five snow pits located at stake 5, 10, 12, 15 and 20 respectively, and at stake 29 where a core was drilled with a PICO-auger (figure 1a and 1b). The density profiles at stake 5 and 10 were shallow and produced unreliable results therefore the depth, d (cm), to mean density, d (g/cm^3), relation was based solely on the profiles from stake 12, 15, 20 and 29 (Figure 2). This relation was fit by a linear function for all depths up to 290 cm yielding: $d=5.22*10^{-4}d+0.31$. For all depths exceeding 290 cm, a mean density of 0.47 g/cm^3 was used. The mean density at each probing site was calculated and used to convert snow depths into water equivalents. A winter balance map (Appendix 1) was created by interpolation using the kriging routine in Golden Software Surpher 7.0. The total accumulation on the glacier amounted to 1.14 m w.eq. (table 1).

The ablation stake network on the glacier (Appendix 2) was during the season maintained and several new stakes were drilled into the glacier to compensate for stakes that melted out. In addition, stakes used in glacier velocity measurement projects were also used for ablation purposes. In total 94 stakes could be used to determine the summer balance. Stake height readings were performed several times during the ablation season with final readings on 20 September 2001. The ablation height for each stake was divided into a snow part and an ice part, based on the snow depth probing.

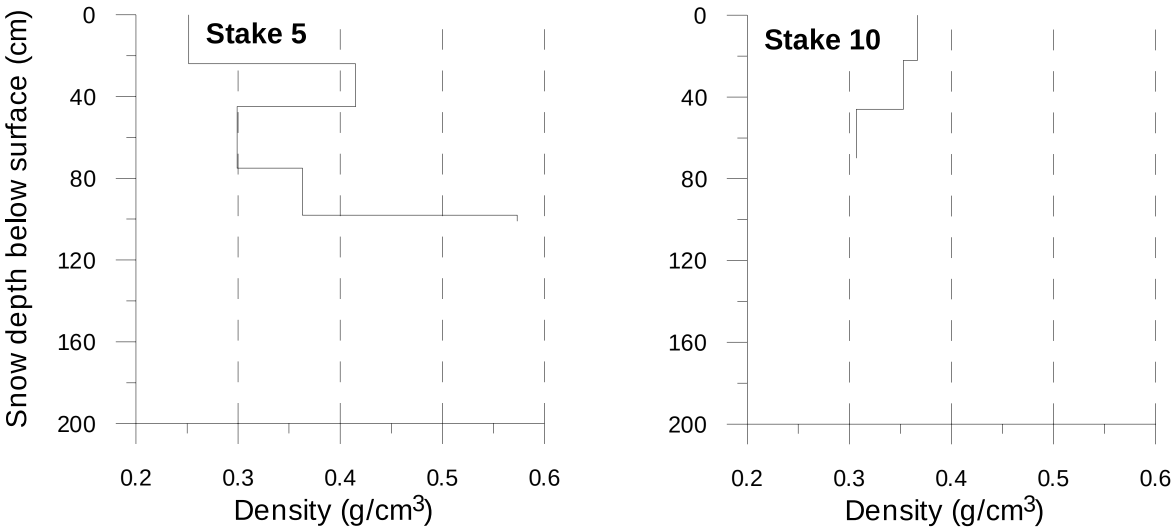

Figure 1a. Snow density profiles at stake 5 and 10. See Appendix 1 for location of the stakes.

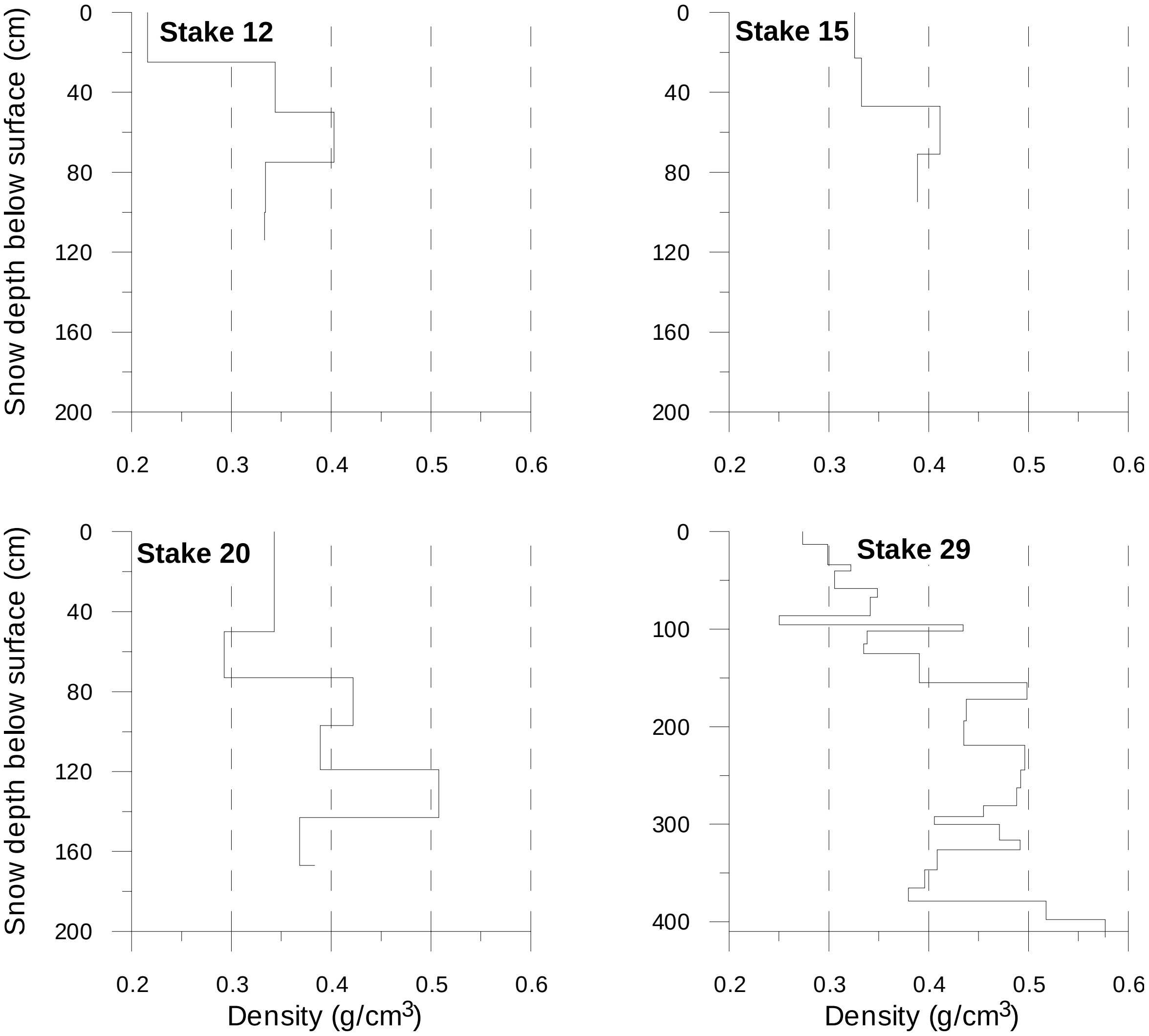

Figure 1b. Snow density profiles at stake 12, 15, 20 and 29. See Appendix 1 for location of the stakes.

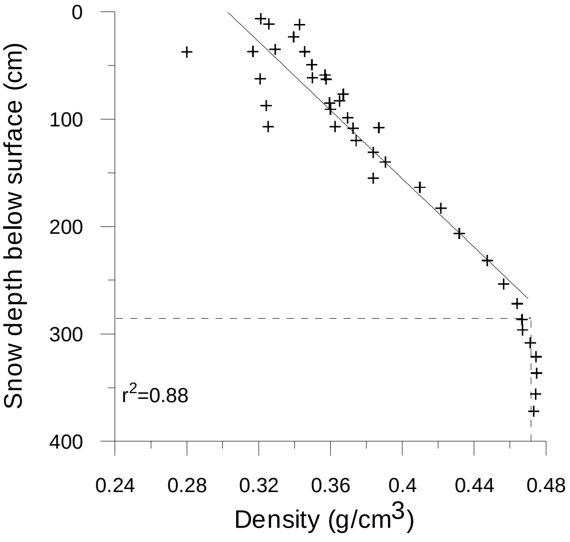

Figure 2. Mean density as a function of snow depth. The linear regression is based on all snow depths up to 290 cm. See text for explanation.

For melted ice a density value of 0.90 g/cm^3 was used. Melted snow in the ablation area was converted into water equivalents by using the same density to depth relation as above. In the accumulation area the difference in water equivalents between the accumu-lation and the remaining snow was calculated using 0.60 g/cm^3 as density for the remaining snow. By kriging interpolation of the stake net data a summer balance map based on a 10*10 m grid (Appendix 2) was created. Summer ablation was determined to 1.84 m w.eq. (table1).

The ablation gradient, based on the elevation, Z (m a.s.l.), and ablation, bs (m w. eq.), for all stakes used in the determination of the summer balance, yielded: bs=-0.00541Z+9.70 (figure 3). Summer balance differed 0.02 m w.eq. whether determined from the interpolated summer balance grid (1.84 m w. eq.) or using the ablation gradient (1.82 m w. eq.).

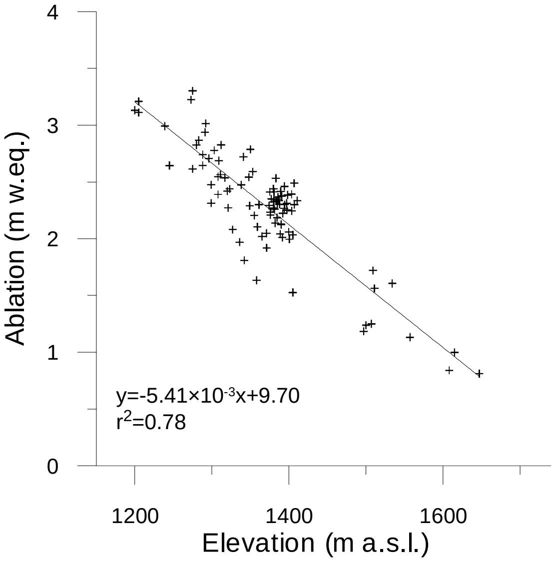

Figure 3. Ablation as a function of elevation (the ablation gradient) based on all ablation stake measurements fit with a linear regression.

The net balance was calculated by subtracting the summer ablation from the winter accumulation in each grid cell using a computer program described by Jansson (1999). The net balance amounted to –0.70 m w.eq. and concludes the 56 mass balance determination on Storglaciären (figure 4). The equilibrium line altitude was determined to 1530 m a.s.l. and the accumulation area to total area ratio (AAR) was 30 %. The distribution of winter, summer and net balance is shown in figure 5 and 6.

References

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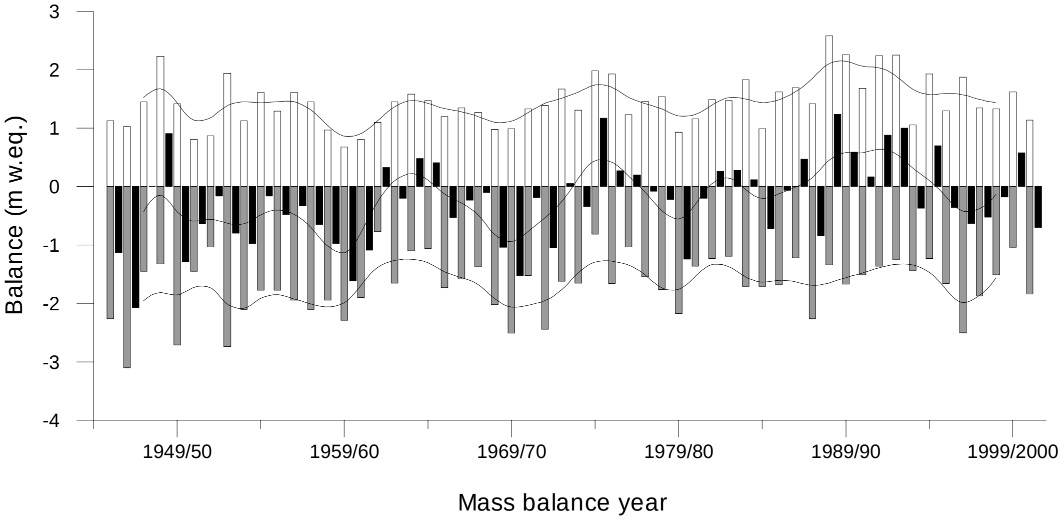

Figure 4. The 56-year mass balance record for Storglaciären.

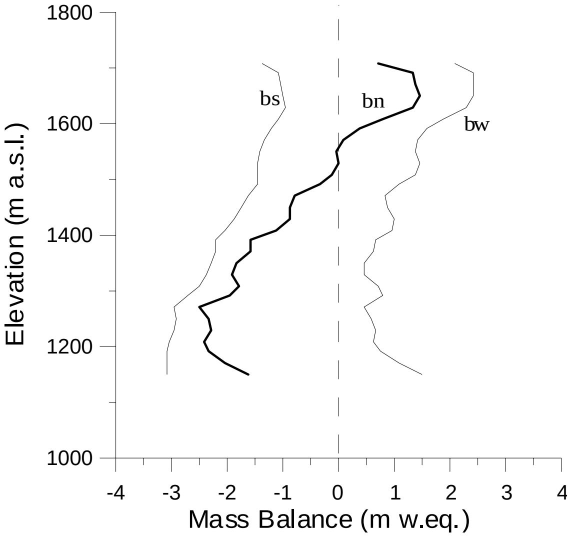

Figure 5. Winter (bw), summer (bs) and net balance (bn) as a function of altitude for Storglaciären 2000/2001.

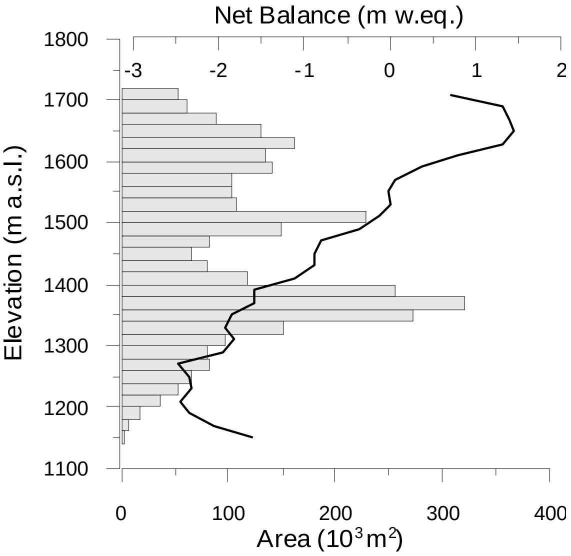

Figure 6. Net balance (line) and glacier area (bars) in elevation intervalls of 20 m.

Table 1. Mass balance of Storglaciären 2000/2001.

Elevation	Area	Winter balance		Summer balance		Net balance	
m a.s.l.	10^3 m^2	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.
1140-1160	3.3	4.89	1.48	10.23	3.10	-5.34	-1.62
1160-1180	7.9	8.13	1.06	23.87	3.10	-15.74	-2.04
1180-1200	16.9	13.01	0.76	53.02	3.10	-40.01	-2.34
1200-1220	36.3	22.71	0.63	109.54	3.06	-86.83	-2.43
1220-1240	52.7	35.28	0.66	158.00	2.96	-122.72	-2.30
1240-1260	64.6	36.74	0.58	185.92	2.92	-149.18	-2.34
1260-1280	82.6	39.24	0.47	246.27	2.95	-207.03	-2.48
1280-1300	80.8	63.24	0.78	220.07	2.72	-156.83	-1.94
1300-1320	96.1	67.59	0.71	240.16	2.52	-172.57	-1.81
1320-1340	150.1	66.30	0.44	353.47	2.36	-287.17	-1.92
1340-1360	271.0	126.52	0.47	626.44	2.31	-499.92	-1.84
1360-1380	319.8	193.85	0.61	701.74	2.19	-507.89	-1.59
1380-1400	255.4	164.43	0.65	566.74	2.23	-402.31	-1.58
1400-1420	117.5	112.85	0.95	243.49	2.06	-130.64	-1.11
1420-1440	79.3	78.07	0.99	148.19	1.89	-70.12	-0.89
1440-1460	66.6	57.66	0.87	116.85	1.77	-59.19	-0.89
1460-1480	81.9	67.83	0.83	133.67	1.63	-65.84	-0.80
1480-1500	149.4	162.29	1.09	215.07	1.44	-52.78	-0.35
1500-1520	228.6	310.10	1.36	335.52	1.47	-25.42	-0.11
1520-1540	107.5	158.54	1.47	158.28	1.47	0.26	0.00
1540-1560	102.5	143.47	1.39	146.97	1.42	-3.50	-0.03
1560-1580	102.6	142.34	1.41	134.98	1.33	7.36	0.07
1580-1600	140.7	224.30	1.58	172.18	1.21	52.12	0.37
1600-1620	134.9	250.14	1.87	143.42	1.07	106.72	0.80
1620-1640	161.8	370.64	2.29	158.74	0.98	211.90	1.31
1640-1660	129.3	312.71	2.43	128.04	1.00	184.67	1.44
1660-1680	87.6	213.00	2.43	90.75	1.03	122.25	1.39
1680-1700	61.0	147.58	2.40	66.03	1.07	81.55	1.32
1700-1720	53.2	111.32	2.08	73.73	1.38	37.59	0.70
1140-1720	3241.9	3704.77	1.14	5961.39	1.84	-2256.62	-0.70

Mass Balance of Mårmaglaciären 1999/2000

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Summary

The winter accumulation was determined on April 14, 2000. Snow depths at 87 probings were performed and snow density was measured in one pit at the altitude of 1684 m a.s.l. The mean density was 0.42 g/cm^3. The relationship between snow depth and snow density was approximated with linear regression (figure 1). The regression equation was used to calculate the mean snow density for each snow depth probing. The mean density was then used to convert snow depth measurements to water equivalents (w. eq.). From the water equivalent values the winter balance map was constructed (figure 2). The winter mass balance amounted to 1,16 m w.eq. (table 1). The winter mass balance has not been compensated for any additional

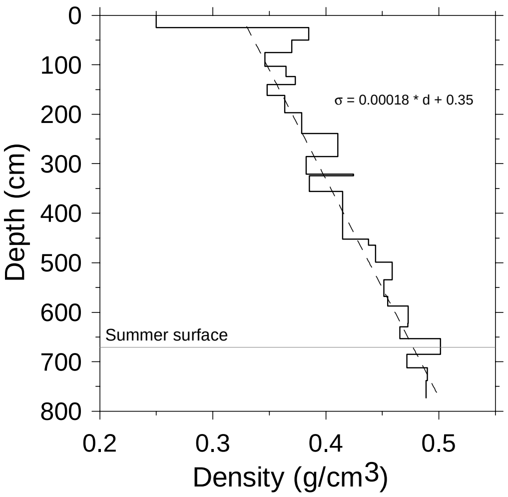

Figure 1. Density as a function of snow depth. The relationship was fitted with linear regression (dotted line).

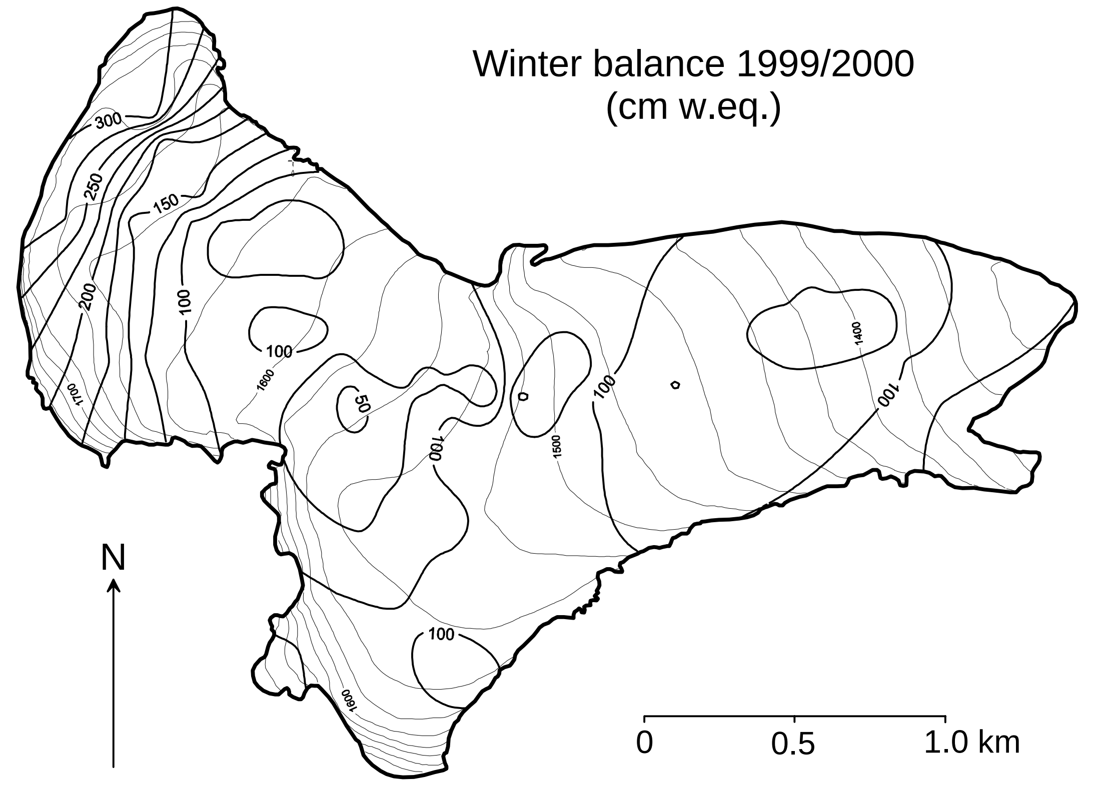

Figure 2. Winter mass balance map for Mårmaglaciären 1999/2000. Values in cm w.eq.

snowfall between April 14, 2000 and the end of the winterseason.

The summer balance was determined by means of three stakes on October 7, 2001. The ablation gradient was calculated by means of linear regression to -0.4 cm/m (figure 3) and was used to construct the summer balance map (figure 4). The summer mass balance amounted to -1.03 m w.eq. (table 1).

Thus, the net mass balance for the glaciological year 1999/2000 amounted to 0.13 m w.eq. (figure 5, table 1).

The equilibrium line altitude (ELA) was calculated linearly between 1660 and 1680m a.s.l. to 1670m a.s.l. (table 1). The net balance gradient was determined between 1330 and 1790 m a.s.l to 0.74 cm/m with linear regression (figure 6). The ratio between accumulation area and total area (AAR) was estimated to 22 %.

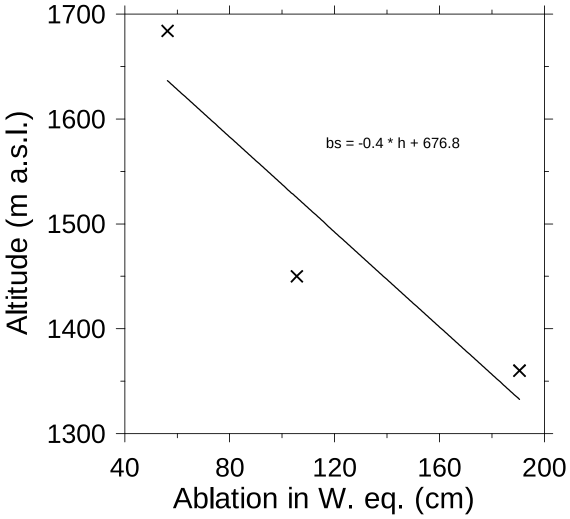

Figure 3. Ablation as a function of altitude (the ablation gradient) 2000.

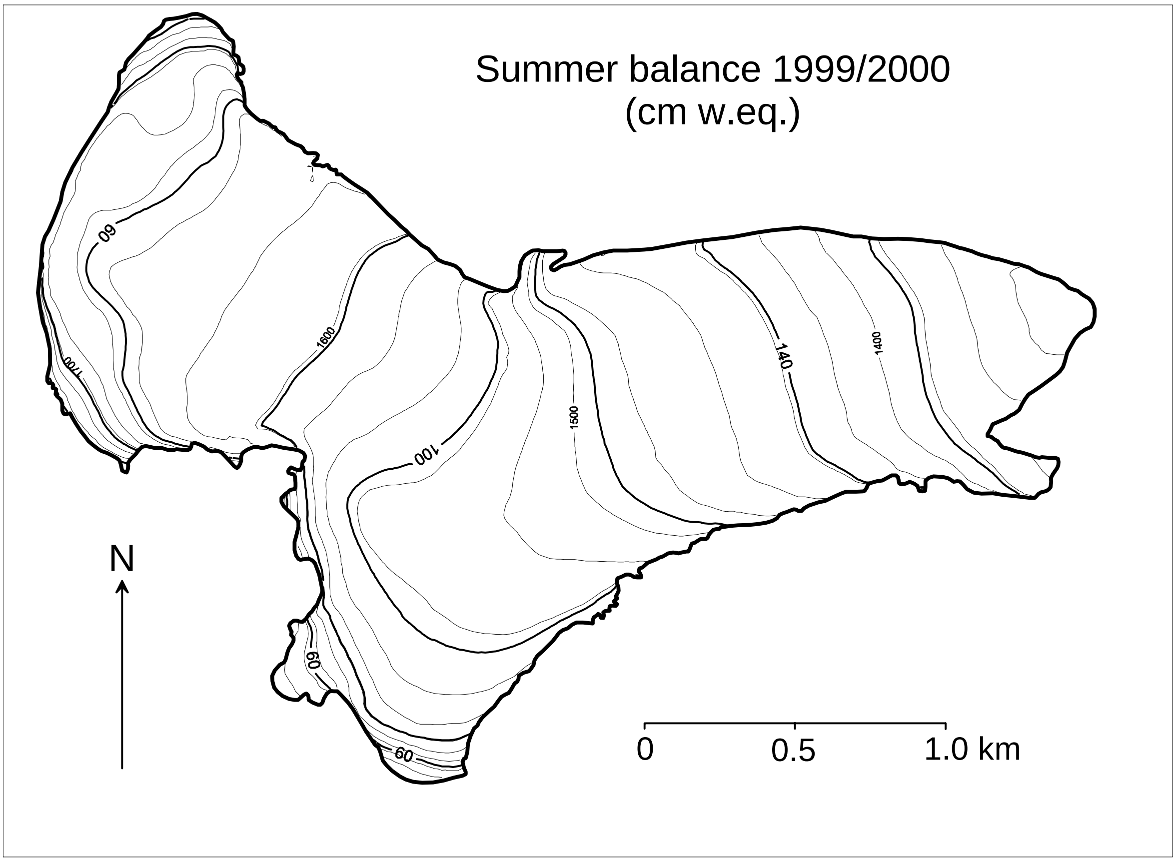

Figure 4. Summer mass balance map for Mårmaglaciären 1999/2000. Values in cm w.eq.

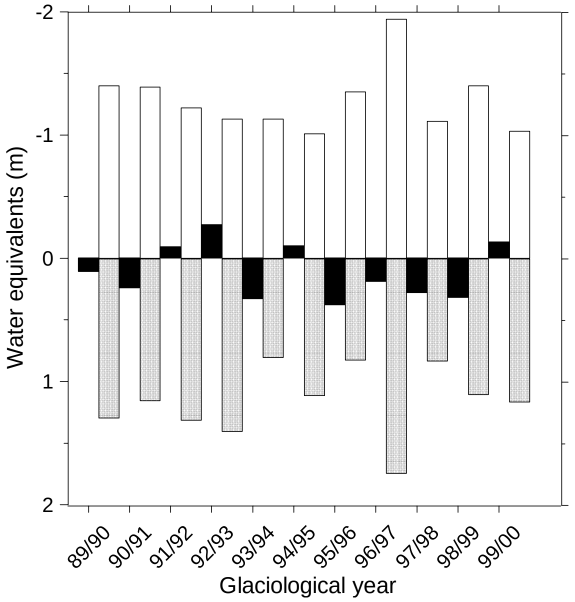

Figure 5. The mass balance record for Mårmaglaciären between 1989/1990 to 1999/2000.

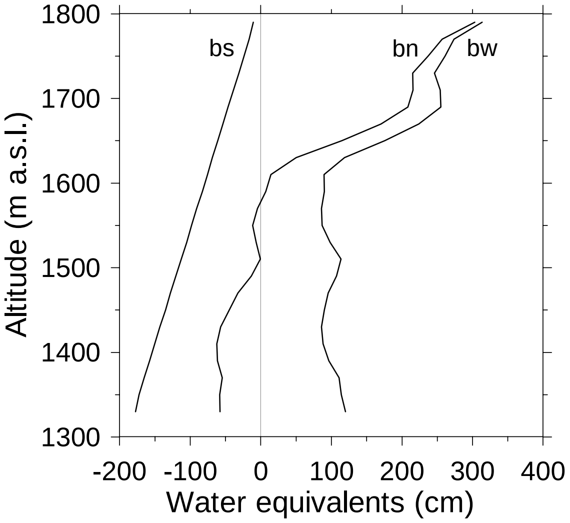

Figure 6. Winter (bw), summer (bs) and net balance (bn) as a function of altitude for Mårmaglaciären 1999/2000.

Table 1. Mass balance of Mårmaglaciären 1999/2000.

Elevation m a.s.l.	Area 10^3 m^2	Winter balance 10^3 m^3	m w.eq.	Summer balance 10^3 m^3	m w.eq.	Net balance 10^3 m^3	m w.eq.
1320-1340	51.0	61.2	1.2	90.6	1.8	-29.4	-0.6
1340-1360	97.5	111.3	1.1	168.1	1.7	-56.8	-0.6
1360-1380	143.6	158.9	1.1	237.0	1.7	-78.1	-0.5
1380-1400	145.9	140.5	1.0	230.2	1.6	-89.7	-0.6
1400-1420	149.8	132.0	0.9	225.3	1.5	-93.3	-0.6
1420-1440	158.8	136.8	0.9	226.9	1.4	-90.1	-0.6
1440-1460	217.0	195.8	0.9	292.8	1.3	-97.0	-0.4
1460-1480	251.0	240.0	1.0	321.4	1.3	-81.5	-0.3
1480-1500	196.8	211.4	1.1	237.4	1.2	-26.0	-0.1
1500-1520	186.0	211.4	1.1	209.8	1.1	-1.6	0.0
1520-1540	363.7	357.9	1.0	381.7	1.0	-23.8	-0.1
1540-1560	345.7	300.5	0.9	339.9	1.0	-39.4	-0.1
1560-1580	228.5	196.3	0.9	207.4	0.9	-11.2	0.0
1580-1600	189.8	170.8	0.9	157.4	0.8	13.4	0.1
1600-1620	311.6	279.6	0.9	235.0	0.8	44.6	0.1
1620-1640	326.0	386.8	1.2	223.2	0.7	163.6	0.5
1640-1660	191.5	336.7	1.8	116.7	0.6	220.0	1.1
1660-1680	204.0	456.9	2.2	109.1	0.5	347.7	1.7
1680-1700	104.0	265.1	2.5	48.3	0.5	216.8	2.1
1700-1720	42.0	106.9	2.5	16.3	0.4	90.7	2.2
1720-1740	29.4	72.3	2.5	9.1	0.3	63.2	2.2
1740-1760	17.9	46.6	2.6	4.3	0.2	42.3	2.4
1760-1780	4.8	13.0	2.7	0.8	0.2	12.2	2.6
1780-1800	0.4	1.4	3.1	0.0	0.1	1.3	3.0
1320-1800	3956.8	4589.9	1.16	4088.7.8	1.03	501.3	0.13

Mass Balance of Mårmaglaciären 2000/2001

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Summary

The winter accumulation was determined on April 9, 2001. Snow depths at 87 probings were performed. The density measurements where unreliable so a mean density was assumed to be 0.42 g/cm^3 which was taken from last year measurements. The mean density was used to convert snow depth probings to water equivalents (w. eq.). From the water equivalent values the winter balance map was constructed (figure 1). The winter mass balance of Mårmaglacären amounted to 0,77 m w.eq (table 1 and 2) which is the lowest value recorded.

