Regional variations of the cold surface layer of northern Scandinavian glaciers

Erik Massih

Department of Physical Geography and Quaternary Geology, Stockholm University, SE–106 91 Stockholm, Sweden

Abstract

The cold surface layer found in polythermal glaciers is considered to be dependent on the prevailing climate conditions. Around 30 glaciers in northern Scandinavia have been surveyed with ground penetrating radar to investigate the thickness of the cold surface layer. The analysis was carried out on a regional scale aiming to increase the understanding of which geographical and climatic parameters affect the thermal regime. The analysis shows that there are relations between the maximum thickness of the cold surface layer and location, elevation, precipitation and local topography. The general trend is that glaciers situated further east and north, develop a thicker cold surface layer. Annual precipitation and local topography also play an important role for snow accumulation and therefore also for the thermal regime.

Introduction

Many glaciers in northern Scandinavia are so called sub–polar glaciers, or polythermal glaciers, which implys that they consist of both cold ice (temperature below the pressure melting point) as well as warm, temperate ice (at or above the pressure melting point) containing inclusions of liquid water. In the accumulation areas the ice is generally temperate while the ablation area hostes a cold surface layer of varying thickness. The depth of the cold surface layer is primarily controlled by factors such as winter precipitation and summer temperature.

The cold surface layer is to a great extent also dependent of the glaciers mass turnover which itself is a function of the prevailing climate (Holmlund and Schneider, 1997). A continental climate is characterized by warm summers, cold winters and low annual precipitation, which as a result leads to lower mass turnover. A maritime climate on the other hand, categorized by smaller annual temperature amplitudes and high precipitation, leads to higher mass turnover. A higher mass turnover results in a thinner cold surface layer.

The climate in northern Scandinavia is characterized by a strong E–W climate gradient. It is strongly affected by the west wind belt and wandering low-pressure systems originating from the Atlantic Ocean. The dominating W and SW precipitation carrying winds as well as the Scandinavian mountain range, which has a SW–NE orientation, results in a maritime climate in western Norway; a locally maritime climate in the mountainous areas and a locally continental climate east and lee of the mountain range.

The study by Massih (2003) aims at analyzing and evaluating how the thickness of the cold surface layer varies between glaciers in northern Scandinavia to increase the understanding of which parameters affects the thermal regime of glaciers. The purpose of the study is also to determine if there are any patterns or trends in the variations and if it is possible to formulate any generalisations regarding this. The parameters the study uses are longitude, altitude, distance to the Atlantic Ocean and precipitation. The cold surface layer on the 33 glaciers (Table 1) that have been studied has, in all cases except one, Engabreen (N), been mapped by high-resolution radar.

Methods

The thermal properties of the glaciers were surveyed by helicopter-based radar in late winter of 1996 by Per Holmlund and Cecilia Richardson–Näslund. Differences in the dielectric properties of the glacier ice causes reflections of the transmitted radar signal. Ice, having a dielectric constant of of 3.2, is relativly transparant for electromagnetic waves at radar frequencies. Water and bedrock on the other hand, having dielectric constants of 81 and 7 respectively, create greater resistace. Therefore, the dielectric difference between ice and water makes it possible to locate the transition between cold and

Table 1. The investigated glaciers in the study. The number below refers to the number in the table heading. All data except column 9, 10 and 12 are taken from Østrem et al. (1973).

1. *The orientation of the accumulation area.*
2. *The highest and lowest altitude (m a.s.l.) of the glacier unit.*
3. *The longitude and latitude of a point near the center of the glacier.*
4. *The glacier type: an ice-field (2), an outlet glacier (3), a valley glacier (5) or a mountain glacier (6).*
5. *The glacier basin: several compound basins (1), a single compound basin with ice flowing from two or more accumulation areas (2), or a single accumulation area (3). (4) Refers to cirque glaciers and (7) to an ice cap.*
6. *Longitudinal profile: an even profile (1), cascading with some crevasses (3), an ice-fall with at least one pronounced step with many or large crevasses (4).*
7. *The length (km) of the glacier along its iceflow line.*
8. *The area (km^2) describes a horizontal projection of the glacier outlines.*
9. *Average steepness (m/km)*
10. *The westerly distance (km) to the Atlantic Ocean.*
11. *Mean annual precipitation (mm).*
12. *The maximum thickness (m) of the cold surface layer derived from radar measurements in 1996.*

