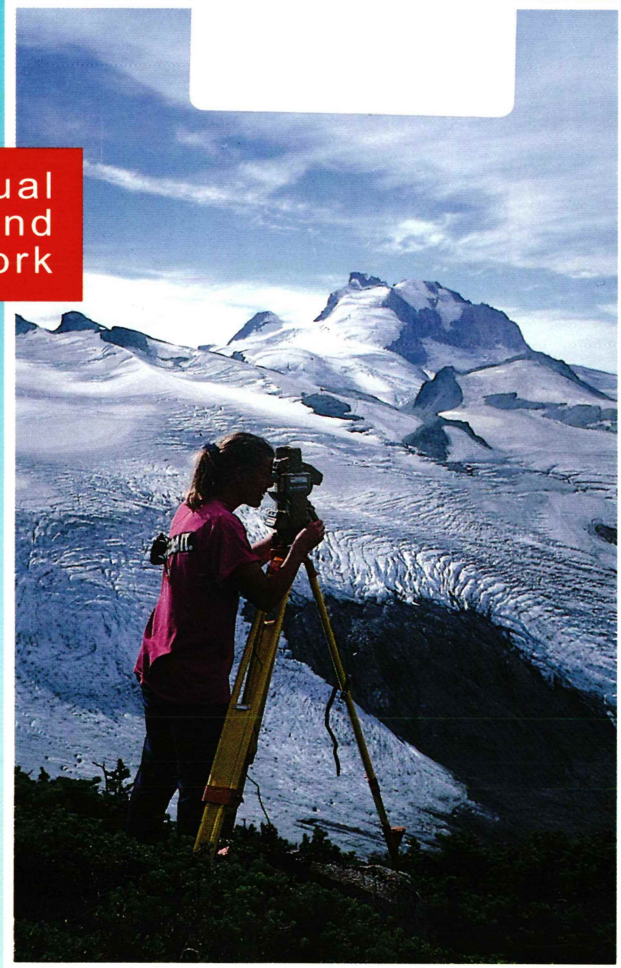
GLACIER MASS-BALANCE MEASUREMENTS

A manual for field and office work



G. Østrem and M. Brugman

NHRI Science Report No. 4

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A manual for field and office work

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NVE
NORWEGIAN
WATER RESOURCES AND
ENERGY ADMINISTRATION

Environment Canada Environnement Canada

National Hydrology Research Institute
Inland Waters Directorate
Conservation and Protection
Environment Canada

11 Innovation Boulevard
Saskatoon, Saskatchewan
Canada S7N 3H5

NHRI Science Report No. 4

Cat. En 36-513/4E
ISSN 0838-9052
ISBN 0-0662-19000-9

PREFACE

During the International Hydrological Decade (1965-1975) it was proposed that the hydrology of selected glaciers should be included in National IHD programs, in addition to various other aspects of hydrology.

In Scandinavia it was agreed that Denmark should concentrate on low-land hydrology, including ground water; Sweden should emphasize forested basins, including bogs; and Norwegian hydrologists should study alpine hydrology, including glaciers. Representative basins were then selected in each country, according to this inter-Scandinavian agreement.

In Norway, the selected alpine basins did not comprise glaciers, so some of the already observed glaciers were included in the IHD program. In Canada, the Geographical Branch, within the Department of Mines and Technical Surveys, initiated mass-balance studies on selected glaciers along an east-west profile from the Rockies to the Coast Mountains.

Canada, and later Norway, felt that glacier field crews and office technicians needed written instructions for their work. This would save time at the start of the IHD program, because new activities were planned at several glaciers almost simultaneously.

Therefore, a "cookbook" was prepared in Ottawa by Gunnar Østrem and Alan Stanley. This first "Manual for Field Work" was printed in the spring of 1966 for use during the following field season. Final revisions to the text were made at a field seminar at South Cascade Glacier in March 1966, in cooperation with glaciologists from the U.S. Geological Survey in Tacoma.

The authors soon felt a need for revising and extending the manual, so in 1969 a "Manual for Field and Office Work" was printed in Oslo. It was stated that:

> *Field procedures followed by the personnel at the Canadian Department of Energy, Mines and Resources and the Norwegian Water Resources and Electricity Board are described in this manual. Originally such field procedures were developed in various countries but - although aiming at the same objective - they differed slightly from country to country and even within the same country, so that direct comparison of results proved very difficult.*

The 1969 manual was used by Canadians and Norwegians for several years. Due to demand, it was reprinted in Ottawa in the 1960s, without further updating. The green cover was replaced with a standard reprint cover used by the Inland Waters Branch (Reprint Series No.66). Since then, the manual was so widely used (e.g., field training courses) that by 1980 the supply of printed copies was exhausted. Even the demand for the old version of the manual remained high.

Instead of once again reprinting the 1969 version, the authors (Østrem and Stanley) decided a revision of the manual was required to bring the book up-to-date, while preserving its unique clarity and simplicity. The purpose is primarily to provide an updated version that can be given to personnel at our Institutions

(National Hydrology Research Institute [NHRI] and Norwegian Water Resources and Energy Administration [NVE]) as a guide in their daily work.

The aim remains the same as it was in 1966 and 1969. The manual is for field officers, technicians, summer assistants, contractors and others who are dealing with mass balance studies, mainly on temperate glaciers in Canada and Norway. The reader is assumed to have only a limited background in glaciology.

Due to the fact that some presently-observed glaciers in Norway and Canada are classified as "sub-polar" (e.g., Svalbard, Yukon, and the Canadian High Arctic), a small section is devoted to special problems connected with "cold glaciers". Detailed information on techniques used on "subpolar" glaciers are included in the appendices.

By using identical or similar field methods and by reporting results in a consistent manner, mass-balance data should be more digestible for our "users", and the methodologies become more understandable for scientists studying, for example, glacier variations and relationship to global change.

This manual represents a consolidation of Norwegian and Canadian methodologies. In this respect, good use was made of the discussions at the Workshop on Glacier Mass Balance Standards, held in Seattle on November 28-29, 1990.

We have not included a section on safety, or how to travel on a glacier (with or without skis), because such information is well presented in the relevant literature, e.g., LaChapelle (1961), Manning (1962), Marnier (1963), Perla and Martinelli (1976) or similar guide-books for mountaineers.

Dr. Alan Stanley did not wish to continue as a co-author, so Dr. Mindy Brugman (of the same institute) was invited to be his successor, because she is presently more actively involved in Canadian glacier studies. This book is a joint venture between our two government organizations.

Several individuals were of great help in preparing the new edition. Simon Ommanney's efforts in editing the text are greatly appreciated and he significantly improved the quality of the text. Philip Gregory and Tracey Scheller prepared the graphics for printing. Hjalmar Laudon also helped prepare the final document together with Karen Ulmer and Karen Morin. We are most indebted to these people for their special efforts and to all others who made it possible to produce this book.

Gunnar Østrem
Hydrology Department
Norwegian Water Resources and Energy Administration, Oslo

Melinda Brugman
National Hydrology Research Institute
Environment Canada, Saskatoon

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CHAPTER 1. INTRODUCTION

1.1. General

Glaciers are important components of the hydrological cycle in mountainous areas and in polar regions. They are key indicators of climate change, and also are important natural resources that must be properly monitored and managed. This is particularly important in Canada and Norway where difficult scientific and ethical questions need to be answered about sustainable development, especially with regard to hydropower, water supply and environmental quality.

In this book we outline the basic techniques used for measuring glacier mass balance in Canada and Norway. Descriptions that follow are designed to familiarize the reader with techniques presently used in the mass-balance programs or being actively developed. As much as possible, reference is made to published literature or other more detailed sources. Some of the information included is derived from techniques that have been used for decades in glacier-monitoring programs, but additional information is provided on new instrumentation and methodologies that are now available. A number of the basic operational details in the original manual were either shortened (e.g., how to build and secure field cabins) or eliminated if no longer used. Because the glacier field stations in Canada have withstood nearly three decades of mountain weather and field use, the huts have proven their reliability. They are included just as an example for the neophyte of how a basic, inexpensive, research hut can be quickly constructed. The reader with no need to understand hut building, or familiar with certain techniques discussed, may want to skip those sections. Safe glacier travel require thorough knowledge of self-arrest, crevasse rescue and avalanche safety techniques; these are covered in recommended mountaineering literature included in the reference list.

This manual is intended to guide and refresh the minds of field personnel in Canada (particularly western Canada) and Norway. For others, it can be used to obtain a more complete understanding of glacier mass balance. Detailed information on techniques used in Arctic Canada are given in Koerner (1986), although the essence of his methods are also included here. After studying this manual a person should be able to participate actively in a glacier monitoring team. We acknowledge that not all our methods are used outside Canada and Norway, however, with the appendix by Larry Mayo (U.S.G.S., Fairbanks), at least most of the techniques used throughout North America have been covered.

1.2. Primary Reasons for Mass-Balance Studies

The primary purposes of glaciological investigations on selected glaciers in Canada and Norway are the same now as they were when originally outlined by Østrem and Stanley (1966), and are as follows:

1. To measure the mass balance of the glaciers and determine their impact on river hydrology.

2. To study the accumulation pattern and, as possible, follow its variation throughout the accumulation season.

3. To study the ablation throughout the summer and correlate variations with meteorological parameters.

4. To analyze apparent correlations between mass balance variations and climate change.

5. To measure the glacier stream discharge continuously throughout the summer in order to check mass-balance calculations.

6. To take water samples from the glacier stream for determination of sediment transport, background water chemistry, and the glaciers' erosional effect.

7. To investigate refreezing of meltwater in snow and firn.

Refreezing is very pronounced on cold glaciers in the Arctic, but the process has still not been fully investigated for alpine glaciers. Measurements of internal temperature, surface ablation and accumulation, and ice surface texture at the study glaciers in southwestern Canada and in southeastern Norway indicate that refreezing within glaciers is not an important process at an annual time scale, but does occur seasonally in the upper layers on certain glaciers.

Where the internal temperature of the glacier is sub-freezing throughout the summer, as in many areas of northwestern Canada, the Canadian High Arctic and on Svalbard, refreezing and the accumulation of superimposed ice within glaciers is quite important, but very labour intensive to measure properly. Such measurements can best be accomplished in conjunction with a well-developed mass-balance program, through which the results may be tested against changes in topography, volume, surface mass balance and terminus stream runoff measurements.

The winter accumulation (e.g. "winter balance", see Chapters 5 and 14) is measured as accurately as possible and the total amount of ablation during the summer season observed at a network of stakes drilled into the glacier. Variations in snow density are observed by pit (and sometimes core) studies throughout the ablation season. The goal is to determine the net balance of the glacier by independently determining the summer and winter balances. In general, annual balances are not observed.

Although it has been a goal to correct discharge observations for rainfall in the catchment area by placing rain gauges at a number of locations, in practice this has not been possible because of gauge inaccuracies due to difficulties in resolving wind-screening and representation problems.

A further goal is to measure the timing and volume of water stored and released seasonally from within the glaciers. To accomplish this task, the measurement errors of surface ablation, stream discharge, ground- and surface-water contributions from the valley sides, and precipitation in the basin must be minimal. An understanding of the internal plumbing of the glacier, as its relates to seasonal fluctuations in ice velocity, must be obtained to evaluate the possibility and extent of seasonal liquid-water storage within the glaciers. Similarly, knowledge of the

subglacial drainage system is important when water power engineers want to construct subglacial water intakes for hydropower production.

Sediment sampling in glacial streams gives information on the effects of glacier erosion and the amount of sedimentation which might be expected in natural or artificial reservoirs.

Water chemistry (major and trace element, major cations and anions, pH) is studied in conjunction with measurements of conductivity to understand the sources and paths of water within a glacier, for environmental assessments, and in the study of geothermal and volcanic areas overlain by perennial ice in western North America.

1.3. Introduction to Glacier Mass-Balance Terms (Fig. 1.1)

Glaciologists used slightly different terms in their mass balance studies which made comparison of results from various countries difficult. At a meeting of the International Association for Scientific Hydrology in Berne 1967, it was agreed to standardize glacier mass-balance terminology. This was the culmination of discussions over several years. One of the most active co-ordinators and standardizers of mass-balance terms has been Dr. M.F. Meier (presently Director of INSTAAR, Boulder, Colorado). His "Proposed definitions for glacier mass budget terms" (Meier, 1962) have been modified, but many are now included in the standardized system described in the UNESCO report (1970).

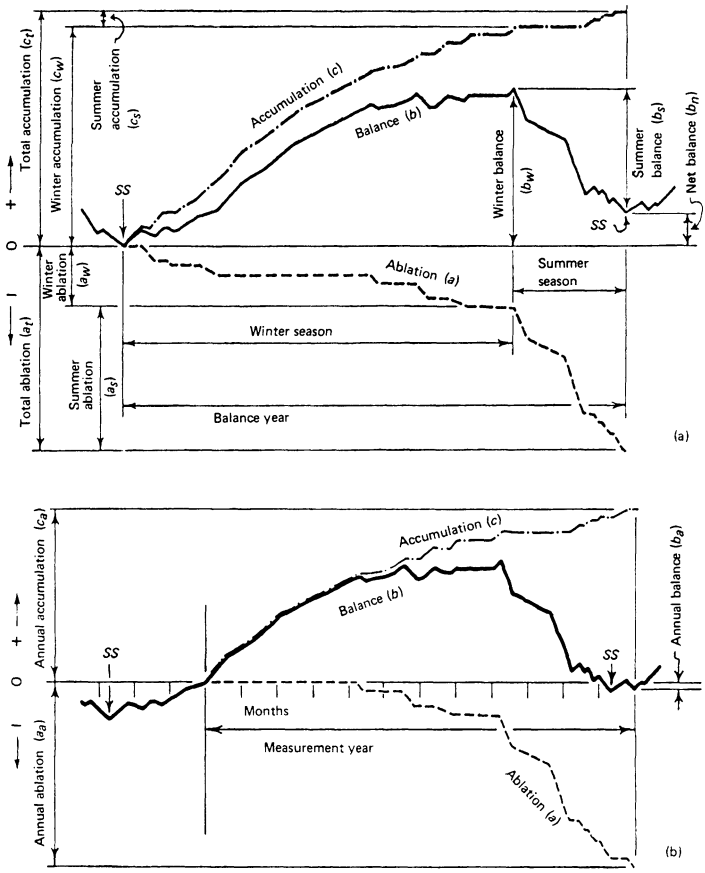
Accumulation includes all processes that increase the glacier's mass; ablation includes all those that remove mass. This definition corresponds to that given previously by Ahlmann (1948, p.15 and 26) and others.

The measurements of glacier mass balance are performed at many points on the glacier surface from which the total values are calculated by integration over the glacier area. At each point the change in glacier mass is measured relative to last year's summer surface; all point measurements are symbolized with small letters. The balance (b) is the change in mass measured at a point at any time. It can be positive or negative.

One balance year can be defined as the time between the formation of two consecutive summer surfaces (ss). (A balance year according to this definition — the stratigraphic system — will seldom be equal to a calender year). It may also be defined in the "fixed-date" system. Its length must then be stated in each case, giving the date(s) when the surveys were made.

In the first part of the balance year a curve demonstrating the balance vs. time will show an increasing trend. The maximum balance value during one balance year is called the winter balance (b_w). The time when this maximum value is reached (i.e., the end of the accumulation period) divides the year into a winter season and a summer season: previously called the accumulation and ablation seasons.

The winter balance was previously termed the total accumulation (at least by some), but it is obvious that more snow may fall on the glacier during the winter than will be left at the end of the winter season: part of the snow may be removed by evaporation, wind action, etc. Thus, the "true" total accumulation will, in most cases, be slightly larger than the winter balance, but it will be almost impossible to observe.



Mass balance terms as measured at a point on a glacier or ice cap
ss = time of formation of a summer surface

Figure 1.1: Basic Mass Balance Terminology
The net mass balance, b_n, of a glacier is determined by the accumulation (c) and ablation (a) throughout the balance year, as described on these diagrams. Accumulation and ablation may occur at any time during the year as shown on these diagrams. The net balance b_n is the summation of winter balance b_w (usually positive during the normal winter accumulation season), and summer balance b_s (usually negative during the normal summer ablation season), which may be stated as $b_n = b_w + b_s = c + a$. Ideally "c" and "a" should be measured, but in practice this is impossible to do accurately throughout the entire year. Normally, only b_w and b_s are measured at each stake and extrapolated to the entire glacier using one of several different methods as described later in this manual. Diagrams are from UNESCO & IAHS Report, 1970.

Changes in mass during the summer season is called the summer balance (b_s). This was earlier termed total ablation which strictly speaking is generally larger. Snow that falls during the summer changes the summer balance and makes it different from the "total ablation". Such accumulation during the summer could be accounted for in a number of ways. If the snow melted immediately, it was included in the accumulation figure and termed "summer accumulation". But then it should also be included in the ablation figure, making the total ablation correspondingly larger.The local net balance (b_n) is the change in balance during one balance year and can be expressed as the algebraic sum of winter balance and summer balance or the sum of total accumulation and total ablation:

$$b_n = b_w + b_s = c_t + a_t$$

Summer balance and total ablation (a_t) are normally negative, winter balance and total accumulation (c_t) positive. Net balance may be positive or negative depending on conditions in the particular balance year. All values are given in metres of water equivalent.

Processes that change the mass of a glacier generally take place in a relatively thin surface layer on the glacier. However, as mass balance is the variation in the total mass of a glacier, the sub- and englacial processes should also be studied. These are difficult to observe and will seldom be measured directly. For temperate glaciers, the subglacial and englacial accumulation and ablation are very small compared with the processes taking place at, or near, the surface. The most important process taking place under the surface is the vertical mass transport connected with the warming of the glacier at the beginning of the summer. Snow melts at the surface and the meltwater percolates to areas where snow temperatures - are still below freezing. When this meltwater freezes it releases a large amount of heat (80 calories per gram: latent heat of fusion at 0°C is 3.34×10^5J/kg). Within a short period (a few days to a couple of weeks) the entire snow pack may become isothermal (0°C).

Most of the vertical mass transport stays within the snowpack originating from the same winter season. However, some of the percolating water may penetrate through the summer surface and freeze within the firn, if the firn has negative temperatures. Firn is snow that has survived at least one year on the glacier and not yet metamorphosed to polycrystalline glacier ice (Fig. 1.2). Its density generally lies between 0.4 and 0.9 gm/cm^3. According to Ahlmann (1935) temperate glaciers are at the melting point and therefore the firn layers normally allow percolating water to penetrate to the glacier bed and leave the basin without refreezing. However, at the end of the summer, part of the firn may be cooled below 0°C initiating some refreezing which would move mass through the summer surface. The water freezing below the "ss", may be termed internal accumulation; an important part of the winter balance on "cold" glaciers. The mass of the percolating water that refreezes in the firn would not be accounted for in those balance years when the conventional methods for mass-balance measurements are used. To avoid such miscalculations, pits for snow density measurements must be dug beyond the summer surface to check density changes in the firn during the first part of the summer. Experience shows

Figure 1.2: Sentinel Glacier
Sentinel Glacier photo (oriented approximately with north upwards) showing clear demarcation between the last years snow and the firn (previous years snow) called the ELA (Equilibrium Line Altitude for a glacier without refreezing within the firn), longitudinal snow dunes in upper glacier, extensive crevassing on west tongue and minimal crevassing on east tongue (right side), and characteristic patterns of foliation, snow runnels, surface rock debris, crevasses, recently deglaciated terrain, lateral moraines.

that these density measurements should be continued some 50 cm down into the firn. As soon as the firn becomes isothermal, there is little chance for refreezing any percolating water.

If firn and ice temperatures below the previous summer surface (ss in Fig. 1.1) remained at the melting point throughout the winter, then it is unlikely that significant internal accumulation occurred below the new snowpack. In the absence of reliable temperature sensors, the presence of abundant water at, and below, the "ss" strongly suggest that internal accumulation is negligible. Temperature measurements are an integral part of present snow pit studies, particularly where there is any possibility of internal accumulation within or below the snowpack.

The refrozen meltwater, calculated from changes in firn density, must be regarded as a part of the glacier's accumulation. For temperate glaciers in southwestern Canada, and in maritime areas in Norway, it is assumed that this internal accumulation is almost negligible.

The winter balance (b_w) and the summer balance (b_s), as observed at single points, must be integrated for the entire glacier. The terms referring to the entire glacier are analogous with those for single points, but they are symbolized with capital letters (B_W, B_S, B_N). They are normally expressed in $10^6 m^3$ of water. Often it is practical to report average values for the entire glacier or for selected parts. Mean values (b_w, b_s, b_n) are expressed in m of water equivalent. For hydrological calculations they may also be expressed as a specific discharge, using a unit such as litres per second per km^2 (common in Scandinavia). The specific discharge is calculated as a mean for one year.

The balance year is normally of different length on various parts of the glacier and the integration therefore cannot be clearly defined with regard to time. The winter balance is observed as close to the end of the winter season as possible but before any ablation has taken place. During the time when the snow becomes isothermal, ice layers may form in the snowpack so that snow soundings to the summer surface will be difficult or impossible to make. It is therefore most important to undertake the snow survey some time before the summer season has really started. The small increase in winter balance after this survey may be directly measured at selected points or estimated from meteorological data. In most cases, the additional accumulation will be small compared to the entire winter's accumulation.

The procedures involved in the integration of point measurements to obtain the winter balance, summer balance and net balance for the entire glacier are described in Chapter 13.

Chapter 14 discusses different reporting systems used and compares them. The field methods described in this manual may be used to calculate glacier mass balance within the systems referred to as "stratigraphic", "fixed-date", and "combined". Other methods, such as the geodetic, hydrological, and the use of index values, etc. are best reported separately. They can provide excellent results for comparison with the three principal reporting systems if the field techniques, analytical procedures and assumptions involved are well documented.

CHAPTER 2. SELECTION OF SUITABLE GLACIERS

Because it is not physically possible to examine all glaciers in a mountain system, or within the catchment area of large streams, it will be necessary to select individual glaciers which are considered representative of the whole area under study. The results obtained from one or more glaciers can probably be applied to the larger glacierized area. It is therefore extremely important that the choice of the representative basin be made very carefully, although practical conditions (mainly accessibility) will also influence the selection, such that it is often necessary to compromise.

A suitable glacier representing each geographical area, climatic zone or catchment area should be selected on the basis of the following considerations:

a) It must have a well-defined, highly-glacierized catchment so that the meltwater stream represents conditions on the glacier rather than those of the surrounding terrain.

b) Its size of glacier should be comparable with other glaciers in the area but small enough that it can be fully examined by a party of 2-3 people. (The upper limit is probably 10-15 km^2). If more staff and more remote-sensing capabilities are available, a larger glacier can be selected.

c) The range in altitude between the glacier tongue and the upper firn area should be as large as possible: at least covering the main range of other glaciers in the area.

d) It should be drained by one meltwater stream, and have conditions favourable for discharge measurements close to the glacier snout.

e) It should have relatively easy access so that it can be visited throughout the year without the use of helicopters, etc. Easy access should, however, not be over-emphasized; an ideal glacier should not be omitted and replaced by another less suitable for reason of accessibility alone. Ultimately, the choice will depend on available resources.

f) It should have few crevasses as they make the work unnecessarily risky for observers and may limit observations to a small area. However, if representative glaciers within an area have many crevasses this point must be considered, and how they change with time.

g) It should be situated in an area for which reliable maps, good air photographs, and, ideally, remote-sensing imagery are available or can readily be obtained shortly after investigations have started. Maps are the vital base on which all accumulation and ablation measurements must be plotted, or from which terrain models will be derived. A scale of 1:10,000 is generally most suitable for this purpose. A contour interval of 10 metres is appropriate for the glacier surface and 50 m for the surrounding area. The map must cover the entire catchment area above the site of river observations.

CHAPTER 3. GLACIER MASS-BALANCE PROGRAMS

3.1. World-Wide Overview

Glacier mass balance is measured throughout the world, although the network is incomplete and methods used differ significantly between countries. The World Glacier Monitoring Service (WGMS) in Zürich, Switzerland, is the present central point to which glacier monitoring information is submitted and from where it is distributed (Haeberli and Herron, 1991; Haeberli and Müller, 1988). It is the agency to which Norwegian and Canadian glaciologists regularly submit mass balance summaries. It is operated under the direction of the International Commission on Snow and Ice (ICSI), part of the International Association of Hydrological Sciences (IAHS).

A listing of glacier research sites worldwide is given in Appendix III and includes data on longitude and latitude, ice-covered area, and years monitored for mass balance. For developed nations such as Switzerland, U.S.A., Canada, Norway, Sweden, Iceland, Japan, Austria, France, and the Soviet Union, many glacier mass-balance studies have been carried out, but for a lot of other countries next to no glacier mass-balance program exists despite the fact that many do contain significant glacier-covered areas. Major gaps exist in our knowledge of glacier mass balance and there is considerable room for expansion and improvement of the world-wide glacier monitoring network.