The summer balance was determined by means of three stakes on September 3th. The ablation gradient was calculated by means of linear regression to -0.4 cm/m (figure 2) and was used to construct the summer balance. The summer mass balance amounted to –1.16 m w.eq. (table 1 and 2). Thus the net mass balance for the glaciological year 2000/01 amounted to -0.39 m w.eq (figur 3, table 1 and 2).

The equilibrium line altitude (ELA) was calculated linearly between 1620 and 1640m a.s.l. to 1621m a.s.l. (table 1). The net balance gradient was determined between 1330 and 1790 m a.s.l to 0.67 cm/m with linear regression (figure 4). The ratio between accumulation area and total area (AAR) was estimated to 24 %.

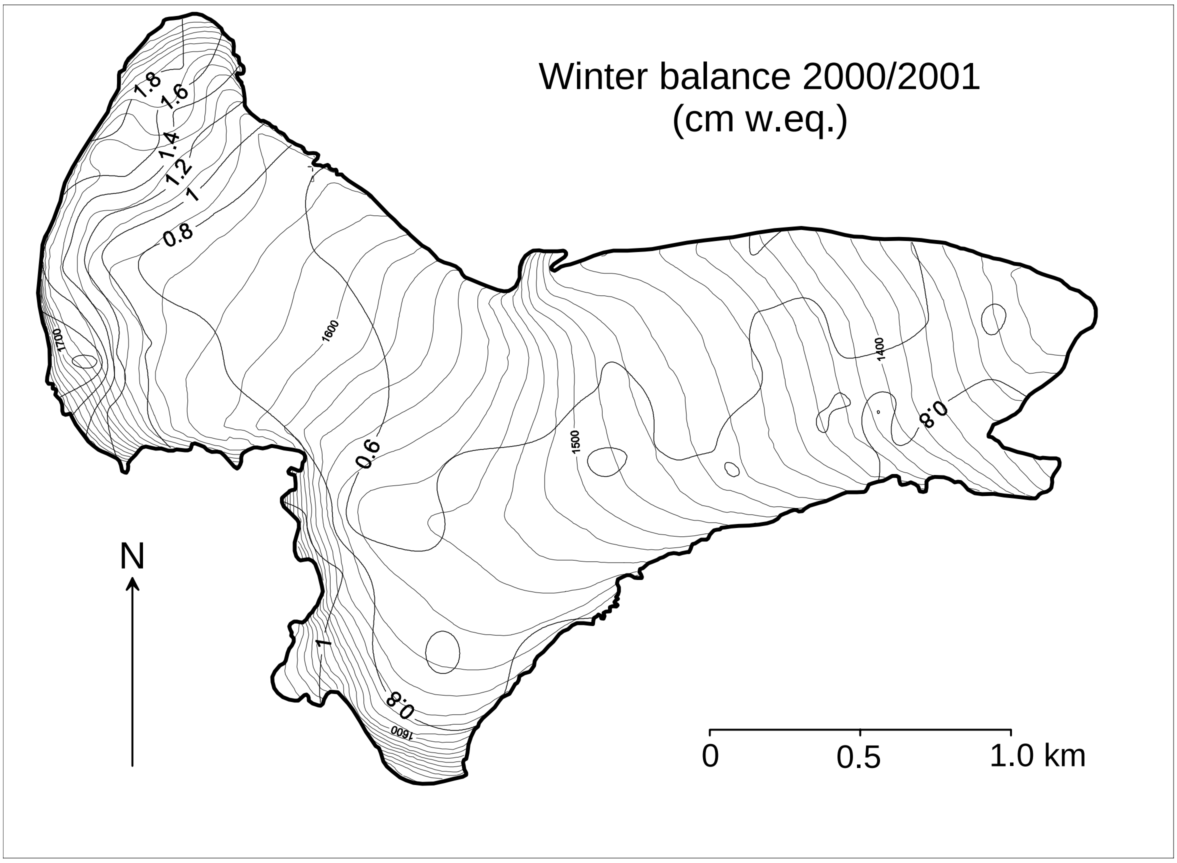

Figure 1. Winter mass balance map for Mårmaglaciären 2000/2001. Values in cm w.eq.

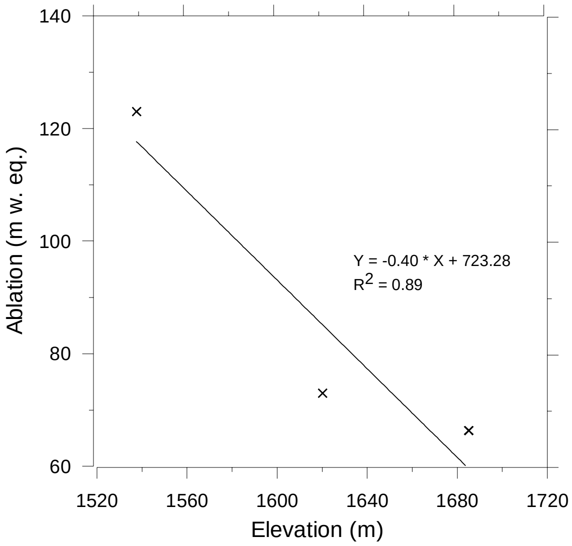

Figure 2. Ablation as a function of altidude based on thre stakes for 2000/2001.

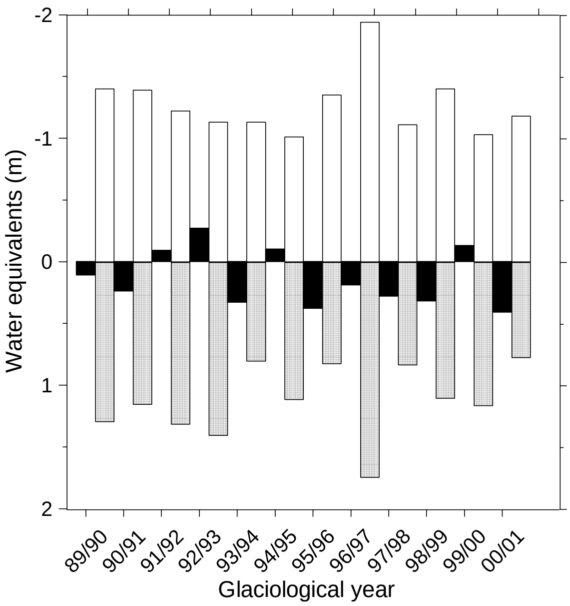

Figure 3. The mass balance record from Mårmaglaciären 1989/1990 to 2000/2001.

Table 1. Mass balance of Mårmaglaciären 2000/2001.

Elevation	Area	Winter balance		Summer balance		Net balance	
m a.s.l.	10^3 m^2	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.
1320-1340	51.0	33.2	0.7	100.3	2.0	-67.0	-1.3
1340-1360	97.5	73.1	0.7	186.4	1.9	-113.2	-1.2
1360-1380	143.6	107.1	0.7	263.4	1.8	-156.2	-1.1
1380-1400	145.9	99.3	0.7	256.4	1.8	-157.1	-1.1
1400-1420	149.8	100.1	0.7	251.6	1.7	-151.4	-1.0
1420-1440	158.8	99.5	0.6	254.1	1.6	-154.6	-1.0
1440-1460	217.0	127.3	0.6	329.1	1.5	-201.8	-0.9
1460-1480	251.0	142.3	0.6	362.4	1.4	-220.1	-0.9
1480-1500	196.8	118.4	0.6	268.7	1.4	-150.3	-0.8
1500-1520	186.0	116.2	0.6	238.6	1.3	-122.5	-0.7
1520-1540	363.7	226.8	0.6	436.5	1.2	-209.7	-0.6
1540-1560	345.7	223.8	0.6	390.7	1.1	-166.9	-0.5
1560-1580	228.5	156.0	0.7	240.1	1.1	-84.0	-0.4
1580-1600	189.8	133.9	0.7	183.7	1.0	-49.8	-0.3
1600-1620	311.6	222.5	0.7	276.9	0.9	-54.4	-0.2
1620-1640	326.0	263.1	0.8	265.8	0.8	-2.7	0.0
1640-1660	191.5	204.7	1.1	140.9	0.7	63.8	0.3
1660-1680	204.0	292.5	1.4	134.1	0.7	158.4	0.8
1680-1700	104.0	162.6	1.6	60.6	0.6	101.9	1.0
1700-1720	42.0	70.2	1.7	21.1	0.5	49.2	1.2
1720-1740	29.4	49.3	1.7	12.4	0.4	36.9	1.3
1740-1760	17.9	30.8	1.7	6.2	0.3	24.6	1.4
1760-1780	4.8	8.3	1.7	1.3	0.3	7.0	1.5
1780-1800	0.4	0.8	1.8	0.1	0.2	0.7	1.6
1320-1800	3956.8	3061.7	0.8	4681.1	1.2	-1619.4	-0.4

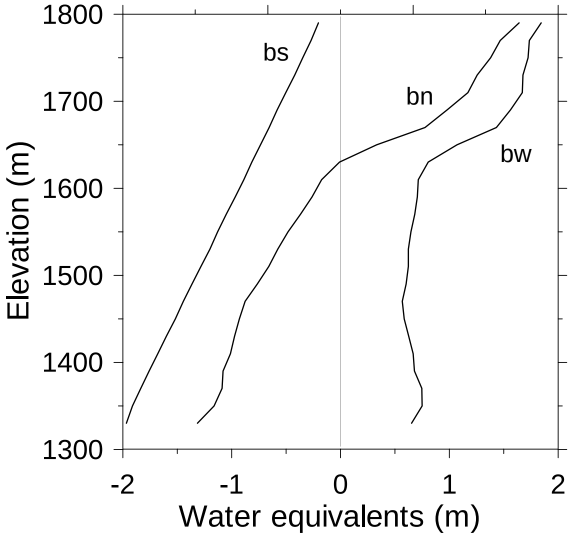

Figure 4. Winter (bw), summer (bs) and net balance (bn) as a function of altitude for Mårmaglaciären 2000/2001.

Table 2. Mass balance data for Mårmaglaciären 1989/1990 to 2000/2001. bw = winter balance, bs = summer balance and bn = net mass balance.

Mass balance year	b_w (m w. eq.)	b_s (m w. eq.)	b_n (m w. eq.)
1989/90	1.29	-1.40	-0.11
1990/91	1.15	-1.39	-0.24
1991/92	1.31	-1.22	0.09
1992/93	1.40	-1.13	0.27
1993/94	0.80	-1.13	-0.33
1994/95	1.11	-1.01	0.10
1995/96	0.82	-1.35	-0.38
1996/97	1.74	-1.94	-0.19
1997/98	0.83	-1.11	-0.28
1998/99	1.10	-1.40	-0.32
1999/00	1.16	-1.03	0.13
2000/01	0.77	-1.18	-0.40

Mass balance of Rabots Glaciär 1999/2000

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Summary

The winter accumulation was surveyed by Mart Nyman, Per Ekman and Truls Neubeck. Snow depth probings were conducted at 59 sites (figure 1). Snow density was measured on April 16, 2000 in one pit at approximately 1530 m a.s.l. The mean density was 0.39 g/cm^3. This value was used at each probing site to convert the snow depths into water equivalents. This data was interpolated ti 10x10m grid across the glacier using the kriging routine in Golden Software Surfer 7.0 (figure 1). The winter balance was determined to 1.15 m w.eq. (table 1.)

Two ablation stakes were drilled into the glacier April 16, 2000 (figure 2). Readings were performed September 12 the same year. However, one stake reading was highly uncertain and therefore the ablation gradient was determined as a mean of 9 previous mass balance calculations of Rabots glacier 1985-1998. The correct stake reading was used to determine the gradient constant assuming a linear relation between ablation and elevation (figure 2 and 3). This method yielded the following relation between elevation, Z (m) and ablation, bs (m w.eq.): bs=0.00285Z-5.25. The summer balance was calculated with this function based on 10 m resolution digital elevation model. The model was created by digitising 10 m contour lines (in areas with complex topography 5m) on a 1:20000 topographic map (Holmlund, 1994). The summer balance amounted to 1.39 m w.eq. (table 1).

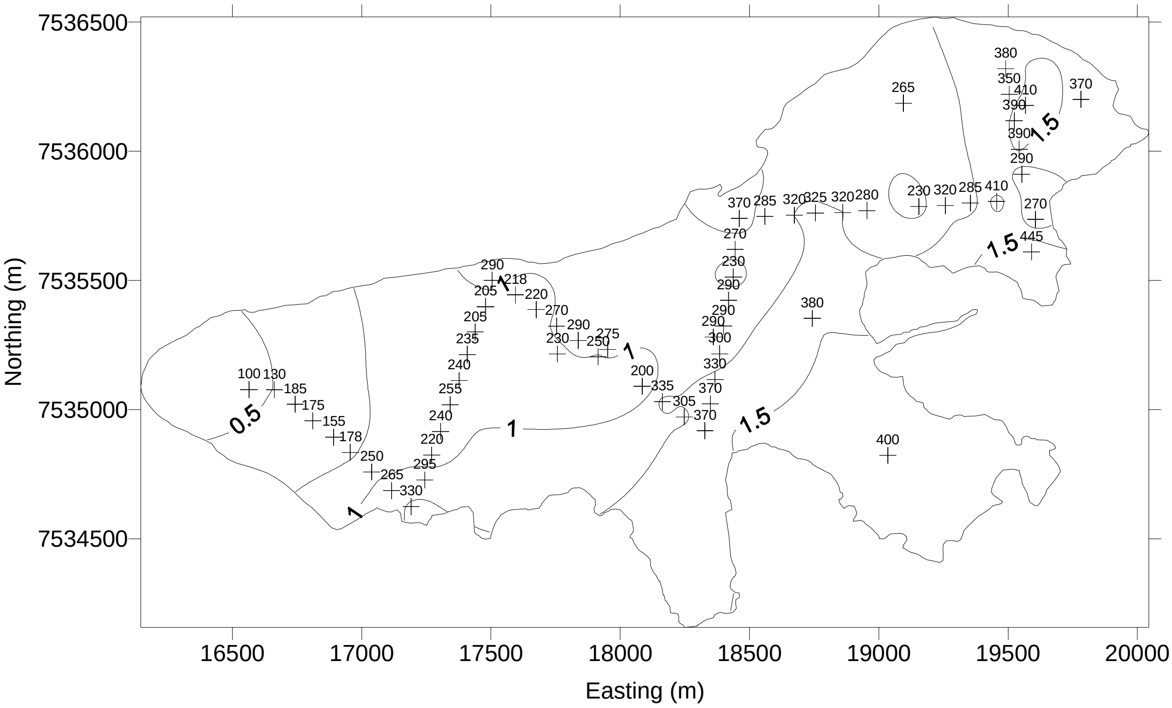

Figure 1. Winter balance map (RT90 0g) over Rabots glacier 1999/2000 (m w. eq.) and snow depth at the probing sites (cm).

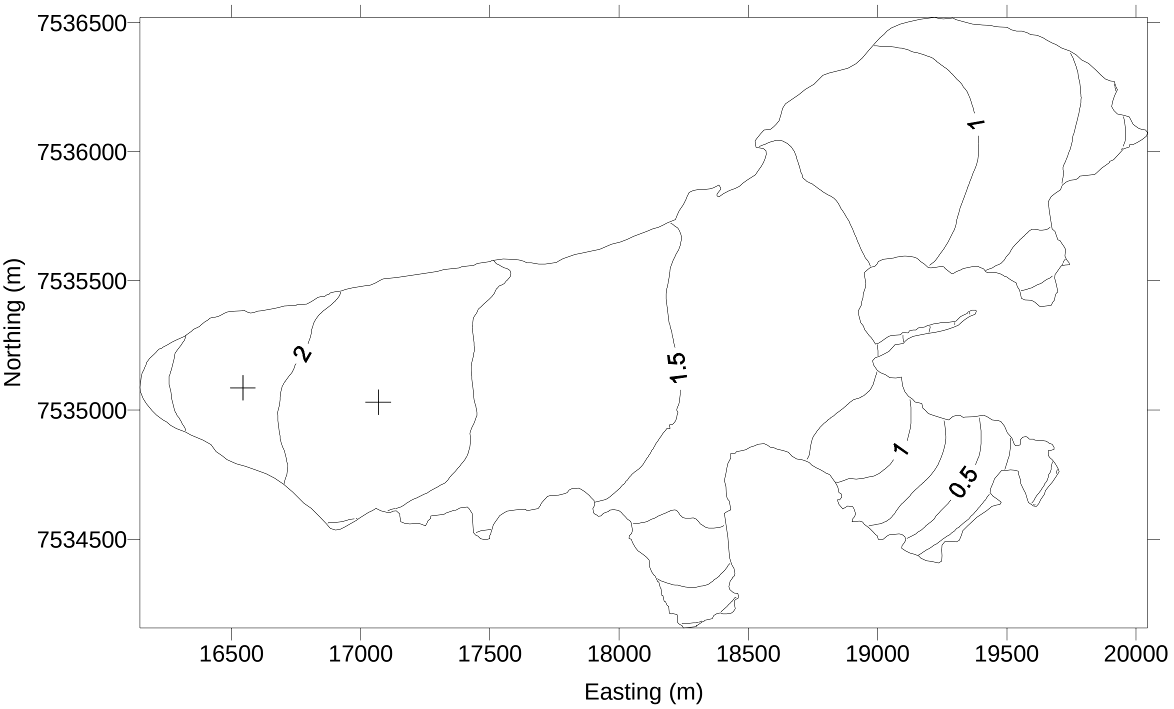

Figure 2. Summer balance map (RT90 0g) over Rabots glacier 1999/2000 (m w. eq.) and location of the ablation stakes.

Table 1. Mass balance of Rabots Glaciär 1999/2000.

Elevation	Area	Winter balance		Summer balance		Net balance	
m a.s.l.	10^3 m^2	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.
1050-1100	43.50	18.34	0.42	98.81	2.27	-80.47	-1.85
1100-1150	128.90	57.72	0.45	276.88	2.15	-219.16	-1.70
1150-1200	219.80	136.42	0.62	440.21	2.00	-303.79	-1.38
1200-1250	398.50	334.90	0.84	735.45	1.85	-400.56	-1.01
1250-1300	543.90	544.85	1.00	929.25	1.71	-384.40	-0.71
1300-1350	377.20	418.53	1.11	583.01	1.55	-164.48	-0.44
1350-1400	635.50	836.53	1.32	897.45	1.41	-60.92	-0.10
1400-1450	277.10	370.67	1.34	346.22	1.25	24.45	0.09
1450-1500	406.80	490.78	1.21	447.47	1.10	43.31	0.11
1500-1550	415.30	574.74	1.38	400.88	0.97	173.85	0.42
1550-1600	202.90	296.54	1.46	164.93	0.81	131.61	0.65
1600-1650	123.00	188.57	1.53	81.11	0.66	107.46	0.87
1650-1700	67.10	105.15	1.57	34.56	0.52	70.59	1.05
1700-1750	47.70	78.07	1.64	17.07	0.36	61.00	1.28
1750-1800	22.00	36.15	1.64	4.85	0.22	31.30	1.42
1800-1850	10.40	17.63	1.70	1.04	0.10	16.59	1.60
1850-1900	13.80	23.46	1.70	0.12	0.01	23.34	1.69
1900-1950	4.70	7.99	1.70	0.00	0.00	7.99	1.70
1050-1950	3938.10	4537.03	1.15	5459.32	1.39	-922.29	-0.23

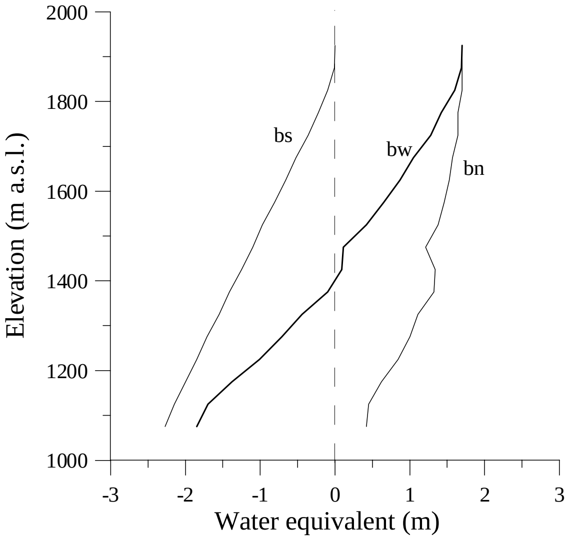

Figure 3. Winter (bw), summer (bs) and net balance (bn) as a function of altitude for Rabots glacier 1999/2000.

The net balance calculation was conducted by subtracting summer balance from winter balance, for each grid cell, using computer software described in Jansson (1999). The net balance amounted to -0.23 m w.eq. (table 1 and figure 3). The ELA was determined to 1411 m and the accumulation area ratio (AAR) to 40 %. This is the 18th mass balance calculation of Rabots glacier since 1982.

References

Holmlund, P., 1984. *Högfjällskartan Kebnekaise* 1:20000. Lantmäteriet/Kartförlaget. Gävle.

Jansson, P., 1999. Effect of uncertainties in measured variables on the calculated mass balance of Storglaciären. *Geografiska Annaler*, 81A: 633-642.

Mass balance of Rabots Glaciär 2000/2001

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Summary

The winter accumulation was surveyed by Mart Nyman, Rickard Pettersson, Jonas Nässén Sara Frödin and Per Ekman. Snow density was measured April 12, 2001 in two different sites at approximately 1380 and 1530 m a.s.l., respectively. A relationship between snow depth and mean snow density was established (figure 1) and used to were convert snow depths into water equivalents at each probing site. Snow depth probing were conducted at 157 sites (figure 2). The converted snow depth data served as base to create a 10*10m grid of over the glacier using the kriging routine in Golden Software Surfer 7.0 (figure 2). The winter balance was determined to 0.52 m eq.w. (table 1.).

Readings of three ablation stakes (figure 3) on the glacier were performed from an hovering helicopter. This data were used to establish an algorithm for calculating the summer balance (bs) as a function of elevation. However, the function produces negative ablation values at elevation above ca 1690 m a.sl. Therefore, the following algorithm was established:

Height intervall	Algorithm
1050-1700 m a.s.l.	bs = $4.1*10^{-3}$Z+6.92 m w. eq.
1600-1750 m a.s.l.	bs = 0.30 m w. eq.
1750-1950 m a.s.l.	bs = 0.20 m w. eq.

The fixed values in the algorithm are what could be expected based on previous mass balance calculations. However, the total area above 1690 m a.s.l. is small, only ca 2.5 % of the total glacier area (table 1), and the effect of the total summer balance is thus minor.

The summer balance was calculated with the algorithm described above with a 10 m resolution digital elevation model (Jonsell, 2002) as input values. The summer balance amounted to 5023.32*10^3 m^3 or 1.28 m w. eq. (table 1).

The net balance, calculated as the difference between winter and summer balance in each grid cell with a computer software described by Jansson (1999), amounted to -0.76 m w. eq. (table 1 and figure 4). This is the 19th mass balance calculation of Rabots glacier since 1982 and the fifth consecutive with negative mass balance (figure 5). The ELA was determined to 1530 m and the accumulation area ratio (AAR) to 12 %.

References

Jansson, P., 1999. Effect of uncertainties in measured variables on the calculated mass balance of Storglaciären. *Geografiska Annaler*, 81A, 633-642.

Jonsell, U., 2002. Mass balance of Rabots glacier 1999/2000. In: Klingbjer, P. (ed). *Tarfala Research Station Annual Report 1999/2000 and 2000/2001*. Stockholm University, Report 1, 21-23.

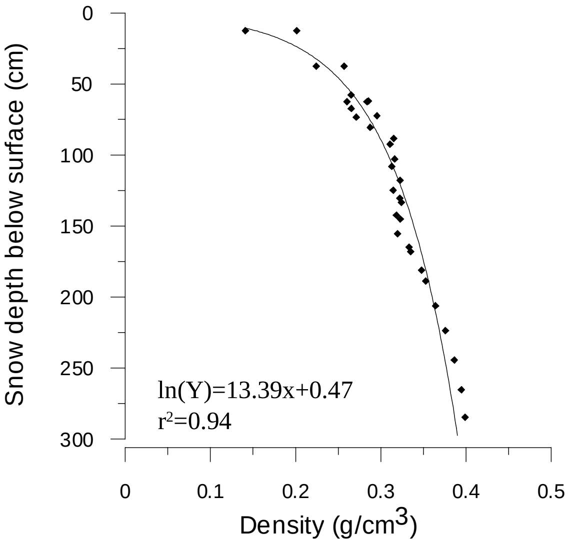

Figure 2. Mean snow density as a function of snow depth.

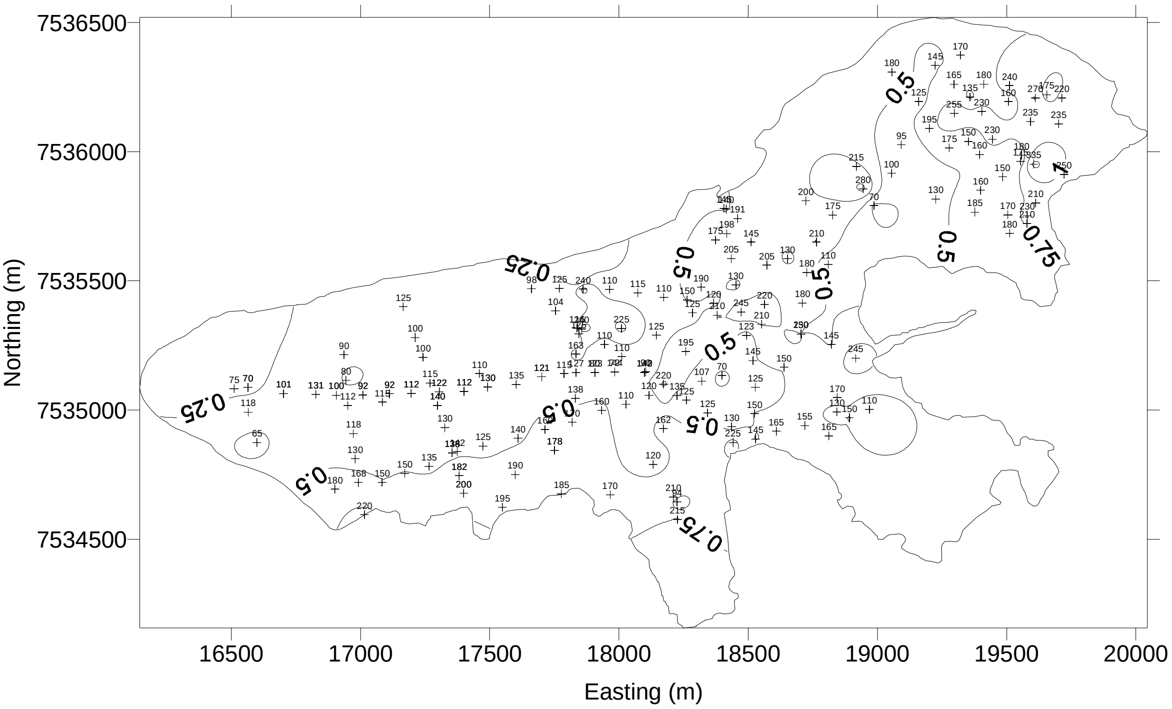

Figure 1. Winter balance map (RT90 0g) over Rabots glacier 2000/2001 (m w. eq.) and snow depth at the probing sites (cm).

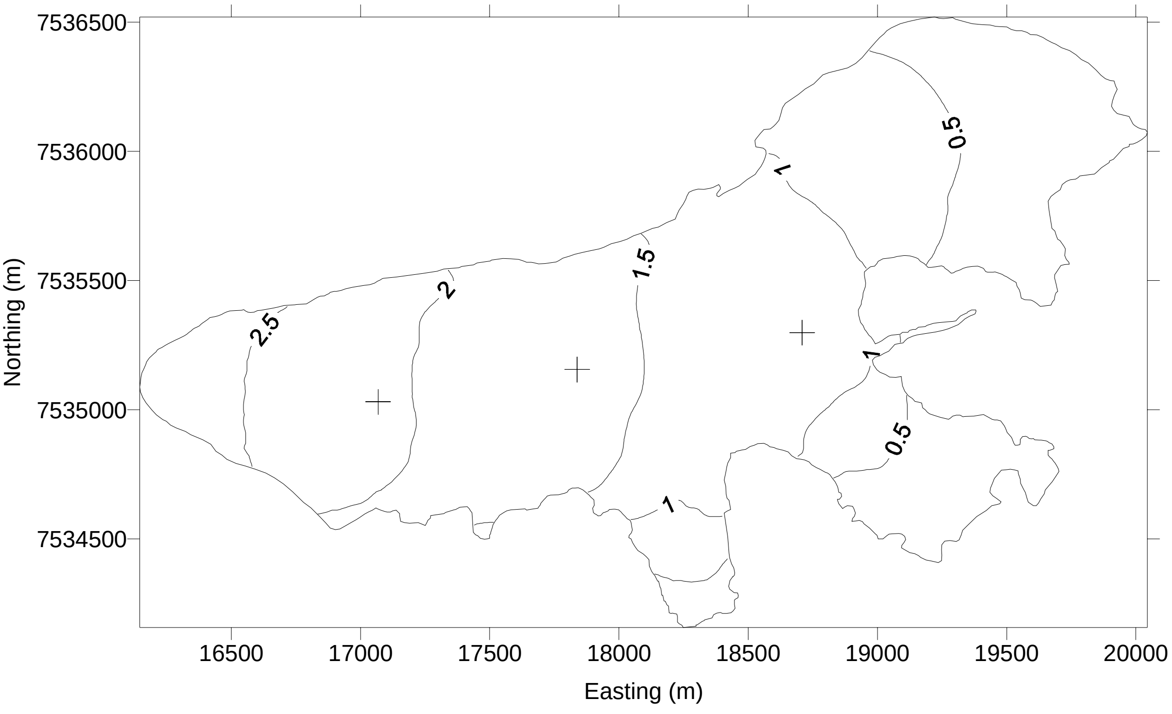

Figure 3. Summer balance map (RT90 0g) over Rabots glacier 2000/2001 (m w. eq.) and location of the ablation stakes.

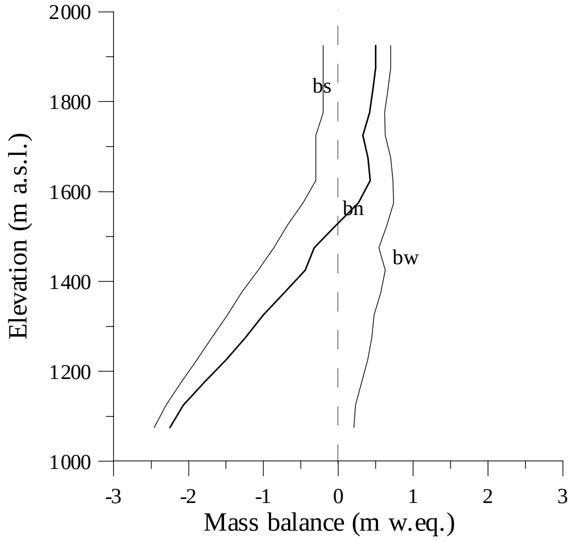

Figure 4. Winter (bw), summer (bs) and net balance (bn) as a function of altitude for Rabots glacier 2000/2001.

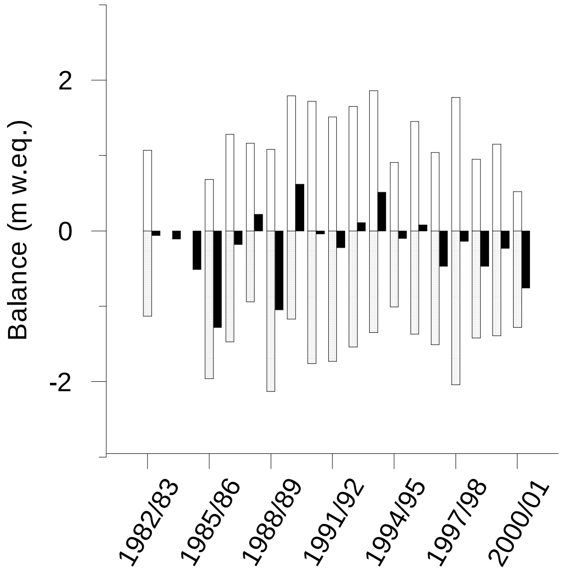

Figure 5. The mass balance record of Rabots glacier 1982/1983 to 2000/2001.

Table 1. Mass balance of Rabots Glaciär 2000/2001.