Glacier	1	2		3		4	5	6	7	8	9	10	11	12
Abisko region														
Vassitjåkka	NE	1570	1430	181910	682240	6	7	1	0.9	0.77	156	160	700	50
Kårsajökelen	NE	1460	940	181940	682140	5	2	1	2.2	1.58	236	160	700	50
Mårmapakteglciären	NE	1630	1300	184110	680610	5	4	1	2.4	1.77	138	140	700	86
Mårmaglaciären	E	1740	1340	184130	680450	5	2	1	3.5	3.93	114	140	700	107
Skårvaglaciären	N	1590	1140	173500	672110	6	3	1	1.8	0.91	250	135	1500	29
Kebnekaise region														
Riukojekna, AV	E	1460	1048	180340	680510	4	3	4	2.4	2.59	172	115	1000	73
Giccecåkka	N	1350	1110	164750	680040	4	3	1	1.8	2.13	133	75	1500	0
Kaskasapakteglaciären, N	N	1600	1115	183330	675700	5	1	1	2.4	1.57	202	150	1000	45
Kaskasapakteglaciären, S	SE	1720	1340	183610	675620	6	4	1	1.4	0.6	271	150	1000	0
Tarfalaglaciären	E	1760	1400	183900	675610	6	3	1	1	0.9	360	155	1000	0
Passglaciären	N	1680	1350	183130	675530	6	3	1	0.8	0.59	413	150	1000	44
Kebnepakteglaciären	NE	1760	1170	183350	675530	6	3	4	1.8	0.82	328	155	1000	47
Isfallsglaciären	E	1750	1175	183420	675500	5	3	4	2.1	1.4	274	155	1000	40
Rabots glaciär	W	1960	1080	182920	675440	5	2	1	4.1	4.22	215	150	1000	80
Storglaciären	E	1828	1125	183430	675420	5	2	1	3.7	3.06	190	155	1000	60
Sulitelma – Sarek region														
Kallaktjekna	S	1780	1180	174850	674250	5	3	4	2.2	2.31	273	130	1000	42
Hyllglaciären	N	1820	1320	172840	673510	6	3	1	2.2	1.45	227	115	700	85
Hambergs glaciär	N	1650	1040	172630	673510	5	3	3	3.2	2.35	191	115	700	71
Suottasjekna	NE	1840	1100	173520	672830	5	1	4	4.4	8.11	168	125	1000	42
Kassaglaciären	NE	1840	1420	173810	672720	6	3	1	2	1.4	210	125	1000	94
Vartasjekna	NE	1800	1260	174000	672710	5	2	1	3	3.64	180	130	1000	51
Vartastjåkkåjekna	NW	1600	1430	173950	672620	6	0	1	1.7	1.3	100	130	1000	93
Mikkajekna	S	1825	960	174200	672450	5	1	1	4.6	7.62	188	135	1000	83
Ålkatjekna, Å	E	1760	1180	173750	671950	5	2	1	4.6	6.56	126	135	1500	61
Ålmåijekna N	E	1480	1100	162410	671700	2	3	1	2.8	3.13	136	90	1500	76
Ålmåijekna S	SE	1540	1040	162300	671600	2	2	1	2.9	9.02	172	90	1500	57
Svennonius glaciär, W	SE	1760	1120	172320	671430	5	3	4	2.6	2.41	246	135	1000	0
Svennonius glaciär, E	SE	1830	1240	172450	671420	6	3	1	2.3	1.09	257	135	1000	0
Palkatjekna	NW	1680	1290	173520	671110	6	2	1	2.3	2.79	170	145	1000	71
Pårtejekna	E	1860	1080	173950	671020	5	1	1	5.4	11.1	144	145	1000	68
Salakjekna	SE	1580	830	162300	670750	5	3	1	10	24.5	75	110	1500	25
Stourrajekna, AV	S	1600	990	162930	670740	5	3	1	5.4	11.8	113	115	1500	77
Engabren	N	1205	820	135100	663930	4	3	3	12	36.2	33	20	2500	0