3.2. Glaciological Investigations in Canada (Fig. 3.1)

As part of Canada's contribution to the International Hydrological Decade, glaciological studies were conducted at a number of glaciers starting in 1965. At three sites in western Canada, annual studies have continued since 1965. Additional studies are carried out in the Canadian High Arctic, Yukon, the Rockies and Coast Mountains by various Canadian researchers; the mass balance techniques of Dr. R.M. Koerner (Energy, Mines and Resources Canada) are included in Appendix IV and discussed in Chapter 14.

At the three intensely studied glaciers in western Canada (b, d, and e below), ongoing measurements include: mass balance; meteorological observations on or near the glacier; measurements of discharge and sediment content in outflow streams. In certain cases studies have been made on the glacier's heat balance, with a focus on the albedo variations of glacier surfaces. Parameterized models of runoff in a glaciated basin have been developed for several basins, but in general lack sufficiently accurate runoff measurements throughout the year.

Other studies have included: ice movement (i.e., "ice discharge" in a glacierized valley); ice formation in the firn area; ice crystallography; ice dielectric properties; sliding behaviour; basal melt; englacial hydrology; and related problems. There is a renewed effort underway to understand runoff processes in glaciated basins and to accurately predict the runoff using both parameterized and physically-based models that can be closely linked to the glacier mass-balance results. Recent efforts in Canadian glaciological programs include incorporating remote-sensing and new ground-based techniques, such as FMCW radar, to improve the quality, and spatial coverage of glacier observations, and to reduce the labour-intensive nature of the research.

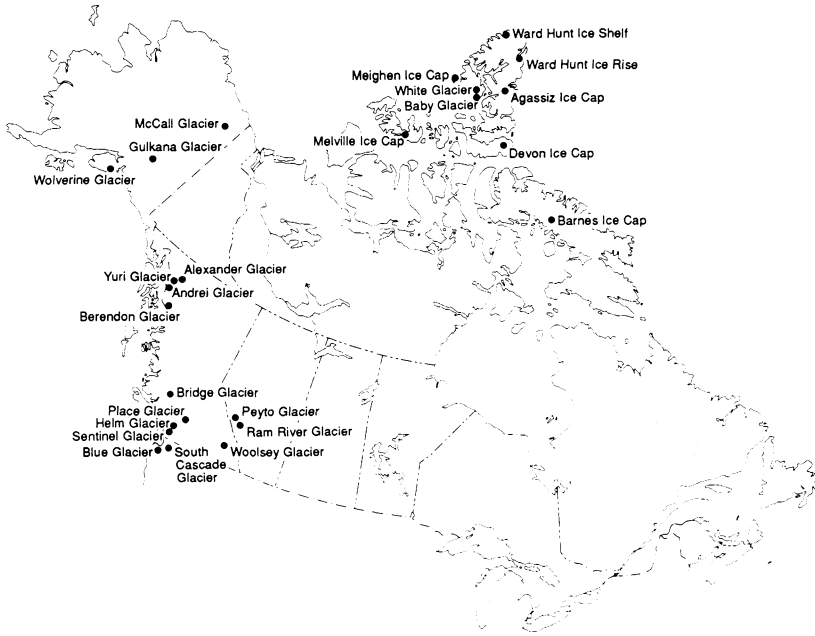


Figure 3.1: Map of Canada
Location map showing the Canadian glaciers selected for mass balance studies; nearby U.S. glaciers in Alaskan and Washington states are also shown. Included in this glacier are primary study glaciers with records of five continuous years or longer. A complete record of all glaciers monitored in Canada is included in Appendix III.

In order to compare results from different climatic areas, a number of glaciers have been selected across the Canadian Cordillera. These glaciers lie close to a line running from the Coast Mountains north of Vancouver, B.C., to the eastern flank of the Rocky Mountains north of Banff, Alberta. The selection was made to include humid coastal areas and the dry eastern mountain slopes. By 1965, five glaciers formed part of this profile (a-e below), and four glaciers lay north of this line (Fig. 3.1) . These glaciers are:

a) Ram River Glacier at the northeastern border of Banff National Park, Alberta.
b) Peyto Glacier at the provincial boundary close to the Banff-Jasper Highway in Banff National Park, Alberta.
c) Woolsey Glacier, part of the Clachnacudainn Icefield in Revelstoke National Park, B.C.
d) Place Glacier, 20 km northeast of Pemberton, B.C.
e) Sentinel Glacier in Garibaldi Provincial Park, B.C.
f) Berendon Glacier near Stewart, northern B.C.
g) Decade Glacier in Inugsuin Fiord, east-central Baffin Island.

In the 1970s this selection of glaciers was modified, for financial and logistical reasons, but also because it was believed that sufficient information on climate fluctuations was being obtained from the three western glaciers Peyto, Place and Sentinel. In 1975, a new west coast glacier study was started at Helm Glacier (in Garibaldi Park 10 km north of Sentinel Glacier) to strengthen the data bases from Sentinel and Place Glaciers and because it was logistically feasible to study both Sentinel and Helm at nearly the same time. Helm is a much simpler and smaller basin than Sentinel Glacier, and has shown itself to be very useful for comparison.

Unfortunately, funding was inadequate to maintain the mass-balance studies at Woolsey, Berendon, Ram and Decade Glaciers, but recent mapping of glacier volume changes have either been completed or are planned at each of these glaciers, where maps were made in the 1960s and 1970s.

The principal Canadian mass-balance glaciers presently under study are:

Western Canada	High Arctic
1. Peyto Glacier	1. Baby Glacier
2. Sentinel Glacier	2. White Glacier
3. Helm Glacier	3. Agassiz Ice Cap
4. Place Glacier	4. Devon Ice Cap
5. Tats Glacier	5. Meighen Ice Cap
	6. Melville Ice Caps

Measurements have been continued at the main study glaciers for 25 years, which is approaching the number of years necessary to apply a reasonable statistical analysis to trends and frequency distribution of fluctuations, and accurately document and correct for measurement errors.

The results of Canadian glacier mass balance studies are now published by NHRI Environment Canada in Saskatoon and Energy, Mines and Resources in Ottawa, and submitted to the World Glacier Monitoring Service.

3.3. Glaciological Investigations in Norway (Fig. 3.2)

Most Norwegian mass-balance studies are concerned with hydrological problems associated with using high-mountain rivers for hydroelectric-power production. Mass-balance studies are therefore undertaken mainly where future power stations are planned. In already developed areas glacio-hydrological data are still needed for managing power stations optimally. Thus, several power stations are financing long-term mass-balance monitoring programs.

Investigations should continue for 5 or 10 years to form a good basis for hydrological calculations. Some glacier basins have now been studied for much longer, and interest in the long observation series is increasing.

In addition to short-term studies, carried out primarily for planning purposes, long-term investigations are being performed at a number of glaciers along an east-west profile across the mountainous areas of southwestern Norway. In all, seven glaciers of different sizes were selected, including corrie glaciers, valley glaciers and small ice caps. The profile extends from the humid western coast to the continental dry inland areas. Annual accumulation and ablation figures range from an average of more than 4 m to less than 1 m of water equivalent.

The Norwegian studies are mainly of mass balance, but often include water discharge, and sometimes meteorological observations. Sediment transport studies have been performed in selected basins. Studies of ice movement and other glaciological parameters are also made in some places.

The primary purposes of the investigations are generally the same as for the Canadian program and will therefore not be repeated here (see Section 3.2). Glacier maps, at a scale of 1:10,000, were constructed for all glaciers under study. Those glaciers where long-term studies are presently (1991) carried out are shown in Figure 3.1.

A base camp was established at nearly all glaciers under study. A complete camp includes an insulated hut for accommodation, another hut serving as a shelter for a snow vehicle and/or a storehouse for supplies, one meteorological instrument shelter and, for most glaciers, an automatic stream gauge. Observations are carried out continuously during the entire melt season. Although the total winter snow accumulation is generally observed early in the spring, it is necessary to visit the glaciers 3-4 times during the winter to inspect the installations and extend survey stakes.

The results of the Norwegian mass-balance investigations are published in annual reports printed and distributed by the Department of Hydrology of the Norwegian Water Resources and Energy Administration (P.O. Box 5091, N-0301 Oslo 3) similar to the format recommended here. The reports are written in Norwegian, but illustrations normally have legends and captions in English. An English summary is included at the end of each report.

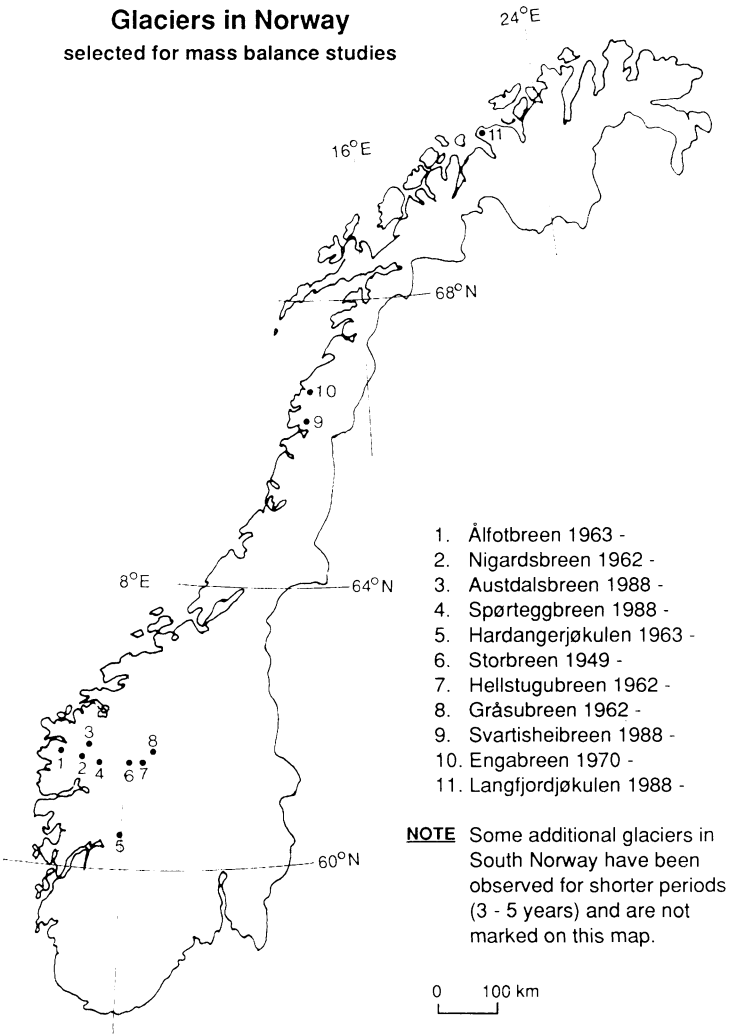


Figure 3.2: Glaciers in Norway
Several glaciers in Norway have been studied during the last decades regarding their mass balance. Due to the fact that some of these studies were requested by water-power engineers who wanted hydrological data for planned power developments, they were mostly terminated after 4-5 years.

Only glaciers where long-term studies are, or will be, performed are included in this illustration. Note that Storbreen has the second longest observation series in the world. Glaciers on Spitsbergen, observed by the Norsk Polarinstitutt, are not shown on this map.

CHAPTER 4. STAKE NETS

Measurements of both accumulation and ablation are referred to stakes placed on the glacier surface. Therefore, it is wise to plan the pattern of the stakes carefully. Ideally, they should be scattered uniformly over the entire surface so that every part of the glacier is covered by an equally dense network of stakes. However, this ideal distribution pattern is not always possible. It is therefore suggested that stakes be arranged in some geometrical pattern to facilitate the daily work. It is impossible to make a rigid recommendation for stake locations which would fit all different-shaped glaciers, but for valley glaciers the most logical and practical is a long line up the centre with transverse lines at regular intervals.

4.1. Stake Types: Wood or Metal

The best material for stakes is probably aluminum. Although bamboo is far cheaper it has some distinct disadvantages. Firstly, its physical strength is insufficient to withstand heavy storms, especially if hoarfrost becomes attached to it, as is normal in humid (maritime) areas. Secondly, the surface becomes bleached and the stake is difficult to find in foggy or overcast weather. Hence, the advantage of a metal stake is obvious. In some extremely humid areas, however (near the western coast of Norway), even aluminum poles are too weak and must be replaced by steel stakes, or special "towers", see below.

For Canadian glaciological work the Alcan "65 ST 6" aluminum alloy tubing was selected with 1¼" outer diameter and wall thickness of 0.083" (= about 2 mm). However, to obtain a stronger stake, particularly when snow creep or strong winds tend to bend them, a thicker wall (e.g., 0.12" or 3 mm) is strongly recommended. The optimal length of the stakes is 4 to 6 metres, but all stakes should be cut so that their length is exactly 4 or 6 m. Usually the tubing is available commercially in standard lengths of 14, 16, or 18 feet etc., but intermediate lengths can be supplied on request.

On Norwegian glaciers two different aluminum alloys are used: 51 SWP/AA6082-T6/6061 T-6 (a fairly strong non-corrosion alloy) and AA7075-T6 (in Sweden termed SM-6958) which has extremely high mechanical strength. The alloy 7075, condition T6, enables the material to reach very high levels of both tensile and yield strength. For both of these the typical values are about 60 kg/mm^2. Elongation of this alloy is typically 9%. The alloy is used, for example, in aircraft construction where extreme mechanical strength is required.

The first mentioned alloy is for general use and the second for use on glaciers where mechanical strength is vital because of riming, high winds or extensive snow creep. The standard outer diameter is 32 mm with a wall thickness of 2 mm. This is very close to the dimensions used in Canada although the type of pole used has, unfortunately, varied somewhat depending upon availability. As a standard length, 6 m has been chosen for normal stakes, and 2 m for extensions. Note: the forces applied to a stake by snow creep may be enormous, and even the strongest material cannot withstand these forces. Therefore, if possible, avoid slopes where snow creep may be expected.

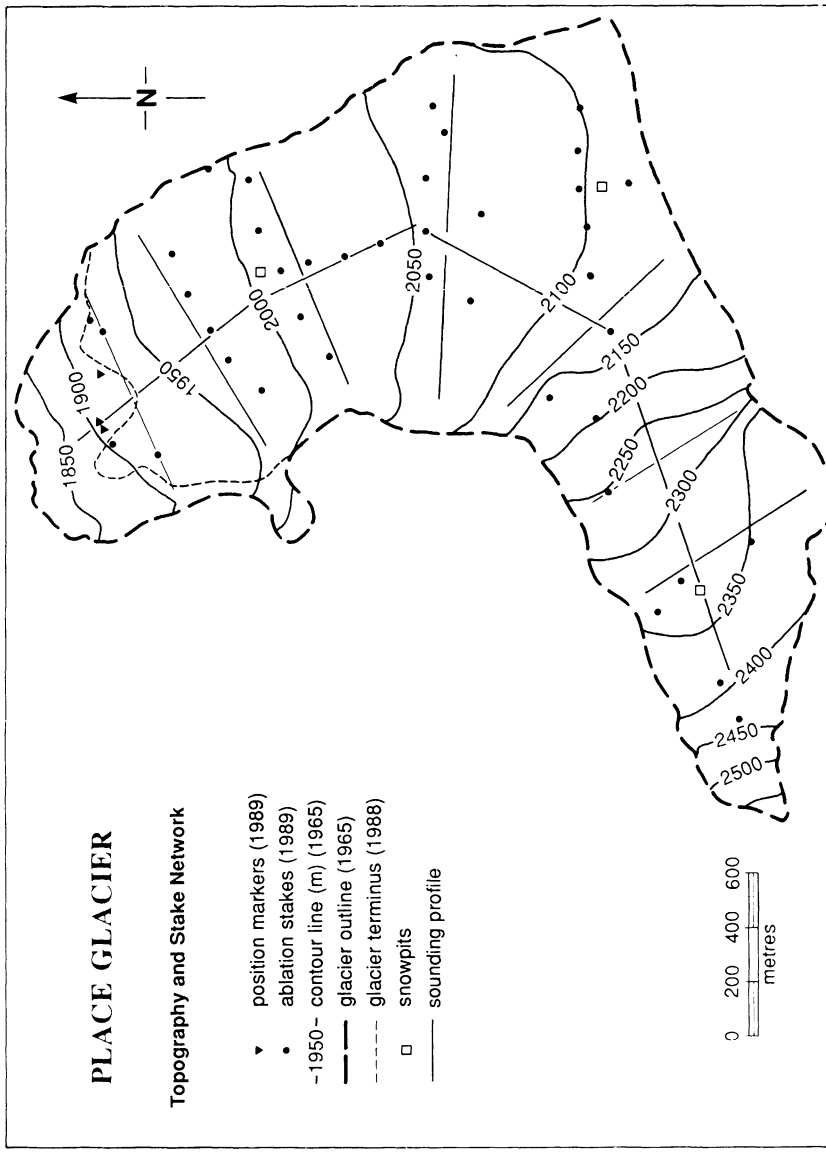


Figure 4.1: Place Glacier Stake Net
The stake net established on Place Glacier 1989 could be taken as an example of a suitable pattern for a valley glacier. However, the number of stakes in the upper part and on the margins of this glacier is still too scarce and should ideally be densified.

Before any stake is inserted in the glacier, it should be marked all around the circumference with pencil and paint every two metres, to facilitate reading after the stake has been inserted.

4.2. Stake Location

Install one longitudinal profile, approximately along the centre line of the glacier (for numbering of these stakes, see below), and several transverse profiles located at suitable intervals across the glacier from the snout to the firn area. The transverse profiles should be at right angles to the longitudinal profile (Fig. 4.1). Crevassed areas and other "difficult" parts of the glacier must also be considered, although a less dense network might result in such areas, for safety reasons. However, as greater melt takes place in crevassed areas, try to insert one or two stakes there to observe the increased ablation.

This general distribution system, used at many valley glaciers, may be modified for glaciers with more complicated topography, and for ice caps. The basic idea is, of course, that each stake should be representative of that part of the glacier where it stands. This means, for example, that windblown areas and locations where heavier snowpacks occur should be taken into account when the stake locations are picked.

4.3. Numbering System

If stakes disappear, or bad weather conditions make navigation difficult on the glacier, a good numbering system makes it easier for the crew to know where they are. To easily identify each stake, it is necessary to have a logical system of numbering. There are several systems, but the following has worked well on valley glaciers.

The "main" stakes, that indicate the centre of transverse profiles in the longitudinal profile, are numbered 10, 20, 30, 40, etc. Stakes in the first transverse profile have odd numbers, 11, 13, 15, etc., on the left-hand side of the glacier, and even numbers, 12, 14, 16, etc., on the right-hand side (stake 10 is in the centre). Similarly, the next transverse profile at stake 20 will carry the numbers 21, 23, 25 on the left-hand side of the glacier; 22, 24, 26, etc. on the right-hand side. If it is necessary to insert more stakes in the longitudinal profile (between transverse profiles) they could be numbered with figures not already used in these profiles, e.g. 18, 19, 28, 29, etc. For most valley glaciers there will be less than 10 stakes in a transverse profile and sufficient numbers will be available for intermediate stakes in the longitudinal profile. An example is shown in Fig. 4.1.

4.4. Replacement of Missing Stakes

If it is necessary to replace a stake which has disappeared, a new stake should be inserted as close as possible to the "original" stake's position. The new stake should carry a number similar to the original but with a prefix which clearly separates it from the other to avoid confusion if the original stake is found later in the season. Example: If stake 24 has disappeared, a new stake numbered 124 should be inserted in the assumed position of stake 24. (If the total number of stakes on the glacier is greater than 100 the prefix should be 2. In this case the new stake would

carry the number 224). If this stake also disappears, the replacement should be given the number 324, etc. If the original stake is found later, the replacements should be removed from the glacier, possibly after a period of "parallel" reading during a week or two in the summer.

NOTE: Presently, in Norway and Canada a slightly different numbering system is in use. Replacement stakes are given a suffix, indicating the inserting year. If stake 24 has disappeared, the replacement is given No.24-91, if it is inserted in 1991. This is now the preferred method as it helps avoid confusion when a pole is buried or reset.

4.5. Duplication of Stakes

To mark the position of a very short stake, so that it can easily be found for triangulation, etc., a duplicate stake should be placed adjacent to the original, but its number should carry a letter prefix. Example: If stake 83 is hard to recognize (e.g., in a concave area on the glacier, or with only a small part above the snow surface) a duplicate would be given the number A83, and inserted close to the original stake. This duplicate stake could then be flagged to make the position of stake 83 clearly visible at a distance. For very accurate determination of its position, the horizontal distance between the two stakes should be measured. In most cases, however, this will not be necessary, unless the stake is used for movement studies.

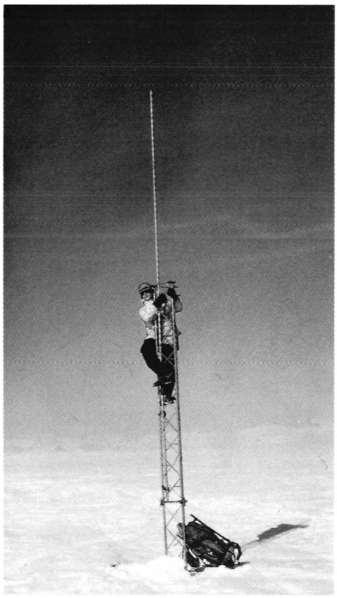
If, for any reason it is necessary to insert another stake (if stake A83 has disappeared or been bent down), this second duplicate stake would be numbered B83. A letter in front of a stake number therefore always indicates a duplicate stake at that particular point. The horizontal distance between a duplicate stake and the original stake should be kept to a minimum (i.e., in most cases less than 1 m). Note the distance between a duplicate stake and the replacement stake mentioned above! The latter will probably be at a greater distance from the original stake, because one may not really know the exact location of the original stake.

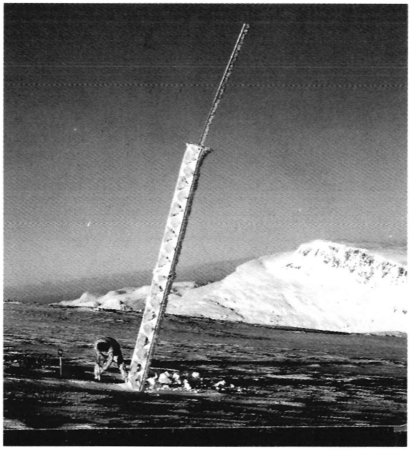
4.6. Stake Extension (Fig. 4.2)

For accumulation measurements made in the spring (see Chapter 5) it is necessary to know the exact location of all sounding profiles. Therefore, it is important to keep at least the main stakes visible during the winter as a system of reference. In the fall it is almost impossible to erect a stake long enough to survive a full winter's snow accumulation, although this has been done on South Cascade Glacier, Washington (Tangborn, 1963). On some Norwegian glaciers the normal stake might be replaced by a "tower", which can survive very heavy snow accumulation (Fig. 4.3).

The simplest way to keep stakes visible is to extend them by inserting a short steel pipe inside the stake and adding a 2-m long extension tube to the top of the original stake (Fig. 4.2). To number the extension, use the same number as the original stake but with a suffix to show that it is an extension. Example: Stake 70 is extended in November by adding a 2 m aluminum tube. This extension piece is numbered 70/1. In February only the upper part of this extension is above the snow surface (with the number 70/1 visible), so if a second 2 m extension piece is put on

Figure 4.2: Stake Extensions
On some glaciers, particularly in maritime regions, stakes may be buried during the winter. Therefore an extension will be required which is normally done by adding a 2-m stake to the top of the original stake. A short (30 cm) steel pipe is used, its diameter just fitting inside the aluminum tubing, held in place by friction tape. This steel pipe will hold the extension (2 m) stake in a vertical position. For numbering, see text.





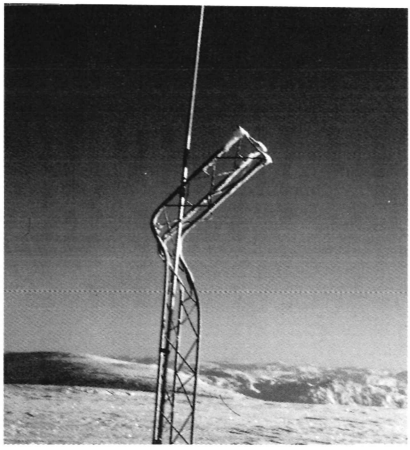


Figure 4.3: Aluminum Towers and Stake
On certain Norwegian glaciers, where large winter snow accumulation is expected, the normal 6-m aluminum stakes are too short - they will quickly be buried. Therefore, aluminum "towers" (in 3-m lengths) are used, and often a normal stake is attached to the tower.
Note the problems of snow creep and settling!

top of the first, its number will be 70/2. From the start of the melt season these extensions are successively removed until the original stake is again visible.