Elevation	Area	Winter balance		Summer balance		Net balance	
m a.s.l.	10^3 m^2	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.
1050-1100	43.50	9.18	0.21	107.18	2.46	-98.00	-2.25
1100-1150	128.90	29.31	0.23	296.48	2.30	-267.17	-2.07
1150-1200	219.80	67.49	0.31	461.16	2.10	-393.67	-1.79
1200-1250	398.50	156.75	0.39	751.88	1.89	-595.14	-1.50
1250-1300	543.90	242.16	0.45	921.06	1.69	-678.90	-1.24
1300-1350	377.20	180.67	0.48	557.42	1.48	-376.75	-1.00
1350-1400	635.50	360.17	0.57	818.91	1.29	-458.73	-0.72
1400-1450	277.10	173.74	0.63	297.51	1.07	-123.77	-0.44
1450-1500	406.80	218.28	0.54	351.43	0.86	-133.15	-0.32
1500-1550	415.30	269.21	0.65	283.25	0.68	-14.04	-0.03
1550-1600	202.90	150.24	0.74	95.53	0.47	54.71	0.27
1600-1650	123.00	89.39	0.73	36.90	0.30	52.49	0.43
1650-1700	67.10	47.00	0.70	20.13	0.30	26.87	0.40
1700-1750	47.70	30.09	0.63	14.31	0.30	15.78	0.33
1750-1800	22.00	13.64	0.62	4.40	0.20	9.24	0.42
1800-1850	10.40	6.86	0.66	2.08	0.20	4.78	0.46
1850-1900	13.80	9.66	0.70	2.76	0.20	6.90	0.50
1900-1950	4.70	3.29	0.70	0.94	0.20	2.35	0.50
1050-1950	3938.10	2057.14	0.52	5023.32	1.28	-2966.19	-0.76

Mass Balance of Riukojietna 1999/2000

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Abstract
The winter balance of Riukojietna in 1999/2000 was 1.41 m w.eq. The summer balance was -1.72 m w.eq, yielding a net balance of -0.31 m w.eq.

Summary

Riukojietna is a small ice cap located 35 km northwest of Kebnekaise in northern Sweden.

The winter balance of 1999/2000 was surveyed on April 20, 2000 by Mart Nyman and and Per Ekman in a total of 46 probings. The snow density was determined in one pit close to an ablationstake at 1404 m a.s.l. The density profile are seen in figure 1. The mean snow density was calculated to 0.42 g/cm^3. During the same period as the winter balance survey, three ablationstakes was established on the glacier at 1308, 1404 and 1452 m a.s.l. (figure 2). The winterbalance amounted to 1.41 m w.eq. (figure 3, table 1 and 2).

The summer balance of 1999/2000 was determined by means of three stakes on September 12, 2000 by Regine Hock. The summer balance was the calculated from the ablation gradient to 1.72 m w.eq. (figure 2 and 3, table 1 and 2).

The net balace for the glaciological year 1999/2000 amounted to -0.31 m w.eq. (figure 3, table 1 and 2).

The quilibrium line altitude (ELA) was calculated to 1394 m a.s.l. (figure 3) and the accumulation-area ratio (AAR) was estimated from fieldobservations during stake readings to 37%.

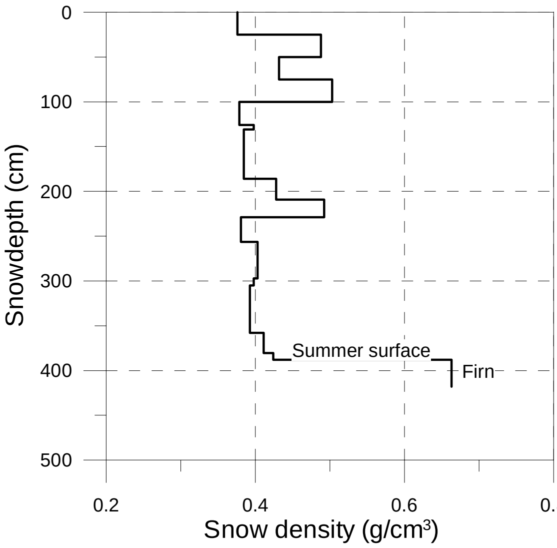

Figure 1. Density as a function of snow depth.

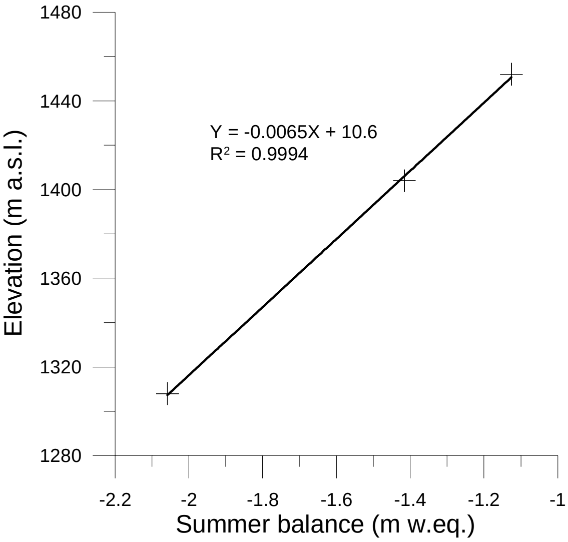

Figure 2. Ablation as a function of elevation (the ablation-gradient).

Table 1. *Mass balance of Riukojietna 1999/2000.*

Elevation	Area	Winter balance		Summer balance		Net balance	
m a.s.l.	10^3 m^2	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.
1140-1160	29	40	1.38	-89	-3.08	-49	-1.71
1160-1180	45	62	1.38	-133	-2.95	-71	-1.58
1180-1200	60	83	1.38	-169	-2.82	-87	-1.45
1200-1220	65	89	1.38	-175	-2.69	-86	-1.32
1220-1240	94	129	1.38	-242	-2.56	-111	-1.19
1240-1260	133	183	1.38	-323	-2.43	-140	-1.06
1260-1280	189	260	1.38	-435	-2.30	-175	-0.93
1280-1300	259	356	1.38	-562	-2.17	-206	-0.80
1300-1320	391	531	1.36	-798	-2.04	-266	-0.68
1320-1340	512	704	1.38	-978	-1.91	-274	-0.54
1340-1360	428	594	1.39	-763	-1.78	-168	-0.39
1360-1380	444	642	1.45	-733	-1.65	-91	-0.20
1380-1400	420	629	1.50	-638	-1.52	-10	-0.02
1400-1420	387	579	1.50	-538	-1.39	41	0.11
1420-1440	676	951	1.41	-852	-1.26	99	0.15
1440-1460	516	725	1.41	-583	-1.13	142	0.28
1140-1460	4648	6556	1.41	-8009	-1.72	-1452	-0.31

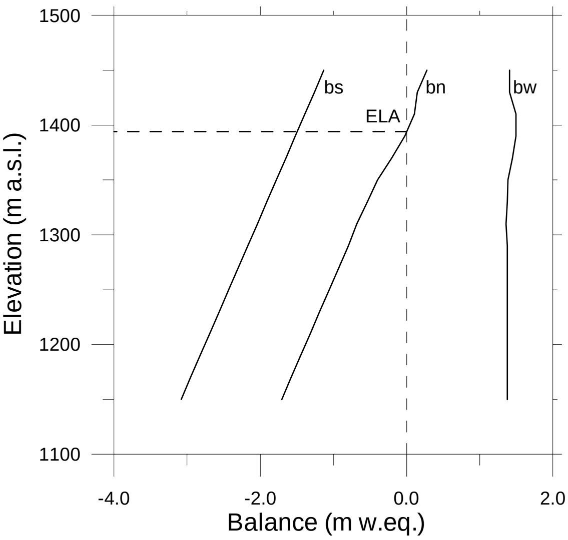

Figure 3. Winter (bw), summer (bs) and net balance (bn) as a function of elevation for Riukojietna 1999/2000.

Table 2. Mass balance data for Riukojietna 1985/1986 to 1999/2000. bw = winter balance, bs = summer balance and bn = net mass balance.

Mass balance year	b_w (m w. eq.)	b_s (m w. eq.)	b_n (m w. eq.)
1985/86	1.23	-1.77	-0.54
1986/87	1.07	-1.33	-0.26
1987/88	1.13	-2.04	-0.91
1988/89			0.89
1989/90	1.41	-1.20	0.21
1990/91	1.24	-1.17	0.07
1991/92	2.12	-1.53	0.59
1992/93	2.18	-1.83	0.35
1993/94	1.00	-1.30	-0.30
1994/95	1.45	-1.20	0.26
1995/96	1.40	-1.45	-0.06
1996/97	1.70	-2.68	-0.98
1997/98	1.36	-2.10	-0.74
1998/99	0.94	-1.72	-0.78
1999/00	1.41	-1.72	-0.31

Mass balance of Tarfalaglaciären 1999/2000 and 2000/2001

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Summary

Here the mass balance of Tarfalaglaciären for two successive mass balance years, 1999/2000 and 2000/2001, are presented. The fieldwork was conducted by the Tarfala Research Station personnel and involved winter accumulation measurements, snow density measurements and ablation stake readings. The winter accumulation was determined by manual probing at 36 sites May 17, 2000 and at 65 sites April 23, 2001 (figure 1). Snow density was both years determined from a core drilled with a PICO-auger. A polynomial relation between mean density and snow depth was established (figure 2) and used to convert snow depths and into water equivalents. Winter accumulation was then interpolated over the glacier in a 10*10m grid using the kriging method (figure 1). Readings from 5 ablation stakes 1999/2000 and on 4 stakes 2000/2001 were performed at the end of the accumulation season and at the end of the ablation season each year. The altitudes of the stake positions were used to establish ablation, bs (m w.eq.), as a linear function of elevation, Z (m), (1999/2000: bs=-0.0075Z+12.18, 2000/2001: bs=-0.0080Z+13.40). However, these functions yield negative ablation values for altitudes above 1620 m a.s.l. and 1670 m a.s.l., respectively. Ablation values on these altitudes were replaced with, based on former mass balance calculations in the area, more likely values (table 1 and 2). The area above 1620 and 1670 m a.s.l. represents ca 18% and 8%, respectivley, of the total glacier area and this could thus be an important source of error in the determination of the mass balance. An ablation stake high up on the glacier would prevent this problem to emerge. The summer balances were calculated based on a 10 m resolution digital elevation model.

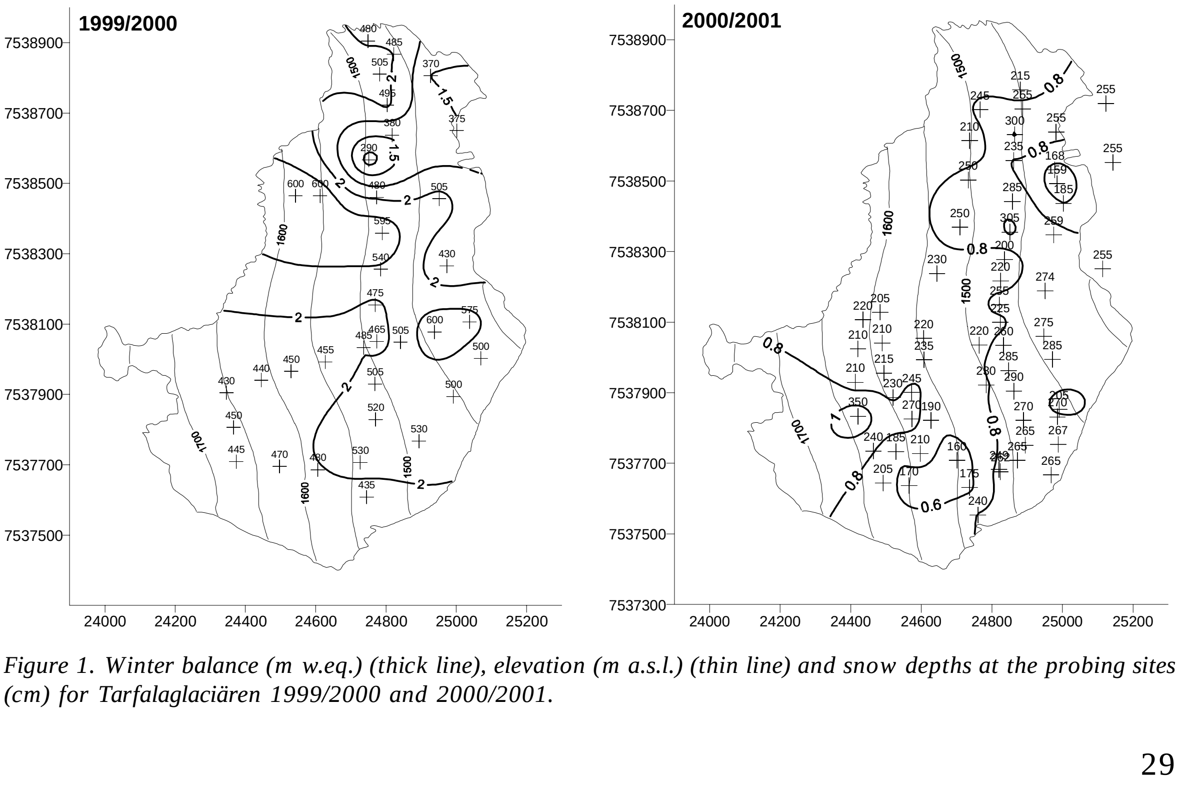

Figure 1. Winter balance (m w.eq.) (thick line), elevation (m a.s.l.) (thin line) and snow depths at the probing sites (cm) for Tarfalaglaciären 1999/2000 and 2000/2001.

Table 1. Mass balance of Tarfalaglaciären 1999/2000.

Elevation	Area	Winter balance		Summer balance		Net balance	
m a.s.l.	10^3 m^2	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.
1350-1400	9.00	19.29	2.07	15.63	1.68	3.66	0.39
1400-1450	182.00	350.54	1.92	267.37	1.47	83.17	0.45
1450-1500	215.90	433.63	2.01	240.07	1.11	193.56	0.90
1500-1550	183.20	375.06	2.03	137.03	0.74	238.03	1.29
1550-1600	156.20	317.20	2.04	56.15	0.36	261.05	1.68
1600-1650	123.80	245.14	1.96	37.53	0.30	207.61	1.66
1650-1700	75.40	137.77	1.82	22.65	0.30	115.12	1.52
1700-1750	46.50	83.96	1.83	9.20	0.20	74.76	1.63
1750-1800	9.70	18.47	1.90	1.94	0.02	16.53	1.70
1350-1800	1001.70	1981.06	1.97	787.56	0.78	1193.50	1.19

Table 2. Mass balance of Tarfalaglaciären 2000/2001.

Elevation	Area	Winter balance		Summer balance		Net balance	
m a.s.l.	10^3 m^2	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.
1350-1400	9.00	8.10	0.90	19.87	2.21	-11.77	-1.31
1400-1450	182.00	149.25	0.82	360.45	1.98	-211.20	-1.16
1450-1500	215.90	182.09	0.84	345.54	1.60	-163.36	-0.76
1500-1550	183.20	137.57	0.75	220.60	1.20	-83.04	-0.45
1550-1600	156.20	110.94	0.71	124.91	0.80	-13.97	-0.09
1600-1650	123.80	91.74	0.74	51.58	0.42	40.16	0.32
1650-1700	75.40	64.49	0.86	22.62	0.30	41.87	0.56
1700-1750	46.50	40.33	0.87	13.95	0.30	26.38	0.57
1750-1800	9.70	7.76	0.80	2.91	0.30	4.85	0.50
1350-1800	1001.70	792.27	0.79	1162.36	1.16	-370.09	-0.37

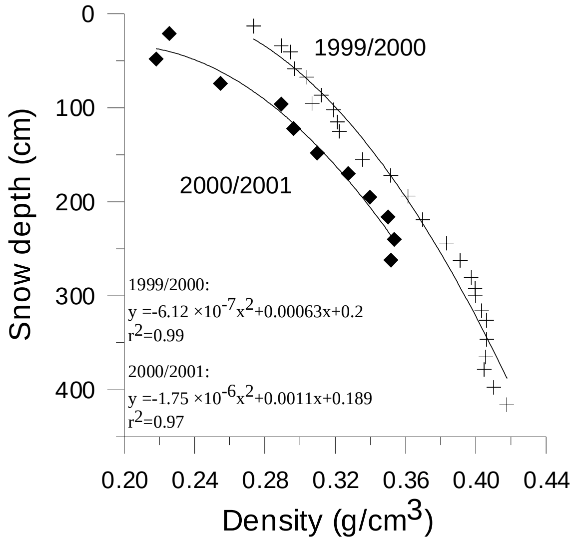

Figure 2. Mean density as a function of snow depth below surface based on density measurements in 1999/2000 and 2000/2001, respectively.

Winter balance for the mass balance year 1999/2000 amounted to 1.97 m w.eq. and 2000/2001 to 0.79 m w.eq. and the summer balance was determined to 0.78 m w.eq. and 1.16 m w.eq. respectively (table 1 and 2). Net balance calculations were conducted by subtracting summer balance from winter balance, for each grid cell, using computer software developed by Jansson (1999). The net balance was positive for 1999/2000 and 1.19 m w.eq. was added to the glaciers mass. For the mass balance year 2000/2001, the net balance was determined to -0.37 m w.eq. The difference in net balance for the two calculated years is mainly due to lower accumulation in 2000/2001.

References

Jansson, P. 1999., Effect of uncertainties in measured variables on the calculated mass balance of Storglaciären. *Geografiska Annaler*, 81A, 633-642.

Mass Balance of Pårteglaciären 1999/2000

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Summary

The winter balance 1999/2000 was determined April 16, by Lars Lidström and the author. Snow depth was measured in approximately 100 points by manual probing. The mean snowdensity was determined from one snowpit at 1340 m a.s.l. to 0.42 g/cm^3. The total accumulation during the winter 1999/2000 was 1.13 m w. eq. (table 1). During the same period, five new ablationstakes was establised. The stakes was drilled along profiles to establish an ablation gradient.

The summer balance 1999/2000 was determined by Maria Holmgren and the author in August 23, by means of 5 stakes. The summer balance was calculated from a ablationgradient based on the 5 stakemeasurements. The summer balance was determined 2-3 weeks earlier than previous years at Pårteglaciären. The summer balance amounted to -1,56 m w. eq. (table 1).

The winter and summer balance yield a net balance 2000/2001 of -0.43 m w. eq. The equilibrium line altitude (ELA) was calculated linearly betwwen 1475 and 1525 m a.s.l. to 1506 m a.s.l. The ratio between accumulation area and total area (AAR) was estimated to 40 % from obliqe photos taken from helicopter.

Table 1. Mass balance of Pårteglaciären 1999/2000.

Elevation	Area	Winter balance		Summer balance		Net balance	
m a.s.l.	10^3 m^2	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.
1050-1100	13	9.8	0.75	29.0	2.23	-19.3	-1.48
1100-1150	128	100.0	0.78	268.7	2.10	-168.7	-1.32
1150-1200	307	383.8	1.25	603.5	1.97	-219.7	-0.72
1200-1250	499	623.8	1.25	914.5	1.83	-290.7	-0.58
1250-1300	701	876.3	1.25	1191.3	1.70	-315.1	-0.45
1300-1350	945	1181.3	1.25	1480.2	1.57	-298.9	-0.32
1350-1400	1348	1634.6	1.21	1931.9	1.43	-297.3	-0.22
1400-1450	1256	1462.4	1.16	1632.8	1.30	-170.4	-0.14
1450-1500	1096	1138.0	1.04	1278.9	1.17	-140.9	-0.13
1500-1550	1357	1486.3	1.10	1402.8	1.03	83.5	0.06
1550-1600	931	969.8	1.04	838.4	0.90	131.3	0.14
1600-1650	707	835.8	1.18	542.6	0.77	293.2	0.41
1650-1700	420	433.0	1.03	266.4	0.63	166.6	0.40
1700-1750	146	236.5	1.62	73.2	0.50	163.3	1.12
1750-1800	54	90.0	1.67	19.9	0.37	70.1	1.30
1800-1850	5	8.8	1.75	1.2	0.23	7.6	1.52
1050-1850	9913	11469.8	1.16	12475.1	1.26	-1005.4	-0.10

Mass Balance of Salajekna 1999/2000

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Summary

The winter balance 1999/2000 was determined on May 23, by Ian Brown, Jonathan Carrivick and the author. Snow depth was measured in approximately 70 points by manual probing. The mean snowdensity was determined from one snowpit at 1080 m a.s.l. to 0.52 g/cm^3. The total accumulation during the winter 1999/2000 was 2.18 m w. eq. (table 1). During the same period, five new ablationstakes was establised. The stakes was drilled along profiles to establish an ablation gradient.

The summer balance 1999/2000 was determined by Maria Holmgren and the author in August 25, by means of 3 stakes. The summer balance was calculated from a ablationgradient based on the 3 stakemeasurements. The summer balance was determined 2-3 weeks earlier than previous years at Salajekna. The summer balance amounted to -1.55 m w. eq. (table 1).

The winter and summer balance yield a net balance 2000/2001of 0.62 m w. eq. The equilibrium line altitude (ELA) was calculated linearly betwwen 1125 and 1175 m a.s.l. to 1142 m a.s.l.

Table 1. Mass balance of Salajekna 1999/2000

Elevation	Area	Winter balance		Summer balance		Net balance	
m a.s.l.	10^3 m^2	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.	10^3 m^3	m w.eq.
900-950	810	1417.5	1.75	2227.5	2.75	-810.0	-1.00
950-1000	714	1249.5	1.75	1835.0	2.57	-585.5	-0.82
1000-1050	1400	2428.0	1.73	3346.0	2.39	-918.0	-0.66
1050-1100	1304	2052.0	1.57	2881.8	2.21	-829.8	-0.64
1100-1150	1654	3010.5	1.82	3357.6	2.03	-347.1	-0.21
1150-1200	2068	4649.0	2.25	3825.8	1.85	823.2	0.40
1200-1250	1620	3965.0	2.45	2705.4	1.67	1259.6	0.78
1250-1300	2040	5242.0	2.57	3039.6	1.49	2202.4	1.08
1300-1350	3080	8010.0	2.60	4034.8	1.31	3975.2	1.29
1350-1400	7328	19968.0	2.72	8280.6	1.13	11687.4	1.59
1400-1450	1137	3126.8	2.75	1080.2	0.95	2046.6	1.80
1450-1500	276	759.0	2.75	212.5	0.77	546.5	1.98
1500-1550	223	613.3	2.75	131.6	0.59	481.7	2.16
1550-1600	112	308.0	2.75	45.9	0.41	262.1	2.34
1600-1650	44	121.0	2.75	10.1	0.23	110.9	2.52
900-1650	23810	51824.5	2.18	37014.5	1.55	14810.0	0.62

Meteorological Observatios at Tarfala 1998-2000

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Abstract
Air temperature, relative humidity, wind speed, wind direction and precipitation are recorded at Tarfala Research Station with hourly resolution. Mean annual air temperature amounted to -3°C in 1999 and -2.4°C in 2000, thus exceeding the 1965-1990 mean of -3.9°C. Most of this increase results from considerable warming during the months September to November, reaching more than 4°C in November 1999 compared to the 26-year reference period. The mean October and November air temperatures recorded for 2000 and 1999, respectively, are the highest since observation start in 1965.

Measurements

At Tarfala Research Station (1135 m a.s.l.) an automatic weather station is operated measuring air temperature, relative humidity and precipitation at approximately 2 m above the ground, and wind speed and wind direction at about 2.5 m. Temperature and humidity are measured by a Rotronic-probe. Wind speed and direction are measured with a Young-wind monitor. Hourly and daily data are stored by a Campbell CR10 datalogger. The tipping bucket precipitation gauge is not heated, and thus measurements during snowfall are considered unreliable.

Between April 17 and May 11, 1998 no data are available. Before July 29, 1998 and between November 28, 1999 and June 15, 2000 precipitation data are missing since the instrument was decoupled during these periods. On August 6, 1998 a ventilated temperature/humidity sensor was added to the station. The data reported here refer to the unventilated temperature measurements, using the same sensor as in previous reports.

Results

Monthly and annual data are given in figures 1 to 3 and in table 1 and 2. Due a data gap, annual and the April and May monthly means cannot be computed in 1998. Mean annual temperature was -3.0 and -2.4°C in 1999 and 2000, respectively, and thus higher than the 1965-1990 mean amounting -3.9°C (Grudd and Schneider, 1996). The summers 1998 and 1999 were characterized by frequent precipitation and fog, in particular during most of July and August. In 1999, the period between the end of July to the end of August was subject to frequent snow fall. In 1998 and 2000, warm December temperatures were recorded rising above freezing several times. In all years, a northern wind direction dominated, with a secondary maximum from the south, indicating strong topographic channeling of air flow through the north-south streching Tarfala valley.

In figure 4 the monthly temperature means are compared to the seasonal cycle averaged over the period 1965-1990. The seasonal cycle in 1998 is in generally good agreement with the 26-year-average except for a larger deviation in December. In 1999 and 2000 this is true for the first half of the year, however for the months September to November considerably higher temperatures are observed compared to the 1965-1990 average. The 1999 November mean (-3.8°C) exceeds the one of the reference period by more than -4°C and is the highest value since the beginning of the measurements in 1965, exceeding considerably the next highest value of -4.7°C recorded in 1967 and

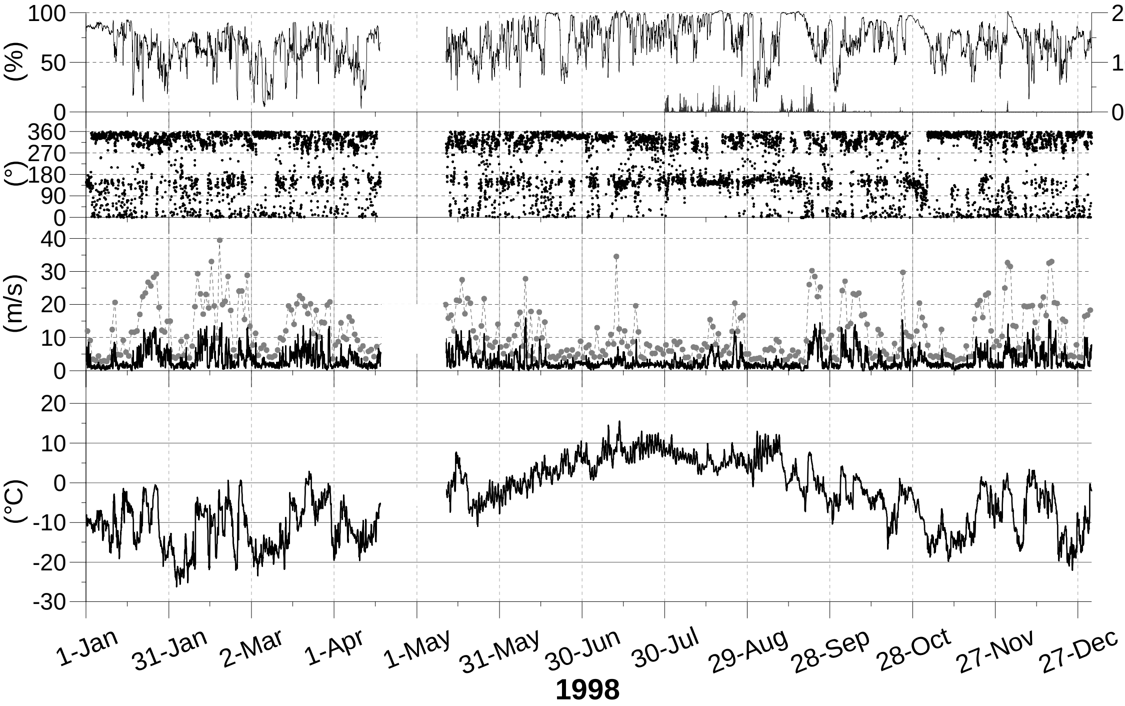

Figure 1. Hourly means of air temperature (°C), wind speed (m s^{-1}), wind direction (°) relative humidity (%), and precipitation (mm h^{-1}) at Tarfala meteorological station in 1998. The dashed dotted line denotes daily maximum wind speed as averaged over 10 seconds. No data are available from April 17 to May 11, 1998. The precipitation gauge was not recording before July 29 and after November 28, 1999.

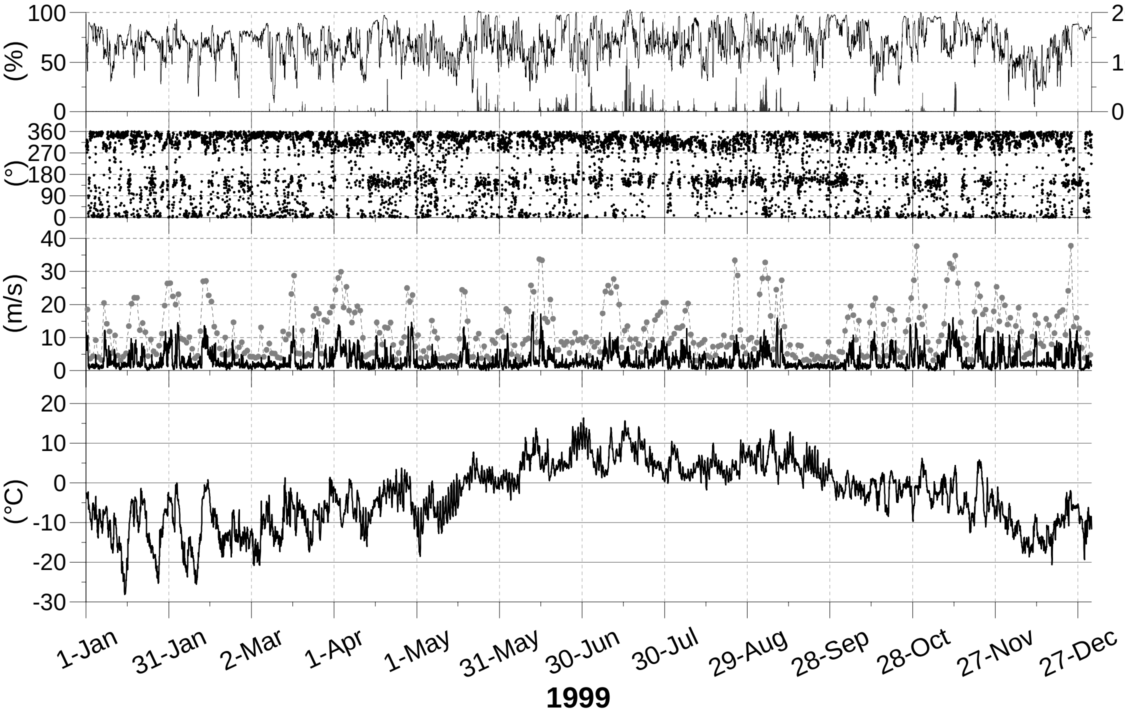

Figure 2. Hourly means of air temperature (°C), wind speed (m s^{-1}), wind direction (°) relative humidity (%), and precipitation (mm h^{-1}) at Tarfala meteorological station in 1999. The dashed dotted line denotes daily maximum wind speed as averaged over 10 seconds. Winter precipitation values are considered unreliable since the gauge is not heated.