temperate ice. A FM–CW radar (Frequency Modulated Continuous Wave radar) with 201 frequencies evenly distributed over the frequency rage 320–370 MHz (TV2–type antenna) (Holmlund *et al.*, 1996). Data sampling was carried out with 2 shots/second. The radar was based on a HP 8753B network analyser. The software used was developed by PFM in Lilleström, Norway. Data were collected onto the harddisc of a laptop computer and later stored on optical discs. The radar data was processed with Geophysical Radar Software, a program written in IDL (Interactive Data Language), which performs an Inverse Fast Fourrier Transformation to compute the time domain signal. When the radar signal travel time is known the depth can also be calculated. The plots of the radar soundings showed echoes from the glacier surface, the underlying bedrock and in many cases an internal reflection horizon, which was interpreted as the boundary between cold and temperate ice.

Information concerning the orientation, position and altitude of the accumulation- and ablation areas as well as data on the glaciers morphology and annual precipitation were obtained from Østrem *et al.* (1973).

To carry out the analysis, it was necessary to classify the glaciers after morphology, location and climatic settings (Table 2). The classification made it possible to compare the cold surface layer of glaciers with similar morphological properties with geographical and climatic parameters. Glaciers in areas receiving the same amount of precipitation where also compared in order to determine how elevation and local topography can affect the thermal regime.

Results and discussion

The analysis has shown that there are relations between the maximum thickness of the cold surface layer and situation, altitude, precipitation and local topography (Table 3).

In general glaciers located further north have a thicker cold surface layer than more southerly situated glaciers. The cold surface layer also seems to be thicker the further east the glacier is located (figure 1 and 2). Looking at glaciers in the same region and with similar morphology, it seems like local topographical conditions, important for the snow accumulation, are the most important factors for controlling the maximum thickness of the cold surface layer.

Local topographical differences play a great roll for snow accumulation (Humlum, 1997), thus being a significant factor controlling the glaciers mass balance and the thickness of the cold surface layer.

Table 2. The properties of the classes and the number of glaciers in each class.

Class	Latitude	Attribute	Nr. of glaciers
Sulitelma-Sarek region	670000–675000		17
Abisko – Kebnekaise region	675000–685000		11
Abisko region	680000–685000		5
Kebnekaise region	675000–680000		6
Valley glaciers Abisko – Kebnekaise region	675000–690000	Valley glacier (5), even longitudinal profile (1)	5
Mountain glaciers Abisko – Kebnekaise region	675000–690000	Mountain glacier (6), longitudinal profile (1)	2
Valley glaciers Sulitelma – Sarek region	670000–675000	Valley glacier (5), even longitudinal profile (1)	7
Mountain glaciers Sulitelma – Sarek region	670000–675000	Mountain glacier (6), longitudinal profile (1)	5
Abisko – Kebnekaise region Precip. 1000–1500 mm/year	675000–685000	Valley glacier (5), even longitudinal profile (1), precip. 1000-1500 mm/year	5
Sulitelma – Sarek region Precip. 1000–1500 mm/year	670000–675000	Valley glacier (5), even longitudinal profile (1), precip. 1000–1500 mm/year	5

The annual precipitation is another controlling factor. Glaciers in areas with low annual precipitation tend to develop a thicker cold surface layer while glaciers in areas in areas with higher annual rainfall show the opposite. This has also been show by Holmlund *et al.* (1996). When comparing glaciers in the same region with the same annual precipitation, it seems as if the altitude of the glacier terminus and the glaciers highest point are important. This can also be explained by local variations in precipitation and snow accumulation caused local topography.

To rank these factors concerning importance of controlling the thickness of the cold surface layer is very difficult, at least via the methods and data used in this study. While comparing the glaciers they have either been too heterogeneous or to few to draw any definite conclusions.

To get a better understanding of which mechanisms control the thickness of the cold surface layer it would be interesting to do the analysis in a GIS with a digital elevation model. This would help to understand the local topography's influence on precipitation and snow accumulation. Comparison between thickness of the cold surface layer, glacier net-balance gradients and accumulation area ratio (AAR) (Holmlund and Schneider, 1997) would also be of interest.