On glacier tongues where normal stakes cannot survive due to extreme melt, it is advisable to insert steel cables, which is easily done by a steam drill or another hot-point drill, as shown on Fig. 4.4.

The cable will freeze solid in the ice, but may be difficult to find, Therefore its upper end is tied to a tetrahedron (wood or metal) which is easier to find. The cable will appear to be longer as melt takes place. NOTE: Readings are unreliable if the cable is not frozen into the ice.

4.7. Techniques for Inserting Stakes: Various Drills

The stakes should be placed vertically in the glacier. The technique used for this depends on the kind of surface where the stake is located. In general, there are two different ways of inserting stakes.

1) In the firn area a stake could simply be pushed into the snow or firn, but recent investigations have shown that such stakes tend to sink into the glacier during the melt season. Therefore, the stakes must be supported at their lower ends to prevent such sinking. Details of the procedure are given below.

2) In the ablation area the stake should be placed in a narrow hole drilled with an ice drill (hand- or motor-operated mechanical drill) or a hot point.

The hole must have a diameter of 1½" and be deep enough that only a small part of the stake remains above the ice surface. Ten to twenty centimetres are sufficient if the hole is drilled at the start of the ablation season, but if it is drilled near the end of the season, 200-250 cm of the stake must be visible above the glacier surface. NOTE: when less than 100-150 cm of the stake remains in solid ice, the stake is no longer reliable. Experience has shown that stakes remain in a fixed position relative to the surface only as long as the stake is anchored firmly into the hole. When the stake is no longer frozen in, the stake must be "redrilled".

Instead of aluminum stakes, one can use wooden stakes (either simple 1" x 1" lumber, bamboo stakes or wooden dowels). However, these do not give reliable results if they float in the meltwater in the hole. Even if they are pushed back into position, stake readings will not be accurate as the meltwater will tend to melt its way down into the glacier ice during the summer season. Consequently, the stake readings will indicate less than the true glacier ablation. The same conditions apply when a metal stake becomes loose. This normally happens if less than 1-1.5 m remains in solid ice. Generally, readings are reliable only when the stakes are frozen solidly in the ice.

Redrilling in the same hole may be impossible, due to wet conditions in the ice. Any stake should be relocated as close as possible to the original position. As a rule-of-thumb, the stakes in the past have been redrilled 1 m upstream from their previous location, but if this area was difficult to drill, a new spot was selected and

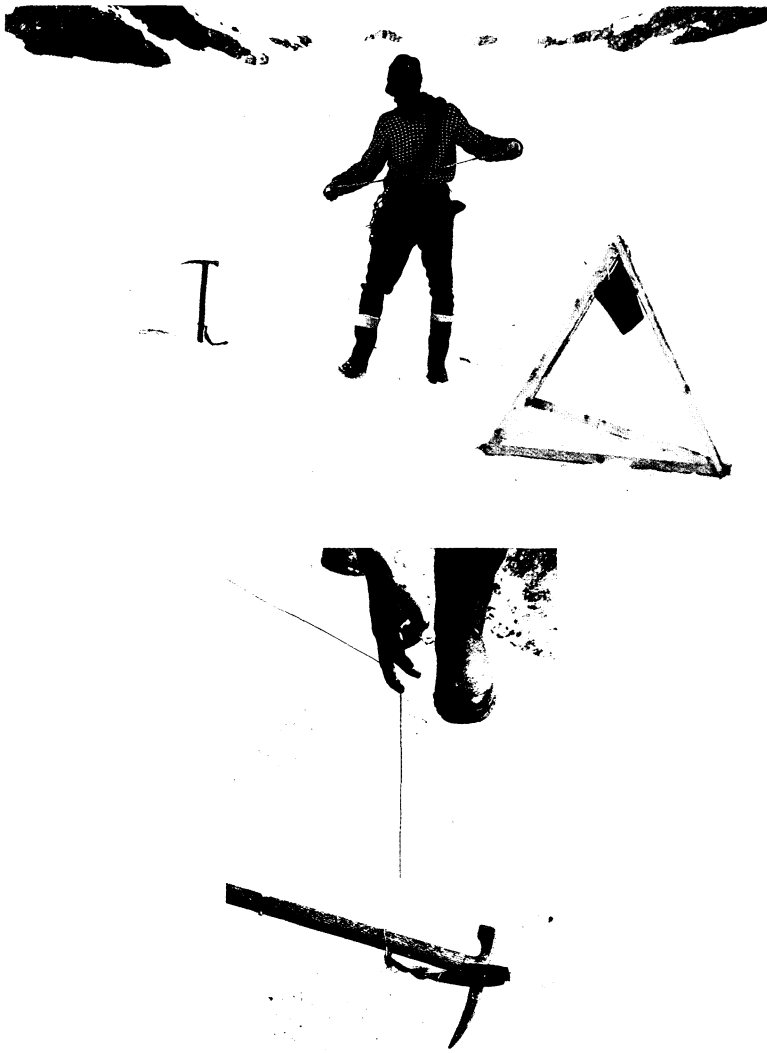


Figure 4.4: Steel Cables in Ice
On glacier tongues where normal stakes cannot survive due to extreme melt, it is advisable to insert steel cables, which is easily done by a steam drill or another hot-point drill.

The cable will freeze solid in the ice, but may be difficult to find, Therefore its upper end is tied to a tetrahedron (wood or metal) which is easier to find. The cable will appear to be longer as melt takes place.

NOTE: Readings are unreliable if the cable is not frozen into the ice.

its position noted. Accurate surveys of glacier stake location and stake resets are highly desirable, if not essential. The techniques involved are described in Chapter 11. For studies of glacier movement this measurement is extremely important. If very accurate measurements are required, special precautions must be taken to ensure accurate calculation of the new position.

Various hand-operated drills are in use. The simplest consists of a seamless steel tube with 4-6 sharp teeth cut into the lower end. The drilling equipment is shown in Fig. 4.5. This equipment was developed in Scandinavia over the last 45 years, but has now almost completely been replaced by the "Fisherman's Drill" which has many advantages (Fig. 4.6).

To use a hand-operated ice drill is something of an art and requires a distinct knack that cannot be explained in detail without simultaneous practical training. When the drill is rotated, ice crumbs will accumulate above the cutting edge and hinder further drilling. Normally 20 cm can be drilled before the drill has to be cleared. Aluminum extensions with brass couplings can be attached to the drill so that holes 4-5 metres deep can be made easily within a couple of hours, depending upon ice conditions, air temperature and the skill of the drillers.

Other kinds of drills have been developed during recent years. Some have a horizontal cutting knife and a long spiral along which ice fragments are raised. When glacier ice is very wet this type of drill can have some advantages, although raising ice crumbs to the surface may still be difficult (Fig. 4.7).

It is always advisable to drill holes when the ice is cold and there is no surface meltwater to percolate into the hole. However, if the air temperature is above 0°C, or there is strong sunshine, the drill warms up and may freeze in the hole if the ice is very cold. Under such conditions it might be necessary to drill during the night. To loosen a frozen drill, alcohol or antifreeze should be poured into the hole immediately. Denatured alcohol ought, therefore, always be carried by the ice drillers.

To insert a stake in the firn area, a hole should be drilled down to the previous summer's surface. Metal stakes tend to sink in the firn so it is important to support the lower end if a stake is to be used to measure any variation in the snow or firn surface (Fig. 4.8). In general, the stake should be placed directly on the previous summer crust; this is a relatively hard surface and offers generally better support than any snow or ice layer. However, when melt water percolates through the crust, its mechanical strength decreases and the stake starts to sink. To prevent this, one of the following methods is recommended:

1) Place the stake on a small "platform" made of any cheap material plugged into its lower end. The simplest method is to insert a cork or a wooden plug before the stake is put in position. This cork will form a supporting area that has a cross section approximately corresponding to the stake diameter and it is likely that the stake will be held in correct position for most of the summer. However, experience has shown that even this support may not be sufficient.

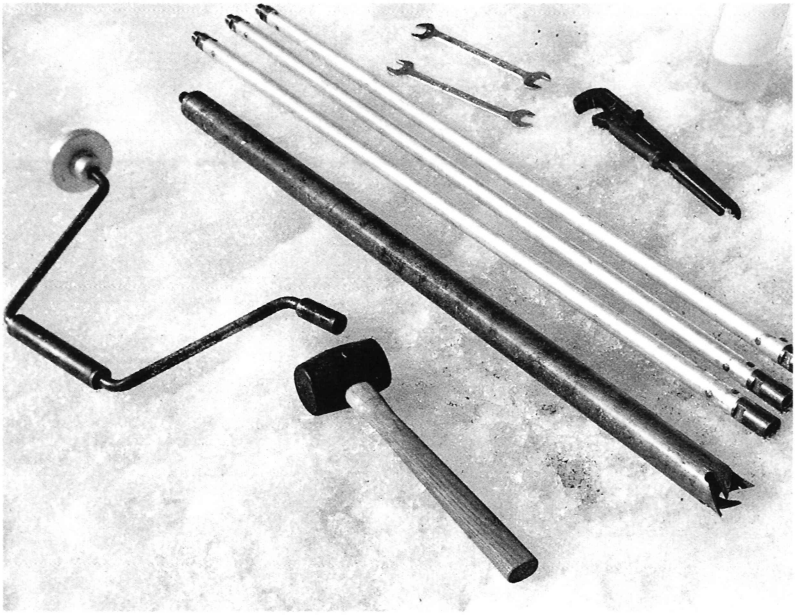


Figure 4.5: Hand Drilling Tools
This picture shows a complete set of tools for hand-drilling in glacier ice. Four-metre-deep holes can be obtained with this auger which consists of a seamless 1½" steel tube; extensions are made of aluminum with 5/8" threads in the brass or bronze end pieces. A bottle contains alcohol to use if the drill freezes in a hole. The rubber mallet is used when clearing the drill, and the open end wrenches are for disconnecting extensions. The weight of the complete set is approximately 10 kilograms.

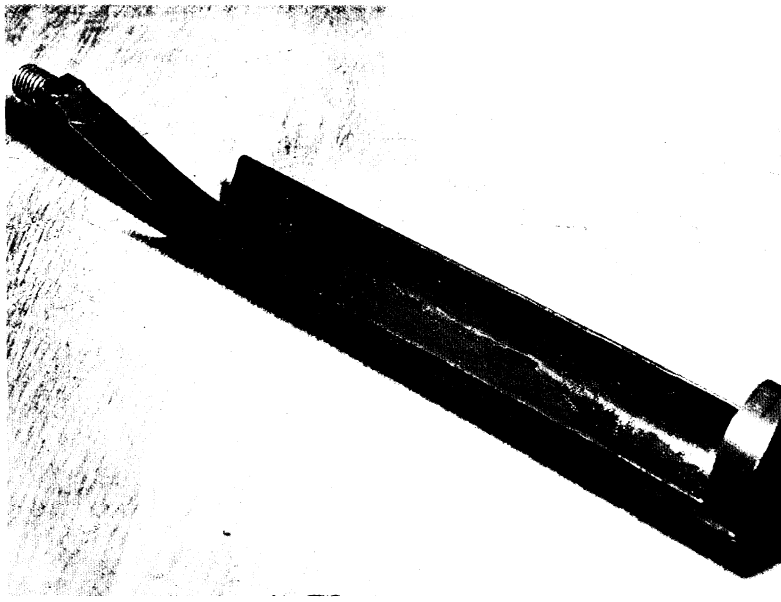


Figure 4.6: "Fishermans Drill"
Upper picture shows a complete ice drill, consisting of brace, extensions and the "Fisherman's Drill" which is shown in detail in the lower photo. A new model of this has also a lid, so that ice crumbs are better collected and raised. The drill barrel has to be raised and emptied at short intervals.

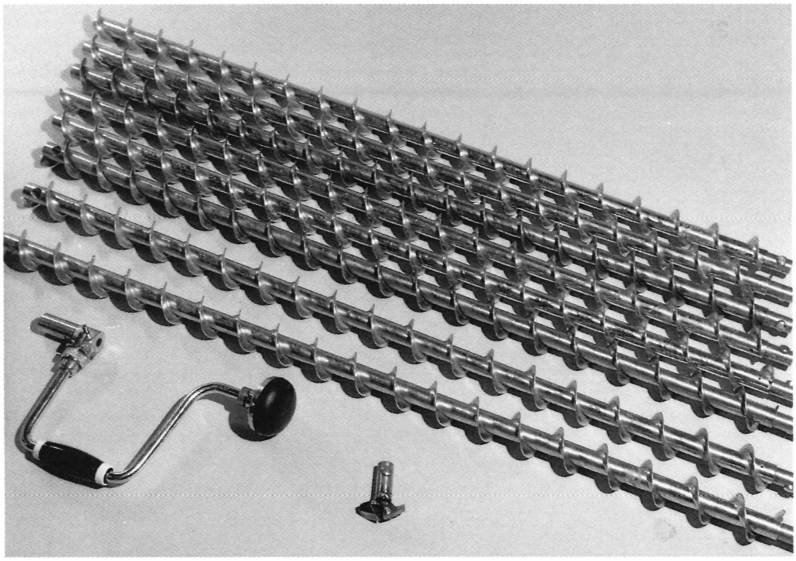


Figure 4.7: Kovacs Drill
The Kovacs drill shown in this photograph is used to drill in stakes on the glacier. The drill is operated by hand and the drill bits are easily replaced in the field. It can be made to move through bare ice in the ablation area quite rapidly, although it is slow drilling in snow. Especially in snow, the bit can become jammed easily if the hole is not continuously cleared by pulling up the entire drill stem. Regardless of the type of ice or snow one is drilling into, this type of drill must be lifted out approximately every 10 cm or less to ensure that the drill stem does not become locked in place by the ice chips spiralling their way up the drill stem to the top of the hole. If care is taken with the equipment and in developing the ability to drill a proper hole then it is possible to drill more than five meters per hour, but often the drill rate is much slower.

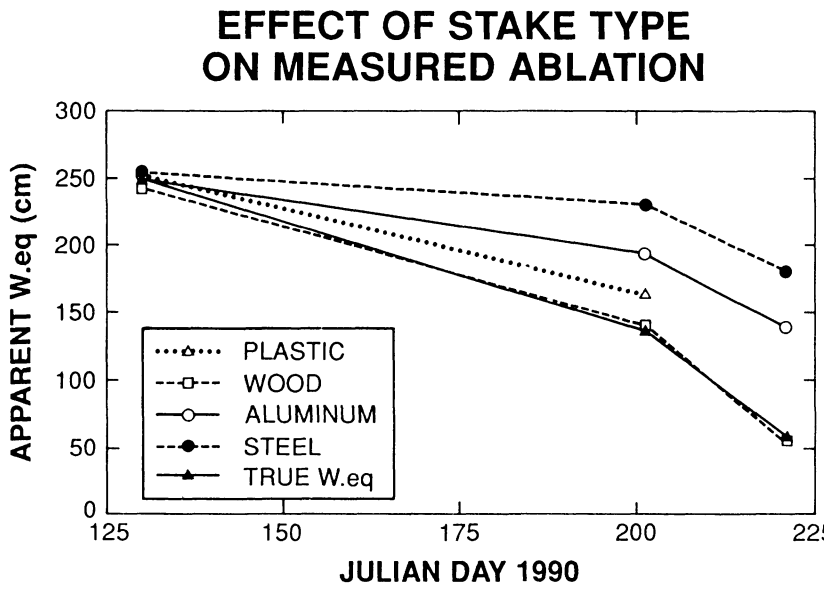


Figure 4.8: Stake Melt Diagram
The melt rate of stake of steel, aluminum, white plastic (PVC), and wood of similar diameters are compared to direct measurements of snow water equivalent obtained using probing, pit and density measurements from spring to summer 1990. Clearly, if poles must be left unsupported then wood poles are the most reliable; still all types must be checked for melt rate errors caused by "self-drilling" due to solar heating or floating due to pole buoyancy effects.

The wood pole is the most useful if the base of the pole can not be properly plugged or supported, provided flotation does not introduce errors or the pole breaks under the snow-creep pressures. "True" water equivalent was measured using probing, snowpits and snow density profiling.

2) Place the stake on a plate that is larger than the stake diameter. This can be done by drilling a large-diameter hole (use a SIPRE-type coring auger or a "Fisherman's Drill") and fixing a circular plate to the stake before it is inserted. This method is satisfactory provided the plate is strong enough. In practice, the simplest method is to use a strong, plastic bottle attached to the stake; the bottom of the bottle forming the supporting "platform" (Fig. 4.9). NOTE: even this support may be insufficient — the stake can cut its way through the plastic! (An empty can might be better.)

3) Dig a pit and place a plate made of plywood or a piece of wood on the summer surface and place the stake on it before the pit is filled up again with snow. This is very satisfactory but requires much labour. The snow stratification close to the stake will be disturbed, but experience has shown that ablation figures will be reliable. Only under extraordinary conditions has a stake penetrated a piece of plywood. However, this could happen if the stake is frozen to a snow layer or an ice lens. When the snowpack settles, it will force the stake downwards.

In remote areas where glaciers are visited at long intervals or on glaciers where melt is greater than 4 metres of ice, it is advisable to use a hot-point drill to insert a chain of stakes so that no redrilling will be required until the ice has melted (Fig. 4.4) some 10-15 metres vertically. No technical description or explanation of the hot-point drill is given here as this is beyond the scope of this manual. However, hot-point equipment used in Norway is shown in Fig. 4.10. A vertical steam-jet melts its way very efficiently down at least 10-15 metres. Drilling speed is about 10 m/h in glacier ice, more than double in snow and firn. Fig. 4.11 shows a commercially available steam generator, used by Swedish glaciologists.

Assistants, working on glaciers where stake chains or cables have previously been inserted, should be aware of the special technique for observing glacier melt at these stake chains or cables frozen vertically into the ice (see Chapter 6).

Complete equipment for hand drilling comprises:

a) A seamless steel tube, 1 metre long with 4-6 teeth cut in the lower end and a 5/8" thread in the upper end, or the "Fisherman's Drill" (Figs. 4.5 and 4.6).

b) Aluminum extensions, 1 metre long with brass couplings fitting the above-mentioned thread. The standard thread is 5/8" Whitworth. This is used on all drills, extensions, and handles (see next).

c) Handle with an operating radius of approximately 20 cm (this is more than a standard carpenter's brace).

d) Rubber mallet to clear ice fragments from within the drill; normally not necessary when using the "Fisherman's Drill".

e) Two open-end wrenches or pipe wrenches to dismantle the drill and the extensions.

f) A bottle containing denatured alcohol to free the drill if it freezes into the ice.

Figure 4.9: Stake Bottom Support
A stake inserted in the firn area <u>must</u> be supported at its lower end. A simple method is to use a cork that may prevent the stake for sinking for at least part of the summer.

A far better support is a circular plate or - simpler - a plastic bottle fixed to the stake. In this case a wider hole should be drilled down to the summer surface. However, experience has shown that snow creep can force the stake through the plastic. Thus a can may be better. The best is to place the stake on a piece of wood, but this requires much labour (pit digging).

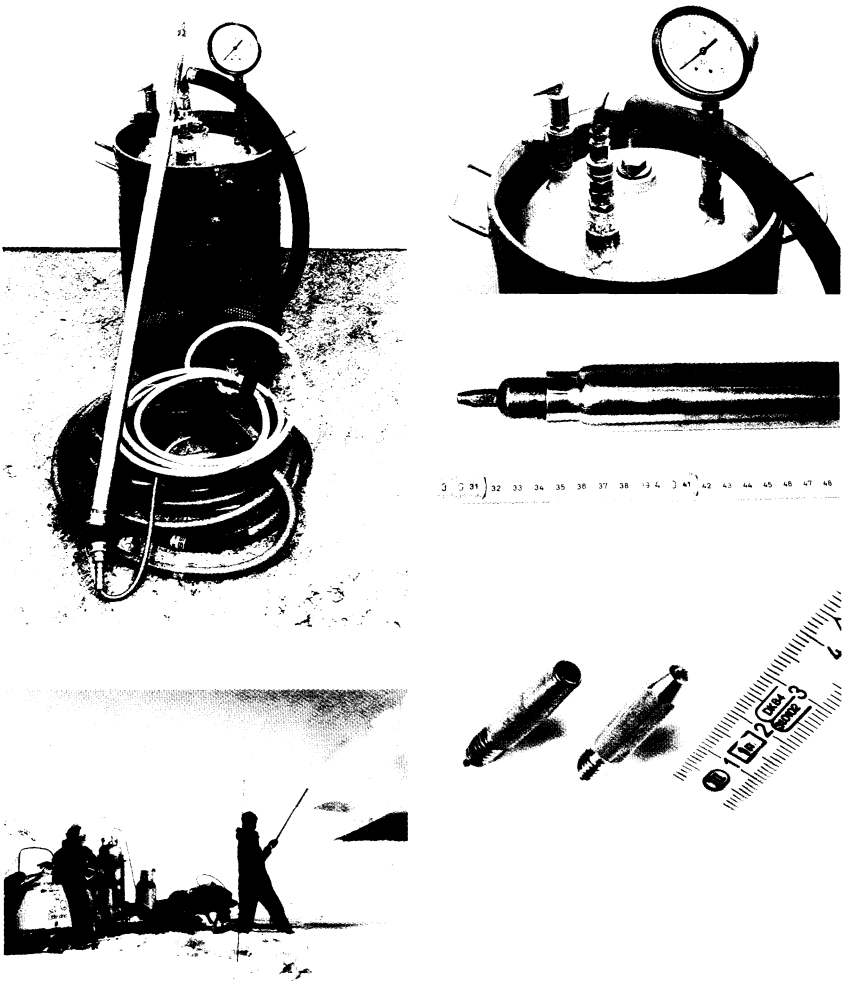


Figure 4.10: Steam Drill
A "hot-point drill" using steam produced in a pressure boiler, heated by propane. An insulated rubber hose, 10-15 m long, delivers steam to the steering pipe which has a 1-1½ mm exchangeable nozzle.

The light-coloured hose is the propane gas feed to the burner.

At a steam pressure of about 6 atmospheres, this drill penetrates 5-8 metres of ice per hour, or twice the amount of snow.

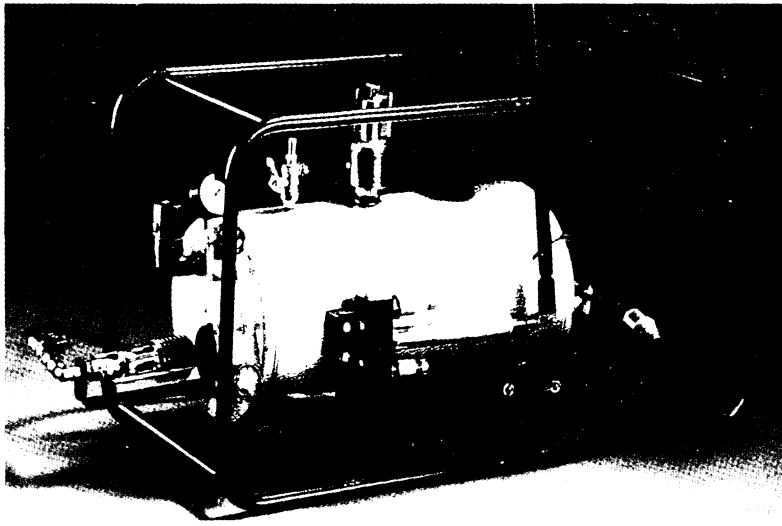


Figure 4.11: Commercial Steam Generator
A commercially-available steam generator is used for hot-point drilling on glaciers in Sweden. The steel boiler is heated by propane, either liquid or gas. It produces about 20 kg steam per hour. Overall size: 51 x 37 x 89 cm, weight 48 kg. Price (1991) about US$3,000 (without hoses or nozzles, etc. for glacier use) from N.E. Olsson A/B, Louisebergsvägen 3, S-14132 Huddinge, Sweden (FAX + 46 + 8-7406090). This steam generator can also be obtained for electric heating from 6 kW up to 3000 kW.

Recently several ice drills have been developed, of various complexities and weights. One example is the "Kovac's Drill" which is shown in Fig. 4.7. This type of drill is efficient to use in the field and is quite portable. If expertise is gained in its use, it may be possible to drill about 5 meters or more per hour in ice, but in snow the drilling rate is significantly slower. The drill bits must be properly sharpened, of course, in order for the drill to move through ice at this speed. In Canada, this type of drill is the preferable method when it is not possible to use the portable hot-water drill recently developed.

4.8. Relocating Buried Stakes

Winter snow conditions vary greatly on most glaciers, and it may be impossible to extend stakes far enough that they do not disappear. Although it is vital to keep at least a minimum of stakes visible throughout the winter, methods have been developed to find buried stakes. These methods can be divided into three groups:

a) Radio transmitters
b) Strong magnets
c) Passive radar reflectors

In all cases, one of the above devices is fixed to the upper end of the stake which is regarded as vital for mass-balance studies. Using a specially constructed radio receiver, a magnetometer, or a radar transmitter/receiver, the location of the stake can be found within 1-2 metres.