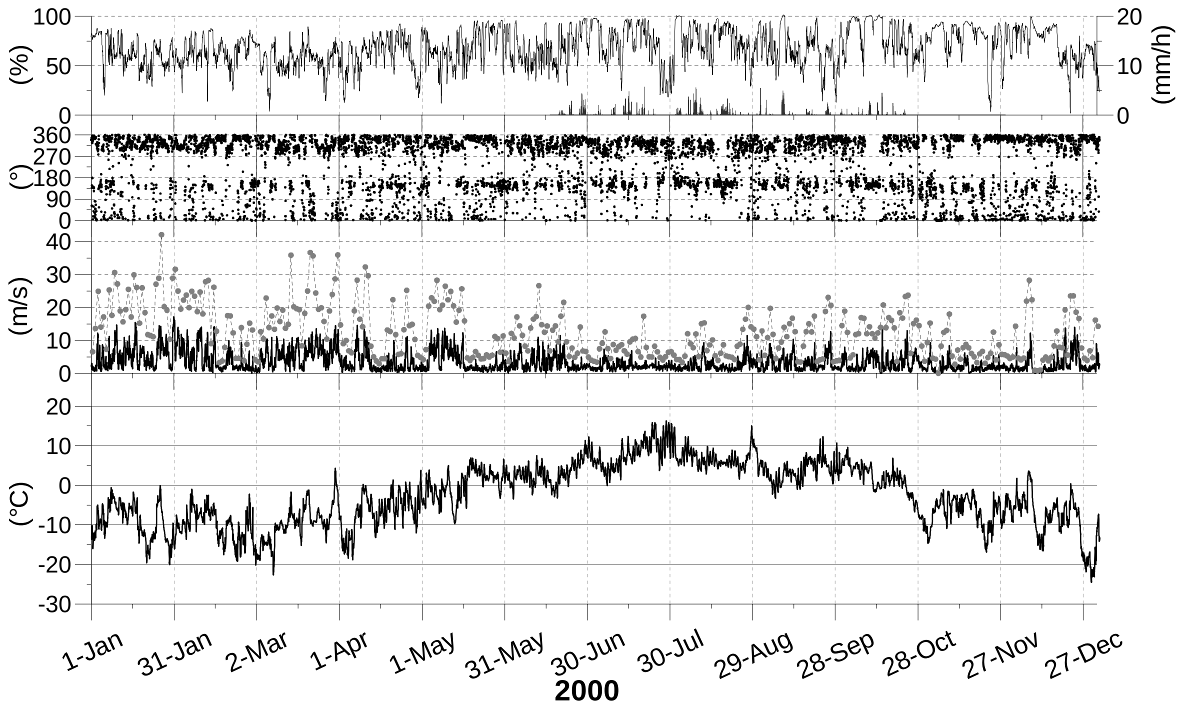

Figure 3. Hourly means of air temperature (°C), wind speed (m s^{-1}), wind direction (°) relative humidity (%), and precipitation (mm h^{-1}) at Tarfala meteorological station in 2000. The dashed dotted line denotes daily maximum wind speed as averaged over 10 seconds. The precipitation gauge was not recording before June 15, 2000.

Table 1. Monthly means of air temperature, relative humidity, wind speed and precipitation totals at Tarfala meteorological station (1135 m a.s.l.) from 1998-2000.

	Air temperature (°C)			Relative humidity (%)			Wind speed (m/s)			Precipitation (mm)		
	1998	*1999*	*2000*	*1998*	*1999*	*2000*	*1998*	*1999*	*2000*	*1998*	*1999*	*2000*
Jan	-10.2	-11.3	-9.3	70.2	68.1	62.5	3.5	3.0	5.4	-		-
Feb	*-12.7*	*-12.3*	*-10.2*	*65.6*	*67.1*	*64.6*	*3.9*	*3.3*	*4.3*	-		-
Mar	*-10.9*	*-9.8*	*-9.6*	*58.5*	*66.0*	*55.3*	*3.5*	*2.6*	*5.9*	-		-
Apr	-*	*-4.9*	*-6.6*	-	*68.0*	*62.7*	-	*3.9*	*2.9*	-	*22*	-
May	-	*-2.8*	*0.4*	-	*66.3*	*70.6*	-	*2.2*	*3.7*	-	*84*	-
Jun	*2.2*	*5.3*	*3.3*	*75.0*	*67.1*	*67.1*	*2.3*	*3.2*	*3.1*	-	*118*	-
Jul	*7.8*	*7.0*	*8.2*	*82.5*	*73.0*	*71.4*	*2.1*	*3.6*	*2.2*	-	*277*	*108*
Aug	*4.9*	*4.3*	*6.6*	*86.2*	*70.8*	*76.6*	*2.5*	*2.9*	*2.5*	*205*	*76*	*187*
Sep	*2.3*	*4.6*	*3.8*	*72.3*	*75.6*	*64.9*	*2.6*	*2.6*	*3.1*	*138*	*171*	*104*
Oct	*-4.1*	*-1.4*	*0.3*	*78.6*	*70.9*	*80.7*	*3.5*	*3.4*	*3.1*	*19*	*29*	*69*
Nov	*-10.2*	*-3.8*	*-6.2*	*66.9*	*78.4*	*77.8*	*2.5*	*4.2*	*1.7*		-	
Dec	*-8.2*	*-11.3*	*-9.1*	*69.6*	*59.8*	*70.5*	*4.1*	*3.4*	*2.7*		-	

*Data gap April 17 to May 11, 1998, and for precipitation also before July 29, 1998 and between November 28, 1999 and June 15, 2000.

1993. The mean October temperature in 2000 (+0.3°C) corresponds to the value obtained in October 1987, and is the warmest October mean since 1965, followed by the mean value in 1999 (-1.4°C). All other previous October means have been below -2°C.

Totalisator

In September 1999 a totalisator (precipitation gauge) was installed in the vicinity of Tarfala Research Station (figure 5). The instrument was received from Abisko Research Station and collects rain and snow precipitation all year around. The opening

Table 2. Annual means of air temperature, T (°C) at 2 m, relative humidity, RH (%), wind speed, u (m s^{-1}) and maximum wind speed (10 seconds integration interval) at Tarfala meteorological station (1135 m a.s.l.) from 1998-2000.

	1998	1999	2000
T	-	-3.0	-2.4
RH	-	69.2	68.8
u	-	3.2	3.4
u_{max}	39.4*	37.8	42.0

*Minimum value due to data gap between April 17 and May 11, 1998

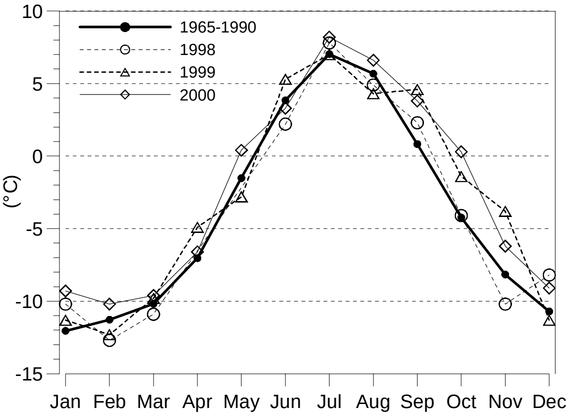

Figure 4. Mean monthly air temperature at Tarfala Reserach Station during 1998-2000 and mean values of the period 1965-1990.

has a diameter of 15.9 cm. The top of the instrument reaches about 2.8 m above the surface. Usually only few cm snow accumulate below the instrument during winter. Several times per year the water level

Figure 5. Totalisator collecting annual snow and rain precipitation. Isfallsglaciären in the background (Photo Mart Nyman).

in the gauge is measured with a measuring tape and water level differences converted into precipitation sums. To melt snow falling into the gauge, several kg salt ($CaCl_2*6H_2O$) are dissolved in a few litres of water. About 1/2 litre oil is added to reduce evaporation. The gauge is emptied every fall.

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Swedish glacier front monitoring program - compilation of data from 1990 to 2001

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Introduction

In 1965 a glacier front monitoring programme was initiated in order to study the regional scale representativity of climate data collected on Storglaciären. Another aim was to study differences in climate types in various parts of the mountain range. 20 glaciers were chosen with respect to their orientation, elevation and distance to the Atlantic Ocean (Schytt, 1968). In the early 1990s the data was compiled (Holmlund, 1993) and it was concluded that many of the Swedish glaciers are now close to a balanced state with the climate, or at least have a positive mass balance (Holmlund, 1993). Now another ten years have passed and the large glaciers are still retreating and we are planning to make a new compilation of data after the field season 2002. In this paper data from 1990 to 2001 is presented. There are gaps in the recordings and there are also some questionmarks to be sorted out after the next field season. Two glaciers are now excluded from the compilation and these are Mårmaglaciären and Kåtoktjåkkoglaciären. The reason to exclude Mårmaglaciären is based on the fact that until the most resent years this glacier has ended against its own ice cored frontal moraines. It has been difficult to distinguish the exact boundary and it has also been difficult to maintain reasonably fixed points in an area where the surface till is resting on solid ice. Mårmaglaciären is at the same time included in the mass balance programme and it is photogrammetrically mapped every ten year, which is sufficient to keep track of frontal changes. Thus, though Mårmaglaciären is excluded in the field monitoring programme, but it is still under observation. Kåtoktjåkkoglaciären is excluded because of its remote position. We judge that it is not cost efficient to keep it within the programme.

Glacier front monitoring data is reported every fifth year to the World Glacier Monitoring Service (WGMS, 1997) in Switzerland, and in various papers and reports. The programme has been funded by the Swedish Research Council and by Stockholm University.

Methods

In this paper, glacier front surveys between 1997 and 2001 have been evaluated. A few measurements have not been possible to evaluate, mainly because of lack of geodetic support, but will be presented in coming annual reports. Additional results for the years 1990 to 1996, not previously published, have also been evaluated. A compilation of the results of the change in glacierfront position during the years 1990 to 2001 is shown in table 1. The table is subdivided geographically, from north to south. The footnotes indicate time between surveys, lack of geodetic support, not visited, not measured, etc. If no indication is given the result is based of the former result given in the table.

The methods used during the front surveys are traditional theodolite measurements, tape-measurements and static GPS measurement. The most common approach has been traditional theodolite measurements. A less number of glacier fronts have been surveyed by tape or GPS. The amount of measured points during the theodolite measurements varies between approximately 10 and 30, which make the accuracy high enough. During tape-measurement, only a few points have been measured, which makes the result more uncertain. Glacier front surveyed with static GPS, with a large number of measured points, show high accuracy. The results shown in table 1 are exclusively average values of the retreat or advance of the front in the direction of the ice flow.

In table 1 and in the following presentation the clarifications mainly concern the glaciers that have been evaluated for this report.

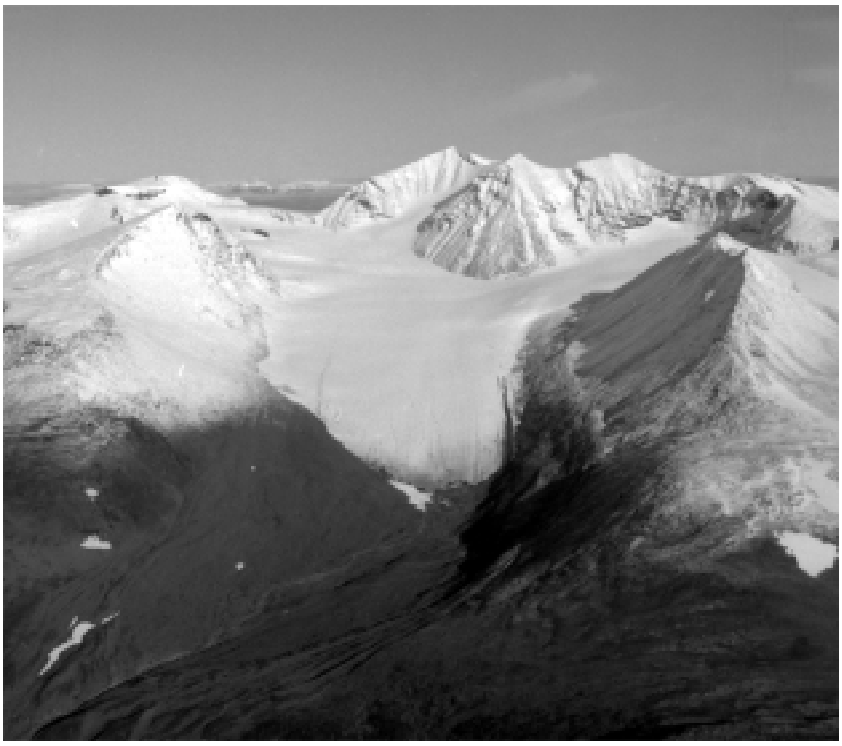

Figure 1. Mikkaglaciären in September 13, 2000 during the glacierfront surveys. (Photo: Per Holmlund)

In the following presentation of the results, the abbreviation of the survey methods has been used; theodolite = TH, tape-measurement = T-M and static GPS = GPS. The date of the surveys is important in the evaluation of the results and the survey date has been reported when it has been available.

Abisko and northern Kebnekaise

Kårsaglaciären

1/9 1992, 2000, 2001.

Riukojietna

1/9 1992, T-M 24/8 1993, 3/9 1995, TH 6/9 1996, 16/8 1997, TH 25/8 1998, TH 3/9 2000.

Västra Påssusglaciären

T-M 14/8 1991, 16/8 1992, 3/9 1995, T-M 15/8 1997, 12/8 2000.

Östra Påssusglaciären

T-M 1991, 16/8 1992, T-M 7/8 1994, TH 3/9 1995, TH 6/9 1996, T-M 15/8 1997, TH 25/8 1998, 1999, 12/8 2000, 2001.

Unna Räitaglaciären

T-M 1991, 18/8 1992, 4/9 1994, 3/9 1995, T-M 15/8 1997.

Stour Räitaglaciären

T-M 13/8 1991, TH 7/9 1996, T-M 15/8 1997, 25/8 1998.

Central Kebnekaise and Tarfala

Storglaciären

1990, 1991, 31/8 1992, 26/8 1994, 1995, 1996, 1998, TH 1999, GPS 2001.

Isfallsglaciären

TH 10/9 1996, TH 8/9 1997, TH 13/8 1998, 1999, 11/9 2000, TH 6/9 2001.

S.Ö. Kaskasatjåkkaglaciären

GPS 2001.

Rabots glaciär

TH 1997, GPS 1999, TH 12/9 2000.

Northern Sarek and Akka

Hyllglaciären

30/8 1992, 26/8 1994, 9/9 1995, 1997, 29/8 1998.

Suottasglaciären

TH 14/8 1984, 1990, 19/8 1991, 15/8 1994, 9/9 1995, TH 8/9 1996, TH 11/9 1997, 29/8 1998, 13/9 2000, TH 19/9 2001.

Vartasglaciären

1990, 1991, 1994, 9/9 1995, 1997, 29/8 1998, 2000.

Mikkaglaciären

TH 8/9 1996, TH 16/8 1997, TH 2/8 1998, TH 13/9 2000 (figure 1), TH 19/9 2001.

Table 1. Change in glacierfront position of the Swedish glaciers during the period from 1990 to 2001. The average surveyed result in metres in the direction of the ice flow.

Glacier \ Year	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Abisko and northern Kebnekaise												
Kårsaglaciären	-2.0	–	0.0	0.0	–	–	-22.3[A]	–			progr	progr
Riukojietna	0.0	–	0.0	-7.6[B]	–	0.0	-3.8	progr	-11.7[C]		-8.3	–
Västra Påssusglaciären	0.0	-10.9[D]	0.0	–	–	0.0		progr			progr	
Östra Påssusglaciären	0.0	–	0.0	–	-5.7[E]	-2.3	progr	-16.5[F]	-20.0	progr	0.0	progr
Unna Räitaglaciären	0.0	0.0	0.0	0.0	0.0	0.0		-2.6				
Stour Räitaglaciären	–	-2.0[G]	0.0	-5.0	-3.0	–	-6.2	0.0	progr			
Central Kebnekaise and Tarfala												
Storglaciären	0.0	0.0	0.0	0.0	0.0	0.0	0.0		progr	0.0		- 1.0
Isfallsglaciären	+4.0	–	+5.0	+3.4	+2.0	+5.0	+1.4	0.0	+3.8	progr	progr	+2.3[H]
S. Ö. Kaskasatjåkkagl.	-2.0	–	+3.0	+1.0	–	–	-4.1					progr
Rabots glaciär	-11.0	–	-14.0	-15.0	-9.3	-9.3	-10.6	-7.5		- 19.3	-7.7	
Northern Sarek and Akka												
Hyllglaciären	–	–	0.0	-38.0[I]	-4.0	0.0		0.0	0.0			
Suottasglaciären	0.0	-2.0	0.0	0.0	0.0	0.0	-36.9[J]	-0.6	0.0		0.0	progr
Vartasjekna	0.0	0.0	-15.0[K]	0.0	0.0	0.0		0.0	0.0		0.0	
Mikkaglaciären	-7.0	-	-10.0	-15.0	-12.5	-13.5	-11.9	-8.5	progr		progr	progr
Ruotesglaciären	0.0	0.0	-6.0	0.0	-10.0	-20.7	-20.4	–	-41.6		–	
Ruopsokglaciären	–	–	-7.0[L]	-4.0	-3.9	-3.4	-9.1	-0.1	-21.7		-19.1	
Southern Sarek and Sulitelma												
Pårteglaciären	-8.0	–	-4.0	-5.0	-12.0	-9.0	-20.9	-10.2	–	-14.9	-10.0	-11.1
Salajekna	-66.0[M]	–	-10.0	–	-14.0	-12.5	-9.7	-9.4	–	-19.3	-5.0	–

A, 1991-1996
B, 1989-1993
C, 1996-1998
D, 1989-1991
E, 1988-1994
F, 1995-1997
G, 1989-1991
H, 1998-2001
I, 1989-1993
J, 1984-1996 with reduction of the front retreat from 1990 to 1991
K, 1984-1992
L, 1989-1992
M, 1984-1990

progr = data in progress
– = the glacier has not been visited, not been possible to survey or data not available

Ruotesglaciären

1991, TH 9/9 1995, TH 9/9 1996, TH 2/9 1998.

Ruopsokglaciären

30/8 1992, 30/8 1993, TH 9/9 1996, TH 16/8 1997, TH 2/9 1998, TH 13/9 2000.

Southern Sarek and Sulitelma

Pårteglaciären

TH 8/9 1996, TH 6/9 1999, T-M 23/8 2000, TH 19/9 2001.

Salajekna

TH 8/9 1996, TH 4/9 1997, TH 6/9 1999, T-M 25/8 2000.

Concluding remarks

The most remarkable conclusion is that many large glaciers are still retreating though the last ten years have been rather favourable for a positive or a balanced glacier mass balance. The glacierdynamic studies by Klingbjer and Neidhart (in prep.) indicate that Pårteglaciären may still need another 100 years to adopt its size to post little ice age conditions. The glaciers in the dry eastern rim of the mountain range may need very long time spans to come to a balanced state with the climate.

One detail worth mentioning concerns Suottasglaciären, which show almost no change over the years except for the year 1996 when a recession of 36.9 metres is recorded. This is most probably due to recession before 1989, followed by a number of years with snow covered snout and then finally a completely snow free front in 1996 showing the real change since 1984.

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Permafrost in Sweden

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Summary

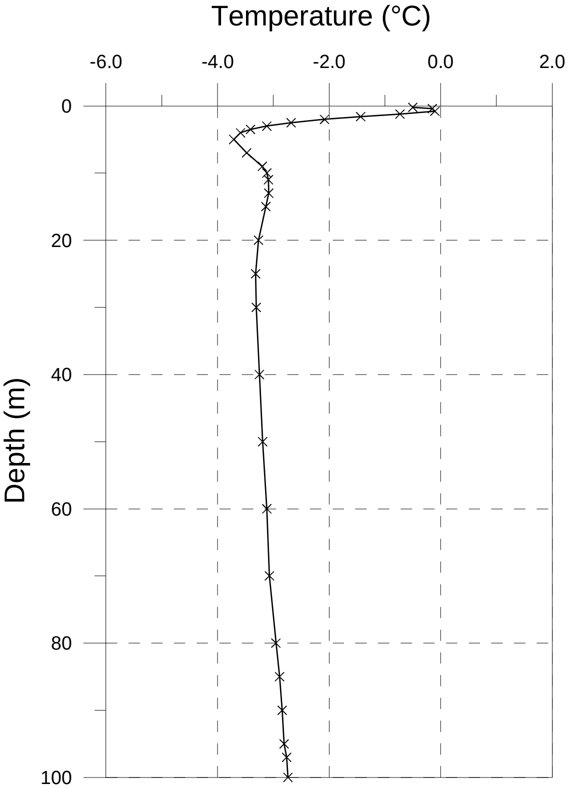
In 1997 a Swedish programme for permafrost monitoring was initiated. Originally it was included in the EU-funded PACE (Permafrost and Climate in Europe) project. PACE provided three years of fundings and Tarfala was a sub contractor associated to Oslo University. The combined Norwegian-Swedish efforts provided data for a PhD thesis by Ketil Isaksen (2001) at Oslo University. The Swedish programme involves both bedrock drillings and ground temperature measurements.

In Sweden permafrost have received relatively little attention, possibly because such areas are generally not inhabited and containing infrastructural constructions. The primary objects of study in Sweden have been Palsas (Wramner, 1973) and ice-cored moraines (Östrem, 1964). Scattered work on permafrost in general that deserves mentioning include Ekman (1957), Rapp (1982), Rapp and Annersten (1969), White *et al*. (1969), Knutsson (1980) and King (1984). King's (1984) study constitutes the only study on the physical relationship between climate and the occurrence of permafrost.

In april 2000 one 100 m and two 15 m holes were drilled into the bedrock close to Tarfala Research Station. One 15 m hole hole was drilled by the station at 1130 m a.s.l. at the site of the weather station which has been during summer since 1946 and automatically all year round since 1965. At Tarfalaryggen, a smooth saddle at 1550 m a.s.l. one 100 m and one 15 m boreholes were drilled and a weather station was errected (figure 1 and 2). The permafrost depth is estimated to exceed 300 m. At Tarfala Research Station the annual mean temperature is -3.9 °C and the annual precipitation

Figure 1. Drilling site at Tarfalaryggen, a smooth saddle at 1550 m a.s.l. One 100 m and one 15 m boreholes were drilled and a weather station was errected.

is about 1000 mm. The boreholes are described by Sollid *et al*. (2000) and Isaksen *et al*. (2001). Data from these boreholes are available through the Tarfala Research Station monitoring programme.



Figur 1. Temperature profile in the 100 m deep borehole at Tarfalaryggen in June 1, 2000.

In addition to these direct studies of permafrost, several studies of the temperature regime of the glaciers and the ground in the Tarfala valley have been carried out over time.

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Radar Investigations of Englacial Water in Storglaciären

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Introduction

The flow of water during the summer melt season from the surface of a glacier to streams emerging at the terminus has been studied with a variety of techniques including dye/salt injections, bore hole water pressure measurements, down-hole video and remote sensing with ground (ice) penetrating radar, GPR. The subject has been reviewed recently by Fountain and Walder (1998) who propose a model of englacial conduits which evolve from water entering crevasses and melting its way toward an equilibrium configuration of passages draining toward the bed. In the present study, GPR was used in conjunction with bore hole video to investigate englacial water movement in the ablation area of Storglaciären. This paper describes the radar contributions to this study after the first year of field work, while a companion paper in this volume by Fountain *et al*., details the results of the bore hole experiments.

Storglaciären (figure 1) is a polythermal valley glacier in northern Sweden with an area of 3 km^2. It has a perennial cold surface layer in the ablation

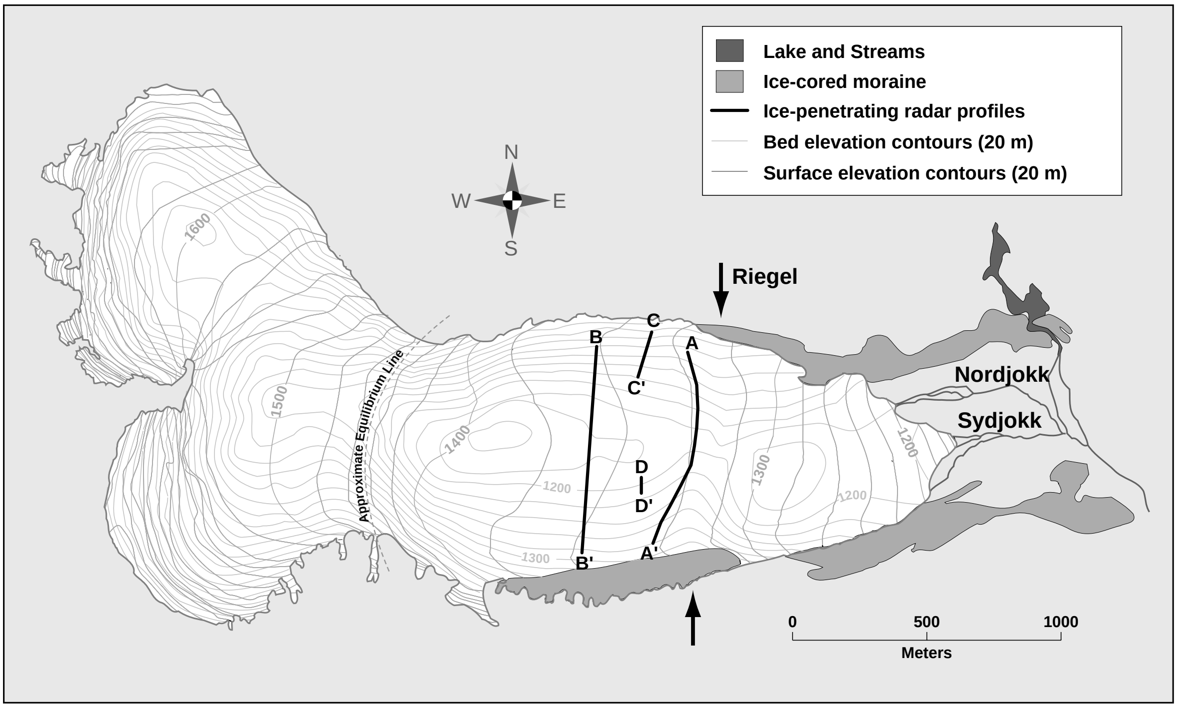

Figure 1. Storglaciären (modified from P. Jansson, Stockholm University). Glacier outline showing surface and bed contours and locations of the four radar profiles (Figures 2-5) described in the text.

area that is 20-60 m thick (Holmlund and Ericksson, 1989). The cold layer is essentially impermeable to water, so surface water in this part of the glacier must enter through moulins or crevasses (Schneider, 1999). According to Östling and Hooke (1986), water storage is generally built up during late May to early June and is more or less constant from early summer to August. The present study was carried out during July, 2001 when englacial storage was likely high. The bed topography in the ablation area beneath Storglaciären is characterized by a riegel (transverse bedrock ridge) near the middle of the ablation area (Holmlund and Ericksson, 1989). Moulins develop in crevasses over the riegel admitting water from the surface in this part of the glacier. Up glacier from this area water is present in slush ponds and streams running over the surface extending back to the accumulation area.

Methods

Radar experiments were carried out with two radar systems each at two different frequencies. A low-frequency impulse radar transmitting pulses at 5 and 10 MHz was used to penetrate the full ice thickness to provide details of the bedrock topography in the study locations. Also a high-frequency RAMAC GPR transmitting at frequencies of 50 and 100 MHz was deployed in grid surveys of selected areas to locate englacial water and possible conduits. Altogether 119 profiles covering approximately 7 km of surface travel were carried out, most of them in closely spaced grids coinciding with the borehole experiments. Results from several of these profiles are discussed in detail below.

Radar profiles were processed in the field to give immediate feedback and guidance for the drilling. Software was developed to view adjacent profiles in grids as sequential frames in a ‘movie’, enabling us to simulate a three-dimensional view of the ice. All profiles were migrated to remove the effects of antenna separation and the finite beamwidth of the radar. A single ice velocity model with v = 168 m/µsec was used in the migration algorithm. This was adequate for the shallow profiles completed with the high-frequency system although it overmigrates ringing echoes from surface water. It also produces reasonable results for the low-frequency deep profiles since only the bed information is used. More complex velocity structures may be required in studies extracting detailed information from a variety of depths, eg. Murray *et al.*, 2000a.

Results

Figure 2 is a typical low-frequency (10 MHz) cross-glacier radar profile in the overdeepening above the bedrock ridge near where bore hole studies were carried out in July 2001 (line A-A’ in figure 1). Englacial echoes show the presence of water within the ice but the distributions are not resolved at these frequencies. Figure 3 shows a second cross-glacier profile at 50 MHz approximately 0.5 km upglacier, line B’-B in figure 1. The cold layer (upper 20 to 40 m) is characterized by the general absence of echoes in contrast to the warmer ice below where echoes from individual scattering sources are prevalent. These are depicted as hyperbolic diffractors in the unmigrated profiles indicating source sizes on the order of the wavelength of the radar, ~ 3 m or smaller. Water in streams and ponds on the surface also gives rise to ‘ringing’ which contaminates upper portions of the record in some places. These echoes are not properly dealt with by the single-velocity migration algorithm and thus show up as concave multiple reflections or ‘smiles’ in the profile. Similar surveys have been used to map the extent of the cold layer in polythermal glaciers (Holmlund and Ericksson, 1989; Holmlund *et al.*, 1996; Murray *et al.*, 2000b.

Based on the initial radar surveys, three locations were chosen to sample potentially different englacial environments with further radar and borehole studies: (1) in the cold surface layer near the north margin of the glacier, (2) in the crevassed zone just north of the glacier center line, and (3) near the valley center where surface water was prevalent. At two of these sites, the presence of water in cavities or drainage channels was suggested by the radar surveys at 50 and 100 MHz and a part of the motivation for drilling bore holes in these areas was to intersect particular water bodies imaged by the radar.

Figure 4 shows a migrated section of a radar profile at 50 MHz traversing the bore hole site #1 and extending toward the north glacier margin at the right, line C’-C in figure 1. The boundary between the cold surface ice (largely without echoes) and warmer temperate ice below slopes downward toward the right as the cold ice layer thickens toward the margin. The bedrock echo clearly present at the right of the figure beneath cold ice slopes downward to the left toward the glacier. Energy at this frequency is scattered from water bodies within the temperate zone and as a result the bedrock echo becomes obscured as the ice thickens. Echoes starting at the surface toward the left side of the profile in two locations at approximately 20 and 40 m are from

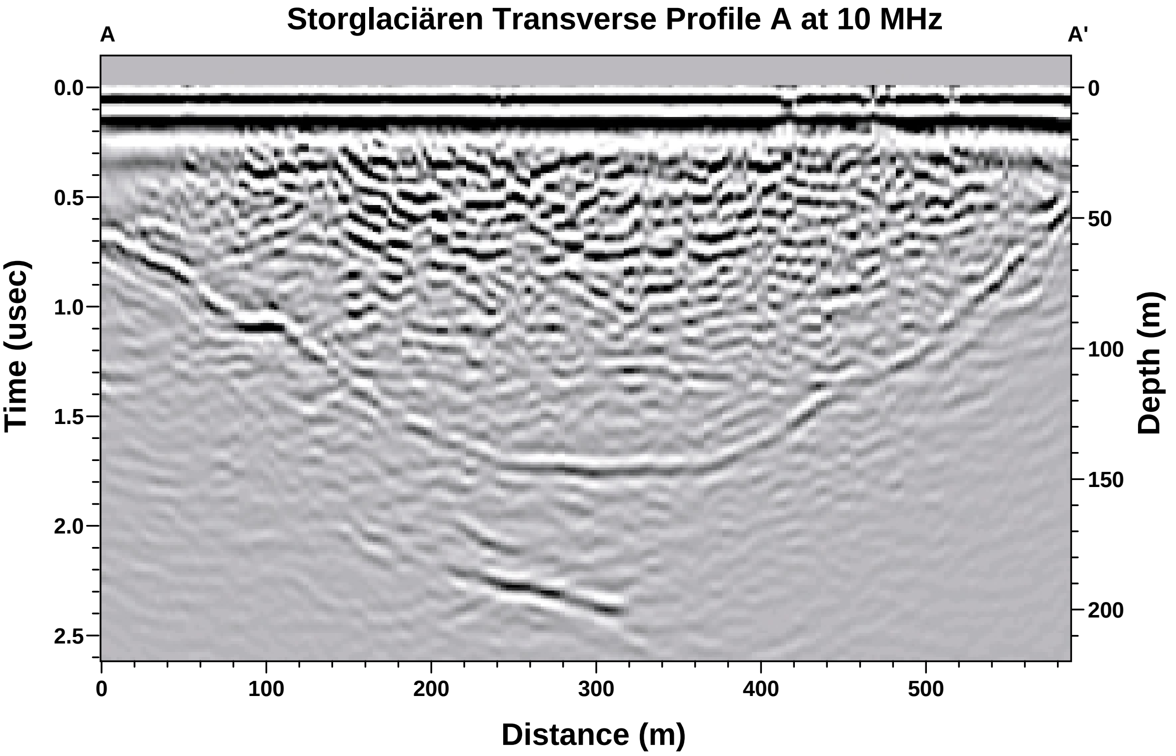

Figure 2. Transverse radar profile A-A' acquired at 10 MHz just up glacier from the riegel. Echoes have been migrated to correct for the finite antenna beamwidth as described in the text. View is downglacier with north toward the left. Bedrock and englacial echoes are prominent, but the latter are not resolved at this frequency. Sloping echo at 200 m apparent depth near the profile center is sideswipe from the riegel on the downstream side of the profile.