Table 3. Linear trends for the different regions. The k-value is the inclination of the line, the m-value expresses the intersection with the x-axis. R^2 is the squared correlation.

Class (nr. of glaciers)		Longi-tude	Dist. to Ocean	Precipi-tation	Front. altitude	Max. altitude
Abisko – Kebnekaise region (11)	k	0.007	-1.1562	-0.295	-0.0152	0.0457
	m	-1212.8	230	84.936	76.782	-18.012
	R^2	0.0893	0.331	0.0296	0.0077	0.057
Sulitelma – Sarek region (17)	k	0.0015	0.4413	-0.0392	0.0887	0.0758
	m	-192.88	8.5564	108.45	-39.87	-66.703
	R^2	0.3328	0.256	0.4353	0.3761	0.2526
Abisko region (5)	k	0.0113	-0.9794	0.0191	0.0066	0.1628
	m	-1985.3	208.01	53.409	59.914	-188.05
	R^2	0.3231	0.3195	0.0064	0.0018	0.3628
Kebnekaise region (6)	k	-0.0506	-1.4994		0.0856	0.1048
	m	9321.1	281.27		152.71	-132.11
	R^2	0.4519	0.0745		0.2952	0.7438
Valley glaciers	k	0.0272	-2.7668	-0.1167	0.1545	0.0322
Abisko – Kebnekaise region (5)	m	-4919.4	482.29	178.28	-108.59	19.236
	R^2	0.3506	0.5912	0.6313	0.5789	0.0387
Mountain glaciers	k	-0.0046	0.5655	-0.0189	0.0707	-0.0514
Abisko – Kebnekaise region (2)	m	893.3	-40.422	63.258	51.026	138.78
	R^2					
Valley glaciers	k	0.0017	0.5794	-0.436	0.0582	0.1509
Sulitelma – Sarek region (7)	m	-226.71	-13.285	114.46	-1.0255	-206.51
	R^2	0.6511	0.6838	0.6078	0.575	0.3957
Mountain glaciers	k	0.0101	-1.0482	-0.0778	0.2207	0.1275
Sulitelma – Sarek (5)	m	-1671.8	210.52	155.15	-217.02	-143.28
	R^2	0.0256	0.1898	0.6941	0.9322	0.3165
Abisko – Kebnekaise region	k	-0.007	-0.4816		-0.3002	0.0182
Precip. 1000–1500 mm/year (5)	m	1335.7	129.26		392.24	28.08
	R^2	0.2887	0.2234		0.6949	0.0423
Sulitelma – Sarek region	k	-0.0015	1.5923		-0.1204	0.2526
Precip. 1000–1500 mm/year (5)	m	313.4	154.6		191.53	402.77
	R^2	0.0016	0.4545		0.5728	0.1999