For the final location, the following method has been used. A metal netting about 2 x 2 m was placed around the stake in the fall (i.e., on the summer surface). With a steam drill, it is easy to locate this netting by making a few "soundings", and then locate the stake accurately. Afterwards it can easily be reached by digging.

Examples of the equipment are shown in Figs. 4.12 and 4.13. together with some technical details.

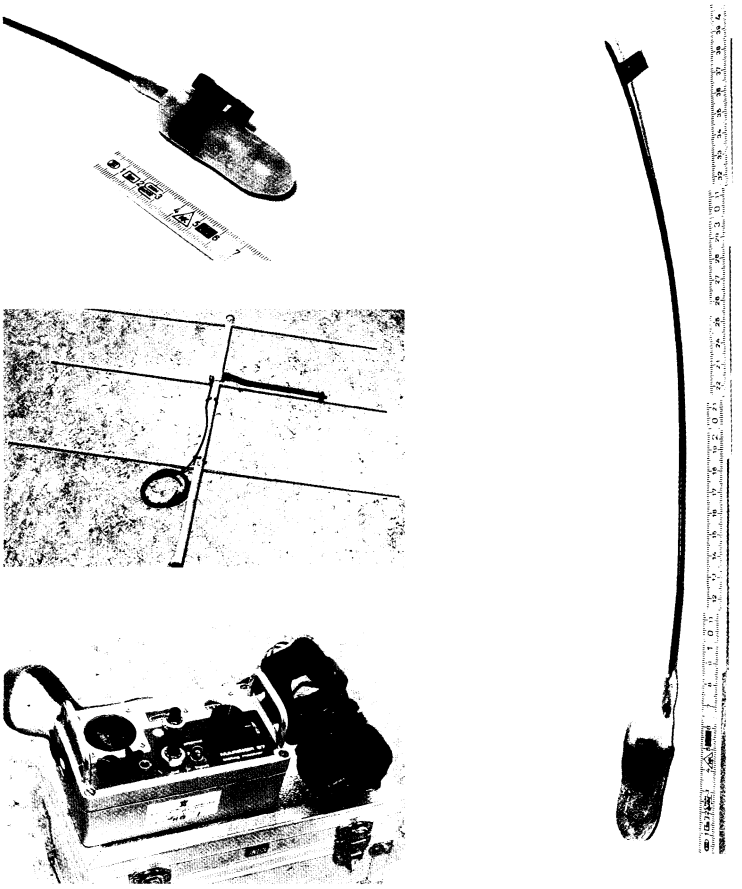


Figure 4.12: Radio Transmitters
Small VHF radio transmitters are attached to stakes so that they can be located even when buried under several metres of snow. The transmitters have a lifetime of 1-2 years and a range of a few kilometres. Length of antenna is about 35 cm. The cost (1991) is around £60, delivered from Biotrack Ltd., Wareham, U.K. (FAX + 44 + 929-554948). Transmitting frequency is about 140 MHz - each transmitter has a slightly different frequency to allow for identification.

To locate buried stakes equipped with these transmitters, a special radio receiver is used. By tuning the receiver to the frequency of a given transmitter, the latter can be located using a directional "Yagi"-type antenna, to the nearest 2-3 metres. The final search may be done by a steam drill, provided netting has been placed around the stake, preferably at the previous summer's surface. The price (1991) for the radio receiver is approximately £400. The receiver is 12 x 22 x 8 cm (+ earphones), the antenna 105 cm long, length of the three traverses about 1 m.

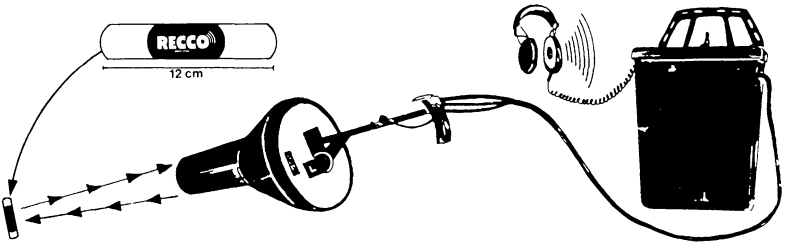


Figure 4.13: Microwave Reflector System for Locating Buried Objects
A special rescue system to find avalanche victims was developed in Sweden as a research project by the Royal College of Technology in Stockholm. The system consists of two units: the detector which is a directional radio transmitter/receiver, and a small reflector tag which every skier should carry. These reflectors will return the radio signal to the detector, but at double frequency. Thus, only these reflections will be known to the rescue crew, and digging can start at the right spot. The range in air is 60 m, much less in snow, but efficient for finding buried stakes on a glacier. Available from Recco A/B, P.O. Box 27122, S-10252 Stockholm, Sweden (FAX: + 46 + 8-7830018). Price about US$12K (1991).

CHAPTER 5. ACCUMULATION MEASUREMENTS

5.1. General

The total thickness of snow that accumulates over the entire glacier surface must be measured at the end of the winter season. For most glaciers in southern Canada and southern Norway this will be in April or May. Snow will then start to disappear (by evaporation) from the glacier surface due to strong radiation, although ambient air temperatures remain below zero. Additional accumulation may occur during May and June and increase the winter balance as measured in April/May.

Due to practical difficulties associated with visiting all glaciers at the right time it will be necessary, at least for some glaciers, to perform a snow survey prior to the actual end of the accumulation season. For such glaciers additional accumulation after the snow survey must be recognized and recorded (see Section 5.6).

To study the rate of accumulation during the winter, it is necessary to make several visits to each glacier and measure the accumulation every time. The methods are similar to those used at the end of the accumulation season which are described in this chapter.

The accumulation, or more correctly the winter balance, is expressed in water equivalent. It is, therefore, necessary to measure snow depth and apply a snow density factor to calculate the water equivalent at each measuring point. However, as snow density seems to be relatively uniform over large areas, whereas snow depth normally shows large variations even in short distances, it is necessary to make many snow depth soundings and relate them to a comparatively small number of density observations. Snow depths are measured directly with a "sounding stick" or probe which is pushed vertically through the snowpack to the previous summer's crust, the "summer surface" (or the ice surface), or one of the markers mentioned earlier (Fig. 5.1). Snow density is measured by weighing a known volume of snow obtained from the snowpack between the existing snow surface and the summer surface (or the glacier ice surface).

Results of water equivalent determinations at numerous places are used to calculate the total winter balance, expressed in millions of m^3 of water equivalent. For various reasons this quantity is normally divided by the total glacier area, thus obtaining an average figure, expressed in m. This is the thickness of a water layer, evenly distributed over the glacier surface, that represents the glacier's total "income" from the last winter season. It may be termed "specific winter balance", and is normally reported for each glacier under study.

5.2. Snow Depth Soundings

Snow depth can be highly variable even within short distances on a glacier, because deposition is greatly affected by topography and wind action. Prevailing winds will probably produce a snow deposition pattern which is similar from year-to-year for any particular glacier. However, great variations may occur even in two consecutive years. Before a "typical" snow accumulation pattern can be established for a given glacier it will be necessary to measure the snow depth at many points for several years. A density of 10-50 points per km^2 will probably be best for a valley glacier whereas a less dense network might be sufficient for a large ice cap where

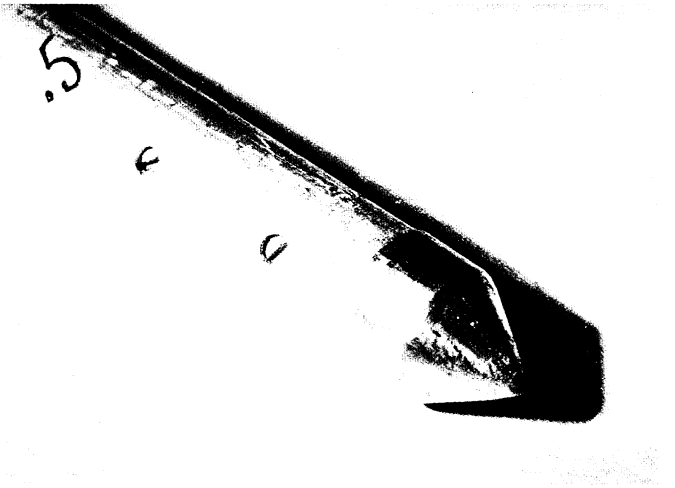


Figure 5.1: Probing Snow Depth
American Military steel tank antennas have proven very useful for probing thick snow packs on Norwegian glaciers. However, they are difficult to obtain. The lower picture shows the steel point of an aluminum probe.

snow may accumulate more evenly. Ideally, the measuring points should be uniformly distributed over the entire glacier surface. However, as this is not practical, soundings along profiles are recommended.

Sounding profiles (i.e., straight lines along which soundings are performed at equal intervals - normally every 50 metres) should be in a pattern which will cover the entire glacier. If snow conditions are relatively well known, a skeleton network could be placed in areas of even snow distribution and a denser network in areas where large local variations are expected. An even distribution generally occurs on the tongue or on the intermediate part of the glacier, whereas wide variations are common in the upper firn areas, that also tend to have greater thicknesses of snow.

It is easiest is to lay out sounding profiles between the "main" stakes down the length of the glacier and extend other lines at right angles to this centre profile.

It is best to plot all field measurements when they are obtained. Although this preliminary plotting will express snow depth only and not water equivalent, it will show any irregularity in distribution and determine the need for additional sounding profiles.

It is advantageous to first sound the snow depth on the glacier tongue, for two reasons:

1. The previous summer surface is represented by glacier ice and there will be no doubt about the location of the lower boundary of the winter's snow.

2. The snow cover will be thinner than on the upper parts of the glacier and untrained personnel will rapidly gain experience in using a snow sounding rod.

As snow sounding profiles are extended into the accumulation area at higher altitudes, it may be difficult to locate the lower boundary of the winter snowpack. During a warm summer a rigid "summer crust" will develop and its location can be detected with a probe. However, during a cold summer, no real "summer surface" develops, and summer snow falls may give a number of poorly developed crusts. It may be difficult to decide which of them should be defined as the previous summer's surface. If such conditions are observed during one particular summer, special measures should be taken by the crew to mark a surface which could be defined as that summer's crust (see Section 5.12.).

Because the greatest variations in snow depth can generally be expected in the upper part of the glacier, it is important to spend more time here and have more sounding profiles than on the tongue. On most glaciers travel is more difficult there and each sounding takes more time (2-3 times longer than on an equal area on the glacier tongue).

Snow depth soundings must be converted into water equivalent using density determinations obtained from snow pit studies.

5.3. Pit Studies (Fig. 5.2)

The density of the winter's snow pack will generally show little variation in areas of approximately equal altitude. The number of pits necessary to obtain accurate accumulation measurements will depend on the range of altitude for each glacier. It is advisable to dig at least 3 pits, one on the tongue, another in the middle part, and one high up in the firn area (Fig. 5.2). Intervening pits could be dug, particularly if snow density shows large variations with height.

Before digging a snow pit, first make a number of soundings to determine the required depth and to ensure that no crevasses are present. The initial hole must be large enough that the final pit will be at least 1 x 1 m at the bottom. Digging should continue approx. 50 cm down into the old snow (firn) below the previous summer's crust. Normally the pit will have a square or a rectangular cross section. Before starting one must decide which of the four sides should remain untouched or it may be impossible to determine the original upper surface of the snow pack. To avoid changes in snow conditions due to direct sunlight, the southern pit wall should be selected for sampling. Snow temperatures and wetness should be measured immediately and snow densities as soon as possible following digging. (See below).

If a pit is dug near an existing stake, it should be dug at a standard distance downstream from it; 5 or 10 m is recommended. The same distance should then be maintained for all pits dug on the same glacier. If there is no stake at the pit site, one should be placed there, so the exact location can be easily recognized at each visit, if repeated pit studies are necessary and surveyed.

Snow samples are taken vertically in the pit wall from the untouched snow surface downwards to approx. 50 cm below the previous summer surface. The samples must be taken continuously, but the length of each sample is arbitrary, normally being determined by the physical condition of the snow, presence of ice layers, etc.

To obtain the sample: insert a steel plate horizontally into the undisturbed pit wall about 20 to 40 cm below the surface, then push a stainless-steel snow-sampling tube vertically downwards onto the steel plate and measure the distance between the surface and plate to the nearest 0.5 cm (Fig. 5.3). This is the length of the sample. Although snow may settle inside the tube, it will not affect the density measurement.

Remove some of the snow from the pit wall to release the sample tube and transfer the contents of the tube into a suitable bag. Weigh the bag and contents with a 1,000 gram spring balance to the nearest 5 grams (Fig. 5.3). Subtract the weight of the empty bag to obtain the net weight of the snow sample.

The length and weight of the sample must be noted carefully (for completion of appropriate forms, see Chapter 13). From these data the snow density and water equivalent can be easily calculated and a diagram of their variation with depth constructed (Fig. 5.4).

If sampling is done in warm weather, or during a day with strong radiation, the sampling tube may become warm and the snow stick to it. It will then be difficult to transfer the snow sample from the steel tube to the bag in which it is weighed. It might be necessary to push out the snow with a piston or work during the nights when temperatures are low. A thin layer of wax on the inside of the snow sampler may help and the tube should be kept in the cool shade.

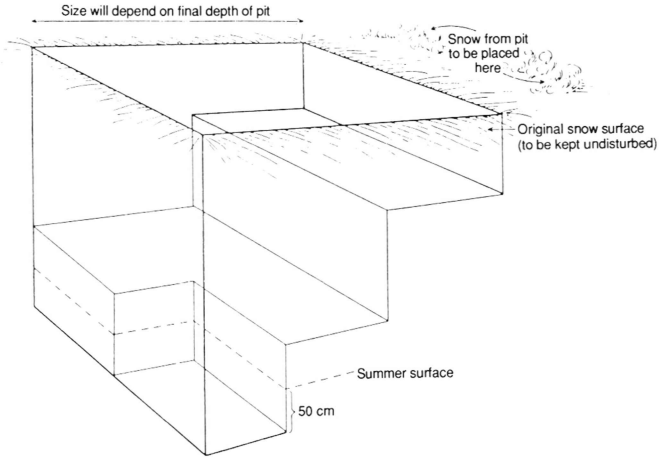


Figure 5.2: Snow Pit
Upper picture shows the start of a snow pit on Sentinel Glacier, B.C. Time and labour can be saved if the pits are planned properly. At least one wall should be vertical (preferably on the southern side of the pit), extending from the undisturbed original snow surface down to 50 cm below the previous summer's crust. Snow dug from the pit should be placed near the edge to facilitate refilling the pit. For deep pits, careful size planning is advised and/or core augering should be used.

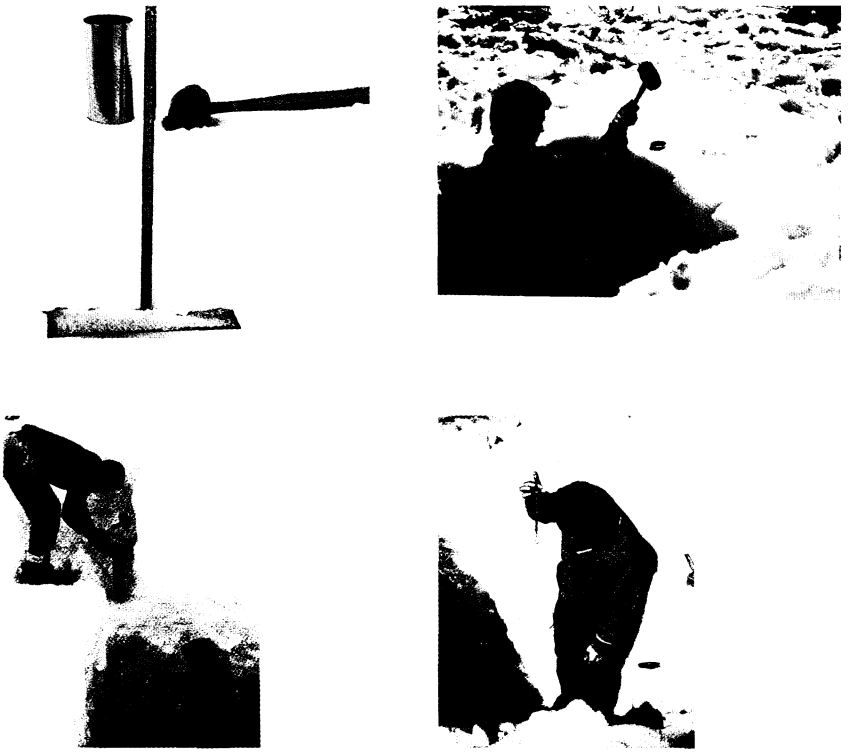


Figure 5.3: Snow Sampling Technique
A steel plate is pushed horizontally into one of the vertical walls in the snow pit (in this case approx. 30 cm from the original and untouched snow surface). The sampling tube is then pressed vertically down to obtain a sample of the upper first section of the snow pack.

When the area of the first sample has been cleared, the steel plate is moved another step downwards and the steel cylinder pressed into its second sampling position. The ruler is indicating the original snow surface, the rubber mallet is resting on the surface introduced by the steel plate.

Instead of a sampling cylinder, rectangular blocks can be cut out of the pit wall by a carpenter's saw. The blocks must be carefully measured to obtain the volume before they are weighed. A small spring balance or other small portable scale, capacity 0-1000 grams, is used to obtain the weight of each sample. Digital scales allow quicker readings but are often less reliable at cold temperatures (less than 10 degrees C) and when wet. The "block method" is probably most accurate but very time-consuming.

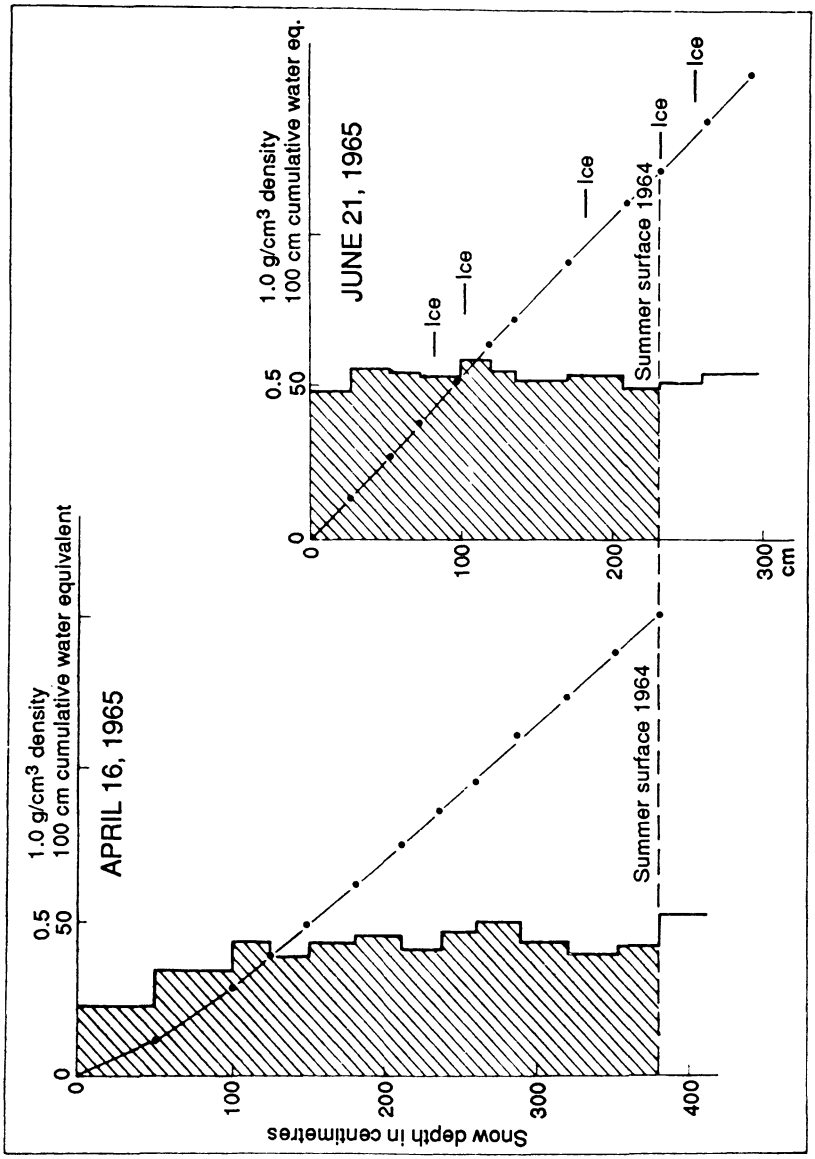


Figure 5.4: Place Glacier, Birken, British Columbia
Density diagrams (shaded) obtained in pits dug at the same location (elevation 2,440 m) in spring and in mid-summer. The dots show the cumulative water equivalent versus depth. During the first part of the summer the density of the snow had increased, partly by settling and partly by refreezing of melt water in the snow pack (producing ice lenses). The total water equivalent, however, decreased in the same time interval from approximately 150 cm to approximately 125 cm of water.

Temperature observations should be made at regular intervals in the snow pack to determine if melting has occurred. If freezing temperatures are present in the lower part of the snowpack, no substantial amount of meltwater has disappeared and the water equivalent observations will be reliable, except for surface evaporation. The amount of evaporated snow is difficult to determine, but for most purposes may be neglected.

Although the density of the firn located just beneath the "ss" should be measured, this is often a very difficult task in areas where there is dense snow or superimposed ice. Measurements of snowpack and the underlying firn and/or ice temperatures (refer to Appendix VI) are taken at the same time as snow and firn density to allow identification of sites where internal accumulation has occurred or develop later. These temperature measurements help to minimize balance error in regions where internal accumulation is suspected, and eliminate concern about internal accumulation where the previous years "ss" has remained at the melting point.

After completing all measurements, mark the previous summer surface with a layer of saw dust, powdered dye or with a plywood or masonite sheet. First, the bottom of the pit must be filled with clean snow to the level of the previous summer crust. The saw dust or powdered dye will make it easier to recognize the actual summer surface later in the season after percolating meltwater forms ice layers in the snow pack and loosens the summer crust. The boundary between last winter's snow and the firn from previous years is gradually obscured. Pits dug later in the summer should be located so that the above-mentioned datum appears in a corner of the new pit.

Even if continuous study of snow-density and water-content variations during the summer is not made, pits should be dug at the end of the ablation season to measure the remaining part of last winter's accumulation (see Chapter 6).

5.4. Simplified Pit Studies

For most glaciers it is possible to determine the average density of the last winter's snowpack by a simplified method. However, several pit studies should have been made on the glacier over a number of years. The average density can be regarded as a function of the density in the upper 2-3 metres of the snowpack. Thus, it may be sufficient to dig a relatively shallow pit, take snow samples as usual, and extrapolate the curve showing density vs. depth from the 2-3 m pit down to the summer surface (determined by normal probing). This method saves time and gives results with errors of ± 5 percent, based on experience from Norwegian glaciers. It is now being used there where snowpack conditions appear to be fairly similar from year-to-year. However, after a winter of abnormal weather conditions, e.g., heavy rain storms, pits must be dug all the way down to the summer surface and a complete sample taken.

5.5. Density Determinations Performed from the Snow Surface

Many attempts have been made to avoid the time-consuming pit digging required to obtain snow density values, but one of the main drawbacks in all the methods is recognition of the previous summer's surface, i.e., to what depth sampling should continue. The summer surface is normally easily detectable in a pit, but not

so obviously found by these other methods that are also of questionable accuracy (see Williams, 1964 or Work *et al.*, 1965). Many of the samplers used in forested areas (e.g., the Mount Rose snow sampler) are difficult or impossible to use on most glaciers, due to much greater snow depths and hard, wind-packed layers.

5.5.1. The Coring Auger (Fig. 5.5)

With a SIPRE-type coring auger it is possible to obtain snow samples similar to those taken with the conventional cylindrical snow sampler. However, due to variations in physical properties (degree of packing, crystal size, density), the snow core breaks most times the auger is raised and part of the sample core is lost before a density measurement can be made. Special precautions must be taken to ensure that the measured densities are valid for the whole snowpack. Example: The auger has cored 50 cm, thus a 50 cm cylindrical snow sample should have been obtained. When the auger is raised the sample is only 45 cm long. The water equivalent of this sample will therefore be approximately 10 per cent less than expected so a correction must be made. A special form has been developed for making such corrections and shown in Appendix VI. At least some of the results obtained by coring should be checked with pit studies at the same location. In loose snow such a check is vital, as the coring auger has a tendency to overregister the density of light snow.