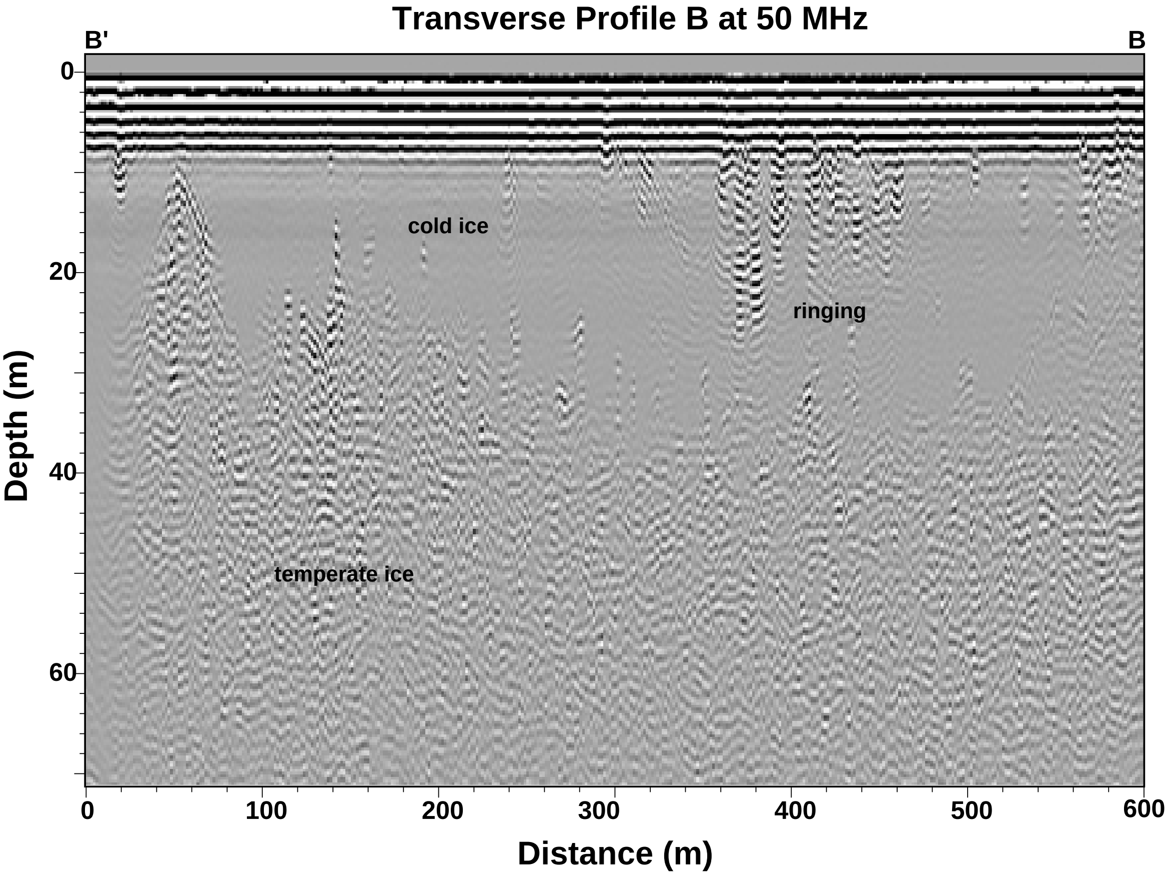

Figure 3. Transverse radar profile B'-B at 50 MHz depicting the boundary between cold ice above and temperate ice below. View is looking upglacier with north toward the right. Ringing echoes at apparent shallow depths toward the right side of the profile are due to water ponded on the surface.

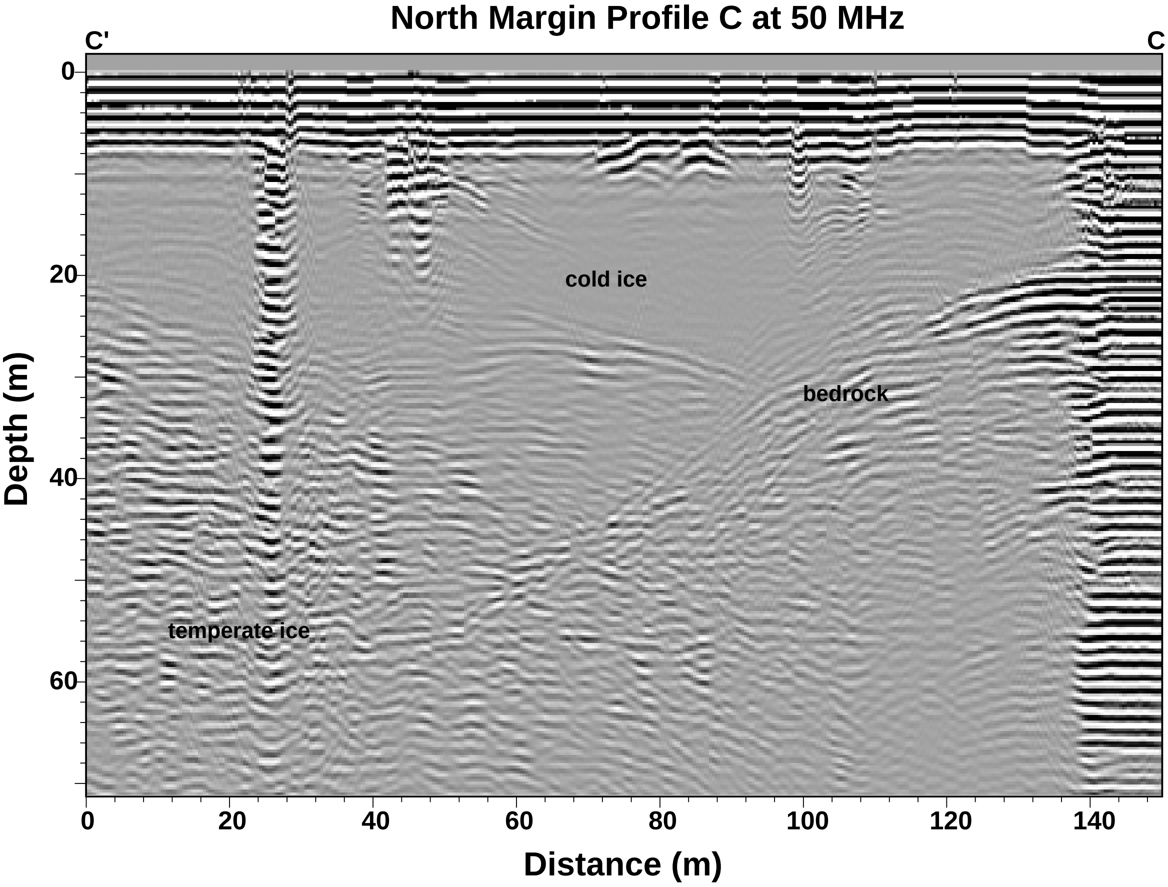

Figure 4. Radar profile C'-C at 50 MHz near the north glacier margin. View is looking upglacier with the north margin to the right. The boundary between cold surface ice and warmer ice below slopes downward to the right as the cold ice thickens toward the north margin. The bedrock echo apparent near the north margin at the right slopes toward the glacier center (left) but becomes undefined as scattering losses increase in the thickening temperate ice.

drilling equipment and a cable down one of the bore holes. Another at approximately 105 m is due to a water-filled crevasse, and rocks in an ice cored moraine appear at 140 m.

Additional radar surveys at both 50 and 100 MHz in this location showed a well-defined boundary between the cold surface layer and temperate ice beneath. The generally high density of scattering sources within the temperate ice indicates that water is present in cavities and channels virtually everywhere. However, unlike the results in other areas, the surveys did not identify prominent reflectors within the cold layer or particular bright echoes in the temperate ice which stood out from the general scattering.

Bore hole site #2 was located in a crevassed region north of the glacier center line where strain rates are increased as ice approaches the bedrock ridge. Radar surveys indicated an extended bright reflector in the cold surface ice layer at a depth of approximately 17 m. The echo source was imaged in several adjacent profiles and appeared to run transverse to the general trend of crevasses. While several boreholes made englacial connections in this area, none could be unambiguously associated with the echoes in the radar profiles.

Figure 5 shows a migrated section of radar profile D'-D, one of the 100 MHz profiles in the grid survey from borehole study area #3 just south of the valley center (figure 1). Ringing in the upper portion of the record is again produced by the copious amounts of water at the surface. Beneath this is a zone of relatively cold echo-free ice ending at about 25 meters depth. Within the warmer ice below are returns from two sloping echo sources, one extending nearly the full width of the profile and the other dipping more steeply toward the glacier center at the right. Both of these sloping echoes are present in adjacent profiles parallel and perpendicular to the one shown, and thus an approximate orientation for the echo sources could be inferred in three dimensions.

Our working hypothesis for these echoes is that they are produced by voids within the ice, possibly air or water-filled channels draining toward the bed. The extended nature of the echoes suggests quasi-

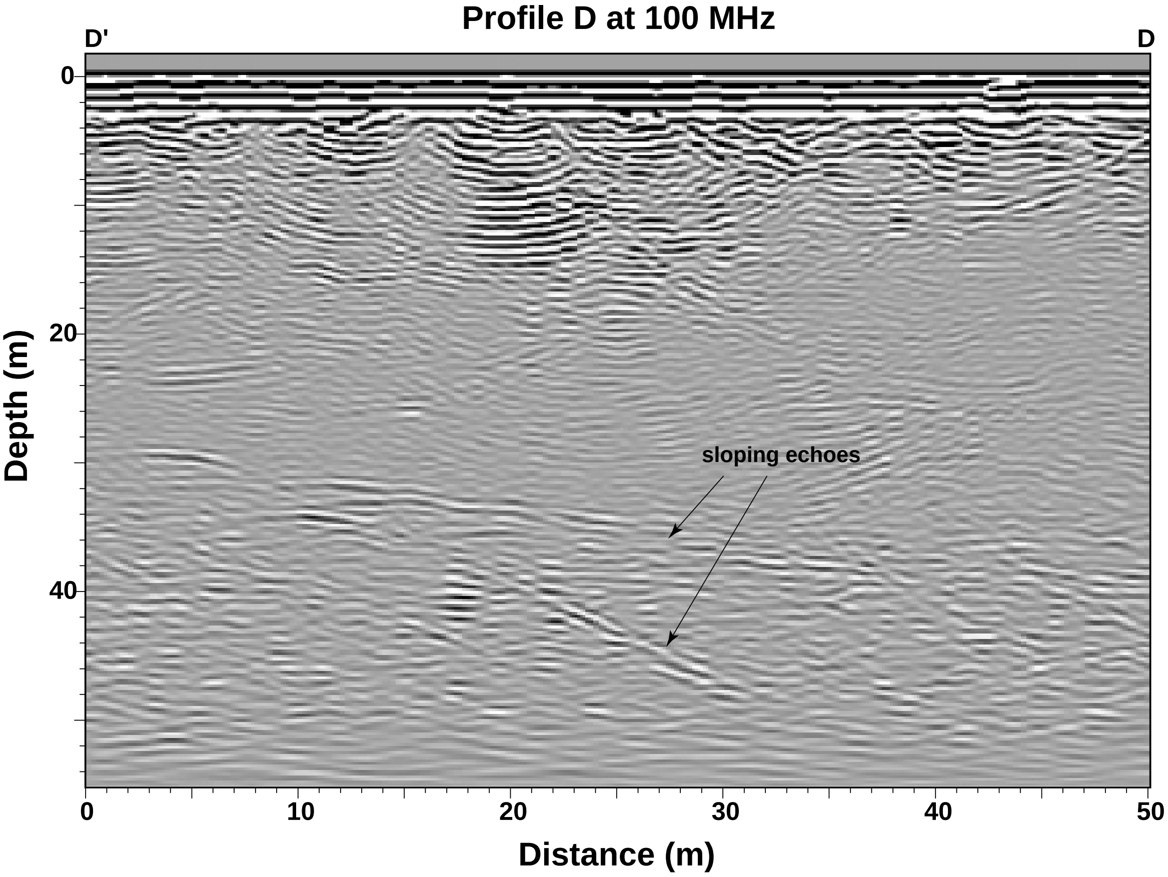

Figure 5. Radar profile D'-D at 100 MHz just to the south of the glacier center line. View is upglacier. Sloping echoes within the temperate ice zone descend toward the glacier center and are suspected voids that were located in three dimensions by radar grid studies of this region. Hot water drilling intersected the upper void and bore hole video and hydraulic studies were carried out as described in the text.

linear structures with cross dimensions approaching a substantial fraction of a wavelength ~ 1 m. The brightness of the echoes and the fact that they are in the temperate layer indicates that they may be at least partly water-filled. The impermeable nature of the surface in this part of the glacier also suggests that the water has likely entered somewhere well upstream.

Hot water drilling near the center point of profile D'-D intersected a void at a depth corresponding to the upper linear echo. Copious amounts of bubbles rose to the surface immediately following the drill connection indicating substantial amounts of air were present in the cavity. Subsequent pump tests with additional water were used to make estimates of the cavity volume and studies with the bore hole camera were undertaken to investigate cavity geometry. This work is described in more detail in the accompanying paper by Fountain *et al.* in this volume.

Concluding remarks

The results from this first year of field work are intriguing but raise a number of questions that can not yet be answered with the field work completed to date. Indeed, even an analysis of the data in hand seems premature based on a single case where radar and bore hole experiments overlap. In particular, it seems important to understand how the voids are maintained if they are at least partly air-filled, so it would be very useful to locate and investigate other examples if they exist. We need to examine more closely the hydraulic properties of the voids and determine more precisely their spatial distribution. Assuming they originate from crevasses upstream in areas with greater longitudinal strain (an assumption not entirely yet verified), we need to discover how they evolve into structures like the one we have imaged. We anticipate being able to address at least some of the issues after further studies in the second field season, 2002.

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The Geometry and Hydraulics of Englacial Conduits, Storglaciären

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Abstract

In July 2001, the first field season of a 2-year study of englacial conduits was initiated at Storglaciären. During this first year, the study was confined to the central portion of the ablation area, on the upglacier side of the riegel. The objective of the study was to measure the distribution of englacial conduits and their structural and hydraulic characteristics. Conventional hot water drilling was used to penetrate the glacier. After connection to a conduit we lowered a borehole video camera to image the geometry, and orientation of the features, and the water flow speed. The ”conduits” observed were 1 to 5 cm wide, and an unknown height, suggestive of relict crevasse structures. The geometry, low water flow speeds (1 cm s^{-1}) as well as sluggish water level responses in the boreholes suggest a hydraulically inefficient flow system.

Introduction

Englacial conduits are the primary structure responsible for transporting surface water to the base of a glacier, where it supplies the subglacial hydraulic system and, in turn affects glacier movement. Röthlisberger (1972) and Shreve (1972) outlined the steady-state mechanics of englacial passageways in theory by assuming circular conduits formed by frictional melting of ice due to water flow and the overburden ice pressure. Shreve (1972) argued that the englacial conduits should form an upward branching arborescent network with a mean flow oriented steeply down glacier. Fountain and Walder (1998) argue that englacial conduits develop from water flow in crevasses. Water flow in the bottom of a crevasse will widen and deepen the crevasse and the creep of ice will eventually pinch off the creavsse above the flowing water to form an englacial passageway. This approach suggests a more gently sloping network of englacial conduits than that predicted by Shreve (1972).

Despite all the theoretical descriptions of englacial conduits few direct measurements have been made. Their presence is typically encountered when drilling boreholes to the bed (e.g. Hodge, 1976; Hooke *et al.*, 1988; Hooke and Pohjola, 1994; Fountain, 1994). Borehole video studies (e.g. Pohjola, 1994; Harper and Humphrey, 1995) revealed that englacial voids were common in the ice column, but no studies focused directly on their geometry and hydraulics.

Methods

Boreholes were drilled at 10 m spacings in grids at three different locations on the glacier (figure 1), using hot water drilling techniques. A 10 meter grid spacing allow the drilling equipment to be centrally located before moving to a new location and the risk of tapping into the same crevasse or another borehole. In area 3 however only a few boreholes were drilled partly directed by ice radar results. As a borehole was being drilled an englacial connection was inferred when the water level in the borehole dropped and remained below the glacier surface despite continued pumping of drilling water. After intersecting an englacial passage, the drilling was terminated. Once an englacial connection was discovered a downhole video camera was lowered into the borehole (figure 2). The camera was maneuvered using a fishing line to better image the geometry of the conduits. A plastic ruler was attached in front of the camera’s

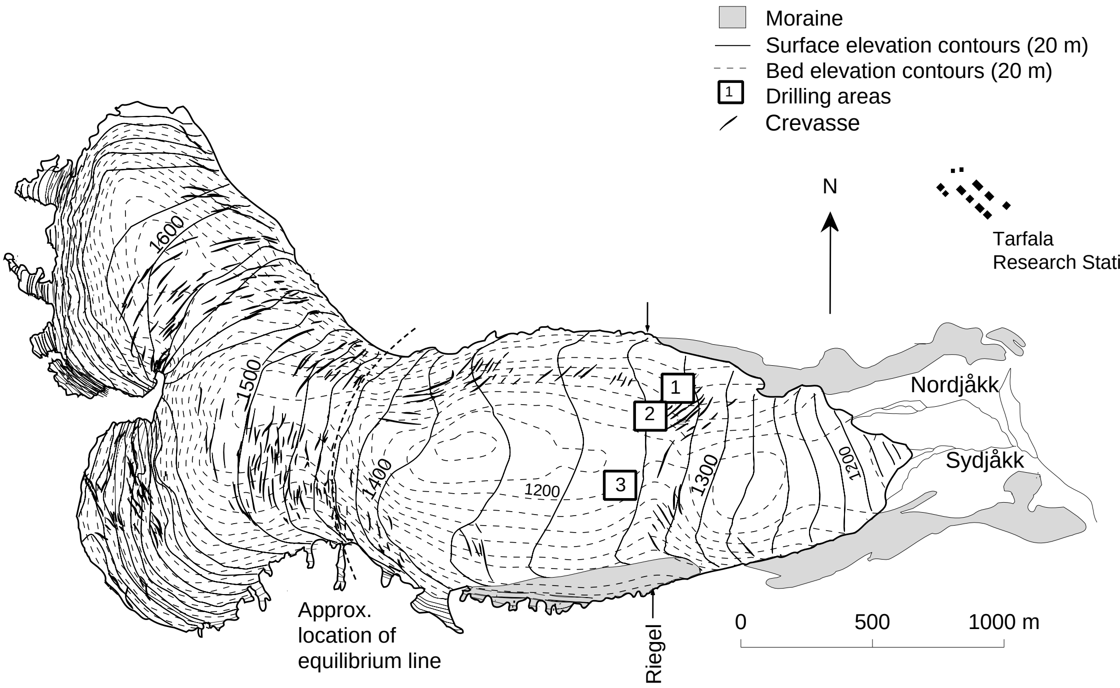

Figure 1. Location map of Storglaciären showing drilling areas.

field of view to provide a scale to measure the size of the conduits. In addition, a compass was attached to provide orientation. Naturally-occuring particles flowing in the water past a calibrated, gridded backdrop were used to estimate flow rates in the conduits.

Figure 2. Borehole video camera with attached compass.

Pressure transducers were installed in seven boreholes to measure the water level variations caused by pressure changes in the englacial system. Transducers were placed in three holes that connected to englacial conduits (in areas 1 and 2), three holes that only connected subglacially (in areas 1 and 2), and in one hole that connected to both englacial and subglacial connections (in area 1). Pressure transducers were arrayed in this manner to fully understand the distinctions as well as the interconnections between the subglacial and englacial systems.

Results

Of a total of 22 boreholes drilled, 17 connected englacially, 3 drained at the bed, and 2 reached the bed and did not drain. The depth to the drainage features varied from 11 m to 101 m (table 1). It is worth noting that englacial cavities were commonly encountered, as revealed by a momentary lowering of water into the borehole during drilling.

The englacial conduits were crevasse-like in their geometry, with near-vertical, planar walls (figure 3). Due to this geometry and the limited viewing field of the camera, the vertical dimension of the channels was difficult to ascertain. The width of the channels varied from 1 cm to 5 cm, and most oriented SW-NE, the downslope direction and parallel to the local crevasses. Flow velocities in the channels were to be about 1 cm s^{-1}.

Table 1. Englacial connections.

Borehole	Conduit depth (m)	Bed depth (m)	Conduit orientation	Width of feature (cm)
1	-	44	-	-
2	-	52,5	-	-
3	27	-	-	-
4	47	67	NE-SW	-
5	51	-	-	-
6	47	-	E/NE-W/SW	-
7	30	-	NE-SW	-
8	57	-	NW-SE	0.3-0.5
9	45	-	-	2
10	-	78	-	-
11	34	-	-	-
21	-	-	-	-
22	34	117	NW-SE	-
23	16	119	NE-SW	0.5-0.7
24	29	-	-	-
25	10	-	NE-SW	-
26	-	126	-	-
27	11	-	-	-
28	101	-	N/NE-S/SW	5.0-7.0
29	71	-	NE-SW	2.0-3.0
34	129	-	NW-SE	10.0-15.0
35	149	156	-	-

Water levels in the boreholes show that the englacial system exhibits rather large diurnal variations in pressure (~meters) whereas the subglacial pressures vary over centimeters (figure 4). Interestingly water levels in the hole that had both an englacial and subglacial connection also showed large diurnal variations, suggesting a strong interaction between the two systems. Subglacial water pressures showed little fluctuation until August 13, whereas the englacial system continued to show variations until August 30.

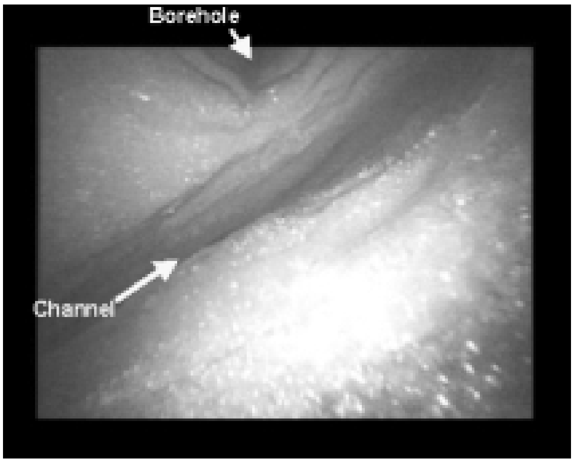

Figure 3. Photo of one of the observed englacial features.

Preliminary conclusions

In contrast to previous studies (Pohjola, 1994; Harper and Humphrey, 1995) conduits of circular cross-section were not observed. The conduits we observed were highly elliptical if not planar and most likely occupy relict crevasses, consistent with proposed englacial origins (Fountain and Walder, 1998; Pohjola, 1994). The observed cross-sectional geometry suggests that melt enlargement is not a significant process in the development of these englacial conduits, and supports the notion of a sluggish englacial water flow system.

The slow water flow speed (~1 cm s^{-1}) and the highly non-circular cross-sectional geometry of the conduits indicates an englacial hydrologic system with a low net discharge within any given conduit. With a small ratio of discharge to cross-sectional area, the drainage area for any given conduit must be small. Hence, numerous conduits must exist with a low hydraulic gradient. This supports the findings of Hock and Hooke (1993) based on dye injections.

Water level data suggests that the hydraulics of the englacial flow system is quite distinct from the subglacial system. The englacial system seems well connected to variations in diurnal surface input

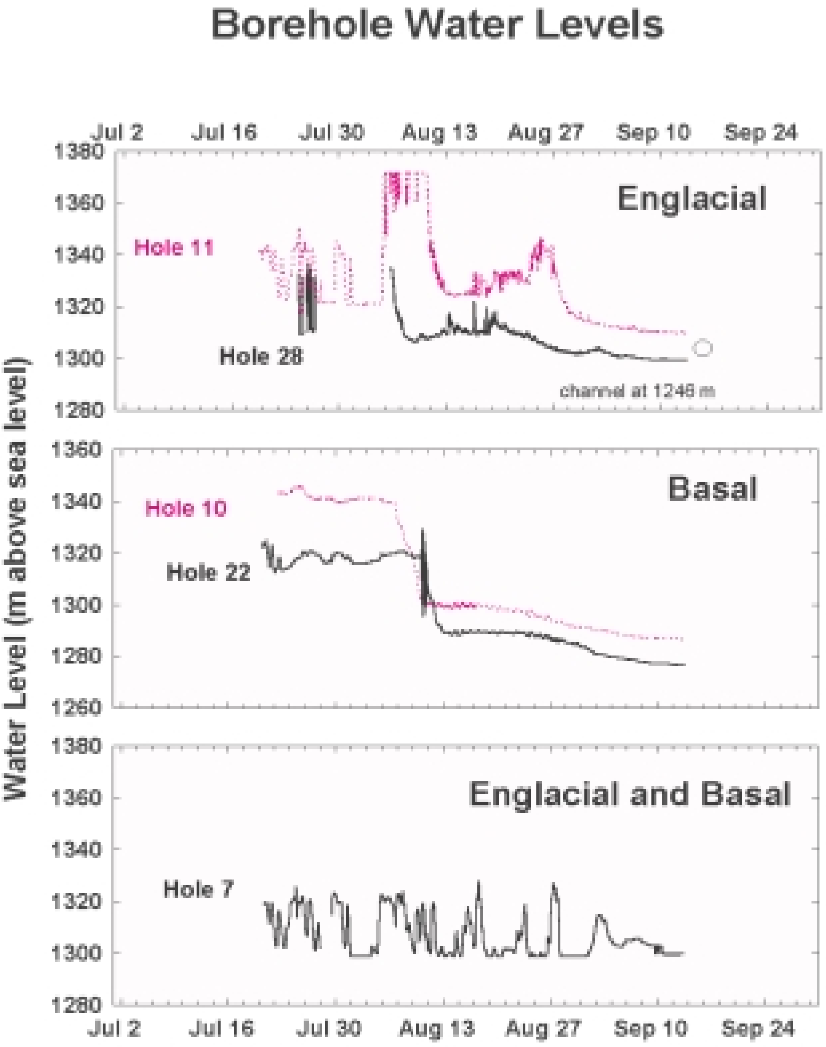

Figure 4. Water levels in boreholes.

whereas the subglacial variations are damped and poorly connected to the surface. The one hole which connected both englacial and subglacial hydraulic systems exhibited large diurnal variations in water pressure indicating substantial interaction beween the two systems. This suggests that such boreholes are not useful for indicating hydraulic conditions in either system.

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Snow temperature measurements on Storglaciären 1998-2000

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Abstract

Hourly snow temperatures at 5 levels were recorded in the ablation area of Storglaciären in spring 1998 and during the winters 1998/1999 and 1999/2000. When snow depths exceeded about 1 m, snow temperatures close to the ice-snow interface generally reached a minimum of about -5°C. Sudden increases in snow temperatures throughout the snow pack occurred each year once or twice in spring, coincident with a significant rise in air temperature above the freezing point, indicating refreezing of melt water to induce the warming. The snow packs becomes temperate within a couple of days. During the warming events the thermistor at the ice-snow interface showed a more abrupt and steeper temperature rise than the thermistors above, which may be attributed to refreezing of water flowing laterally along the ice surface and forming superimposed ice.

Introduction

Over a winter season the temperature of a snow pack fluctuates below zero. However, before melting can occur snow temperature has to be raised to 0°C at the surface. Hence, the timing when a snow cover turns temperate is crucial for the onset of runoff from a snow-pack.

The processes that bring about the warming of the snow pack are primarily:

1. release of latent heat from refreezing of percolated melt or rainwater
2. heat conduction
3. absorption of incoming short wave radiation penetrating the snow pack.

The release of latent heat by refreezing of percolated melt or rainwater is by far the most efficient process for warming up the snow-pack. The winter snow acts as an insulator and dampens temperature variations and heat loss of the underlying ice layer. This also means that near-surface winter ice temperatures in the ablation area will be higher than they would be in the absence of a snow cover. This project looks at hourly snow temperature data from Storglaciären over 3 winter seasons between 1998 and 2000, and at profiles showing the variation of snow temperature with depth during different stages of the spring.

Methodology

Snow temperatures were recorded in the upper ablation area during spring 1998 and over the winters of 1998/1999 and 1999/2000 (figure 1). In May 1998 a pit was dug for the installation of the thermistors and was subsequently refilled with snow. For the winters of 1998/1999 and 1999/2000 the thermistors were installed before the accumulation season so that each thermistor snowed in gradually as snow depths increased. Thermistors were removed after the entire snow pack had remained temperate for several weeks. Data was collected from May 1 - July 16, 1998, September 12 , 1998

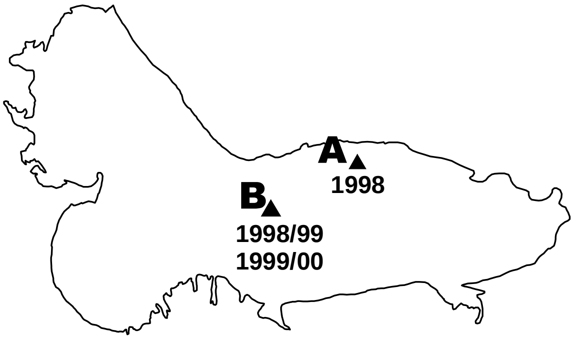

Figure 1. Locations of continuous snow temperature measurements on Storglaciären in 1998 - 2000. An automatic weather station was run at site B during parts of the melt seasons.

- June 22, 1999 and Septempber 19, 1999 - July 4, 2000.

For each period a stake was drilled into the ice and 5 thermistors were attached at approximantly equidistant points from each other (the lowest close to the ice surface and the highest about 2 m above). The thermistors were not attached directly on to the stake but to the end of 20 cm long poles fixed parallel to the ice surface. This was to avoid channelling of percolated rainwater along the stake to affect thermistor measurements.

Temperature measurements were taken every 5 minutes and hourly averages were stored on a Campbell datalogger. An offset was calculated from thermistor data during the time when snow was assumed to be temperate, i.e. when the snow was notebly wet and all thermistors recorded temperatures close to zero degrees and showed little or no fluctuation. This offset was calculated as 0.241 for every sensor in each time period and was added to all sensor measurements. All readings taken when a sensor was assumed to be above the snow surface were removed from each data set. For each year there were between 5 and 10 snow depth measurements taken at the thermistor stake. Additional snow depth data were inferred from the snow-in and snow-out dates of the sensors, which were of known height. It is possible to locate snow-in and snow-out dates fairly accurately because of dampened temperature fluctuations observed at the sensors when insulated by a snow cover, and the significantly larger fluctuations observed when they are exposed to the air (figure 2). A continuous snow depth curve was created for each year by linear interpolation between the thermistor stake measurements and estimated snow depths inferred from dates when sensors snowed in or melted out. It was then possible to create temperature profiles showing the diurnal variation of snow temperature with thermistor depth for any day.

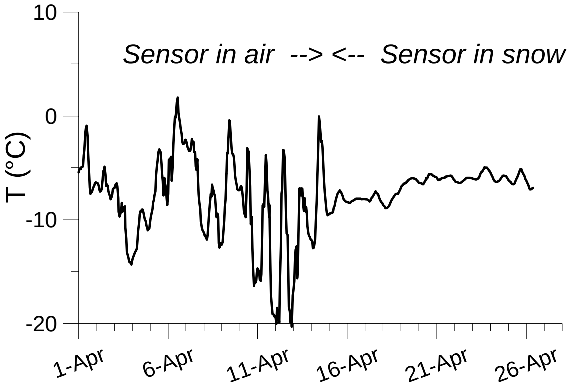

Figure 2. Temperature fluctuations of the highest thermistor in 1999, as it gradually snows in. Presumably on April 15 the sensor became snow-covered as indicated by the strongly dampened temperature fluctuations compared to the preceeding period.

Results

Temporal Variations

Figures 3, 4 and 5 show snow temperatures recorded during the three periods 1998 to 2000. The position of the snow thermistors relative to the snow surface varies during the season as winter snow gradually builds up and starts melting in spring. Hence, large temperature fluctuations at the beginning of each time series indicate a thin snow cover, while fluctuations are significantly dampened when the snow cover exceeds a few decimeters. When snow cover is thin especially during sunny periods measurements are affected by absorption of incoming shortwave radiation by the thermistor penetrating the snow pack.