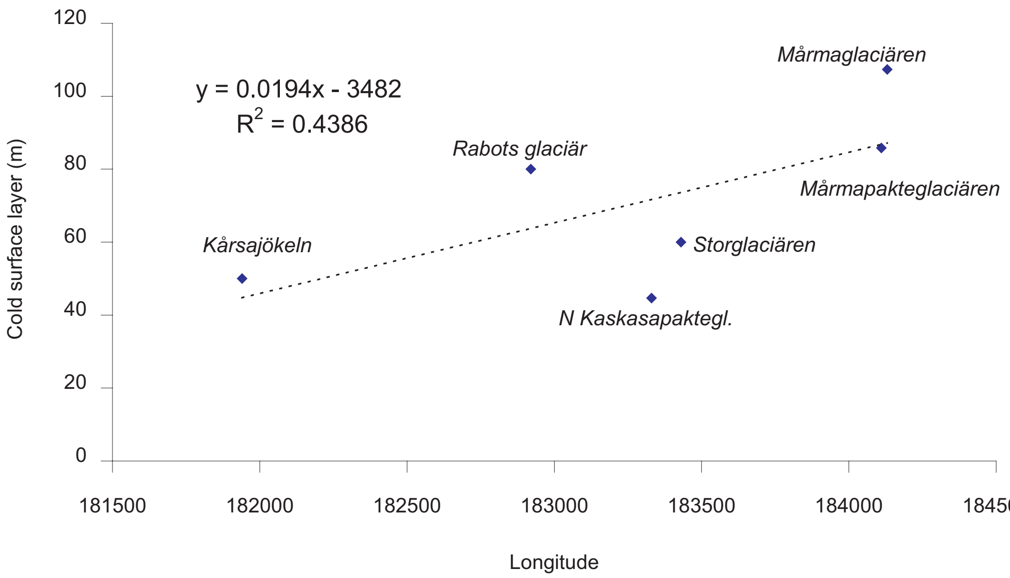

Figure 1. Maximum thickness of the cold surface layer plotted against the longitudinal location of valley glaciers in the Abisko – Kebnekaise region.

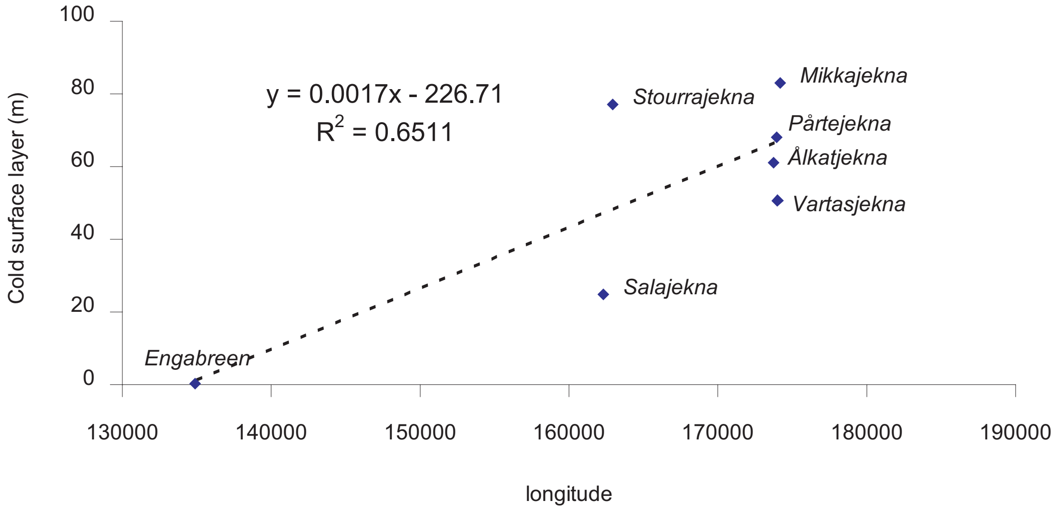

Figure 2. Maximum thickness of the cold surface layer plotted against the longitudinal location of valley glaciers in the Sulitelma – Sarek region.

Acknowledgements

This project was conducted as a degreeproject for an undergraduate paper. I whish to thank my supervisors Jens–Ove Näslund and Cecilia Richardson–Näslund, for all support during the project. I also wish to thank Rickard Pettersson for all technical support.

References

Holmlund, P., Näslund, J. O. and Richardson, C. 1996. Radar surveys on Scandinavian glaciers, in search of useful climate archives. *Geografiska Annaler* 78A (2–3): 147–154.

Holmlund, P. and Schnieder, T. 1997. The effect of continentality on glacier response and massbalance. *Annals of Glaciology* 24: 272–276.

Humlum, O. 1997. Younger Dryas glaciation in Söderåsen, South Sweden: An analysis of meterologic and topographic controls. *Geografiska Annaler* 79A (1–2): 1–15.

Massih, E. B. 2003. *Regionala variationer av det kalla ytskiktet hos Nordskandinaviska glaciärer*. Examensarbete 20 p. Institutionen för naturgeografi och kvartärgeologi. Stockholms universitet.

Østrem, G., Haakensen, N., and Melander, O., 1973. *Atlas over breer i Nord-Skandinavia.* Meddelande nr 46 från Naturgeografiska inst. Stockholms univ. 315 p.