5.5.2. Radioactive Methods

A method based upon radioactive penetration is described by Danfors *et al.* (1962), Leighty (1966), and others. A specially designed probe is lowered into a hole and the average water equivalent determined for snow within a radius of 10-40 cm from the probe. With this device it is essential that the hole has parallel walls because air between the probe and the snow will give erroneous figures for the water equivalent. There are also some problems with calibration. As the total weight of necessary equipment is greater than that of a complete SIPRE coring auger, it may not be practical for field use. The gamma probe is also useful for measuring snow density, but requires specific training in safe use of radioactive substances. Normally these methods are not used in our studies since the health and safety threat they impose is not warranted, when other methods are possible.

5.5.3. Free Water Content (See Fig. 5.6)

The dielectric "constant" of wet snow is determined by the relative amounts of water, ice and air within the snowpack. Free water content may be measured using a device which detects the dielectric properties near the surface measured. A snow dielectric device has been developed and is sold by Institute für Experimental-Physik at the Universität Innsbruck, and operates at a frequency of 20 MHz. The dielectric properties of the snow within 1.5 cm of the sensor plate will affect the capacitance of the large plate and consequently be measurable using a finely tuned twin-T-bridge (together with an oscillator and a detector). Using this instrument the dielectric constant of the snow is directly determined, and used together with snow density information to compute snow wetness as described in Appendix VI. These measurements are necessary if radar in the GHz wavelength or high MHz band is being used to measure snow or ice depths, or snow areal extent.

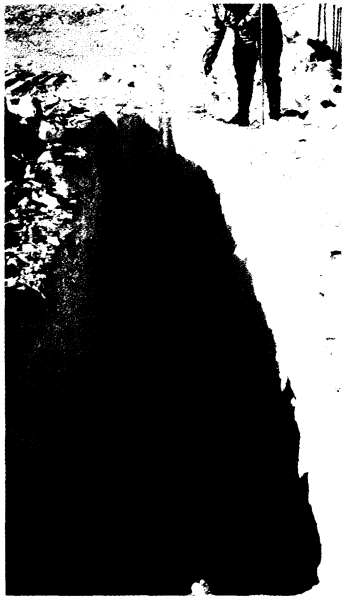
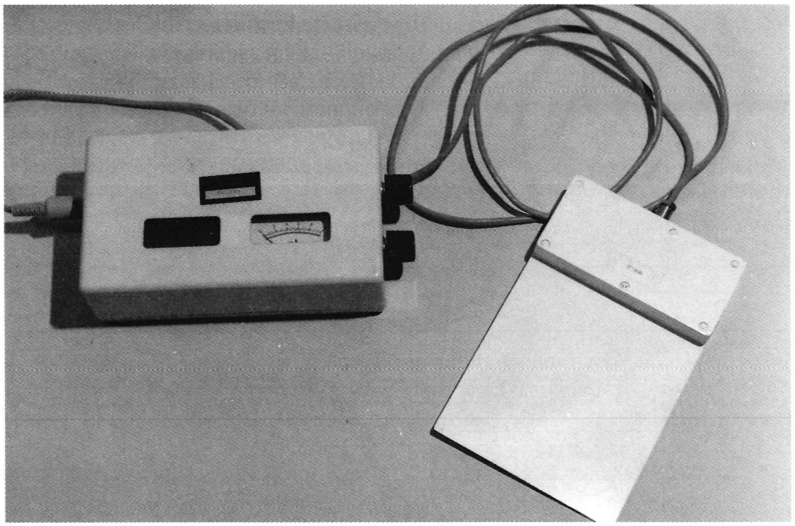


Figure 5.5: Snow Pit and Coring Auger
In areas of very heavy accumulation the snow pit work may be accomplished using a bucket and rope (upper).

In such areas the snow samples can more easily be taken with a coring auger instead of the normal sampler (lower picture).



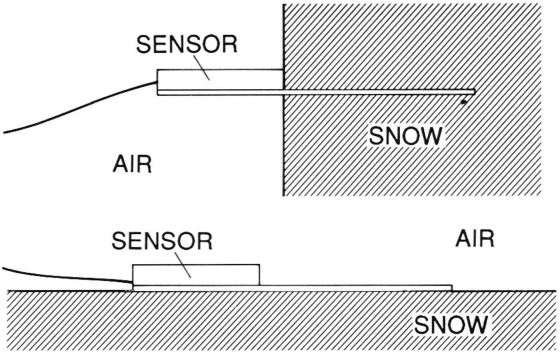


Figure 5.6:
Capacitance Probe
Snow surface dielectric device for measuring the snow wetness is shown on the photograph. The instrument was designed by Denoth at the Swiss avalanche Institute in Davos, Switzerland, and is often referred to as the "Denoth" probe, and costs approximately $1,200 Canadian in 1991. This is a capacitance probe that operates at a frequency of 20 MHz with four 1.5 Volt, alkaline, type AA batteries. It has a measuring range of 0 to 10% water content by volume. The lower diagrams show how the sensor is placed for full-space (upper sketch) and half-space (lower) measurements; a slightly different equation is used to compute snow wetness depending upon which of these measurement methods is chosen. The probe itself is quite fragile and can be easily damaged in hard or icy snow. Special care must be taken not to touch (or cover) the screw on the centre top of the probe during measurements. Repeated dry measurements in air must be made between readings to better ensure accuracy of snow wetness values.

5.6. Additional Accumulation. Internal Accumulation.

Snow that falls after spring accumulation measurements have been made, should ideally be accounted for before the total winter balance is computed, but this may be difficult in practice. A correction for "additional accumulation" can be made either by using precipitation observations from a meteorological station or by direct measurements on the glacier surface. In the first case, the amount of precipitation between the snow survey and the end of the winter season can be used together with a correlation coefficient and calculation of prevailing temperatures on the glacier. In the second case, a real measurement is made of the actual snowcover which has developed between the snow survey and the beginning of the ablation season. This method is the most reliable and should be used whenever possible. It can be facilitated by marking the surface at the time of the snow survey with masonite sheets anchored to the stakes or scattering sawdust or powdered dye near the stakes. Chicken-wire netting can be used as well, as this has little influence on the snowmelt at the stakes. It will also to strengthen the summer surface after cool summers (see Section 5.3) and facilitate recovery of buried stakes.

During a short period in the spring additional accumulation can result from rain falling on snow that remains well below 0°C. The rain freezes within the snowpack and forms layers that increase its total water equivalent. This kind of additional accumulation, however, is assumed to be negligible in temperate areas. To check it, a pit could be dug at the start of the ablation season (especially in the firn area) and the total water equivalent measured. Comparison with figures obtained from the snow survey in April/May will indicate whether a correction is necessary.

A direct measurement of additional accumulation (deposited since the main snow survey) should be made immediately after arrival at the glaciers in May/June. NOTE: The project manager must decide how much efforts should be put into the determination of additional accumulation.

The meteorological method, using precipitation data from a weather station, is very complicated because one must known if precipitation is falling as snow or rain at the glacier on each occasion, and also whether rain will freeze within the snowpack. If it does not, it is assumed that the rain drains completely off the glacier and does not increase the amount of accumulation. This is based on the assumption that the temperature of the firn is at the melting point. Such conditions are generally assumed to be valid for glaciers in temperate areas. (The conditions of additional accumulation are completely different for a "cold" glacier in the Arctic, see Appendix V (by Mayo). Even when it is assumed that the air temperature at the glacier is above 0°C, this does not necessarily mean that the precipitation is falling as rain. Snow may fall at air temperatures up to approx. +1.5°C. Thus, a calculation of the additional accumulation could be very ambiguous.

Internal accumulation means that percolating meltwater refreezes in lower layers and does not drain off the glacier.

5.7. The Snow Pillow

During recent decades a special instrument has been developed for direct observation of snow accumulation. It is generally well known that conventional precipitation gauges do not operate well in a snow storm and false values are

frequently obtained. Therefore, direct observation of the snow accumulated on a representative area on the ground would probably give far better results (Fig. 5.7). The data from a snow pillow gives the time and amount of each snowfall during the winter with a detail that cannot be obtained by any conventional snow survey. Even decreases in the snow pack during the winter (caused by evaporation or snow drift) will be recorded; information not normally obtained by other methods. For further details on snow-pillow installation, necessary corrections for temperature variations and other sources of errors, see for example Beaumont (1965, 1966) and Penton and Robertson (1967).

5.8. The "Snow Stick" (Fig. 5.8)

On Nigardsbreen, part of the largest ice cap on the European mainland, heavy snowfalls often bury important stakes. Various methods were tested to alert the Head Office before these stakes disappeared. The solution was the "Snow Stick", a plastic tube fixed to a strong, steel stake at a representative position, near the base camp.

At 20-cm intervals the Snow Stick has light sensors which can report light conditions in the snowpack via the ARGOS satellite. Every day reports are received in Oslo, and the winter crew can be sent out to extend the stakes before they are buried (Fig. 5.8, Østrem 1984).

A similar sensor has been developed in Canada using thermistors and photo-cells attached to a pole. The temperature and photo-resistance values are either telemetered to the office or retrieved from the data logger in the spring.

5.9. Active Microwave Radar (FMCW)

The FMCW radar (Frequency Modulated Continuous Wave Radar) is used to scan across a ramp of frequencies that are sent through the snow pack and received at a second specially constructed microwave horn which is tuned for the frequencies used and the beam focused with special lenses (as shown in Fig. 5.9). It is critical that snow wetness, snow density and crystal size and shape are measured simultaneously to calibrate the system and check readings. The GHz frequency range is only useful on this type of radar for low snow-water contents (less than about 2% water by volume) or for a firn or snowpack that is completely drained of water (such as early in the morning).

The FMCW radar is a ground-based "active microwave" system that has been applied to snow by H. Gubler and others at the Swiss Federal Institute for Snow and Avalanche Research in Davos, and has been developed and utilized by a number of other researchers such as H. Boyne of CRREL and R.A. Schmidt of the U.S. Forest Service in Fort Collins.

Gubler and Hiller (1984) give a good description of the system which operates in X-band, which has been proven to be highly useful for non-destructive studies of snowpack and avalanche conditions, as well as for monitoring avalanche velocities if two or more of the instruments are used. It can sense snow depth up to at most six meters. Because the dielectric properties at these wavelengths are still strongly affected by snow-wetness, grain-size and grain-shape and stratigraphy, then each of these parameters must be understood at least one location before spatial mapping of snow-depths or snow-water equivalent can be made. For snow that is composed of

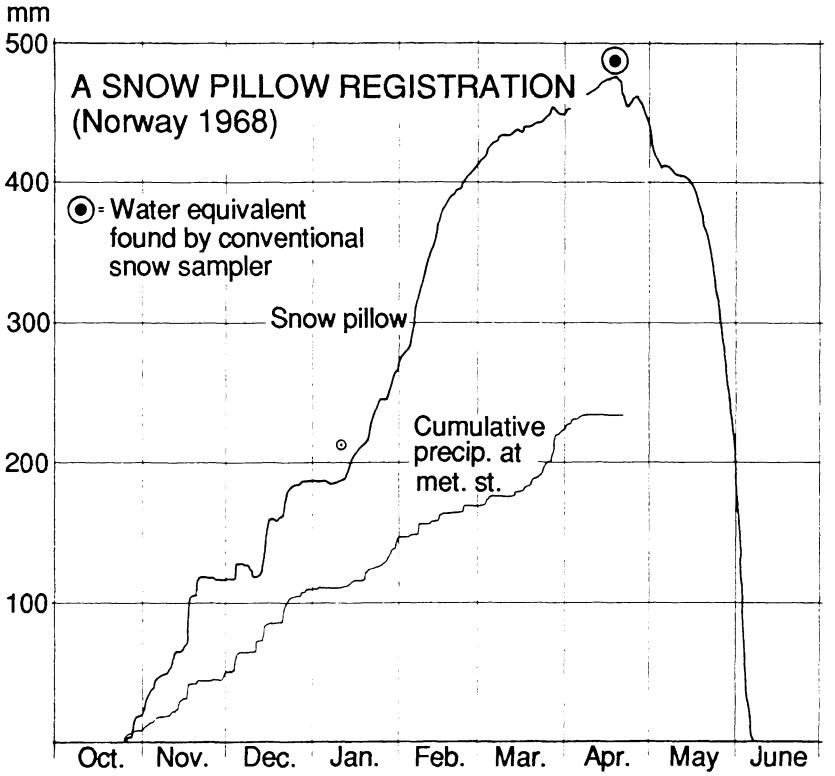
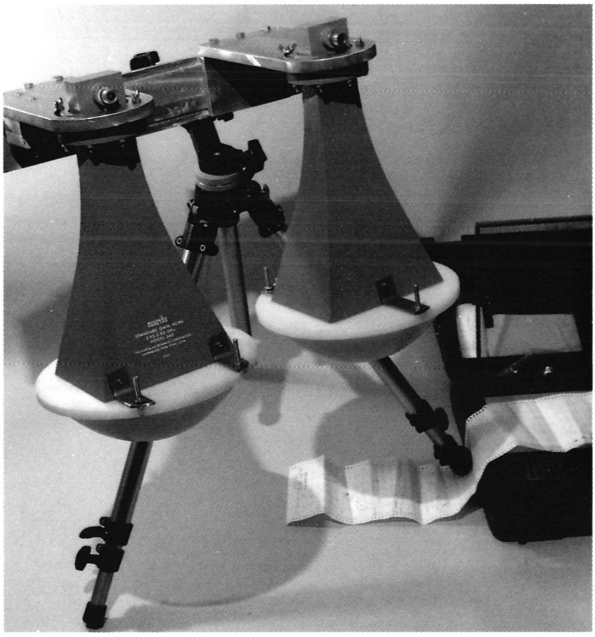


Figure 5.7: Snow Pillow
A diagram showing snow pillow data compared with cumulative precipitation data from a conventional gauge in the vicinity. The result from two direct water equivalent measurements made in January and April are also shown.

The snow pillow recorded less accumulation than the precipitation gauge only during a short period on October (on account of wind action); in April the total snow pack on the ground proved to contain 100% more water equivalent than was collected in the conventional precipitation gauge during the corresponding time period!

Figure 5.8: The Snow Stick
The snow stick was developed in Norway to monitor snow accumulation on Nigardsbreen. It consists of a plastic tube with light sensors every 20 cm, and is tied to an existing solid stake inserted in the glacier. An electric wire system connects the sensors to a satellite transmitter (not shown) in the ARGOS system. Sensors under snow will report darkness, the rest bright light.

Thus it was possible to determine where winter snow increased sufficiently to send out a field crew to extend stakes before they got buried (see Østrem, 1984).



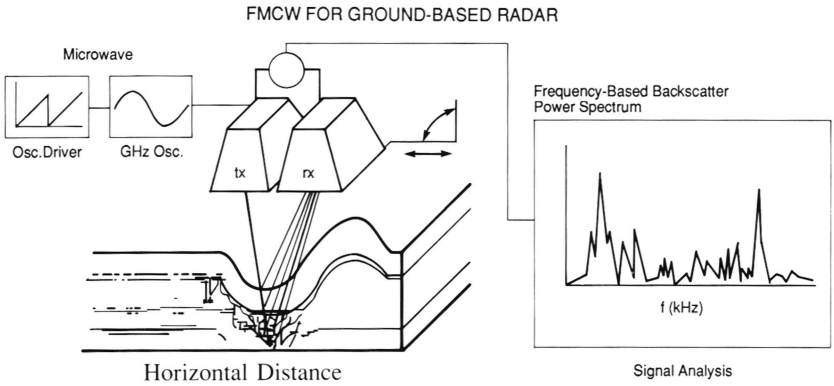


Figure 5.9: FMCW Radar
Frequency Modulated Continuous Wave Radar is a ground based active microwave (or also called a type of impulse radar) that may be used to map the stratigraphy and depth of snow. It operates generally in the GHz frequency range. Both a photograph and a diagram of how the system works is shown.

more than a few percent water, the FMCW is unlikely to be of any use in determining anything other than the fact that the surface is wet and highly reflective in the X- or C-bands. If the snow is composed of well rounded ice grains that can easily be completely drained of water during the evening hours, it is possible that the FMCW radar can detect the firn-snow interface if it is the location where snow-drainage water is ponding.

Complementary, ongoing ground-based studies will be continued using our operative C-band scatterometer (multi-polarization) and FMCW (2-8 GHz) radar (in development). This FMCW system (see Fig. 5.9) is under development at NHRI for use in monitoring the depth of snow, and instead this system operates in the C-Band range. This longer wavelength was chosen in order to hopefully minimize the interaction of the radar with water in the snowpack, and to directly complement radar data to be obtained by RADARSAT after 1994.

The radio-echo sounding device described in Section 11.3.8. operates also as a ground-based impulse radar, but at much lower frequencies (between 5 and 200 Mhz).

5.10. Recording Data and Completing Forms

In this section data forms for snow-pit work and core drilling will be described as well as a table for snow-density calculations. It is essential that the forms be completed in the prescribed manner.

5.10.1. The Snow Pit Form

The first three columns should be completed at the pit. The next three columns are for calculations and the last is for remarks. The following should be observed when the form is used:

1. The name of the glacier, the date etc., on the top of the form.

2. Column 1 — the depth from the original snow surface to the lower end of the snow sampler (i.e., to the horizontal steel plate). Note: this column will show the <u>total</u> depth measured. If possible, use a hanging tape fixed at the original snow surface.

3. Column 2 — the length of the snow sample, or more correctly the vertical distance between the positions of the horizontal steel plate. It is important that the distance be measured before snow is removed to release the sampler. Note: the actual length of the snow sample in the steel cylinder may be less, as snow can compact during the sampling procedure. The cumulative value of figures in Column 2 (left side) should agree with the figures shown in Column 1.

4. Column 5 — the net weight of the sample
(less the weight of any bag used in the weighing procedure).

5. Calculations necessary to complete Column 8 can be simplified using a table that shows the density for a sample 10 cm long. If a snow sample is not 10 cm the obtained density must be multiplied by a factor. The inner diameter of snow samplers is seldom exactly the same, so individual tables should be constructed for each sampler.

A diagram showing variations in density with depth must be constructed as well as a diagram of the cumulative water equivalent vs. depth. Both diagrams should be plotted on the same graph paper. An example of a combined diagram is shown in Fig. 5.4.

5.10.2. The Coring Auger Form

This form is a more complicated than the snow pit form, but follows the same format with the following exceptions:

1. Column 1 — the depth from the original snow surface to the lower end of the auger. This can be measured along the drill extensions or on a probe carefully lowered into the hole.

2. Column 2 — the distance of the drill between each sample: calculated as the difference between the depth of each sample.

3. Column 3 — the actual length of the sample measured when it is removed from the auger. This will normally be slightly less than the distance between sample depths. The sample may have to be trimmed at the ends to make a proper cylinder.

4. Column 4 — the net weight of the snow sample.

5. Column 5 — the volume of the sample. This can be obtained by multiplying the cross-sectional area by the length of the sample. There is no standard sized coring auger and consequently no standard table has been constructed to calculate the sample volume.

6. Column 6 — the density of the snow sample. Note: this is an actual density, calculated from the weight and volume of the snow sample (which is generally shorter than the drill penetration). This figure should be used when plotting the depth/density diagram (with depths taken from Column 1).

7. Because the figure in column 7 is a subjective judgment made in the field, it is vital that the column be properly completed. Parts of a sample can be lost and thus no actual density measurements obtained for some of the snowpack. The missing piece might have the same density as the previous snow sample, the same density as the next sample, or it might come from very loose and light snow which cannot be sampled.

   Any decision is difficult to make, but when using an auger the operator may be able to judge when the snow is heavier or loose. The decision must therefore mostly be based upon the working conditions when the snow sample is taken.

   The cumulative value of figures in Column 7 must agree with the figure in Column 1.

8. Column 8 — the water equivalent assumed to be present in the area indicated in Column 7. Note: this figure is the adjusted water equivalent and not the actually measured value for the individual snow sample.

9. Column 9 — the cumulative values of figures in column 8, which can be plotted directly on the diagram.

5.10.3. Other Useful Forms

In addition to the above two forms, a number of other forms are used to help organize and compute field data results. Examples of these are summarized in Appendix VI.

5.11. Winter Survey

Some glaciers in maritime areas receive such large amounts of snow during the winter that the stakes are completely buried. As they are often used for navigation on the glacier, it is desirable to have them visible throughout the winter. Furthermore, in areas of very large snow accumulation, it may be difficult to measure the total thickness of the snow pack at the end of the accumulation season. Therefore, one can divide the total accumulation measurements into smaller units, i.e., measure the accumulated snow at various intervals during the winter and add the results at the end of the accumulation season. This requires some visits to the glaciers during the winter.

It is not possible to apply this method to all the snow-depth measurements. However, it can be considered for the density measurements, performed in pits as described previously in this chapter. This is most time-consuming and laborious work and it is recommended that pit studies should be included when glaciers are visited in the winter for stake extensions.

At the end of the melt season a crust will generally develop on all snow surfaces in the upper part of the glacier. The previous winter's snow will have partly

recrystallized during the summer, rock particles and plant fragments may have blown onto the surface, so it is more-or-less grey in colour. The snow is transformed into firn (snow that has survived one melt season) and this firn has a "summer surface" (the border or division between the firn and the succeeding winter's snowfall). The summer surface will normally form a relatively stable crust that can be detected with a probe, even through a heavy snowpack. All accumulation measurements are aimed at determining the water equivalent of the snow resting on top of the summer surface. The summer surface is therefore an extremely important reference datum for all mass-balance investigations. If this crust is poorly developed, due to unfavourable weather conditions in the summer, it may be necessary to mark its position by artificial means.

5.12. Emphasizing the Summer Surface

A thin layer of powdered dye, sawdust or chicken wire have been used with success on various glaciers. The marked surface must be large enough to be easily found later in the accumulation season, but should be placed so that it does not influence the stake readings the following summer. An area measuring 3 x 3 m should be placed 10 m from the stake in a down-stream direction from it (Fig. 5.10). If this standard distance is always used, the winter crew can easily dig down to the surface and find it, even if a small error is made in the distance and direction determination. The "ss" surface marker is also easily seen when the coring auger is used to take snow samples.

At the first winter visit, preferably when 2-3 m of snow have fallen, a pit should be dug to the summer surface (either the natural "dirty" summer crust or the artificially-marked surface). Snow-density measurements in the pit will give the total water equivalent for this snow pack. If the snow surface is then marked by sawdust or similar material, it will facilitate the work at the next visit to the glacier, as the second pit need be dug only down to this surface. Information about the water equivalent of the lower part of the snow pack has already been obtained from the first visit.

It is obvious that extending the stake is very important, as it identifies the pit location. If the stake is completely buried, the above-mentioned surfaces are lost and it will be necessary to dig all the way down to the previous summer surface. Glaciers in maritime areas may be buried under 5-10 m of snow by the end of the winter. Then even snow-density measurements with the coring auger (see Section 5.5.) may be difficult to perform. It is therefore important to follow the meteorological conditions throughout the winter, so that winter visits can be made at times suitable for stake extensions. Another way to monitor the increase of the snowpack is to install a snow stick, which is able to report almost continuously on the growth of the snowpack (Section 5.8.).

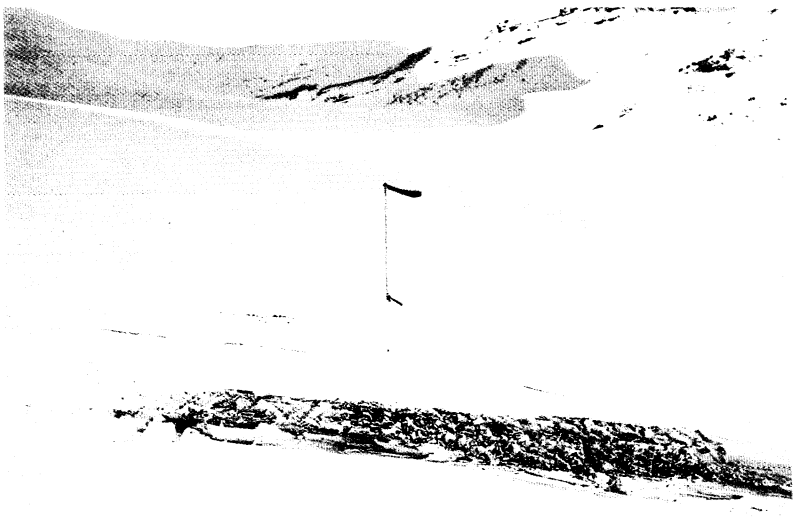


Figure 5.10: Marking the Summer Surface
After a cold summer, possibly with summer snowfalls, the summer surface will be poorly developed. To emphasize the "ss" location in the stratigraphic record, it is recommended to mark an area (near a stake) with a thin layer of sawdust which will easily be found in a pit or detected in a core taken with a coring auger.

Another method is to place a "chicken wire" or similar netting about 2 x 2 m around the stake. This can be easily probed, e.g., by steam drill, when the snow survey is made the following spring.