During all years the temperature close to the ice-snow interface remained rather constant at approximately -5°C as soon as snow cover had reached at least 1 m. For each year there is a clear point at which all thermistors show a distinct rise in temperature. This can be linked to a time (middle to end of May) at which air temperatures rose significantly above 0°C for the first time (figure 6). The sudden rise in temperatures is attributed to the production of melt water which in some cases combined with rain fall, penetrates the snow-pack, releasing latent heat when refreezing. The efficiency of this process is indicated by the speed at which the snow pack is brought up to melting point. If water supply is sufficient the snow pack turned temperature within a couple of days.

In 1998 and 1999 there were two distinct warming events and in 2000 only one after which the snow cover remained temperate. The first event in 1998 began on May 15 and lasted only 3 days. The second event began on June 12 and all sensors were temperate by June 17. In 1999 the first event was initiated on May 21 and lasted around 4 days while the second event began on June 9, all sensors becoming temperate by June 14. In 2000 all sensors reached zero degrees in 8 days (May 17 to 25). In 1998 and 1999 snow temperatures gradually dropped below 0°C after the first warming events and the subsequent warming events coincided almost exactly with the point where 0°C air temperature was exceeded again.

During the warming events, the closer the sensors were to the surface, the faster they reached 0°C, indicating that the warming is as result of

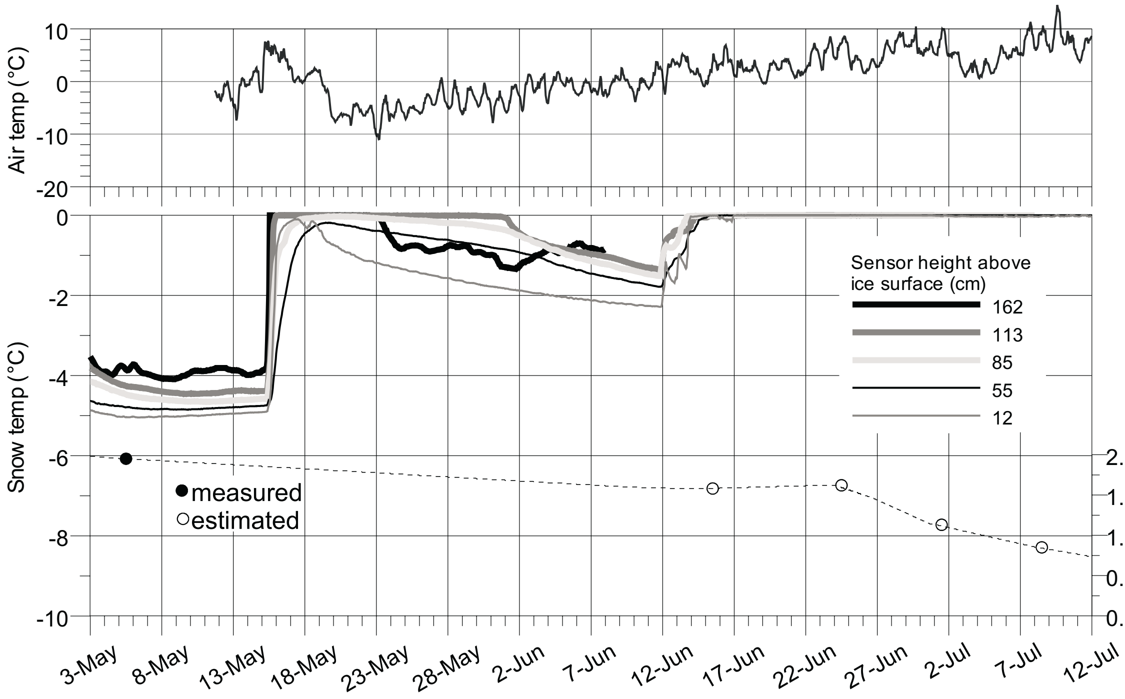

Figure 3. Snow temperatures recorded at site A on Storglaciären (figure 1) from May 3, 1998 to July 11, 1998 and air temperature data recorded at Tarfala Research Station.

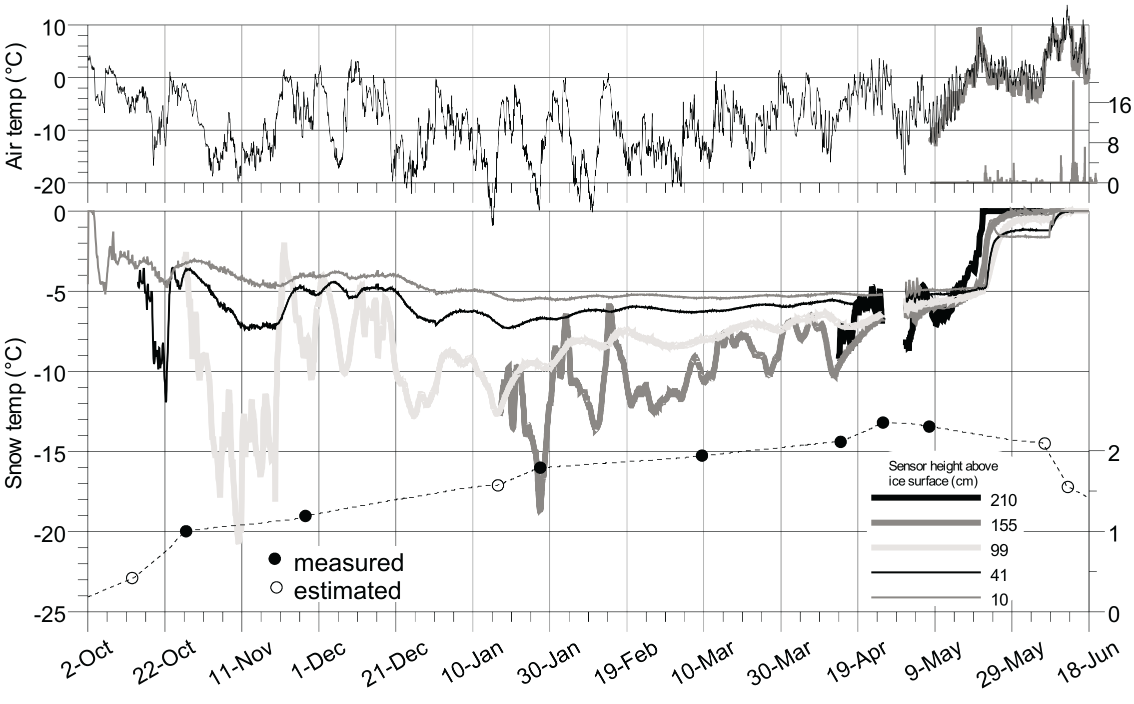

Figure 4. Snow temperature recorded at site B on Storglaciären (figure 1) October 1998 to June 1999. Air temperature (thick line) and precipitation data from the automatic weather station on Storglaciären and air temperature data (thin line) from Tarfala Research Station.

water percolating through the snow pack from above. However, it is interesting to note that at site B in both years the temperature of the lowest sensor positioned just above the ice surface showed a more rapid and pronounced temperature rise than the sensor above. This suggests that other processes must be active. We suggest that energy is provided by water flowing laterally along the ice-snow interface. Alternatively, water percolates through the snow pack along preferential pathways until the ice surface is reached where it refreezes and forms superimposed ice.

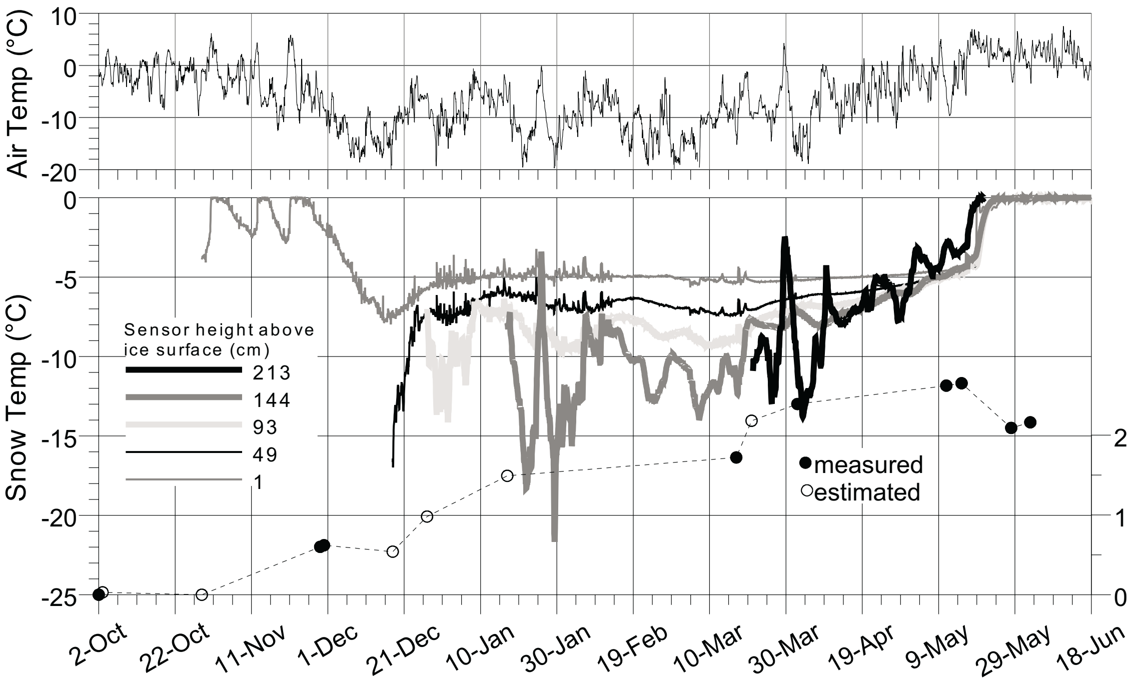

Figure 5. Snow temperature recorded at site B on Storglaciären (figure 1) October 1999 to June 2000. Air temperature from the automatic weather station at Tarfala Research Station. Precipitation data are not available.

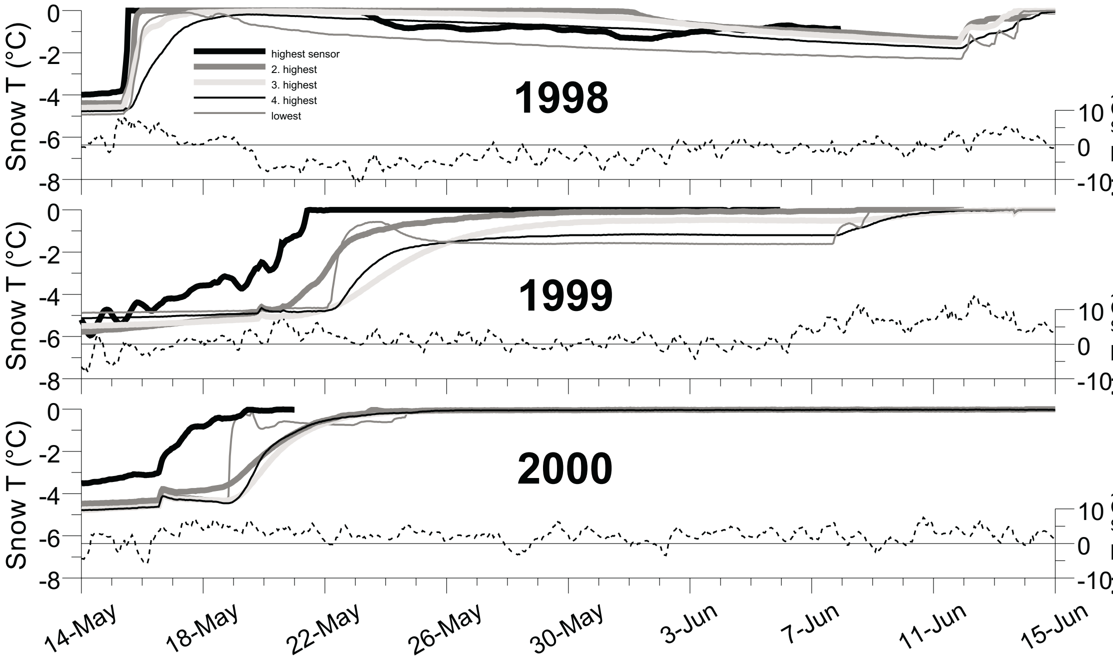

Figure 6. Hourly snow temperatures at 5 levels on Storglaciären and air temperature at Tarfala Research Station for the period when sensors turned temperate 1998 - 2000.

Temperature Profiles

Figure 7 shows some temperature profiles for the period of rapid temperature rise in May 1998. The significant increase in snow temperature on May 15 at all depths clearly reflects the release of latent heat by refreezing melt water produced as a result of rising air temperature (from –2 to +7 °C) on the same day. The highest two sensors recorded temperatures that increased from –4 to 0 °C within one day. The fourth sensor did not show much response until two days later when obviously water supply was sufficient to reach its depth. As discussed above, the lowest sensor reacted more rapidly than the one above. On May 20 most of the snow pack was still temperature despite of a significant drop in air temperature indicating that cooling by conduction occurs much slower than warming by release of latent heat due to refreezing of percolating water.

Figure 8 shows some snow temperature profiles from May to June 1999. On May 14 snow temperatures increase slightly with depth, indicating that the cold wave penetrated from above during the preceeding period of sub-zero air temperatures. Only the highest sensor (about 20 cm below the snow surface) fluctuates in response to diurnal variations in temperature and global radiation, becoming colder by midday and warmer in the evening. On May 21 the temperature profiles showed a rapid increase in temperature towards the snow surface as a result of refreezing of percolating water. Two days later the lowest sensor was affected by refreezing water, as indicated by the strong rise in temperature, while temperatures above were still lower.

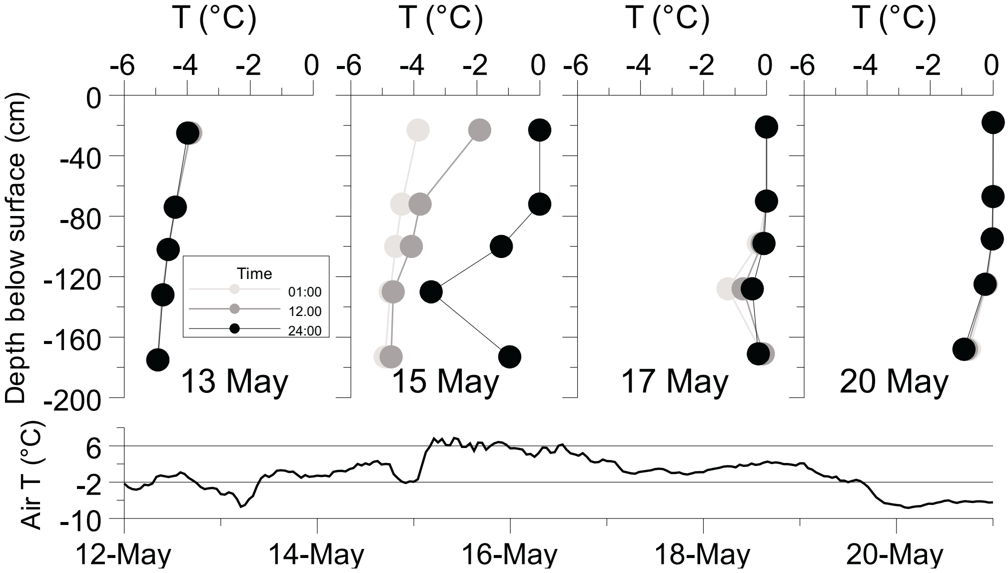

Figure 7. Snow temperature profiles at site A on Storglaciären between May 13 and 20, 1998, and air temperature at Tarfala Research Station.

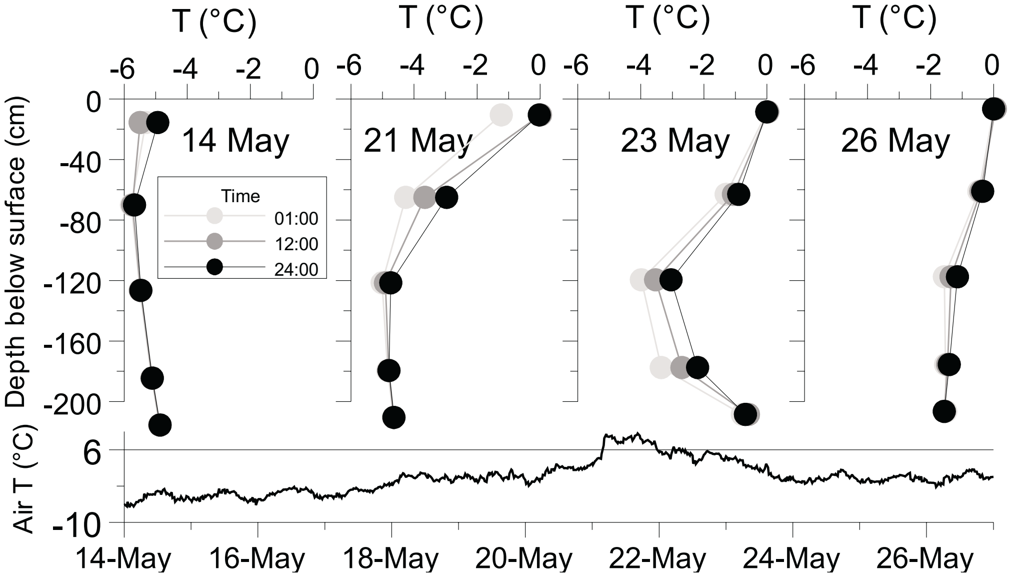

Figure 8. Snow temperature profiles and air temperature at site B on Storglaciären between May 13 and June 9, 1999.

Conclusions

During all years the temperature close to the ice-snow interface remained rather constant at approximately -5°C as soon as snow cover had reached at least 1 m. Each spring there is a clear point at which all thermistors show a significant increase in temperature. This can be linked to a time at which air temperatures rise significantly above 0 degrees for the first time, causing the production of melt water, which percolates into the snow pack and refreezes releasing latent heat. During these warming events snow profiles indicate a more rapid warming of the lowest thermistor (at the ice-snow interface) compared to the thermistor above. This may result from refreezing of water flowing along the ice surface.

The data are useful for analysing the delay between melt water production and runoff, thus the onset of runoff, and for quantifying formation of superimposed ice and energy transport into the underlying ice.

Micro-scale spatial variability in surface snow chemistry - sastrugi studies in Tarfala, northern Sweden

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Abstract
The aim of this study is to describe the patterns of ion concentration within the snow of wind formations called sastrugi. This study shows that primary deposited chemical signal in the snow pack could be reshaped by post-depositional processes such as the redistribution of snow by the wind. Snow was collected from sastrugi in Tarfala valley, in northern Sweden. Nine major ions (Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^-, SO_4^{2-} and $CH_3SO_3^-$) were analysed with ion chromatography. The variability was most pronounced before and at the proximal side of the sastrugi where snow layers from different precipitation events become exposed to the wind. If sastrugi formations become preserved they could influence the interpretation of chemical records from ice cores, where the influence is dependent on the sastrugi height in relation to the snow accumulation rate at the site.

Introduction

Chemical records from snow and ice cores yield excellent information about past changes in both climate and other environmental conditions (e.g. reviewed by Legrand and Mayewski, 1997). One advantage with ice cores is that the atmospheric components for several 100 000 of years can be obtained with precision. The disadvantages of stratigraphic analysis of ice cores are associated with uncertainties in regional representativity and variabilities of chemical signals caused by depositional and post-depositional processes. However, the effect of local depositional noise in the surface layers will be reduced when averaging over several years as described in a Greenland study by Steffensen *et al.* (1996).

Snow and air bring different chemical components to the snow surface and processes affecting the pattern in chemical deposition was discussed by Davidson *et al.* (1996). It was found that dry and fog depositional mechanisms are significant and must be considered along with wet deposition in Greenland. New precipitation is added and previous surface layers become preserved. After the snow has been deposited, several factors have an influence on how well a chemical signal will be preserved in the snow. For instance, strong wind may reshape the snow surface in some areas and create sastrugi (wind formations in the snow). The snow will be eroded in one area, while the eroded snow accumulates in a neighbouring area. In a study by Dibb (1996) spatial distribution and composition of snow in Greenland was investigated and large depositional noise were found, partly due to the formation of sastrugi. Another process of importance for the variability of the chemical signal is the action of the wind pumping through the porous surface snow (e.g. Waddington *et al.*, 1996 and Harder, 1996). This process will be more important in low accumulation areas where the sastrugi are exposed to the wind during longer periods. All these processes could cause micro-variations in the chemical distribution pattern within sastrugi that have to be taken into account when interpreting the signal of chemical information stored in the snow and ice. To a certain degree areas with high frequents of sastrugi could be avoided when choosing a drill site, but the sastrugi history of a site will still be unknown.

Fieldwork and methods

In Tarfala valley (figure 1), which is situated in northern Sweden (67°55’N, 18°37’E, 1150 m a.s.l.), a pilot study was carried out in April 1997, with a more thorough sampling being performed in April 1999. The annual mean temperature at Tarfala Research Station is -3.9 °C and the winter mean is -8.9 °C (Grudd and Schneider, 1996). The annual mean accumulation rate exceeds the height of several sastrugi. The area is dominated by westerly winds from the Atlantic Ocean that often reach 40-50 m/s during winter storms, but wind speeds exceeding 80 m/s have been registered. The windy climate favours the formation of sastrugi and the access to the cold laboratories, etc. at Tarfala Research Station facilitated the sampling in Tarfala valley.

In 1997, two sastrugi that were, 15-20 cm high, 20-50 cm wide, 100-120 cm long and situated 300 m Northeast of Tarfala Research Station, were sampled vertically and horizontally for chemical analysis. The samples were collected at 10-20 cm point intervals, and directly put into pre-cleaned 60 ml polypropylene bottles (Nalgene). All sampling was done under clean conditions using plastic tools and clean suits, gloves and face masks. A snow pit was dug through one of the sastruga to a depth of 1.5 m. Another snow pit was then dug close to the first one, on the side facing the sun. The two pits were separated by a thin wall of about 5-10 cm. When the sun shone through the wall, structures in the snow became visible (figure 2). This was done in order to study the preservation of sastrugi and the variability at depth.

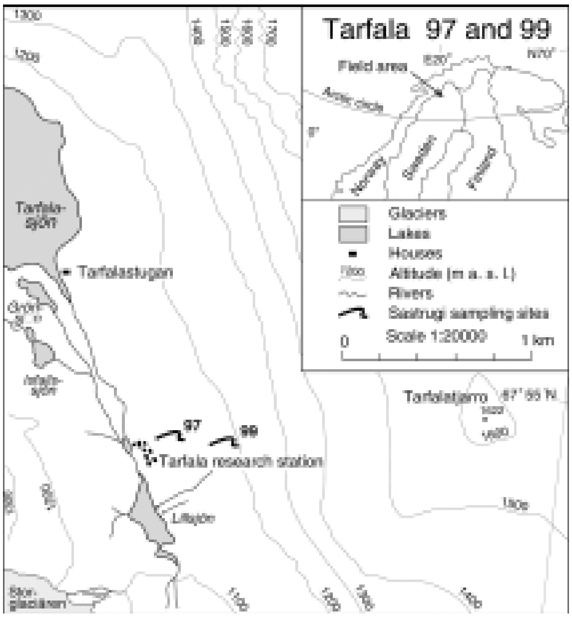

Figure 1. Map describing the fields sites at tarfala where samples from sastrugi have been collected.

Complementary high-resolution sampling of two sastrugi was performed in Tarfala valley in April 1999. A recent storm from north-west had formed 10-30 cm high, 20-50 cm wide and 1-2 m long sastrugi. A good site for sampling was found 500 m east of the research station. Using the same clean sampling procedure as described above, snow from two sastrugi was sampled at 5 cm intervals, both horizontally at the surface and vertically to 50-100 cm depth. These samples for chemical analysis were put into 30 ml Accuvette sample vials made of polystyrene. From the surface, samples reached down to about 2-3 cm in the snow. Two parallel profiles 10 cm apart were sampled on the surface of each sastrugi as duplicates. Horizontal profiles at depth intervals between 5 to 20 cm were also collected from the interior of the sastrugi. In addition, a relatively flat surface was sampled at 10 cm resolution in two different wind directions (N-S and W-E) as a reference.

Double samples and blanks were collected at every site in order to check for any possible contamination. The samples were kept frozen during transport and then melted prior to analysis. The bottles with chemical samples were only opened in a clean air bench at the time of analysis. Cations (Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}) and anions (Cl^-, NO_3^-, SO_4^{2-}, $CH_3SO_3^-$) were measured using a Dionex ion chromatography system at the Department of Meteorology, Stockholm University (Stenberg *et al.*, 1998). The average error in the analysis was less than ±10% for all ions.

Figure 2. The photo shows a cross-section of a sastruga. Structures in the snow become visible when the sun shines through the wall.

Results and discussion

The sampling of two sastrugi in 1997 in Tarfala valley was done at point intervals 10-20 cm apart along the sastrugi. The sampling interval was too large to give a continuous chemical record of the sastrugi surfaces. However, the results showed substantial micro-variability, with the largest fluctuations in the steep proximal side of the sastrugi. The general picture obtained from the results from both sastrugi was that the highest concentrations of NO_3^-, SO_4^{2-} and NH_4^+ were before and at the steep proximal side of the sastrugi, whereas the highest concentrations of Na^+, K^+, Mg^{2+}, Ca^{2+} and Cl^- were at the distal side (figure 3). The variability in the concentration of some ions within one of the sastrugi was almost of the same magnitude as the variability at depth. For example, the variability of chloride varied with a factor of 6-7.

The 1999 sampling was done at 5 cm intervals along the continuous surface profiles of two sastrugi. Duplicate profiles were sampled 10 cm apart. The parallel profiles showed the same features in the ionic pattern for all ions. Again the largest fluctuations were found before and at the steep proximal side of the sastrugi, whereas more constant values were found at the distal side. In one of the sastrugi two groups of ions could be identified showing two different patterns. For example, a very good correlation between NO_3^-, SO_4^{2-} and NH_4^+ was found, with lower concentrations before the steep proximal side. Na^+, K^+, Mg^{2+}, Ca^{2+} and Cl^- covariated with high values before and at the steep the proximal side. The signal of $CH_3SO_3^-$ was a combination of the pattern of the other two groups. The other sastruga showed a pattern where all ions, except NO_3^-, had higher concentrations before the proximal side and with a change at the proximal side to lower and more constant values towards the distal side. Even though some patterns were evident, two sastrugi sampled only 20 metres apart showed significantly different patterns in ion concentrations. However, a look at a wind reshaped snow surface gives the picture of a very uneven distribution of snow, even over small distances, as measured by Dibb (1996) in Greenland.

Snow collected inside the two sastrugi along homogeneous of snow at a depth of between 5-20 cm showed lower variability in ion concentrations than that along the sastrugi surface for the deeper layers. The homogeneous layers within the sastruga are probably from single stratigrafic layers, while the profile of the sastrugi surface crosses different layers. Two vertical profiles through two sastrugi

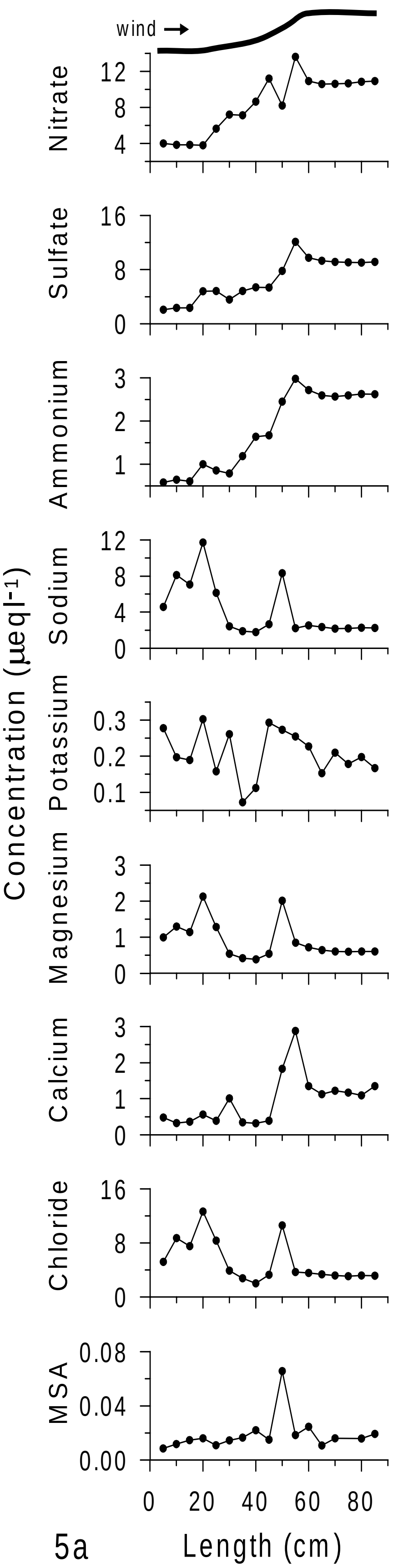

Figure 3. Chemical trends in ion concentrations (mEq/l) from a sastruga sampled in Tarfala, Sweden in 1999. The sastrugi surface is indicated by a schematic line above the plot.

were also sampled and the results showed high variability. These profiles cut through different snow layers and a higher variability (a factor of 3-6) in ion concentration could therefore be expected.

A relatively flat reference surface was also sampled, at a 10 cm sampling interval, in Tarfala during the spring of 1999. Variability of some ions (Na^+, K^+, Mg^{2+}, Cl^- and NO_3^-) from within a sastruga was up to 3-5 times higher than the variability of the ions in samples taken from a relatively flat surface.

In order to quantify the influence this variability has on chemical records from ice cores a larger collection of chemically investigated sastrugi is needed to confirm the patterns within sastrugi as well as the active processes.

Conclusions

The micro-scale pattern in the snow chemistry of a sastruga is clear, with a high noise level and significant peaks, as compared to that of a snow sample taken from a relatively flat surface. For most of the ions, the surface variability is of the same magnitude as the seasonal variability at a depth scale. The highest fluctuations were found before and at the proximal side of the sastrugi and for the ions Na^+, K^+, Mg^{2+}, Cl^- and NO_3^-. In general, two groups of ions could be identified that showed covariated patterns: one group being Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^- and sometimes $CH_3SO_3^-$ and the other group being NO_3^-, SO_4^{2-}, and NH_4^+. Different trends for each group could be identified, with high or low concentrations in the surface snow before and at the steep proximal side of the sastrugi, and low concentrations at the distal side. However, in individual sastrugi the trends shifted, and except for the high noise level (a factor of 3-7), no typical pattern describing a sastruga was found. The results from this study indicate that two ice cores taken from sites quite close together could yield quite different stories about climatic history, depending on the variability pattern of the surface chemistry on a micro-scale. Of course, the significance of this depends on the resolution and the time scale used in order to interpret the climatic story preserved in the snow and ice.

Acknowledgements

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Investigating ice dynamics across a bedrock threshold of Storglaciären, Sweden, using force budget analysis

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Abstract

A force balance model was set up to calculate the ice dynamical parameters of the lower part of Storglaciären, using mainly ice geometry and ice surface deformation for data input. The geometry data was provided by earlier radio echo soundings and surface deformation data was collected during a GPS campaign 2000-2001. The results of the force balance calculation reveals two zones of different dynamical character separated by a bedrock threshold. This difference is evident in both surface deformation and basal stress patterns, *i.e.* driving stress and frictional drag. The study was carried out as part of a calibration procedure to establish a safe modeling technique for the use in future investigations of ice streams in polar regions.

Introduction

A study of the ice dynamical parameters of Storglaciären was introduced as a part of a PhD-project in the summer of 2000. The project intend to map strain and stress conditions as well as total iceflux through a section in the lower part of Storglaciären, where the ice flows over a bedrock hump, riegel. In context, the project is a calibration procedure for a force budget model that calculates iceflow taking glacier surface movement, geometry and ice temperature conditions as input. On the basis of its long history of scientific records, Storglaciären qualified as the best testing ground for the development of this model (Hooke *et al.*, 1983; Holmlund and Ericsson, 1989; Jansson and Hooke, 1989; Hooke *et al.*, 1989; Hooke *et al.*, 1992; Jansson, 1992; Jansson, 1997).

The ice flow is calculated in a topographically well-defined cross section and compared with upstream accumulation to provide knowledge about the state of the glacier in terms of mass balance. Considering the response time of the ice system, the glaciers dynamical character may be related to climate change (not discussed here). In addition, the calculated patterns of strain and stress can reveal subglacial friction conditions, *i.e.* highlighting the spatial and temporal variations in the extent of the drainage system etc.

Conclusions from this project will guide additional investigations of ice flow in polar regions (e.g. Svalbard, Tierra del Fuego, and Antarctica), where the information available is limited but adequate for similar ice flow modeling. The fieldwork for this purpose was undertaken on Storglaciären throughout the years of 2000-2001 and concluded in autumn 2001. The following is a brief presentation of material and methods used, together with a very limited part of the result.

Method

The method described here is based on the force budget technique used by Van der Veen and Whillans (1989). It comprises of two major stages. Initially a force balance budget is set up to establish the balance between driving and resistive forces acting throughout the geometry of the ice body. Knowing the pattern of these forces it is then possible to establish a flow field in a chosen cross section and further determine the total ice flux. The method mainly requires knowledge of the ice bodies surface

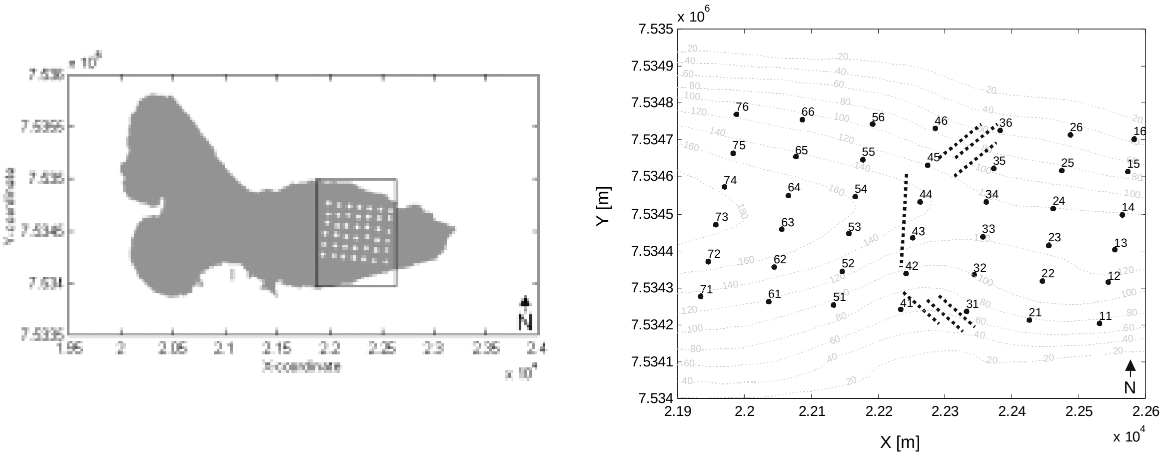

Figure 1. Drilled and measured stake net on Storglaciären; a) overview, and b) subsection of rectangular area. Measured stake-net (white diamonds in a) is labelled in a row-column fashion from 11 to 76 (black in b). Crevasses (generalized) are shown as dashed lines in b. The ice depth is shown as contours (faint gray in b). Coordinates are in Swedish RT90 0.0 gon

movement (i. e. deformation pattern), geometry, and ice temperature.

Data collection

Markers for surface movement, 42 aluminium stakes, each ca 5 m long, were placed in bore holes making up a rectangular grid of 7 by 6 elements (Figure 1a). The drilling was carried out using a steam-pressure drill capable of drilling 5 m ice in ~ 10 minutes. The bore holes were made approximately 4.8 m deep, leaving 0.2 m of the stakes above the ice surface for easy access with GPS antenna.

The grid elements (stakes) were labelled based on row 1-7 and column 1-6 (Figure 1b). The stake grid coordinates were measured kinematically with a differential GPS on two different dates separated by 52 days (Figure 2). The first survey was performed in July 2000, and the second in September 2000, wich assumingly will represent a time period of fast flow for Storglaciären. The processing of GPS data and extraction of ice surface velocity vectors was performed at Tarfala Research Station for easy correction of misstakes. Additional surveys of the stake grid has been performed but are not presented here. The bedrock topography is well known by previous radar soundings (Björnsson, 1981; Eriksson *et al.*, 1993) providing the neccesary ice depth. The ice temperature is assumed to be 0 °C.

Calculation

Ice is a crystalline solid, whose mechanical properties are described by Glens law, giving the strain rate / stress relation (Nye, 1952):

Figure 2. Images from field site showing a) the steam-pressure drill used to drill the 210 m of ice required for 42 stakes, and b) GPS surveying with Trimble's system 4000.

where:

ε_e	is the effective strain rate
τ_e	is the effective stress
B	is the temperature dependent viscosity
n	is the flow exponent ($1 < n > 5$, depending on the maturity of the ice, and the orientation of single ice crystals to the stress axis)

The force budget scheme uses the relation that the driving stress must be balanced by the vertically integrated resistive stresses working on the ice (Whillans and Van der Veen, 1989):

$$\tau_{di} = \tau_{bi} - \frac{\partial}{\partial x}\left(HR_{xi}\right) - \frac{\partial}{\partial y}\left(HR_{yi}\right)$$

where:

i	is geometry dimensions x, y, z
H	is ice thickness
t_d	is driving stress
t_b	is basal resistive stress
R_{ii}	is a function of deviatoric stresses, $f(\sigma_{ii})$
σ_{ii}	is deviatoric stresses, $B\varepsilon_\varepsilon\varepsilon_{ij}^{(1/n)-1}$
ε_{ij}	is strain rates, $f(du_{ij}/dx_{ij})$
u	is surface deformation

The velocity profile, and hence, total ice flux, is given by an integration with ice depth according to (Whillans and Van der Veen, 1989):

$$U_{iz} = U_{i(z-1)} \frac{-\partial U_i}{\partial z}$$

where the index z represents ice depth ranging from one level below the ice surface to the total ice thickness for the ice column, one step being equal to one unit of length.

Results

Here, the results are presented in figures 3-8 showing: (i) measured surface movement; (ii) calculated longitudinal stretching, ε_{xx}; (iii) calculated driving stress, τ_d; (iv) calculated basal drag, τ_b; (v) calculated basal drag / driving stress ratio, τ_b/τ_d and; (vi) total ice flux through a chosen cross section.

Discussion

The overall velocity pattern (Figure 3), with a velocity increase over the riegel and a decrease

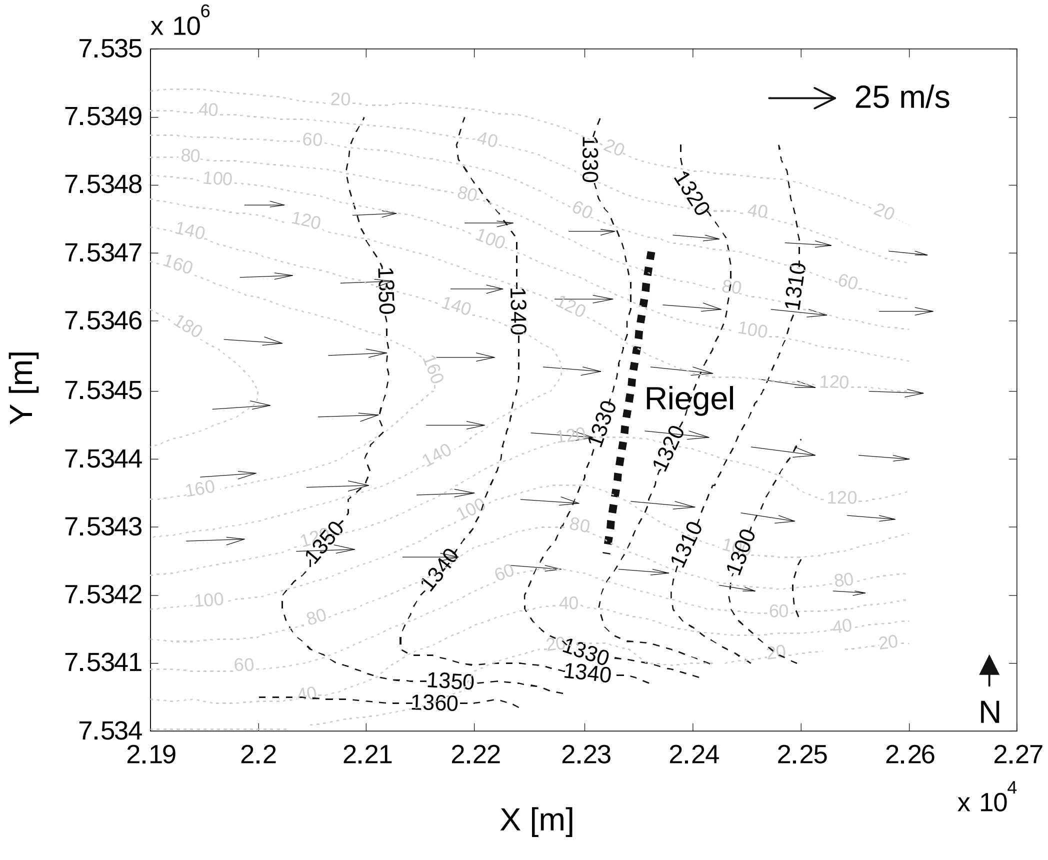

Figure 3. Obtained velocity field (black arrows) on ice surface (dashed thin black) and depth (faint grey). The velocity vectors indicate a slight turning of flow from north upstreams to south downstream. Some divergence is visible slightly upstream from a riegel (dashed thick black) at X~22300 m and in the southeast corner at X~22300 m.

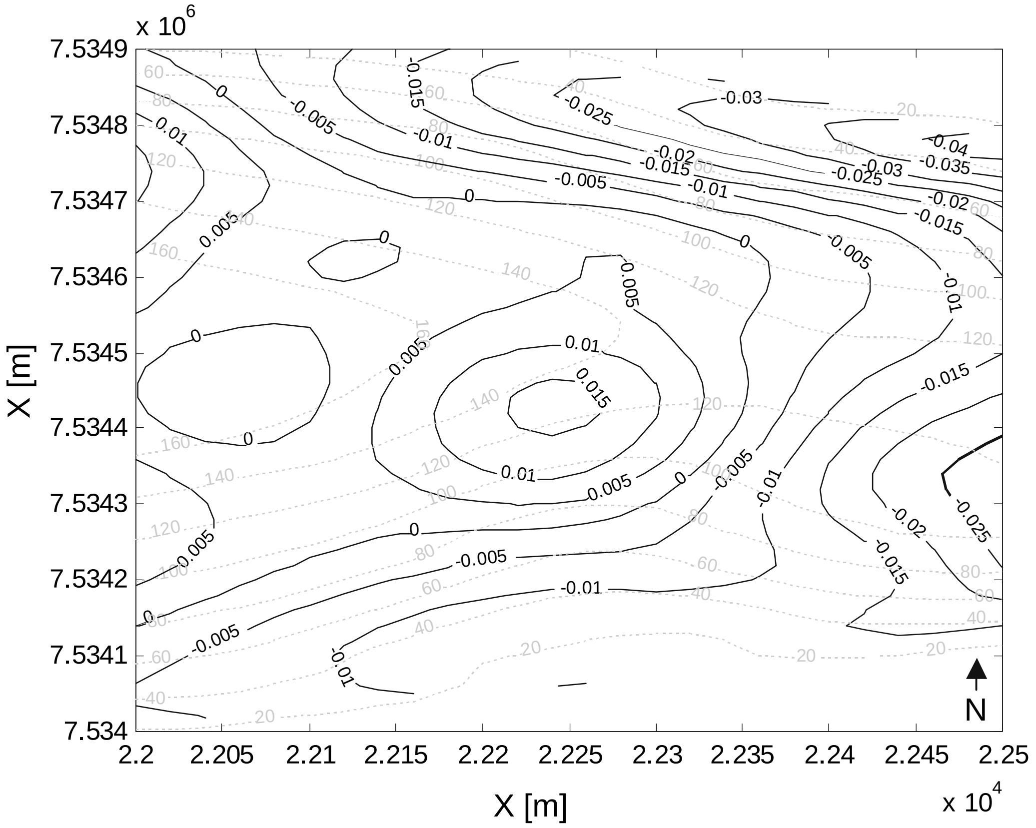

Figure 4. Calculated longitudinal strain rates, e_{xx} (a^{-1}). Maximum extension occur around the glacier centerline upstreams from the riegel at X~22250 m, followd by a zone of compression below the riegel, beginning at X~22400 m. Compression is also found to reach upstreams (to X~ 22000 m) along both sidewalls. Ice depth in faint grey.

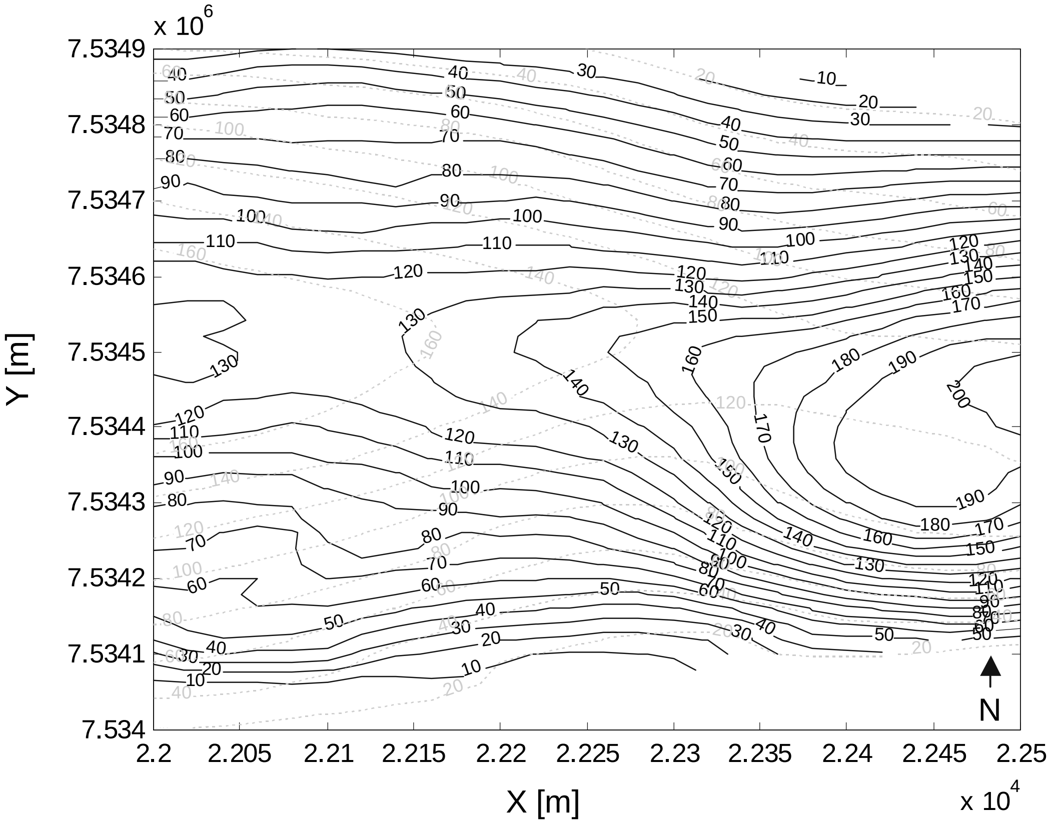

Figure 5. Calculated basal driving stress in the X-direction, t_{dx} (kPa). Large driving stresses are found in the overdeepenings with a maximum of ~200 kPa downstreams the riegel near X~22400-22500 m. Ice depth in faint grey.

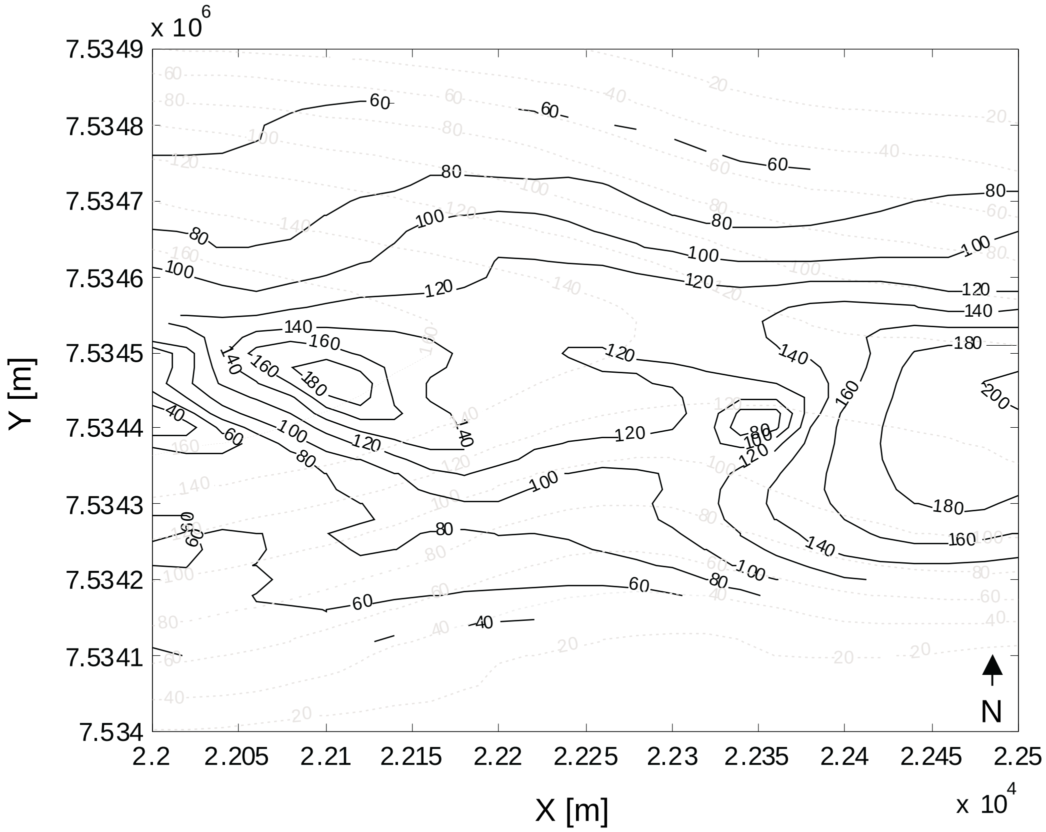

Figure 6. Calculated basal drag in the X-direction, t_{bx} (kPa). Large basal drag are found in the over-deepenings with two maxima of ca 160-180 kPa located at X~22200 m and X~22400-22500 m. An area of locally low basal drag is penetrating northeasterly across the south part of the riegel at X~22200-22400 m. Ice depth in faint grey.

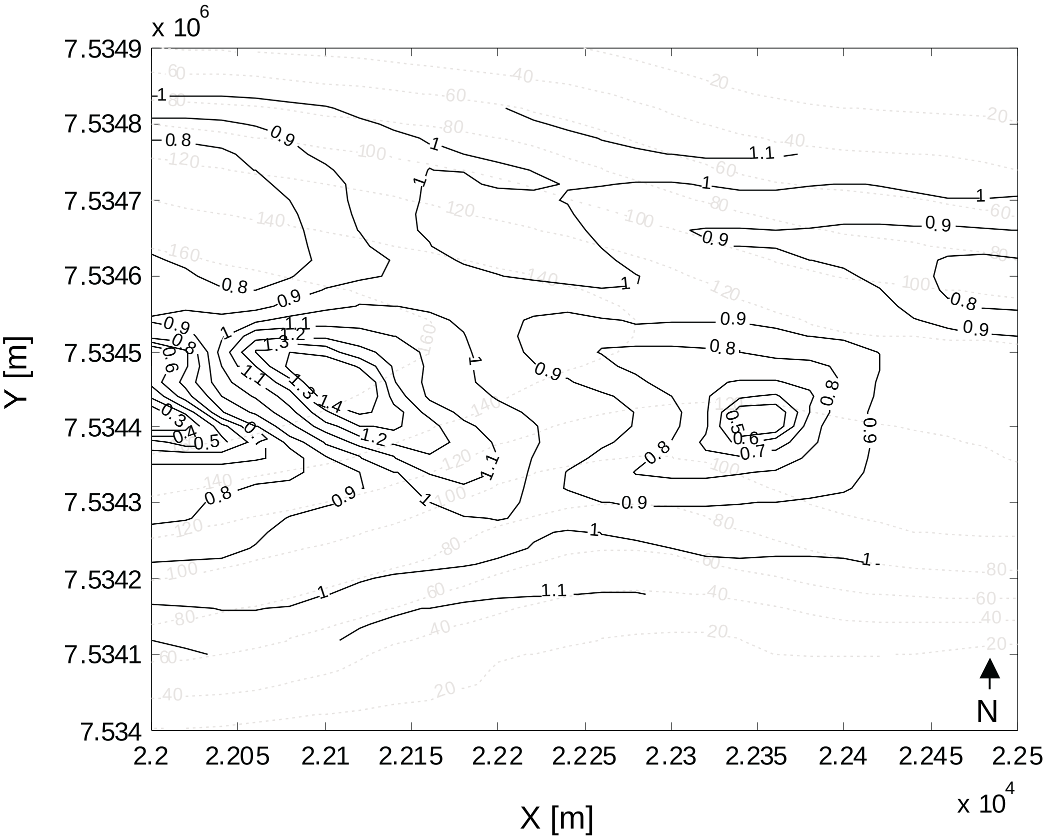

Figure 7. Calculated t_{bx} / t_{dx} ratio. Areas where t_{bx} / t_{dx} >1 indicate that flow is driven, in part, by other forces than driving stress. Areas where t_{bx} / t_{dx} <1 indicate basal slip, and consequently, that resistance to glacier flow comes, in part, from non-local forces. Ice depth in faint grey.

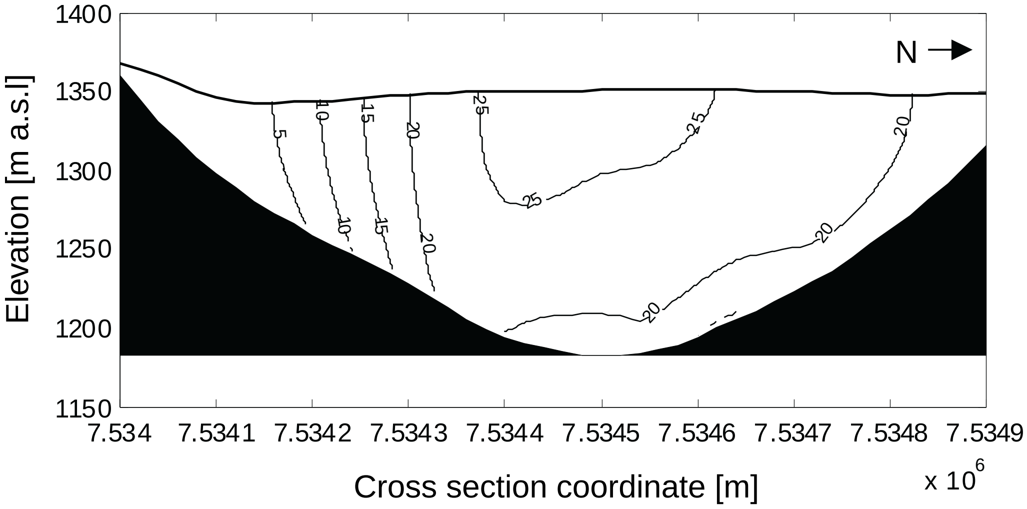

Figure 8. Calculated velocity with depth, Ux(m/a), through a section looking upstream at X~22100 m. The model was calibrated for ice viscosity and ice density to give the same outflux, Qx ~1400000 m^3/a*, as a zero net balance year would give at this location (Grudd and Bodin, 1991). In addition, it was calibrated for basal sliding velocities, which have been found to reach ca 70-90 % of the surface velocities in this area (Pohjola, 1993; Hooke et al., 1992; Jansson, 1994). Considering the glacier centerline, these results show a displaced velocity maximum towards the south margin, and hence, a stronger velocity gradient at this side (within this data-range).*

downstream from it, agrees well with previous studies (Hooke *et al.*, 1989; Hansson, 1995)The location of the measured velocity divergences (known to indicate so called sticky spots), correspond well with the location of high calculated basal drag (Figure 6), and the highest calculated extensional flow (Figure 4) is found to align well with a major transverse crevasse found in aerial photographs (Figure 1b). The area of high calculated compressional flow (Figure 4) posesses little or no crevassing and the high driving stress (Figure 5) in this area (due to a high surface gradient) seem to be balanced by equally high basal friction. This suggests a lack of basal lubrication in this area at this time. Also, the vertical shear rate, e_{zz} (a^{-1}) (not shown in any figure), indicate a build-up of ice in the same zone of compression. The zone of low basal drag (Figures 6 and 7), directed northeasterly, covering the south part of the riegel, could indicate a zone of local plug flow being a result of coupling forces acting somwhere upstream the measured area. The fact that this part of the riegel could be feed by subglacial water which enters through several moulins observed upstream to the south, is confirmed by the modeled dynamics, but this is only a speculation. On the contrary, it has been shown that the hydrology changes from englacial on the upstream side of the riegel to subglacial on the downglacier side (Jansson, 1997). It has been shown in this study, also confirmed by Jansson (1992), that the dynamics of this section of the glacier is highly controlled by the riegel, dividing the area into two dynamically different parts. Also, in this model, Storglaciären is asumed being 0°C throughout its physical extent, which is not the case in reality. The glaciers polythermal properties have been revealed by Holmlund and Ericsson, (1989), and more recent measurements also indicate the presense of a cold surface layer (R. Pettersson, pers. communication). Consequently, this cold surface layer posesses a higher viscosity causing the ice to deform slower than the surrounding warm ice. This fact must be taken into account when calculating ice velocities with depth, and is currently under investigation. The future plans include: (i) running this model for Storglaciären velocity data covering different seasons in order to determine spatial and temporal variations in the ice dynamics; (ii) the implication of this tested and calibrated modeling technique on data collected from glaciers/ice streams in polar regions.

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Frontvariations of Isfallsglaciären during the 20^{th} century

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Summary

Isfallsglaciären is a small, polythermal valley glacier in Lapland, northern Sweden. Previous work on Isfallsglaciären is limited, but the ice margin position has been measured regularly. By compiling and reworking information on all available previous positions of the ice margin, the behavour of glacier snout has been studied. The aim was to investigate how Isfallsglaciären has been reacting to 20th century climate changes. The results clearly show that the ice margin mainly has been retreating since the glacial maximum around 1910. But since the end of the 1980s the snout has started to advance due to increased winter precipitation, perhaps due to a more maritime climate (figure 1).

Another purpose of the study has been to study the behaviour of the ice margin today and in a near future. Ice velocity and ablation was measured during two field periods, april/maj 2000 and august 2000. Ice depth in a cross section downstream the icefall was measured with radar. A stake net was put out, from the cross section and downwards, which was positioned with a differential Global Positioning System (dGPS). Results from the

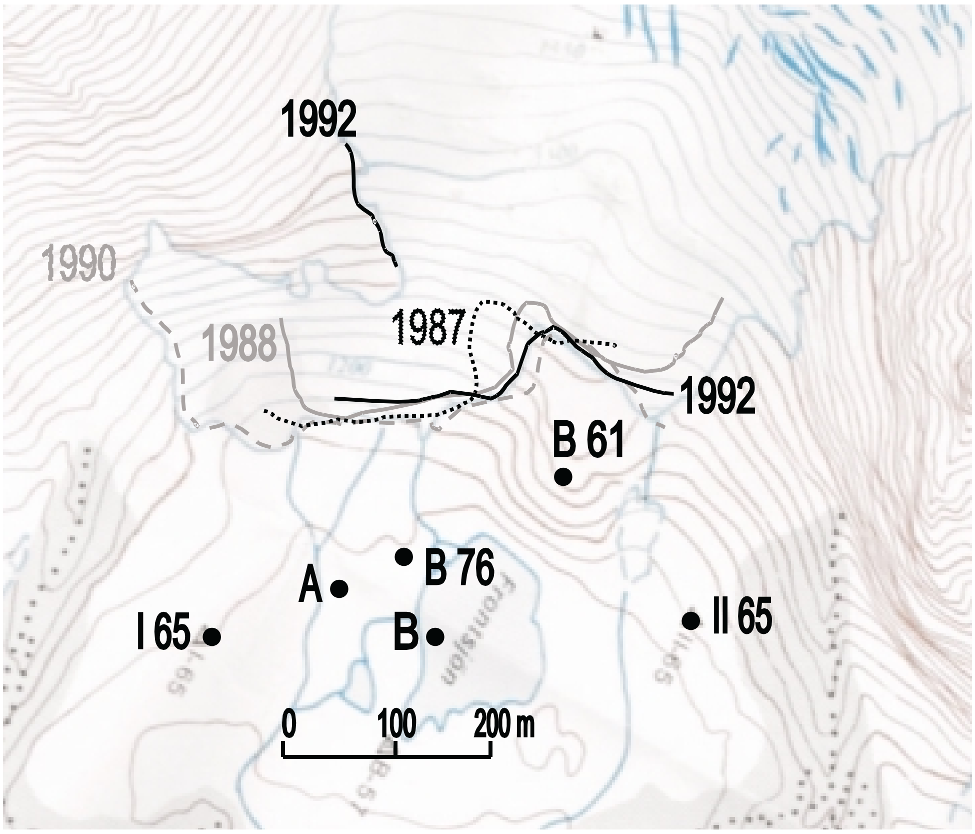

Figure 1. Positions of the ice margin of Isfallsglaciären 1987 - 1992.

measurements of ice velocity and ablation were used to calculate emergence velocity and balanced flow. Comparisons between emergence velocity and ablation showed that the frontal area of Isfallsglaciären gets a net contribution of mass, meaning that the lower part of the glacier still is in a growing state (table 1).

By calculate specific areas of Isfallsglaciären, we could get the balanced flow. The result was a water volume of 129700 m^3 in the interval 1240-1260 m a.s.l. It gave an ice volume of 119000 m^3. In the interval 1260-1280 m a.s.l. we get a water volume of 11000 m^3, which gave an ice volume of 10100 m^3. The total ablation was 129000 m^3/y of ice. This can be compared with the flow through the cross section which is 299200 m^3/y. The difference was 170100 m^3/y. The result of the balanced flow calculation show an excess of mass in the snout, because the ice flow through the cross section exceed the ablation. This is clearly indicate a growing front.

Two push moraines observed in connection to the glacier margin gave a further indication of that Isfallsglaciären still is advancing. The push moraine at the northern part of the ice margin was not created in 1999-2000, while, on the other hand, the push moraine in the southern part, was created in 1999-2000.

It can be establish that Isfallsglaciären have undergone a major change in behaviour during the last part of the 2000th century. A continuous retreat since 1910 has changed to a clear advance. The results (emergence velocity, balance flow and push moraines) also indicate that Isfallsglaciären is going to continue to advance also in the near future.

Acknowledgements

This project was conducted as a degree project for an undergraduate paper. I whish to thank my principal supervisor Jens-Ove Näslund, Dept. of Physical Geography and Quaternary Geology, Stockholm University, for all suport during the project.

*Table 1. Emergence velocity of all stakes compared with the net ablation of Storglaciären as function of heights above sea level. * = Stakes in or downstream the cross section, which were used in measuring emergence velocity.*

Elevation m a.s.l.	Stake	Emerge velocity Isfallsglaciären m/y	Net ablation Storglaciären m w.eq./y	Emerge velocity - net ablation m/y
1 240.14	10 *	6.28	2.25	4.03
1 252.426	500 *	3.80	2.25	1.55
1 252.695	200 *	5.69	2.25	3.44
1 256.212	20 *	3.87	2.25	1.62
1 258.251	30 *	2.81	2.25	0.56
1 261.774	40 *	6.64	2.21	4.43
1 262.004	2 *	-7.01?	2.21	?
1 263.517	3 *	21.68	2.21	19.47
1 264.097	1A *	3.43	2.21	1.22
1 264.197	1 *	7.96	2.21	5.75
1 268.207	4 *	4.56	2.21	2.35
1 277.707	5 *	-11.75?	2.21	?
1 281.86	11	4.49	1.67	2.82
1 283.135	6 *	-4.31?	1.67	?
1 284.348	41	6.28	1.67	4.61
1 291.388	31	0.77	1.67	-0.90
1 292.122	51	1.53	1.67	-0.14
1 301.478	42	3.10	1.35	1.75
1 313.06	12	2.34	1.35	0.99

Abstracts from the Tarfala student course papers 2000

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Field courses in glaciology have been given at Tarfala research station since the late 1950s. Today, 10 to 20 undergraduate students are educated in glaciology and related topics such as glacial geology, hydrology, geomorphology and different field methods. The course is divided in two periods. First period includes lectures and preparations in Stockholm at the University. The second period at the research station includes seminars, lectures, excursions and fieldworks. The fieldworks are reported in individual written reports. The reports are compiled in a final report available at the research station and at the department in Stockholm. In 2000 there where 16 students participating in the course, which was lead by Peter Jansson, Krister Jansson and Rickard Pettersson.