CHAPTER 6. ABLATION MEASUREMENTS

6.1. General

Glacier ablation comprises all material which is removed by melting, calving, evaporation or wind erosion (Ahlmann; 1948, p. 26). The most important component on mountain glaciers is melt, most of which occurs on the surface. Wind action is negligible and evaporation is dominant only for short periods during the spring. The loss by evaporation is commonly only a fraction of the material removed from the glacier by melting. The relationship between the many factors and the influence of meteorological parameters (air temperature, wind speed, humidity, radiation etc.) is described extensively in the literature and is not dealt with here (e.g., see Wallén, 1948; Hubley, 1957).

The total amount of material lost from the glacier during the summer could be called "total ablation". However, during one summer season, some accumulation may take place, e.g., in the form of summer snowfall. Normally, this snow will disappear again later in the summer. This means that not only has the "normal" melt taken place, but also some "extra" melt has occurred, which has, of course, consumed energy.

It is important to relate ablation to meteorological factors in detail, all such summer snowfall must be recorded. However, this may be complicated and expensive. Therefore, for most glaciers under study, possible summer snow falls are treated as normal rain on temperate glaciers — it is assumed that liquid precipitation drains off the glacier, not really influencing the mass balance.

The difference between the glacier volume at the start and end of the summer season is termed "Summer balance", and can best be obtained from observing the relative lowering of many points on the glacier surface. (Ablation within or under the glacier ice is negligible compared with the melt on its surface.) Changes of surface elevation can also be measured by photogrammetric means; a method still used to measure the volume change of a large number of glaciers in Europe and North America.

For a number of Canadian glaciers, terrestrial photogrammetry has been used in the past by the Water Survey of Canada to determine volume changes of the tongue. However, as this method only covers the lower part of the glacier, a figure for the total balance was not obtained. The mass balance for the glacier over a period of several years may be obtained by photogrammetric means only if the entire glacier is photographed at the beginning and end of the period. The annual variations, however, are more difficult to determine by this method, as the accuracy is not sufficient to give results within the error limits normally accepted in mass balance studies. This is particularly true for accumulation areas where the white snow provides insufficient contrast for accurate mapping. For a number of Norwegian glaciers, repeated mapping from air photographs has been used to determine volume changes for periods of 10-15 years. Large-scale photographs and plotting based on good ground control gave results with an accuracy of 1-2 m in the vertical (Haakensen, 1986).

The annual variation in a glacier's mass results from both accumulation and ablation and is defined as the glacier's mass balance. (A negative balance means that the glacier volume has decreased; a positive balance that it has increased.) NOTE:

the terms used in this kind of investigation have been defined and later revised by Meier (1962). Based on decisions made at the Berne meeting of ICSI in 1967, these revised terms are presently used in glacier mass-balance studies. A list of the terms and their definitions has been published by UNESCO (1970) and a short description is given in Chapter 14 and Appendix II. The revised terms have been generally adopted for use in this manual.

Information on ablation can be obtained from the position of the snowline (the lower border of last winter's snowcover) at the end of the ablation season. Under equal melting conditions it will be situated higher in a year of less winter snow accumulation, so it is difficult to base calculations of the summer balance on this concept. However, a series of photographs showing the position of the transient snowline throughout the summer will be valuable for constructing ablation maps. Such photographs should be taken by the field crew at intervals during the summer from suitable well-defined points. In addition, direct surveying or satellite mapping of the late-fall snowline should be made (see Appendix VIII, Chapter 11).

6.2. Stake Readings (Fig. 6.1)

Lowering of the ice surface can be measured directly by comparing the visible length of a stake over a given period. Example: A stake inserted in the ice has only 20 cm visible, but one month later it extends 120 cm above the ice surface. This means that 100 cm of ice has disappeared which represents an ablation of approximately 90 cm of water equivalent.

To obtain valid comparisons, all stake readings must be made in the same manner and some "rules-of-thumb" should be followed:

6.2.1. Stakes Drilled into Ice

A measurement is taken from the top of the stake down to the glacier surface and recorded to the nearest cm. The top of a stake is always easy to locate, whereas the glacier surface might be very uneven and difficult to determine accurately. To avoid large variations due to uneven topography, the ice surface should be defined by an ice axe placed on the ice touching the stake and resting in a direction perpendicular to the ice flow. If an ice axe is not available any straight rod or plank approximately 1 m in length can be used. This method is good for glaciers of large total melt during the summer (several metres of ice). For glaciers with less melt, say under 1 m per year, or with extremely undulating surfaces, a more detailed reading may be required (not described).

6.2.2. Stakes Drilled in Ice still Covered by Snow

One measurement must include both the visible length of stake (i.e., from the top of the stake to the snow surface defined similar to the ice surface above) and the snow depth at the stake. The snow depth is measured with a snow probe as outlined in the previously. The probe is pushed down vertically in at least three places within 1 m of the stake. The arithmetic mean of these soundings is used for the snow depth figure and is noted on the stake form (see Chapter 13). NOTE: as snow depth alone does not give information on the water equivalent it will be necessary to determine the snow density from time-to-time (see Section 5.3).

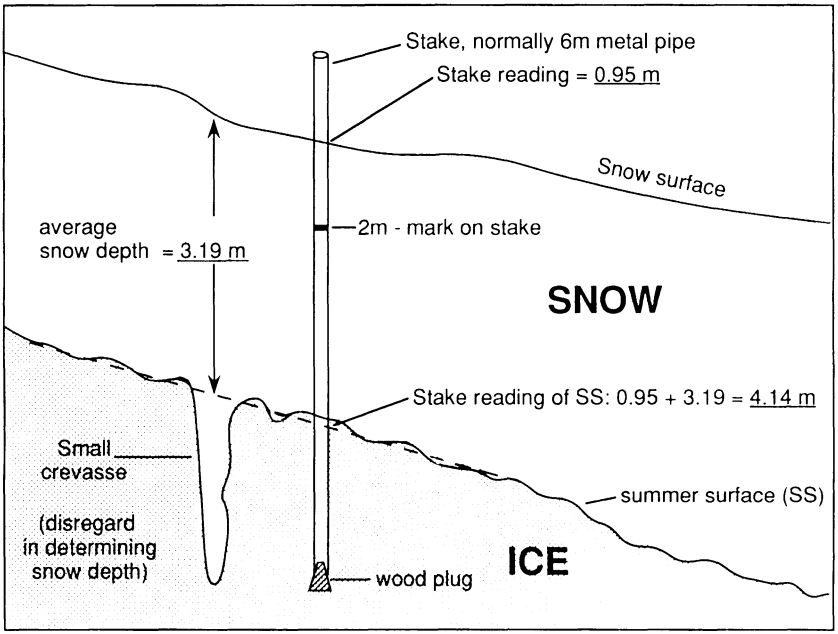


Figure 6.1: Pole Measurements
Example of how to read a stake when snow is covering the glacier ice. The stake is drilled into ice and will normally be frozen solid.

The reading at this stake will produce two quantities: the visible length of the stake (here 0.95 m) and the average snow depth at the stake (here 3.19 m) obtained by at least three snow depth soundings in an area not more than about one metre from the stake. NOTE: Suddenly found uneven features (e.g. a small crevasse) shall be disregarded.

Finally, one can calculate the stake reading above the average ice surface 0.95 + 3.19 = 4.14 m.

Note that when the snow disappears, it will be difficult (if not impossible) to use a measuring tape from the stake's upper end. Therefore, a 2-metre mark is painted onto the stake before it was inserted.

At the start of the ablation season the glacier ice is relatively cold and percolating meltwater refreezes at the ice surface to form superimposed ice (Schytt, 1949). Superimposed ice disappears later in the summer, at least on the lower parts of the glacier. It must, however, be taken into account when short-term studies are made of ablation variations. The amount of superimposed ice can be calculated from stake observations and must be shown on the stake forms. Superimposed ice is always a part of the "winter balance".

6.2.3. Stakes in the Firn Area

Stakes in the firn area are not normally supported in a solid mass similar to those drilled into rigid glacier ice. Therefore, some artificial support must be used to prevent the stake from sinking into snow or firn (Fig. 4.10). If a stake is not supported at its base it may suddenly start to sink at any time during the summer and all subsequent readings will be false.

If a stake has an effective support at its base, the following measurements should be made at each reading:

1. Length from stake top to snow surface in cm.

2. Snow depth from the present surface to the previous summer's crust. This measurement is performed with a snow sounding stick and the summer crust identified by feeling a hard layer at or near the expected depth, based upon previously observations. (Compare accumulation measurements in the area). Formation of numerous ice layers within the snow pack might confuse the measurement of snow depth. To overcome this problem snow depth measurements should be made to a plate previously placed on the summer surface. The stake form (Chapter 13) gives information on whether a plate is present or not.

Variations in snow density, mentioned above, also apply to the snow cover in the firn area. Consequently, for detailed studies of ablation variations throughout the summer, it is important that the snow density be determined several times during the summer so that the water equivalent of the snow pack can be calculated and hence the ablation rate.

6.2.4. Stake Chains or Cables

As mentioned previously, in areas of great ablation the normal stakes may be replaced by a stake chain (or a steel cable) frozen vertically in the ice in a deep hole made with a steam or hot-water drill. These stake chains or cables will not be visible until the snow has disappeared; readings will give information on ice ablation only. Reading a stake chain or a cable is basically identical to reading a normal stake. The length of the stake chain or cable from its free end to the ice surface corresponds to the normal distance from the top of the stake to the ice surface. The only difference is that a considerably higher number may appear in the stake form because the stake chain or cable is several metres long.

To locate a stake chain or a cable on the glacier surface, it is advisable to insert a normal stake and mark it with a flag, or to tie the end of the cable to a small construction (a tetrahedron) that can be seen from a distance (Fig. 4.4).

6.3. Completing the Stake Diagram

All stake readings should be recorded so that the data can easily be processed in the office. This can be ensured by transferring the data from field note-books to special stake forms, on which all observations concerning one stake for the entire summer season are collected. The completion of the stake form is described in Chapter 13. To avoid simple mistakes in the handling of the data, it is strongly recommended that the field crew construct a stake diagram that gives them a continuous picture of the conditions at all stakes on the glacier under observation (Fig. 6.2).

In the stake diagram (Fig. 6.2) time is plotted along the X-axis and stake elevations along the Y-axis. Variations in the glacier surface, measured from the top of the stake, are plotted so that surface lowering or ablation is shown as a descending line and accumulation as an ascending line. A horizontal line indicates that the balance between observations has been zero, or that accumulation and ablation are equal at the stake. Normally surface lowering will occur during warm periods in the summer. As ablation is greater in the lower part of the glacier than in the upper part, this is reflected in the stake diagram as different slopes of the lines. If a summer snow storm causes accumulation on the glacier, it is likely that more snow will fall in the upper part of the glacier than on the tongue. On the snout it may happen that the precipitation falls as rain which does not produce any accumulation at the stake. Stakes with the same elevation interval will normally show similar trends in their surface variations and the curves for them will be very similar. Therefore, if stake readings are wrong, or data have been interchanged, this can be detected immediately through the stake diagram.

On the diagram shown (Fig. 6.2), an interchange of readings was made for stakes 27 and 30 on July 22nd, or some incorrect figures were obtained on July 17th, when stake 25 also showed anomalous conditions. For the latter, all other readings indicate that ablation had taken place since the last reading, but for stake 25 the diagram indicates an accumulation. As this is most unlikely, a check of the figures in the note-book should be made and, if appropriate, the stake should be visited for a new reading.

The stake diagram should be plotted immediately after each stake reading so that anomalous results can be identified at once. It has proved to be a most valuable tool for the field crew in their continuous observations of ablation during the summer. If it shows "normal" conditions throughout the summer for all stakes, the readings have probably been made correctly and the results are reliable. However, the stake diagram cannot be used directly to calculate the actual ablation at stakes in the firn area, as the surface lowering may have been caused, to some extent, by snow densification and settling. The amount of actual ablation, expressed in centimetres of water equivalent, can only be calculated when the stake readings proper are compared with variations in the snow depth and the snow density at the stake location. This is dealt with in Chapter 13.

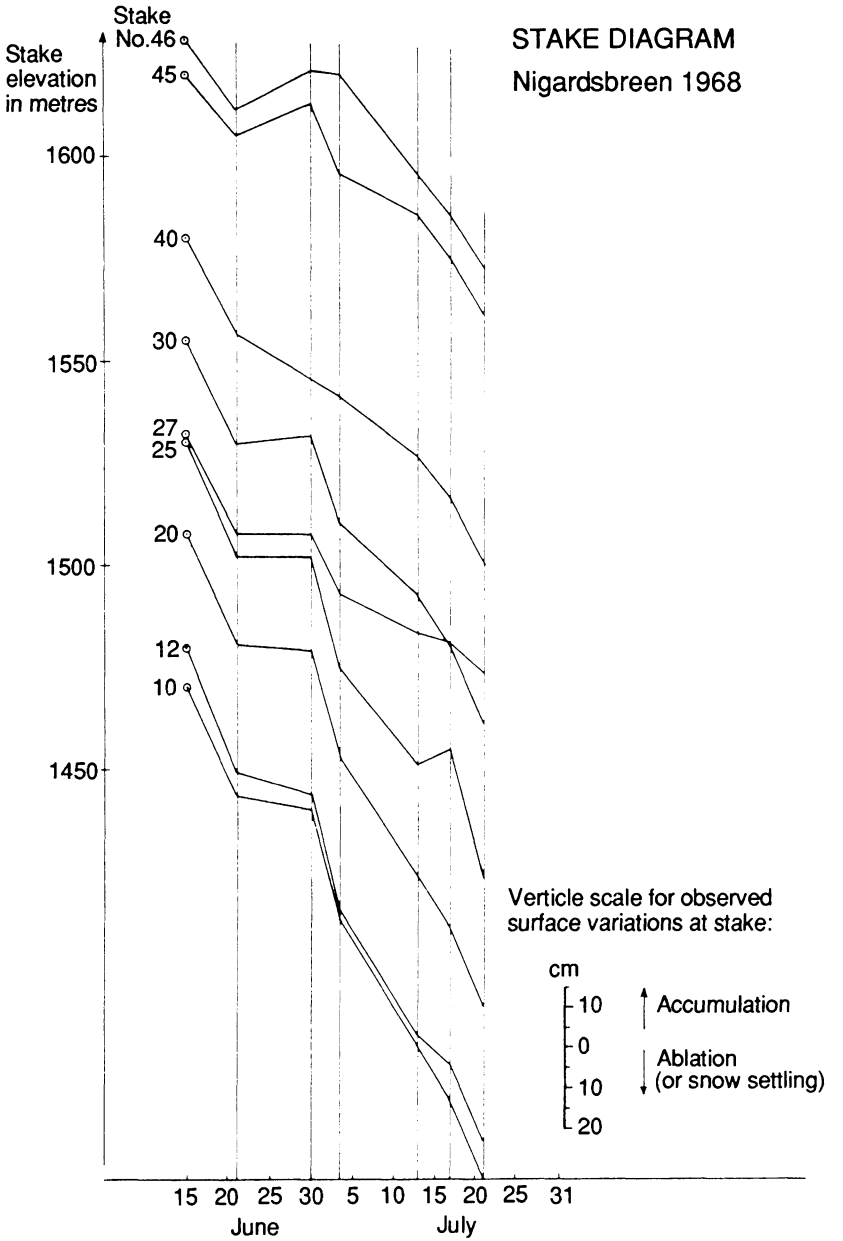


Figure 6.2: Stake Diagram
Diagram of stakes and their melt rates that greatly helps in analyzing field data and checking for possible errors.

Figure 6.2: Comments
Stake reading on each glacier may be plotted in the type of diagram shown on Fig. 6.2 to check that they are reliable. Time is plotted along the X-axis, stake elevations on the Y-axis. For each visit (stake reading) the change in individual stake length is plotted, using the scale shown at bottom right of Fig. 6.2. All single points are connected by straight lines. A horizontal line indicates no change in stake reading between visits. Normally, all stakes show a similar pattern. Thus, some error seems to be made at Stake 25 on 17 July, so that stake should be re-observed.

For Stakes 27 and 30 there seems to be an interchange of readings! Such errors are difficult to find without a stake diagram, which is highly recommended for each glacier.

6.4. Pit Studies at the End of Ablation Season: Remaining Snow

The summer balance must be determined at the end of the ablation season. On the glacier tongue this is easily done at stakes where the entire winter accumulation has disappeared and glacier ice is exposed. In the upper part of a glacier, normally only part of the winter's snow will disappear and it will be necessary to determine the water equivalent of the remaining snow. Depth soundings may be difficult because the boundary between the winter's snow cover and previous year's firn may have been obliterated or obscured during the summer. However, recognition of the summer surface can probably be done in pits: work that will be greatly facilitated if layers of sawdust, dye or other materials were placed at the bottom of a pit in the spring. If stakes in the firn area are inserted so that the lower end rests on the previous year's summer surface, the thickness of the remaining snow can be readily observed, even when snow depth soundings are impossible to obtain. The density of the remaining snow cover, however, must be observed in pits redug at locations where the summer surface has been marked. The technique of measuring snow density has been described in the Chapter 5. Normally the density of remaining snow at the end of the summer is in the order of 0.50-0.55 g/cm^3, but both smaller and larger densities have been observed.

6.5. Transient Snow-Line Observations

At the beginning of the melt season the whole glacier surface is normally covered by snow that has accumulated during the previous winter. Exposed ice may be visible only on small, convex parts of the glacier or in crevassed areas. When melting starts, the snow will normally first disappear on the glacier tongue. The lower border of last winter's snow is called the transient snow-line. This border will continuously move upglacier during the summer and reach its highest position at the end of the melt season. This highest position of the transient snow-line will normally (or, more correctly, in years when the glacier's balance is 0, i.e. when it is in a "steady-state" condition) be located very close to the equilibrium line. At the equilibrium line proper the ablation is exactly equal to the accumulation (summer balance and winter balance are equal). An example of ELA location can be seen on the air-photograph of Sentinel Glacier (Fig. 1.4), and is equivalent to the late-fall snowline on this temperate glacier.

NOTE: as superimposed ice is a part of the glacier's accumulation there may be a small vertical difference between the equilibrium line and the highest position of the transient snowline in a balanced year on certain glaciers. (The transient snowline is slightly higher.) For most "temperate" glaciers, however, this difference is only of academic interest, unless the glacier surface is very flat in the equilibrium zone.

The position of the transient snowline throughout the summer depends on both the rate of melt and the original amount of snow deposited on various parts of the glacier. Information about the location of the transient snowline during the summer will therefore be a valuable guide in the compilation of an accumulation map. A record of the snowline migration can be obtained by different methods:

(1) Sketching the transient snowline in the field onto a glacier map at various occasions throughout the summer season.

(2) Noting its position with reference to stakes at each reading, e.g. "Snowline today is 50 m upglacier from Stake 32".

(3) Taking black-and-white photographs from selected points, so that the location of the transient snowline can be plotted on a glacier map for various periods throughout the summer. These photographs can then be used together with the sounding data (obtained in the spring), when the final accumulation map is constructed. NOTE: An "accumulation map" is strictly a "winter balance map".

4) Using remotely-sensed images for mapping when accuracies in the order of 10 to 100 metres are sufficient. Radar instruments can sense surface roughness and surface wetness characteristics, even through clouds. In colour-enhanced multi-frequency and multi-polarization images, the positions of the ELA and superimposed ice zones appear strikingly different from the surrounding ice surfaces (Appendix VIII).

The photographic stations should be selected in such a way that large parts of the glacier can be seen, as well as suitable reference points. Photographs must be taken from the same stations and accurate records must be kept, giving all details of the photographs (date, station number, direction, etc.).

6.6. ELA, AAR and Mass Balance (Fig. 6.3)

The Equilibrium Line Altitute (ELA), the accumulation area ratio (AAR) and the mass balance of a glacier are all related. Since the ELA is often computed from the net balance, instead of being measured separately, it cannot really be considered an independent variable. If the maps on which the mass balance data are plotted are out-of-date then the ELA vs. balance plot will be slightly wrong. It would be better if the value could be obtained by surveying or from image analysis.

Due to the flow field on a glacier, the vertical component of velocity is generally downward in the upper elevations and upward below the equilibrium line.

Consequently, if the glacier has experienced a net negative balance during the measurement interval, the glacier surface would be expected to respond by thinning both in the accumulation and ablation areas, but would remain largely unchanged near the mean equilibrium line. This pattern shows clearly for Sentinel Glacier over a 24-year period (Fig. 11.4). However, the effect of density changes must be incorporated into these calculations if comparisons between balance and topographic change are to be made accurately. The effect of such a glacier thinning pattern would be to cause slight errors in the plotted ELAs in Fig. 6.4. The plotted values should lie slightly above the actual line in both the highest and lowest elevations but remain close in the middle. As new maps become available adjustments will have to be made.

The "Runoff-line", as defined by Koerner in Appendix IV, is equivalent to the lower limit of the superimposed-ice zone shown by Mayo in Fig. V.1. In order to properly describe the balance of any glacier, each of these balance horizons or zones should be mapped where applicable and/or measurable; these include:

1. Snow-line (directly observed)
2. ELA (computed and/or directly observed)
3. superimposed-ice zone (directly observed)
4. runoff-line (directly observed)

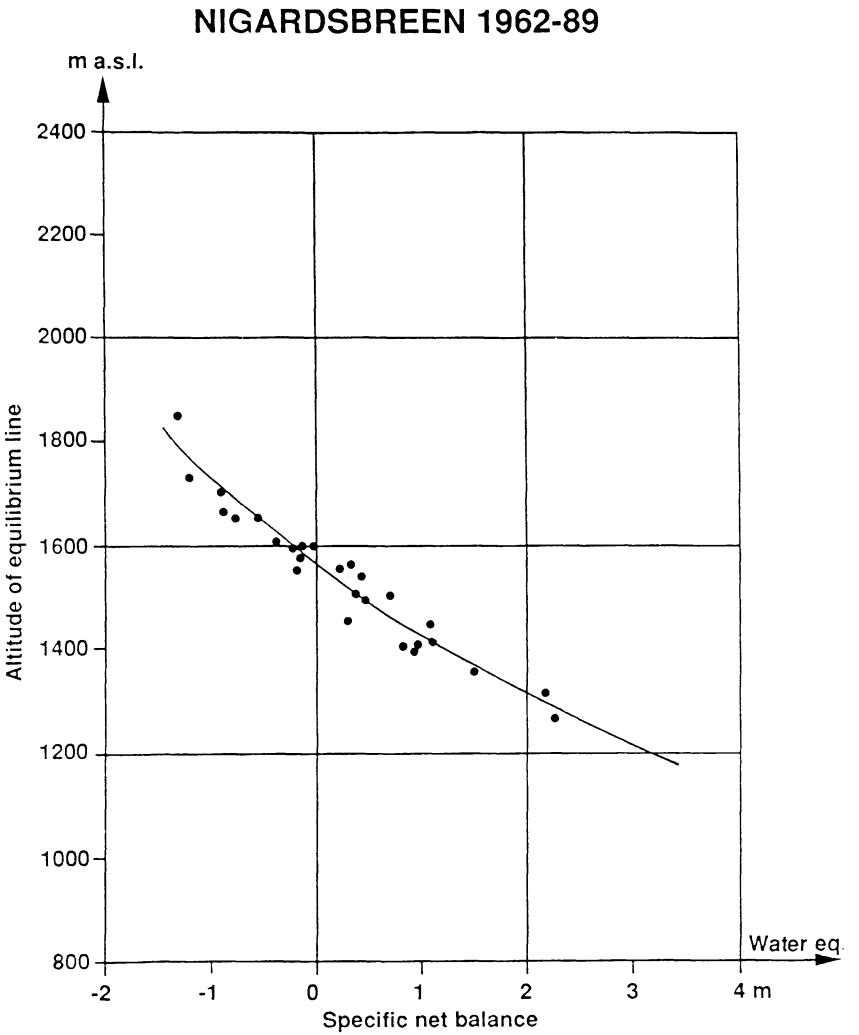


Figure 6.3: Net Balance and ELA of Nigardsbreen, 1962-89
There is a definite relation between the net balance and the height of the equilibrium line. Each dot in this diagram is the result of work done during one complete balance year, but the years are not given (e.g., in 1962 this glacier had the largest positive balance ever observed, +2.2 m, and the equilibrium line was as low as about 1250 m). For a well-studied glacier like this, a satellite image from the end of the summer may indicate the approximate net balance by using a similar diagram.