Flow measurements on Isfallsglaciären

Ola Brandt, Karin Ebert & Lasse Orbring

Between July 24 and August 1, 2000, measurings were carried out on the Isfallsglaciären in the Kebnekaise area in Swedish Lappland. The glacier has been studied since 1886, when the first photographs were taken. Isfallsglaciären reached a maximum extend in 1910, and has retreated since 1920. Since the beginning of 1990s it has started to advance again and will further advance in the near future. The southern part of the glacier started to advance recently. This is indicated by a push moraine, consisting of very fresh material right in the front of the southern glacier tongue. Before, the glacier only advanced on the northern part, indicated by a push moraine in front of the northern glacier tongue. Two GPS measurings and heights measuring were made during a nine-day period at 20 stakes, which were installed on the glacier. Also, a radar measuring was carried out. The average surface melting was 38.7 cm, but with very different results for each single stake. The average surface speed was 4.6 cm/day. The amount of ice transported through a transverse section with an area of 16000 m^2 along stakes 1-6 was 290000 m^3/year. The whole area in front of the profile was calculated on 64000 m^2. The ice flow through the transverse section was much lower than the ablation down the profile, the difference was 2000 m^3/day. During the measuring period, ablation was bigger than emergence velocity. For all results should be noted, that the measuring were carried out during a very warm summer period. This period was only during a nine-day interval, which is not long enough to draw long-reaching conclusions.

Fabric analysis and flutes mapping at Isfallsglaciären, Tarfala

Ulrika Eriksson, Helen Holgersson & Paula Lundin

The formations of fluted surfaces are still debated. According to the literature there are several possible origin of the formation. The most widespread theory are that till material are squeezed in the cavity behind rocks and boulders and that a new cavity is formed behind the till material. We examined the fluted proglacial area in front of Isfallsglaicären, Tarfala to possible draw conclusions of their genesis. In a till fabric we find that there is a preferred orientation in the transverse direction. The flutes has often a constant height and width. Our till fabric analysis show that the most probable cause of formation are in squeezing in cavities behind subglacial obstacles. The morphology of the flutes supports that conclusion.

Salt tracing in moulins

Joakim Evertson och Anja Riise

Storglaciären is the 20th largest glacier of Sweden and its drainage system has been investigated since the late sixties. To be able to find out if its drainage pattern has changed or if the system still drains the accumulation area in Nordjokk and the ablation area in Sydjokk, salt was poured into the glacier's moulins. First the right measuring apparatus for the project had to be chosen. After evaluating the poor values received by the conductivity gauge, it was found that its sensitivity to low concentrations of salt wasn't high enough. Therefore another instrument, a multimeter connected to a logger, was evaluated. This apparatus proved to be much more sensitive and thus the choice of the multimeter for the project's measurings. Most of the glacier's moulins are located in the centre of its ablation area. Here 8 kilos of salt was poured into each moulin at different points in time and the multimeter, together with the logger, were placed in Sydjokk at the mouth of the glacier The instruments measured and logged both time and values, every 15 seconds, of the different salt pulses. Ten moulins were used in the attempt, of which six gave pulses strong enough to be used in further discussions. This may seem too few to draw any conclusions, but when compared to previous attempts the results are obvious. All the moulins in the ablation area drain in Sydjokk, even those located close to Nordjokk. It is also clear that the time between salt injection and salt pulse increases with the distance from the moulin to the measuring point in a north- south direction, while the east- westerly distance seems of no great importance to the water transport time.

Isfallssjön – development between 1977 and 2000

Maria Hollsten och Mårten Strömgren

Isfallssjön is one of several small sedimentation basins where the eroded material from Isfallsglaciären deposits. The lake and its two deltas were surveyed in 1977. Between 1977 and 2000 the two deltas have extended, while the volume of Isfallssjön has diminished by 4000 m^3. The lake has, despite the smaller volume, become 1.5 metres deeper compared to 1977. One possible explanation is that some of the ice that underlies Isfallssjön has melted.

Ice velocity measurements and radio-echo soundings on Tarfalaglaciären

Martina Kammler och Håkan Larsson

Tarfalaglaciären is a small glacier in the Kebnekaise Mountains, northern Sweden. In this study we examined the ice-velocity, with differential Global Positioning System (dGPS), and the ice thickness, with pulsed radio-echo sounding equipment.

The purpose of our project on Tarfalaglaciären is to find out how the relatively huge moraines developed, considering the small size of the glacier, and if todays climate would be able to create something similar.

Our results support the main idea of growing glaciers in northwestern Scandinavia because of a maritime climate, with relatively high winter precipitation. Tarfalaglaciärens mean velocity is about 1 cm/day, and an estimated ice thickness is between 40 and 65 metres in the interior area of the glacier. This suggests that Tarfalaglaciären may be partly warm based in its deepest parts. And if the glacier continues to grow in its vertical dimension we think that it will retain its former erosional capacity, which once formed the huge terminal moraines.

Ice velocity across supra glacial moraine ridges on the snout of Storgalciären

Fredrik Lindgren och Sofia Österdahl

Storglaciären is a polythermal glacier in northern Sweden with a cold surface layer and coldbased terminus and margins. During the summer of 1994 a series of low, supraglacial ice-cored moraine ridges were melting out at the terminus of Storglaciären. These ridges are parallel to foliation in the ice and arise from differential melting of the ice surface where sediment rich layers in the ice emerge. The sediment probably has a subglacial origin since the material is unsorted and somewhat rounded. The sediment is frozen on at the glacier bed in the transition zone from cold based to warm based ice. Ice velocity measurements indicate that the horizontal velocity and the emergence velocity decrease gradually down glacier the moraine ridges. The frozen terminus of the glacier slow down the ice movement and forces the temperate ice to move upwards. The sediment-rich ice is probably transported towards the ice surface in big ”packages” in this transition zone and not along discrete shear planes.

Geomorphological map over Tarfala valley and vicinity

Anja Olsson och Anna Åhr

The morphology of the Tarfala valley and its surroundings is mainly characterized by glacial influence. In the area, three glaciations event types can be indicated: 1. cirque glacier, 2. mountain ice sheet (MIS) and 3. Fennoscandian ice sheet (FIS). Since the core areas of the FIS and MIS mainly have been dry based, they have not been able to erode the landscape notably on intermediate altitudes, and preglacial landforms have been preserved. Therefore it is most likely that the cirque and valley glaciers to a large extent have formed the alpine landscape in the Kebnekaise area. The morphology has also been shaped by processes such as frost action, slope- and fluvial processes during earlier inter-stadials/interglacials and since the last deglaciation.

This map and adherent description is made to give the viewer knowledge of the morphology in the area by choice and also a survey of glaciations events and bedrock composition.

Abstracts from the Tarfala student course papers 2001

Abstracts compiled by Rickard Pettersson

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Field courses in glaciology have been given at Tarfala research station since the late 1950s. Today about 10 to15 undergraduate students are educated in glaciology and related topics such as glacial geology, hydrology, geomorphology and different field methods. The course is divided in two periods. First period includes lectures and preparations in Stockholm at the University. The second period at the research station includes seminars, lectures, excursions and fieldworks. The fieldworks are reported in individual written reports. The reports are compiled in a final report available at the research station and at the department in Stockholm. In 2001 there where 11 students participating in the course, which was lead by Per Holmlund, Hans Linderholm and Rickard Pettersson.

Development of the englacial draining system on Storglaciären

Mikael Bergholtz och Patrik Hultstrand

This paper deals with the englacial drainage system of Storglaciären in northern Sweden and includes a mapping of glacial moulins. At a depth of about 70 m one of the investigated glacial moulins showed a tendency for deviation in the same direction as the ice movement, all accordingly to a theoretical model by Shreve (1972). Down to this depth all of the moulins indicate a drainage pattern along the crevasse in which they originally were formed.

A comparison between tree-ring width, summer mass balance and summer temperature in Tarfala valley, northern Lappland

Veronika Hohl

Trees growing on the tree line and the net balance of a glacier are good climate indicators. A change in the climate will cause an instant change of the annual growth of tree-rings and net balance. The purpose of this study is to correlate annual growth of tree-rings from Nikkaloukta with the net summer balance of Storglaciären in Tarfaladalen and the summer temperature. This was done with one already existing and a newly taken chronology of tree-rings. For the new chronology the skeleton plot method was used for analyzing the tree-rings. The two chronologies correlate well which each other an other data until about the 1960s. Then the new chronology does not correlate well with any data, while the older chronology correlates well. This is probably caused by human errors when using the skeleton plot method.

Geomorphologic map of northwestern Kebnekasie with focus on Koupervagge and Passglaciären

Maria Lenngren och Ulrika Lindberg

No one has ever before conducted a thorough geomorphologic mapping northwest of the Kebnekaise area in north-western Lapland, Sweden. Therefore a mapping of the area became an interesting task to do. In the study area there are several glaciers whereas one amongst them is a small cirque glacier called Passglaciären. This glacier is not eroding its cirque form at any larger extent today as it is largely frozen to its bed. The investigation of the geomorphology in the valley Koupervagge below, which is Passglaciärens drainage path, could help to find evidence that would reveal weather this glacier has been larger and thereby have had potential to erode its own cirque form.

Coupling effects between cold based and temperate ice on Storglaciären, northern Sweden

Nina Johansen och Emma Mattisson

Coupling mechanisms between temperate ice and the cold-based glacier front, on Storglaciären in the Kebnekaise massif northern Sweden, was investigated during three days at the end of July 2001. Using differential Global Positioning System (dGPS) measurements from two stakes, one situated in temperate based ice and one in cold based ice, we measured the short-term variations in ice flow. The parameters looked at in the investigation were precipitation, air temperature and water pressure under the ice. Close relationship between the two ice masses was recognised. The temperate ice seems to initiate the movement in the cold front. We expected to see a close coupling between air temperature, water pressure and glacier movement, which our investigation also shows. No evidence for coupling between precipitation and glacier movement was recognised.

Changes in geometry and temperature distribution as a consequence of mass balance change on Storglaciären

Laila Johansson, Karen Lundholm och Erik Massih

Storglaciären is a polythermal glacier situated in the Tarfala valley, northern Sweden. The glacier has been studied extensively and can proudly present the longest continuous record of mass balance in the world. The thickness of the cold layer of temperate glaciers is considered to be climate dependent. Radar surveys of the cold surface layer made in 1989 and 2001, as well as surveys of the ice surface made in 1987 and 2001 were compared with each other. The aim of this study is to see how the ice surface and the cold surface layer react on changes in the mass balance. During the last decade Storglaciären has increased in thickness and the cold surface layer has decreased suggesting the change to a more maritime climate regime in the area.

Tracer experiment in the lower part of ablation area on Storglaciären

Anders Salomonson och Daniel Hjelm

A number of five salt tracer tests were conducted to determine the development of the drainage pattern/system of the lowermost part of the ablation area in Storglaciären, a valley glacier in Northern Sweden, during Aug 3-5, 2001. Three of the tests generated distinct response curves, while the first two tests did not yield any curve. The first two tests did not generate a response curve, while the remaining three tests show a good connection between the crevasses and moulins and the proglacial stream. The time from pour to peak, correspond well to previous studies on this glacier. A simple system for estimating flow speed within the glacier is applied and shows speeds between 0.225 and 0.3879 m/s. The few results of this study indicate that the drainage system is well developed.

Litterature concerning the Tarfala valley and its close surroundings

Compiled by Per Klingbjer

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Årsberättelse 2000 och 2001

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2000

Rickard Pettersson och Mats Nilsson deltog i Swedish Antarctic Research Programme 99/00 och utförde massbalansmät-ningar i Västströmmen samt radarmätningar i södra Vestfjellaområdet, Dronning Maud Land, Antarktis.

I samband med deltagande i ett symposium i Tokyo kring miljöforskning i Arktis, där våra Mårmaglaciärborrningar presenterades, fick vi nya skär till vår PICO-borr som är avsedda för isborrning.

Tester med GSM-telefoner visar att förutsättningen för att bygga en telelänk i Tarfala är god. Finansieringsplan saknas dock.

En digital terrängmodell över Kebnekaisemassivet och Tarfala färdigställdes under mars månad av Margareta Johansson.

Den 25-26 mars borrades ett 100 meter djupt borrhål i Tarfalaryggen på ca 1540 meters höjd. Ett 15 meters borrhål invid Tarfalastationen färdigställdes en vecka senare.

Ett MAGICS-SCANTRAN kontor upprättades i Abisko-Kiruna med medel från Climate Impacts Research Centre, CIRC. Jan Johansson-Klein hade först tjänsten och han efter-träddes av Margareta Johansson.

Under påskveckan hölls en workshop vid Tarfalastationen där svenska planer för de närmsta åren inom European Project for Ice Coring in Antarctica, EPICA, drogs upp.

Under maj månad transporterades en båt upp till Tarfala för att nyttjas för studier i Tarfalasjön. Ägare av båten är Sven Blomqvist från institutionen för systemekologi.

Arméns flygövning genomfördes programenligt den 2-4 maj.

Vi fick ett större anslag från det naturvetenskapliga forskningsrådet för att färdigställa en lärobok i glaciologi och en populärvetenskaplig skrift om Tarfalaverksamheten.

Den 18 maj disputerade Malin Stenberg på avhandlingen ”Spatial Variability and Temporal Changes in Snow Chemistry, Dronning Maud Land, Antarctica”. Professor Jon Ove Hagen från Oslo var Fakultetsopponent.

I mitten av juni lämnades en ansökan in till Knut och Alice Wallenbergs stiftelse om medel för att bygga ut Tarfalastationen. Underlaget till ansökan hade arbetats fram i samråd med Statens fastighetsverk och universitetets byggenhet.

Studentkursen bestod av 16 studenter. Projekten handlade om balanserat flöde på isfallsglaciären, Spårämnesförsök på Storglaciären, Bottentopografi på Tarfalaglaciären, Hypsografi i isfallssjön, Glacialmorfologisk kartering, Isdeformation vid Storglaciärens front samt en studie av flutes framför Isfallsglaciären.

Sydtoppen mättes in den 8 och 13 augusti. Vid det senare tillfället var höjden 2108 möh.

Väderstationen på Riukojietna byttes ut i början av augusti efter diverse driftsstörningar

Den 11 augusti inträffade en tragisk helikopterolycka i Tarfala. Under ett räddningsuppdrag kolliderade en av arméns Pumahelikoptrar med Kaskasapaktes sydvästkam. Helikoptern störtade och de tre besättningsmännen omkom.

En preworkshop exkursion hölls i Tarfala den 13-16 september inför SCAR-ANTIME mötet som senare hölls i Abisko. Exkursionen kunde hållas i strålande sol.

Under september-oktober arbetade Eva Sahlin fram ett underlag för en turistinformation om geovetenskaplig forskning i Kebnekaiseområdet. Arbetet fick dock avbrytas pga avbruten finansiering från Miljö och Rymdforsknings Institutet, MRI.

I oktober inrättades ett glaciologiskt/geomorfologiskt modelleringslabb i geovetenskapens hus. Huvudman för labbet är Jens-Ove Näslund.

Mårmaglaciären besöktes den 7 oktober och en 14 meter lång iskärna och ytprover togs i förlängning av den tidigare uppborrade iskärnan. Det var vid tillfället snöfritt i Mårmamassivet samt i Tarfalaområdet.

Den 27-28 oktober hölls IGS Nordic Branch möte i Tallin.

Den 21 december beslutades om medel för en avveckling av CIRC-programmet under loppet av år 2001.

2001

Vid årsskiftet slogs de naturgeografiska och kvartärgeologiska institutionerna samman till institutionen för naturgeografi och kvartärgeologi.

Den 12-13 februari arrangerades en IASC-MAGICS workshop i Stockholm. Förexkursionen arrangerades på Mälarens isar.

I februari flyttade Margareta Hansson över till Institutionen för naturgeografi och kvartärgeologi från sin tidigare hemvist vid Meteorologiska institutionen vid Stockholms universitet. Hon tillträdde en tidsbegränsad vetenskapsrådsfinansierad lektorstjänst. I samband med detta övertog hon koordinatorrollen för det svenska EPICA-insatserna, samt ansvaret för köldlabbet i Stockholm.

Den 20 februari försvarade Per Klingbjer sin licentiatavhandling ”Paleoklimat och recenta glaciärer i norra Skandinavien”.

Data från permafrostborrningarna i Tarfala presenterades vid ”First European Permafrost Conference” i Rom 22-29 mars.

I slutet av april råkade Per Klingbjer ut för en allvarlig olycka i samband med fältarbete på Salajekna. Hans ena hand fastnade i en roterande borr och handen skadades mycket illa.

Den 3-4 maj hade lärare från Hjalmar Lundboms skola i Kiruna fortbildning i Tarfala med medel från Vetenskapsrådet, lärare under fortbildningen var Peter Jansson.

Den 10 maj gick tre slasklaviner i Tarfala, en vid Nordjåkks överfall, en vid Rännan och en nedströms dalkröken.

Den 14-16 maj genomförde armén sin årliga flygövning i Tarfala. Denna gång i strålande väder.

Den 18 maj försvarade Cecilia Richardson sin doktorsavhandling ”Spatial distribution of Snow in Antarctica and Other Glacier Studies Using Ground-Penetrating radar”. Fakultetsopponent var professor Bob Jacobel från St Olafs Collage, USA.

Den 21 maj reste Margareta Hansson till borrplatsen vid NordGRIP för att delta i borrningarna.

Den 23 maj försvarade Thomas Schneider sin doktorsavhandling ”Hydrological processes in Firn on Storglaciären, Sweden”. Fakultetsopponent var professor Andrew Fountain, Portland State University, USA.

Den 8 juni reste Margareta Johansson till NordGRIP och stannade där till 1 juli.

Professor Gunnar Hoppe skänkte Tarfalastationen de senaste elva årgångarna av Journal of Glaciology.

I juni förhyrdes en tvårumslägenhet på Konduktörsgatan 1, 2tr, i Kiruna för CIRC/Tarfalaaktiviteter.

Den 8-10 juni genomfördes en summerande workshop till vetenskapsakademiens symposieserie om ”Mountain Research”. En slutrapport ställdes samman vilken ska ligga till grund för policybeslut under 2002 som FN har utsett till Year of Mountains. Ett planerat studiebesök i Tarfala fick ställas in pga dåligt väder.

Under juli startades ett större flerårigt glacialhydrologiskt projekt på Storglaciären med Bob Jacobel, Andrew Fountain och Peter Jansson som huvudmän.

19-21 Juli var Peter Jansson inbjuden talare på IAHS Annual Assembly.

Tarfalakursen genomfördes med 12 deltagare.

Den 3 augusti mättes Sydtoppens höjd in från Tarfaladalen. Toppen var 2107,5 möh, vilket är rekordlågt.

Den 6 september inträffade en dödsolycka i Tarfala. En deltagare i en av STF arrangerad kurs störtade i en glaciärspricka och omkom.

Under september inleddes arbetet med ett Visitor Centre i Kiruna. Tarfala och Abisko ska tillsammans ta fram ett förslag till en natur- och miljöavdelning. Cajsa Martinsson får i uppdrag att ta fram ett förslag.

I början av september hålls en workshop i Kebnekaise/Tarfala för att ta fram underlag för ett projekt som syftar till att ta fram en klimatkurva för Norrbotten som sträcker sig 400 år tillbaka i tiden. SMHI, Tarfala och Miljödepartementet var representerat vid mötet.

De nya lokalerna i Tarfala invigdes högtidligen den 17 september av universitetets rektor. Representanter för Statens Fastighetsverk, Wallenbergsstiftelsen, Vetenskapsrådet, Kiruna kommun och institutionen medverkade.

Den nordiska grenen av IGS hade sitt möte i Rovaniemi 27-28 oktober.

I november stod det klart att Regine Hock fått en forskarassistenttjänst beviljad av vetenskapsrådet. Även Peter Jansson och Margareta Hansson fick projektmedel från vetenskapsrådet. Forskarassistenttjänsten placerades vid institutionen för naturgeografi och kvartärgeologi.

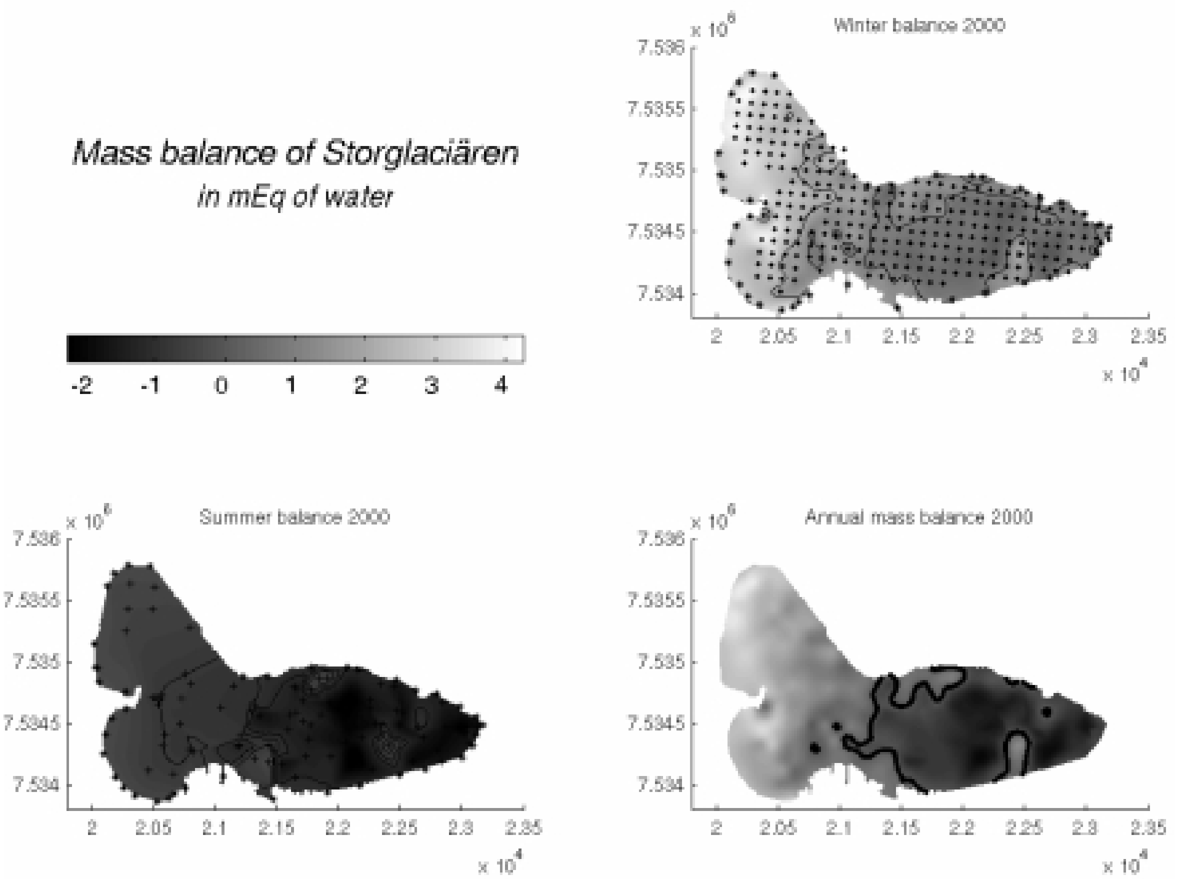
I slutet av november reste Mart Nyman som svensk representant inom EPICA till Dome C för att delta i borrningarna.

I december beslutade Polarforskningskommittén att satsa på fyra monitoringprojekt i anslutning till Wasastationen i Antarktis. Det var ett glaciologiskt, ett meteorologiskt, ett atmosfärsfysiskt och ett geodetiskt projekt. De två förstnämnda berör den glaciologiska forskningen direkt.

I december inställdes den planerade expeditionen till James Ross Island pga logistikproblem i Argentina.

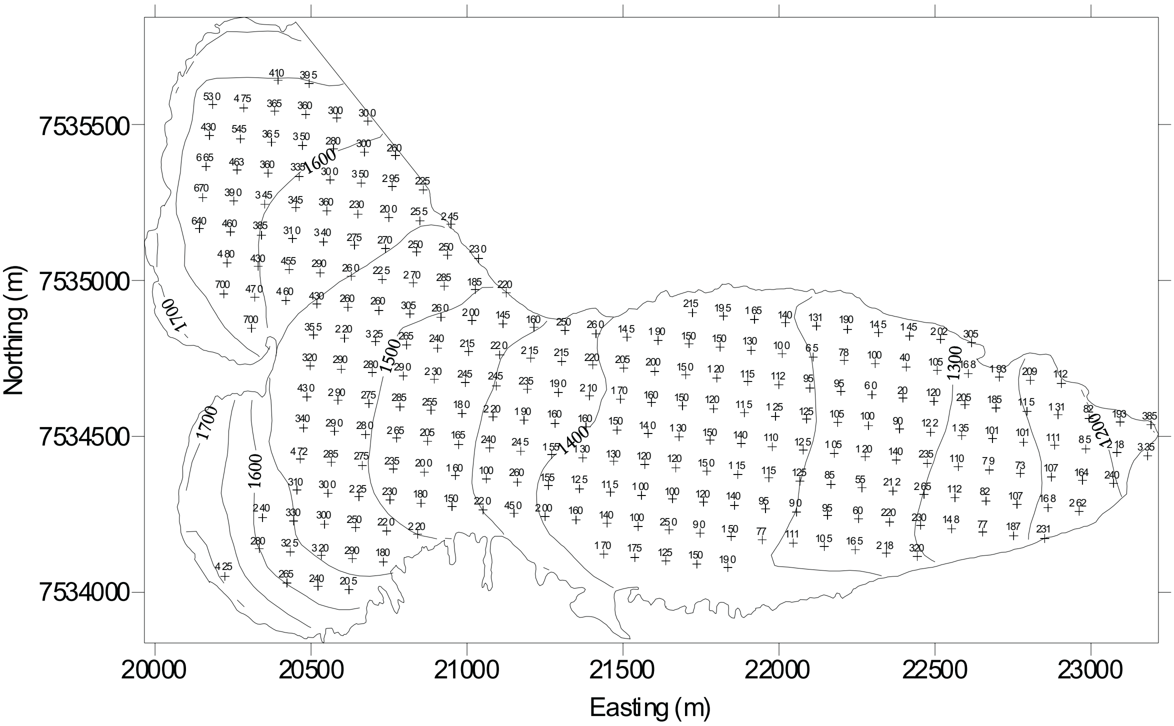
Appendix 1

Winter, summer and net balance for Storglaciären 1999/2000.



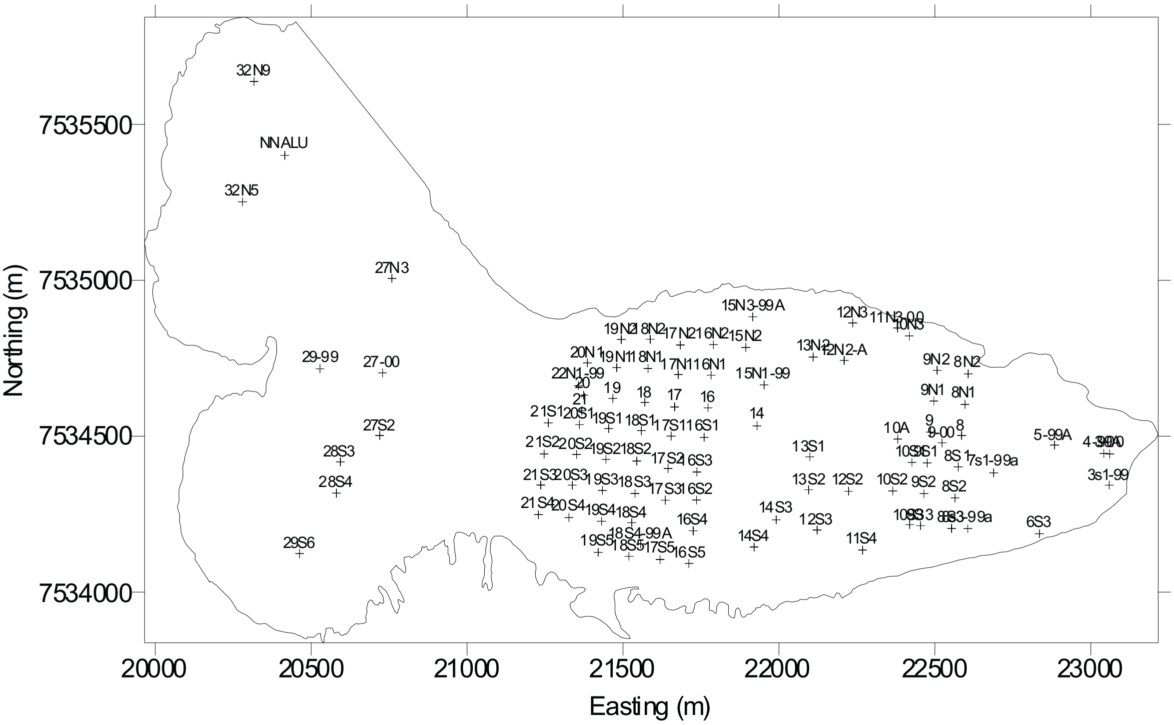
Appendix 2

Snow depth survey 2001 on Storglaciären



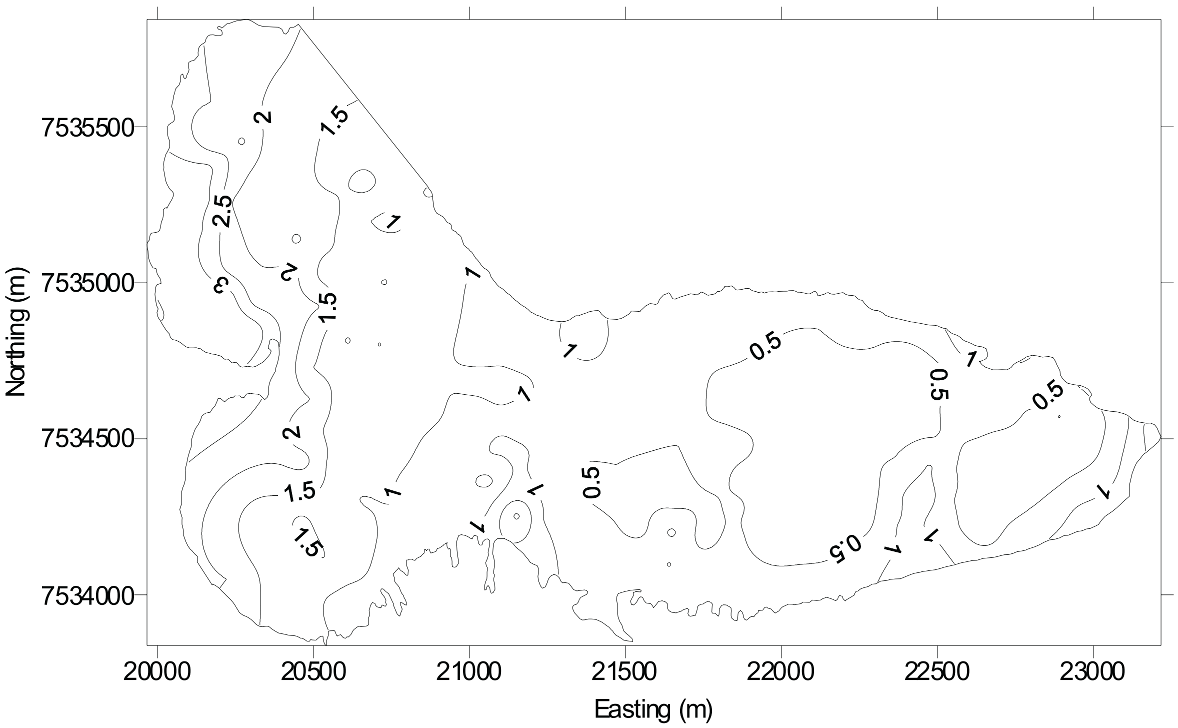
Appendix 3

Stake locations 2001 on Storglaciären



Appendix 4

Winter balance map for Storglaciären 2000/2001



Appendix 5

Summer balance map for Storglaciären 2000/2001