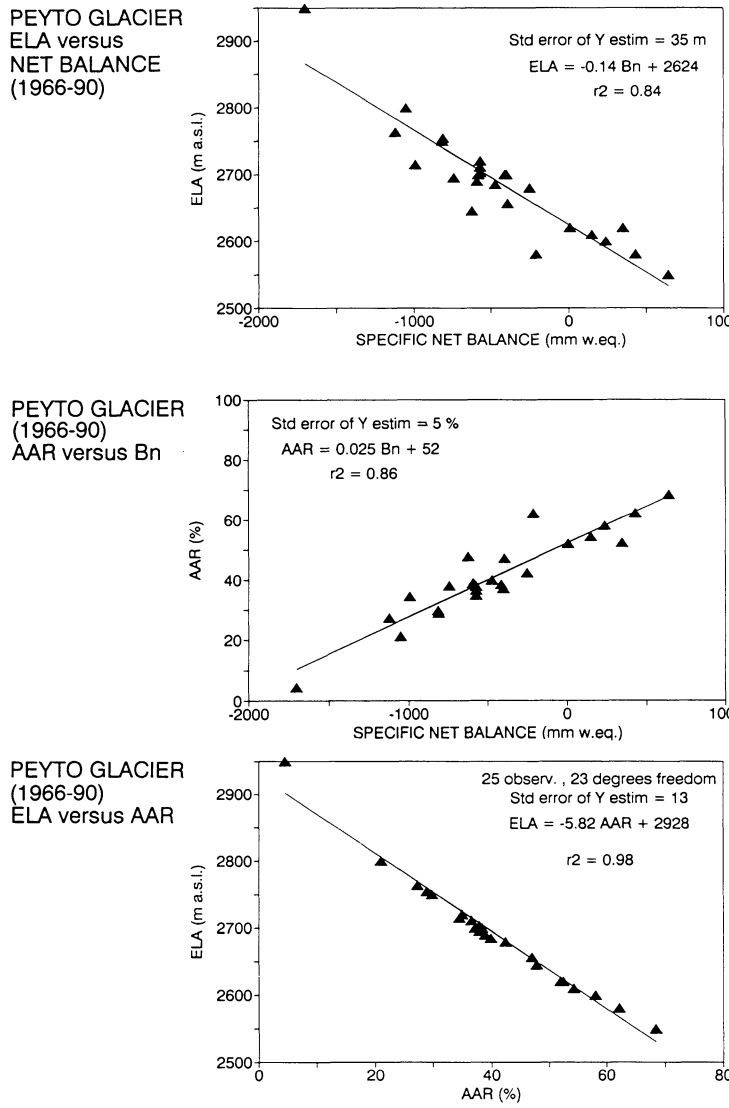


Figure 6.4: ELA, AAR and B_n for Peyto Glacier
The upper two diagrams show ELA versus net balance at Peyto Glacier and AAR versus net balance with their respective regression lines and linear correlation coefficients shown. The corresponding plot for ELA versus AAR for the same glacier is shown below. The significance of the correlations is discussed in the text, but it is clear that either ELA or AAR are useful estimators of net balance. NOTE: B_n here signifies mean balance for entire glacier and is = b_n.

CHAPTER 7. PLOTTING AND CONTOURING

Much of the data from glaciological mass balance studies are processed graphically and some of the basic methods are mentioned briefly in this manual. It is desirable that most preliminary data processing be done in the field, in order to obtain the final results as quickly as possible for distribution and publication. In recent years some of the routine work has been taken over by small portable computers.

7.1. General

All accumulation and ablation measurements as well as some meteorological results should be plotted on a large-scale map of the glacier. A scale of 1:10,000 with 10 metre contour intervals has been recommended. Such maps will normally be required for field use and a sufficient number of copies should be available before the field work starts.

On the accumulation map (or more correctly: the map of winter balance) the position of the main stakes are marked together with sounding profiles showing the location of all snow depth soundings, which are given in actual snow depths, together with the calculated water equivalents. Isolines are sketched to divide the glacier into areas of equal accumulation intervals. Example: Isolines could be drawn between areas that have accumulations of 100 cm, 150 cm, 200 cm etc. of water equivalent. The interval between the isolines is particular to each glacier (e.g. 50 cm or 100 cm, etc.), as it may be necessary to decrease or increase the intervals if the accumulation is unusually small or large. An example of a completed accumulation map is shown in Fig. 7.1.

Similarly an ablation map (i.e., a map showing the summer balance) may be constructed. The ablation is more closely related to elevation and isolines will usually follow the contour lines on the map, although exceptions may result from the shadow effects of mountains, etc. This strong correlation between ablation and elevation may mean that construction of ablation maps can be replaced by the simple determination of the ablation curve, as mentioned elsewhere.

7.2. Ambiguities

When isolines are constructed it may be necessary to use "common sense" to decide between two or more different possibilities. Although for most options the resulting maps will give almost the same result for total accumulation or ablation. However, for some choices the differences may be considerable (Dodd *et al.*, 1965.) If an ambiguous situation is discovered before the crew leaves the glacier, sufficient additional readings should be taken in the doubtful area. This is why it is absolutely necessary to plot results immediately in the field.

A contoured map can be used to calculate the total accumulation or total ablation, using a planimeter as described in various reports by Østrem (1966). This will normally be done in the office after the field season (see Chapter 13).

7.3. Use of Colours on Manuscript Maps

Contour lines will normally be drawn on base maps to show areas of equal accumulation, ablation, etc. Practice has shown that such maps are improved

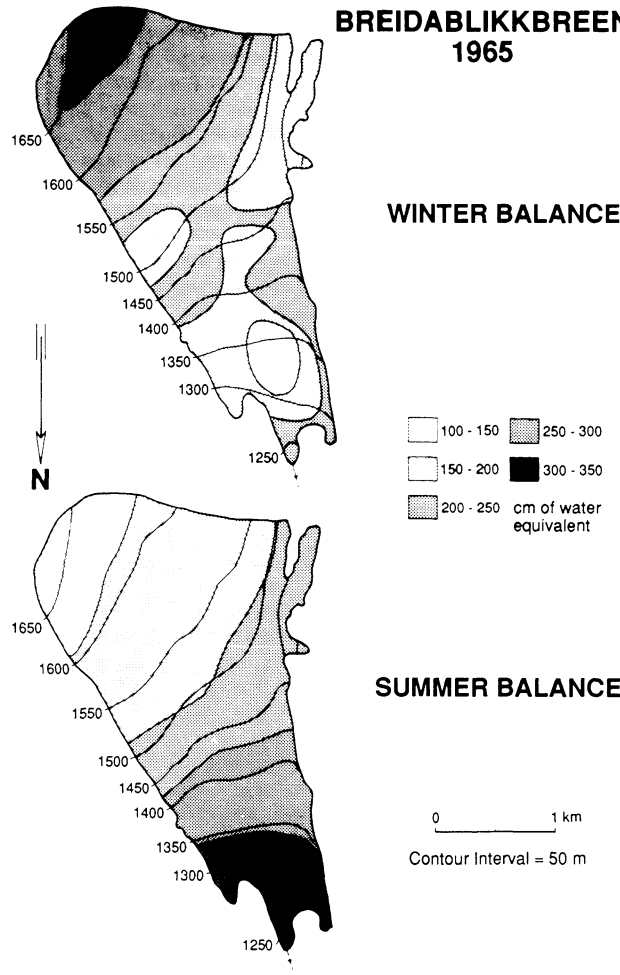


Figure 7.1: Breidablikkbreen
Actually measured data for snow depth, converted into water equivalent, are plotted on a map and isolines are drawn for 100, 150, 200 etc. cm of w.eq. (upper map). By use of a planimeter (or computer and digitizer) the upper winter balance table is constructed (upper table).

Similarly, the ablation is plotted on an identical map and isolines are drawn (lower map). A table for summer balance is constructed (middle table).

Finally, by subtraction, the resulting net balance table is derived (lower table) which shows the net annual balance = +0.16m. The net balance computations should be made available on an easy-to-access, computer data-base format (such as comma or column delineated Lotus 123, D-Base, or Quatro-Pro spread-sheet format, or simple column delineated ASCI files).

BREIDABLIKKBREEN 1965

Winter balance

Elevation m	100 - 150 cm Area km^2	100 - 150 cm W.eq. $10^6 m^3$	150 - 200 cm Area km^2	150 - 200 cm W.eq. $10^6 m^3$	200 - 250 cm Area km^2	200 - 250 cm W.eq. $10^6 m^3$	250 - 300 cm Area km^2	250 - 300 cm W.eq. $10^6 m^3$	300 - 350 cm Area km^2	300 - 350 cm W.eq. $10^6 m^3$	Total Area km^2	Total W.eq. $10^6 m^3$	Specific m	Specific 1/s km^2
1650-							0.221	0.608	0.014	0.046	0.235	0.654	2.78	86.3
1600-1650							0.436	1.199	0.309	1.004	0.745	2.203	2.96	91.9
1550-1600					0.268	0.603	0.814	2.239			1.082	2.842	2.63	81.7
1500-1550			0.325	0.569	0.453	1.019					0.778	1.588	2.04	63.4
1450-1500			0.442	0.774	0.226	0.509					0.668	1.283	1.92	59.6
1400-1450			0.271	0.474	0.314	0.707					0.585	1.181	2.02	62.7
1350-1400	0.061	0.076	0.291	0.509	0.155	0.349					0.507	0.934	1.84	57.2
1300-1350	0.196	0.245	0.204	0.357	0.029	0.065					0.429	0.667	1.55	48.1
1250-1300	0.001	0.001	0.105	0.184	0.091	0.205					0.197	0.390	1.98	61.5
1200-1250					0.004	0.009					0.004	0.009	2.25	69.9
1200-1650	0.258	0.322	1.638	2.867	1.540	3.466	1.471	4.046	0.323	1.050	5.230	11.751	2.25	69.9

BREIDABLIKKBREEN 1965

Summer balance

Elevation m	100 - 150 cm Area km^2	100 - 150 cm W.eq. $10^6 m^3$	150 - 200 cm Area km^2	150 - 200 cm W.eq. $10^6 m^3$	200 - 250 cm Area km^2	200 - 250 cm W.eq.	250 - 300 cm Area km^2	250 - 300 cm W.eq. $10^6 m^3$	300 - 350 cm Area km^2	300 - 350 cm W.eq. $10^6 m^3$	Total Area km^2	Total W.eq. $10^6 m^3$	Specific m	Specific 1/s km^2
1650-	0.235	0.294									0.235	0.294	1.25	38.8
1600-1650	0.414	0.518	0.331	0.538							0.745	1.056	1.42	44.1
1550-1600			1.082	1.764							1.082	1.764	1.63	50.6
1500-1550			0.620	1.163	0.158	0.356					0.778	1.519	1.95	60.6
1450-1500			0.009	0.017	0.659	1.483					0.668	1.500	2.24	69.6
1400-1450					0.382	0.860	0.203	0.558			0.585	1.418	2.42	75.2
1350-1400					0.022	0.050	0.485	1.333			0.507	1.383	2.72	84.5
1300-1350							0.054	0.149	0.375	1.219	0.429	1.368	3.19	99.1
1250-1300									0.197	0.640	0.197	0.640	3.25	101.0
1200-1250									0.004	0.013	0.004	0.013	3.25	101.0
1200-1650	0.649	0.812	2.042	3.482	1.221	2.749	0.742	2.040	0.576	1.872	5.230	10.955	2.09	64.9

BREIDABLIKKBREEN 1965

Mass balance

Elevation m	Area km^2	Winter balance Total $10^6 m^3$	Winter balance Specific m	Winter balance Specific 1/s km^2	Summer balance Total $10^6 m^3$	Summer balance Specific m	Summer balance Specific 1/s km^2	Net balance Total	Net balance Specific m	Net balance Specific 1/s km^2
1650-	0.235	0.654	2.78	86.3	0.294	1.25	38.8	+0.360	+1.53	+48
1600-1650	0.745	2.203	2.96	91.9	1.056	1.42	44.1	+1.147	+1.54	+49
1550-1600	1.082	2.842	2.63	81.7	1.764	1.63	50.6	+1.078	+1.00	+32
1500-1550	0.778	1.588	2.04	63.4	1.519	1.95	60.6	+0.069	+0.09	+ 3
1450-1500	0.668	1.283	1.92	59.6	1.500	2.24	69.6	-0.217	-0.32	-10
1400-1450	0.585	1.181	2.02	62.7	1.418	2.42	75.2	-0.237	-0.40	-13
1350-1400	0.507	0.934	1.84	57.2	1.383	2.72	84.5	-0.449	-0.88	-28
1300-1350	0.429	0.667	1.55	48.1	1.368	3.19	99.1	-0.701	-1.64	-52
1250-1300	0.197	0.390	1.98	61.5	0.640	3.25	101.0	-0.250	-1.27	-40
1200-1250	0.004	0.009	2.25	69.9	0.013	3.25	101.0	-0.004	-1.00	-32
1200-1650	5.230	11.751	2.25	69.9	10.955	2.09	64.9	+0.796	+0.16	+ 5

considerably by the use of colour. Coloured maps will serve as a base for further calculations (such as area measurements by planimeter) and for drafting. They will generally not be reproduced directly, but are considered as manuscript maps and kept in the files.

A standardized and consistent use of colours will facilitate future work on the manuscript maps so the following system should be used whenever possible:

0 - 50 cm	water	equivalent		: yellow
51 - 100 "	"	"		: light red or pink
101 - 150 "	"	"		: light green
151 - 200 "	"	"		: light blue
201 - 250 "	"	"		: orange
251 - 300 "	"	"		: grey or brown
301 - 350 "	"	"		: dark red
351 - 400 "	"	"		: dark green
401 - 450 "	"	"		: dark blue

If the maps only have a 100 cm w.eq. contour interval, the colours will be light red, light blue, grey or brown, etc. As some agencies follow other practices, this list is just a recommendation for new programs.

7.4. Computer Plotting

Recently powerful software programs have become available. It is not within the scope of this manual to describe them all, but particularly mention is made of the program "SURFER" from Golden Software, Inc., which has proven useful for various plotting and mapping procedures used for mass balance calculations (Fig. 7.2).

Computation and plotting of glacier mass balance can now be done almost completed by the computer programs presently available, but are still of questionable reliability. Unless the stake network is very dense and extensive, or the representativeness of each balance pole is frequently verified with high-density grids, and changes programmed into the model, then the computer is far inferior to the human plotter. Contour packages have difficulty recognizing deep gullies, crevasse fields and other obvious topographic features. The type of grid used in the model — triangular or rectangular — dramatically affects the accuracy of the final plot. The human operators must have a good knowledge of the glacier characteristics.

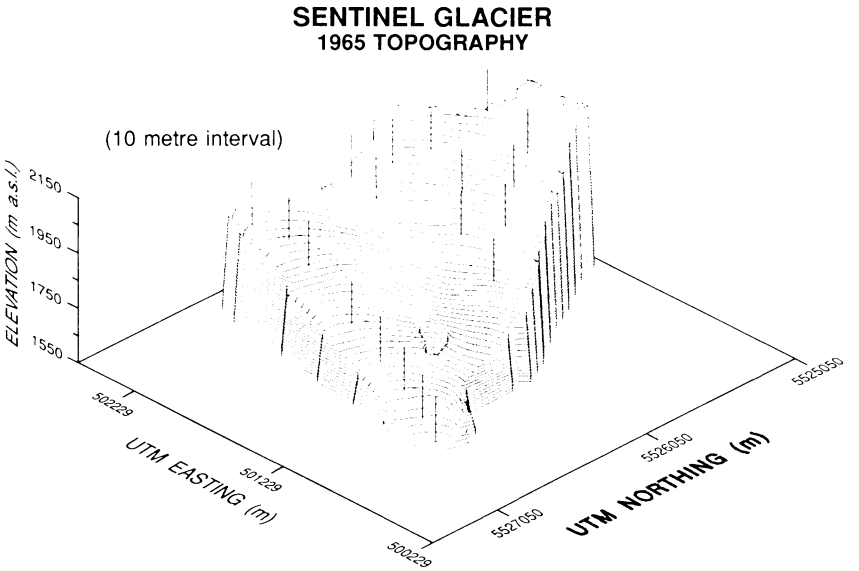


Figure 7.2: "Surfer" Plot of Sentinel Glacier
Topographic model of Sentinel Glacier (for 1965) showing stake locations produced using the contouring and plotting package called "Surfer". A rectangular grid model of the glacier is computed for the coordinates directly surveyed using this highly flexible software that costs approximately $400 Canadian.

CHAPTER 8. METEOROLOGICAL OBSERVATIONS

8.1. General (Fig. 8.1)

In order to correlate ablation and run-off with meteorological conditions, daily weather observations are required. Such observations consist of a few relatively simple data sets which should be made whenever possible. In addition, some more advanced observations can be added when detailed studies are desired. Only the basic observation program is dealt with here.

The times of observation area chosen so that they conform with meteorological observations at permanent weather stations in the area. Thus the data will be comparable with standard data from these sites.

The basic observations made should include: air temperature, humidity, precipitation, wind direction and wind speed. At some stations incoming and outgoing radiation or hours of sunshine may be observed. The glacier ablation is greatly dependent upon variations in meteorological parameters; in some areas more energy is transferred to the glacier surface by warm and moist air masses than by incoming radiation. In other areas radiation may be the most important factor.

8.2. Air Temperature, Moisture, Wind Speed

Because many meteorological parameters are interrelated, one cannot really postulate that any one of them is more important than another. However, experience has shown that air temperature (which in most cases is dependent upon incoming radiation) is closely correlated with the ablation. Therefore, temperature observations should be given priority when only a limited observation program can be carried out. In maritime areas, wind speed and air humidity measurements should also be given serious consideration because condensation of moisture on the glacier surface is an important ablation factor.

8.3. Precipitation

Precipitation is usually measured in a standard precipitation gauge, but measurements at a single point will normally <u>not</u> be representative of the whole catchment area or the whole glacier. For a detailed study of precipitation distribution in the entire basin it is necessary to make observations at numerous points. This can be done by placing small rain gauges of the "Pluvius" type (manufactured by Nyströms Bläckkärls-fabrik, Torshälla, Sweden, for less than $30 each) on the glacier and adjacent ground. This little rain gauge is fairly accurate for observations of liquid precipitation, and probably for wet snow as well; the latter must be melted before the measurements are made. Precipitation occurring as dry snow will often be blown past the gauge so readings will not be reliable. During the summer, however, most precipitation will be in the form of rain, so the observed "Pluvius-values" should be reliable, provided readings are made regularly, e.g., every 5 days. If heavy precipitation has occurred, the rain gauge may overflow and more frequent readings will be necessary.

The "Pluvius" will normally collect up to 35 mm of rain, before it must be emptied. The gauges must be checked before evaporation has occurred. Animals

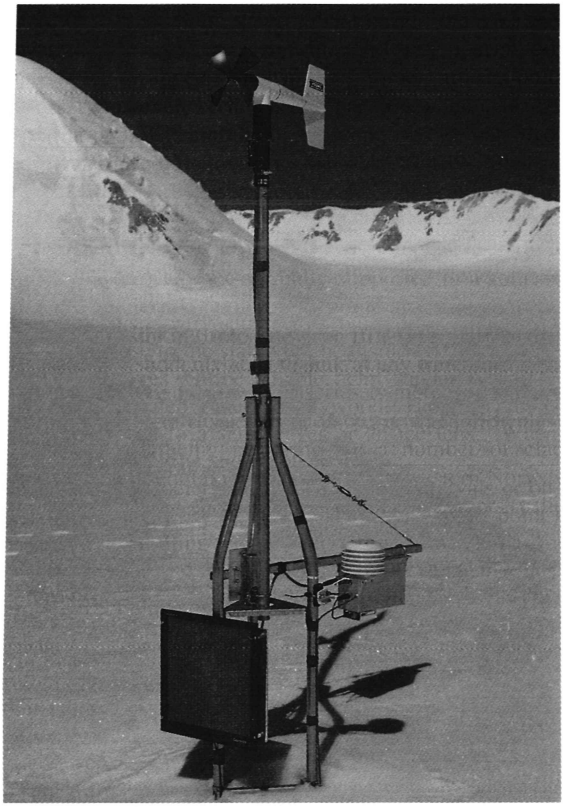


Figure 8.1: Mount Logan Meteorological Station
Meteorological stations such as the one shown on this photograph are installed at glacier research sites. Normally solar radiation, precipitation and humidity is also recorded, but in the case of this instrument set-up the important variables measured were wind speed and direction, snow thickness and air temperature. It is not an easy task to keep such a station erect throughout even a single year, especially when the station is mounted on the glacier surface. In the case of this met station the wind is measured with a very heavy duty wind sensor, air temperature is measured with a 107F thermistor in a 6 inch gill shield, and distance to the snow surface is measured with an ultrasonic depth sensor (UDG01). The temperature measurement is used to correct for the speed of sound in air needed by the distance measurer. The data is stored in a CR10 data logger with a SM192 storage module, buried beneath the winter snow in a data logger box (in this case it was buried by about 3 metres of snow during one winter, but luckily the entire pole station was not buried). The data logger batteries are charged using a solar panel that is also fixed to the met station mast, and the entire station is steadied using heavy-duty guy wires.

have been known to use these small gauges for various purposes; so special care should be made to place the gauge high enough that the gauge will not be affected by the animals or cause them harm. For continuous measurements, the "Pluvius" rain gauge has been replaced with a tipping bucket gauge that is connected directly to a data logger.

Daily precipitation observations will normally be made only at the camp or in its vicinity, whereas precipitation for several days may be collected in more distant gauges.

During cold periods glycerin or an anti-freeze is used to prevent collected rainwater from freezing in the gauge. A known amount (corresponding to a few mm of rain) is placed in the gauge, and corrections to the readings made accordingly. Solid precipitation cannot easily be recorded in any type of gauge; in general only an index value will be obtained.

The measurement of precipitation is subject to numerous errors primarily due to the effect of wind. With proper wind screening the amount of rain and snow collected by the gauge increases but does not entirely eliminate measurement error. Snow is particularly a problem, and because of this other methods (acoustical sounder, snow pillow, specially heated gauges) should be used for wintertime measurements.

If enough gauges are available in the basin or remote sensing of rainfall allows estimation of spatial distribution of rainfall amounts, then maps of precipitation may be formulated for a glacierized basin. This was done, for example, at Ålfotbreen, W. Norway. where all "Pluvius" gauges - numbering more than 20 on a total of 8.6 km^2 drainage area - were observed after two main rainstorms in 1966, and isolines were drawn for selected values in each case.

Maps of the total precipitation were shown for the summer season. All maps showed a similar precipitation distribution pattern - most rain was definitely falling at about 1200 m a.s.l. that season.

The total volume of rain water can be found by measuring the various areas on a such a precipitation map. This calculation is desired to check the discharge measurements. The runoff is the sum of ablation and precipitation in the basin.

In practice the precipitation is nearly impossible to accurately measure at a single point, let alone across an entire drainage basin. Consequently, although precipitation should be measured, its accuracy and spatial distribution should be carefully considered before any conclusions are drawn regarding computed and observed discharge. This is one of the primary reasons for why the Hydrologic Method for measuring glacier mass balance is not considered reliable.

8.4. Some Practical Hints

To obtain reliable figures for daily mean temperature and air moisture, a recording instrument (preferably a thermohygrograph) should be installed in a Stevenson screen near the base camp. A second screen should, if possible, be placed near the equilibrium line on the glacier or in the firn area.

The daily mean wind speed can be obtained from a counting anemometer. This instrument gives the total wind distance (in kilometres) from which the daily

mean wind speed can be easily calculated. This figure is more useful than spot measurements of wind velocity made with a hand-held instrument or similar device.

The total amount of rain for the whole catchment area is calculated by plotting all single gauge observations on the map. Assuming each gauge represents a separate area, the total amount of water can be found graphically. Precipitation maps can be made for the whole summer or for each rain storm. The total amount of rain can be found by methods similar to those used for accumulation maps.

If wind speed and direction are not being recorded automatically, observation of wind direction should be made every morning and evening; usually at the time of temperature readings in the screen. The direction from which the wind travels is noted as well as the number recorded by the anemometer (in miles or kilometres). The difference between the present figure and that noted the day before (if in miles this must be converted into kilometres) is multiplied by 1000 and then divided by the number of seconds between the two observations. Thus, the mean wind speed will be obtained in m/sec. If no anemometer is available, the wind speed should be estimated.

At unmanned stations it is advisable to install an automatic weather station. Various types are available commercially for different prices. A selection should be made after consultation with a meteorological institution.

CHAPTER 9. WATER DISCHARGE MEASUREMENTS

9.1. General

The water draining from a glacierized basin originates from mainly four different sources:

1) Glacier melt
2) Rain falling on the glacier
3) Rain falling on the glacier-free parts of the basin
4) Inflow of ground water

Apart from some water loss to the atmosphere through evaporation (or water gained by condensation in humid areas), the sum of the measured ablation on the glacier and the total volume of precipitation (found by calculations described previously) will be discharged in the glacier stream. To check short-term ablation measurements, it is necessary to measure the water discharge as accurately as possible.

The glacier stream also transports most of the material originating from the glacier's erosion. A continuous observation of the sediment content in the river can therefore be used to study the amount of material eroded beneath the glacier under different conditions (see Chapter 10).

Such gauging stations provide a unique, long-term record from a glaciated alpine basin where complementary long-term records of glacier topography and mass balance fluctuations are obtained. This type of information is essential for glacier hydrologic studies and runoff modelling, but unfortunately to date has not proven very useful for calibrating glacier mass balance. This is because the hydrologic method of mass balance (described in Chapter 14) can only be used in basins where very high quality stream discharge and precipitation measurements are being made. Quite often neither are obtained to the degree of accuracy required. Still, proper physically-based models of alpine areas can only be developed if high-quality runoff data are available over a long time period, and if glacier accumulation and melt studies are conducted at the same time. Vast alpine and arctic regions of Canada are covered by glaciers, yet very few of basins are gauged near the source of this water. Many large river basins in Canada are strongly influenced by glaciers, particularly during late-summer months.

Operating stream-gauging stations, especially those with weirs already installed, are essential if mass balance data obtained from glacier basins are to be fully utilized in physical models. Consequently these stations must be properly maintained by trained staff and stage-discharge rating curves be regularly tested at all water levels.

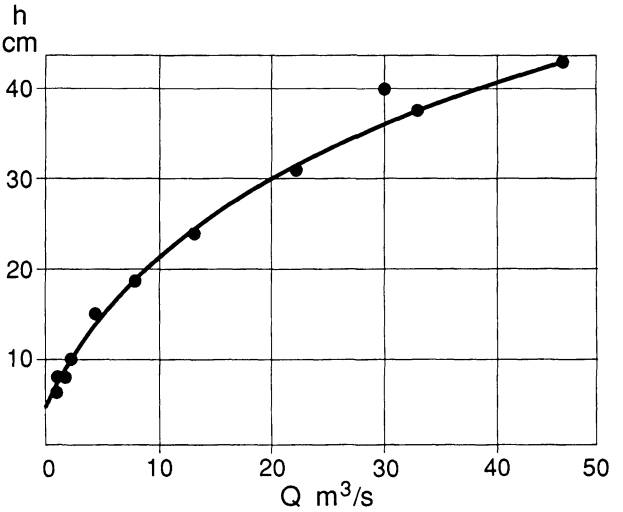
9.2. Rating Curve and Number of Readings

Discharge calculations are generally based upon water-level readings on a vertical gauge or on data from an automatic water-level recorder. The relationship between the water level at a given site and the actual discharge (expressed in m^3/sec) must be determined by many direct measurements of river flow for different gauge

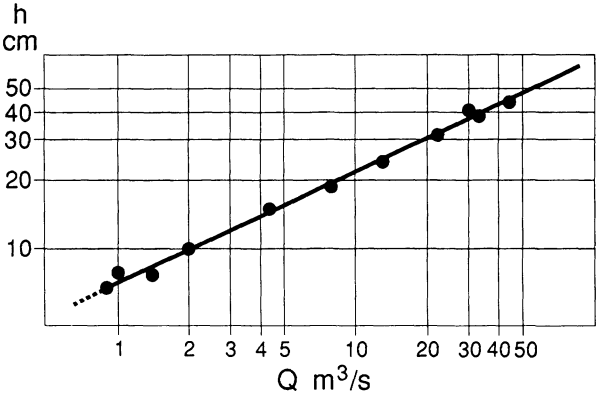
RATING CURVES

Observations

Water level h (cm)	Dis-charge Q(m^3/s)
7	0,9
8	1,0
8	1,4
10	2,0
15	4,3
19	8,0
24	13,0
31	22,0
40	30,0
38	33,0
43	45,0



Linear Plot



Logarithmic Plot

Figure 9.1: Rating Curves
A rating curve for Place Glacier was measured to relate stream discharge to water level at the weir located below the glacier.

readings to obtain a graph of levels vs. discharge, the rating curve (Fig. 9.1), for each measuring site.

It is assumed that the river discharge conditions will not be disturbed by changes in the river bed. Ideally, the cross-sectional area should be controlled by bedrock and the vertical gauge placed in a little pool above this control. If the channel changes, the rating curve is no longer valid and a new curve must be constructed, i.e., a new series of direct discharge measurements must be made.

Direct measurements of water discharge can be obtained in many ways. For streams with "laminar flow", a standard current meter can be used to measure water velocity, but this method is difficult to use in glacier streams because they are often highly turbulent. Turbulent streams can be measured using colorimetric or fluorometric methods, but this is not recommended if the sediment content is high or for environmental reasons. It is best to use a method which is independent of the sediment content in the water, such as the "salt method". Here, an agent is poured in the river in one point and measured at another point downstream, the dilution will reflect the water discharge.

All direct discharge measurements are difficult to perform without training and specialized equipment. The methods will not be described in detail in this manual; for further information see Østrem (1964) or basic reference texts such as Dackombe and Gardiner (1983).

Once a rating curve has been established all future gauge readings can be easily transformed to discharge figures. However, if the river cross section changes or the gauge is moved relatively to the river bed, it is obvious that a previously obtained rating curve will no longer be valid and a new series of direct discharge measurements will be necessary to establish a new rating curve. It is therefore important that the crew observe conditions in the river and check the position of the gauge several times during the summer.

Water discharge in glacier streams is normally subject to great daily variation, so to obtain accurate information about the total discharge, numerous staff readings must be taken throughout the day and night, or recorded automatically. In addition, the velocity distribution of the stream and the cross-sectional area must be measured regularly, especially at a range of water levels.

From data obtained during the summer it will be possible to construct a curve showing water level variations during a normal day.

Shortly after heavy rainfalls or during periods of very high temperatures a river will not follow the normal daily variation pattern so frequent observations then become essential. Under special circumstances when extremely high discharge is expected the gauge must be observed almost continuously, or at least every hour.

9.3. Water Level Recording

9.3.1. Staff Gauges

A gauge is a vertical rod marked in metres and centimetres and placed so that the height of the water level can be measured. The gauge should be placed in the river where the water is as tranquil as possible. A pool in bedrock may be the best

site to erect a gauge, but it must be located so that both a small discharge and a very large discharge can be measured directly.

In the fall, or when the water discharge is very low, it is necessary to determine a reading on the gauge that corresponds to zero water discharge (i.e., generally the height of the threshold in the pool). This reading gives important information for construction of the rating curve. A staff gauge is required for calibration purposes, even if an automatic gauge is installed.

9.3.2. Automatic Gauges for Stage Recording

To reduce the time-consuming observation program described above, an automatic gauge can be installed. This, however, is not dealt with to any great extent in this manual. In principle, the original automatic gauge consist of a float, a counter-weight and a recording device, and these are still used in many locations. Variations in water level move the float and the counter-weight and the movement is transferred to a pen that registers the movement on a paper-wrapped drum. The drum is driven by a clock and one rotation may be completed in 24 hours, one week or a month. For glaciological use, one must select the most suitable period related to the frequency of summer visits to the glacier.

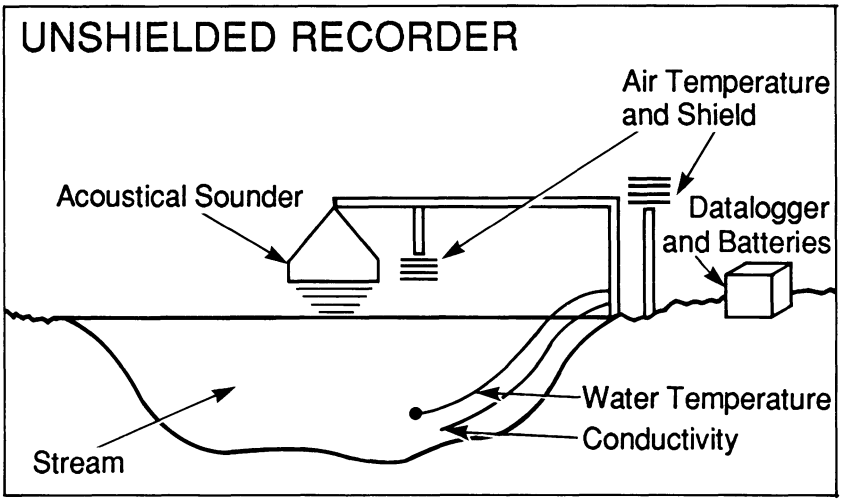
Every time the chart is changed or data retrieved from the data logger, and, if possible, once or twice in between, the water level, as read on the vertical gauge, should be written directly on the chart together with information about date and time and noted. This check is important when the record is used for calculating total water discharge. There is a brief discussion of data loggers in Appendix VII.

As the records from an automatic gauge give information about water level (cm) it is necessary to convert the data into discharge figures (m^3/sec) before further calculations are made.

9.3.3. Gauging Methods

Several methods can be used to monitoring stream stage, which must then be related to stream discharge. This is done through a rating curve mentioned previously (Fig. 9.2). Both a float gauge and an acoustical sounder (UDG01) have been used in the weir at the Place Glacier stream since July 1990; prior to this just a float gauge was used. The placement of the acoustical sounder in the stream is shown in Fig. 9.2. Both methods proved reliable when the acoustical sounder was placed within the stilling well of the weir.

A similar acoustical sounder was also used at Sentinel Glacier, with relatively good success. Its placement is sketched in Fig. 9.2). As might be expected, the instrument within the Place stilling well was less prone to erratic fluctuations than the unshielded, suspended sounder at Sentinel. Accurate measurement of air temperature along the sounder path length is critical. When the temperature gradient between the instrument and the stream was minimal, and the temperature gradient fluctuations were also minimal, then the data showed the least amount of erratic fluctuation. When the acoustical sounder was completely shielded from irregular heating effects at the stream gauging station (Fig. 9.2), then the data proven it to be a more reliable stream stage monitoring tool. Bubble gauges and pressure transducers are more expensive alternatives for measuring water levels, but these are



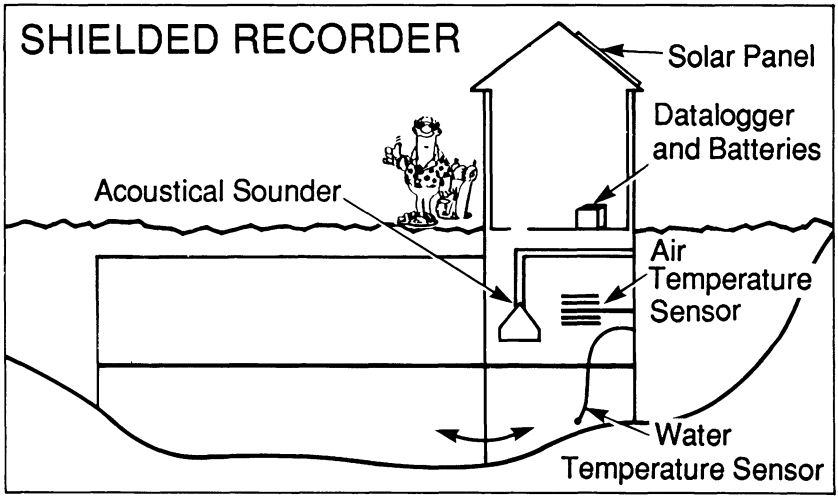


Figure 9.2: Float Gauge and Acoustical Sounder
A float gauge or an acoustical sounder are examples of water level recorders that may be used in conjunction with a rating curve to obtain continuous measurements of stream discharge. The diagrams show how an acoustical sounder may be suspended over a stream with no permanent weir, as compared to how it may be placed in the stilling-well of a weir for maximum accuracy. Also shown is how the data should be recorded with air temperature and water temperature, and by using a well protected data logger.

easily affected by bedload transport and are more difficult to maintain at glacier terminus streams.

As data loggers become more affordable, they should provide the best method for recording the data. A program used for a 21x data logger and the equipment used on this sketch is given in Appendix VII. The logger used is shown in Fig. 9.3, together with equipment necessary for retrieving the data and a small computer. Telemetry is also becoming more affordable and methods already exist whereby data can be sent using relatively inexpensive radios connected to phone jacks. The data should always be stored in the logger at the field site in case the telemetered data is somehow lost during transmission.

9.3.4. Calculation of Discharged Water Volume

Calculations of water volume discharged during a given time interval can only be calculated if a rating curve has been established. From the readings on the gauge (the vertical scale), from the automatic gauge chart, or the data logger file, it will be possible to calculate the water discharge for any period. If the water level shows rapid fluctuations within short time intervals, it may be necessary to calculate the discharge every hour or at even shorter intervals. When the water level shows small variations, i.e., when the discharge is fairly constant, periods of several hours can be used for the calculation. Generally a 6-hour period will be sufficient.

For each selected period, a mean water level should be determined. The corresponding water discharge is found from the rating curve or from a nomogram. It is anticipated that it will be representative of the period and the total volume of water can be found by simple multiplication.

When necessary, the volume of water discharge should preferably be calculated for the following 6-hour periods: 0000-0600, 0600-1200, 1200-1800 and 1800-24 (midnight). The greatest discharge will probably occur during the last two periods so special attention should be given to possible variations within them. The results of the calculations should be recorded on summary forms. The sum of the discharged water volumes in the above-mentioned 6-hours periods is called the daily discharge. Variations in daily discharge may later be compared with meteorological parameters, such as daily mean temperature, daily precipitation, etc. (see Chapter 13).

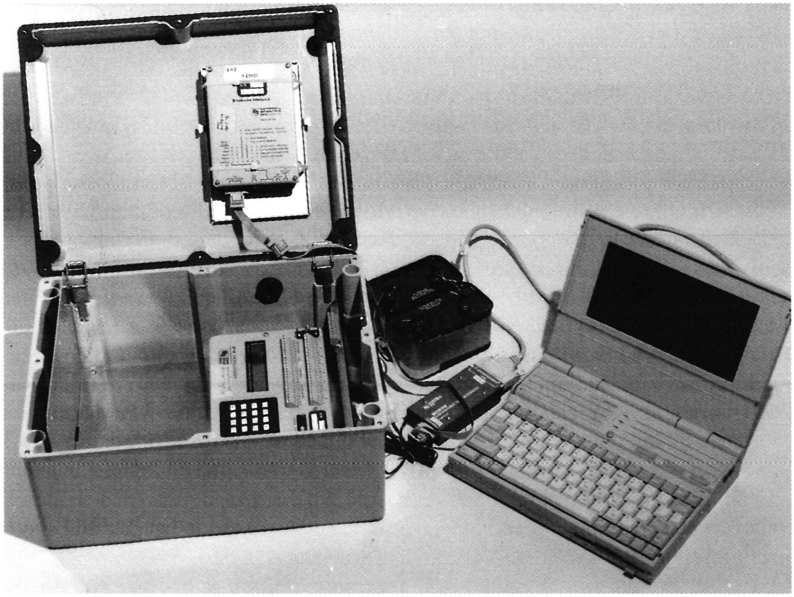


Figure 9.3: Data Logger, Storage Module and Computer
A data logger is used to record instrument data such as for wind, air temperature, solar radiation, stream water level, FMCW radar data, and can be used to FFT (Fast Fourier Transform) frequency data, plus many other tasks. In this photo a Campbell CR21x data logger is shown with a CR21 storage module, keyboard, RS232 interface, interface battery, and laptop computer used to retrieve the data. A direct wire connector is also useful, as well as a storage module (SM62 and SM192 storage modules shown). The CR21 can not be used with the UDG01 to measure distance to water or ice surfaces. Instead, the CR21x, CR10 (not shown) must be used; these newer models are much more versatile.

Chapter 10. MEASUREMENTS OF SUSPENDED LOAD

10.1. General

Glacier streams transport great loads of sediment (silt, sand, gravel, rocks and boulders) that result from glacier erosion. Part is carried in suspension, and some is moved along the bottom. The sizes of the particles that can be moved by the stream at various water velocities are not dealt with in this manual (see Hjulström, 1935; Sundborg, 1956; Østrem, 1975; and others).

As the bed load is only a relatively small part of the total material transport in the stream, good information about the rate of glacier erosion can be obtained by taking samples of river water, analyzing it for suspended material, and calculating the sediment transport. The bottom transport of fragments, including boulders, is difficult to observe and, until reliable methods for its determination have been developed, must be estimated. From experience at several Norwegian glaciers, where simultaneous observations of both suspended and bottom load were possible (e.g., by measurements of delta growth or by collecting the total bedload in a glacier stream), it is assumed that the suspended load accounts for about 40 to 50 per cent of the total load carried by the glacier stream — at the ice front. The amount of suspended material is relatively easy to determine, as it can be calculated from known water discharge and laboratory analysis of water samples.

Results of sediment studies will not only give valuable information about glacier erosion under various conditions but also indicate the possible rates of sedimentation that can be expected in reservoirs and lakes along rivers from glacierized areas. Natural or artificial lakes are greatly affected by sedimentation and, in the case of water utilization, the capacity of storage dams will be gradually reduced (e.g., Østrem and Olsen 1987). The smaller fractions which pass through the lakes and reservoirs will, in the case of water-power stations, drastically increase the wear on turbines, etc. Thus, studies of sediment transport in glacier streams are of direct practical importance.

10.2. Location of Sampling Site

Water samples should be taken as close to the glacier as possible, but below any confluence of melt water channels originating from the glacier. Sampling sites are selected anywhere the flow is turbulent so that the sample is representative of the total discharge past the site at the time of sampling. This means that the sample could be taken just below a small waterfall or in a section of extremely turbulent water.

10.3. Sampling Method

Numerous water samplers have been designed but most are developed for laminar flow and are not suitable for highly turbulent streams. Experience has shown that simply lowering a bottle into the turbulent water and then raising it after filling is probably as good as using any complicated water sampler. It is important that the bottle be raised immediately after it has been filled, otherwise additional sediment will enter it (Hjulström, 1935, p.386). The size of each sample should be 1 litre, but as most readily available bottles are not calibrated to this volume, it is necessary to

measure their exact volume. The volume of the water sample must be noted on the form on which all sediment sampling data are collected. If shipping numerous water bottles to the laboratory is not easily arranged, the samples should be filtered in the field. If chemical analyses are to be done on the sediment and water samples, they should be stored at about 4°C and kept in a light-proof container during shipment.

10.4. Filtering

The filter paper will be further processed in the laboratory (see below). The filtering procedure should be carried out where no additional material can blow into the sample or filtering equipment. A tent (without a floor) may be used for this purpose. The filtering can be done either by vacuum filtering or by pressing the water through the filter paper. In the latter case, the filtering procedure takes only a few minutes for a 1-litre sample. It is simple to use in the field, whereas the vacuum method is more difficult to obtain.

Paper filters, such as Munktell No. OA, give reliable results when sediment concentrations are high. If concentrations are low, or if studies of organic content are of special interest, a glass-fibre filter may be used (Whatman GF/C is recommended). This filter retains its net weight when it is burnt (see below), but it has to be dried and carried to the laboratory in Petri dishes.

A pressure filtering device for field use is shown in Fig. 10.1 as well as a vacuum filtering device for laboratory work.

After filtering, one should check that all sediment which may have settled in the bottle is included in the sample. Only sediment-free water should be used to rinse the bottles. The filter paper is left to dry in the air and is then wrapped and placed in an envelope marked with the sample number and other pertinent data. Only one filter paper is placed in each envelope, but several envelopes from one day's sampling may be collected and transferred to a larger plastic bag.

Information about all samples should immediately be transferred to a standard form on which the sample number and other data are noted (see specimen form in Appendix VI). The form should be completed in duplicate, one copy inserted in a separate binder, the other packed together with the samples. This is required for proper handling of the samples in the laboratory.

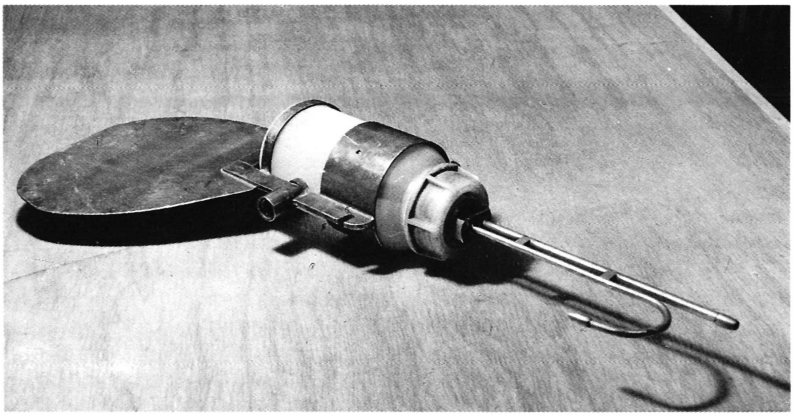
At the end of the season all sediment samples should be packed (including the above-mentioned forms) and brought to the head office for laboratory analysis. Samples should not be sent by mail or freight, but brought personally by a member of the field party as hand luggage.

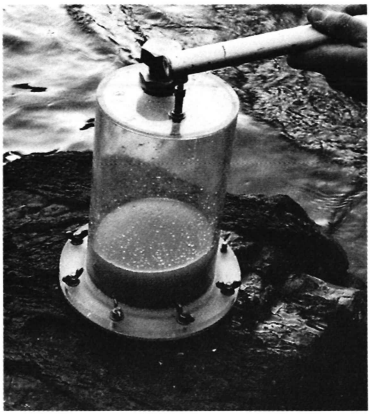
10.5. Numbering of Samples

A special numbering system has been developed for sediment samples. Each number consists of eight digits, the first four indicate the date, the last four the time of the day when the sample was taken. Example: 07131145 means that the sample was taken on July 13 at 11.45 hrs.

10.6. Turbidity Meter

The amount of sediment in a stream may be monitored using a simple, sunlight-protected, photo-sensitive device separated from a known light source at





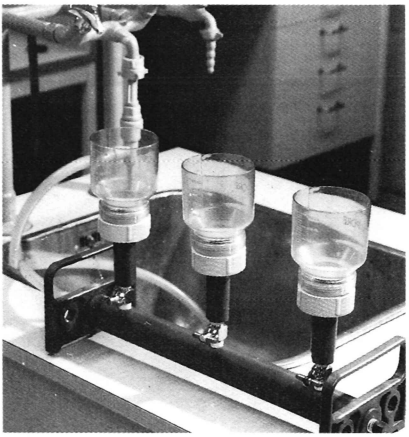


Figure 10.1: Depth-Integrating Sampler/Filtering Equipment
This photo shows a depth-integrating sampler and related filtering equipment. In laminar streams, a representative water sample can be obtained by a depth-integrating sampler, (upper picture).

The pressure-filtering equipment consists of a plastic cylinder with a perforated metal bottom. A water sample is poured into the container after that a filter paper is placed on its bottom. The pressure is raised with a bicycle pump so that the water is pressed through the filter. A 1-litre sample can be processed in a few minutes.

A suction filtering equipment needs vacuum, which can be obtained by a simple ejection pump. The equipment shown utilizes glass-fibre filters.

a determined and fixed distance. As the amount of suspended sediment in the water increases, the light reaching the photo-cell will be reduced and the turbidity reading will be correspondingly higher. The turbidity meter must be regularly calibrated and shielded unless a light source of a wavelength greatly different from sunlight is used.

10.7. Grain Size

Grain size distribution is best measured once the samples are returned to the laboratory. Once there a number of different techniques can be applied ranging from basic filtering, pipette and weighing methods, to more complicated laser scattering and surface adsorption methods (Brugman, 1986). A discussion of these is beyond the scope of this manual.

10.8. Laboratory Procedures for Ashing Sediment Samples

This section describes an ashing procedure originally tried in the Institutes of Geography at the Universities of Uppsala and Stockholm, Sweden. For several years thousands of sediment samples from glacier streams have been processed uniformly, so it is strongly recommended that the same procedure be followed to allow for comparison of the results.

In addition to the traditional ashing procedure, experiments have also been made with methods that do not include ashing. Filtering, drying and weighing the paper (with corrections for the weight of the filter paper) and the use of membrane filters, glass-fibre filters, and suction pumps have been tried. The results showed fairly good agreement with data obtained by the ashing procedure except in cases of very low sediment concentration, when the moisture in the filter paper caused unexpected large errors.

When samples arrive at the laboratory; they should be checked, as regards sampling place, so that no confusion may arise between samples from different areas. The samples from one and the same location should generally be handled consecutively and the results transferred to a laboratory form or a diary. The laboratory work is briefly described below

(1) A number of empty porcelain crucibles with lids are weighed. They are then placed in an ashing oven and kept at 700°C for two hours. After cooling off, they are weighed again to ensure that no weight differences appear. For new and unused crucibles, the weight will normally change slightly during this first procedure.

(2) One filter paper is placed in each crucible.

(3) One crucible at a time is carefully heated by Bunsen burner so the paper starts burning. The lid is placed so that is covers only part of the crucible to enable the smoke to escape.

(4) After this procedure, i.e., when the smoking has almost ceased, the crucibles are placed in the ashing oven, at a temperature of 600-650°C, with the lids

covering them completely. NOTE: For glass-fibre filters the upper temperature limit is 500°C.

(5) After two hours at this temperature, the crucibles are transferred to a drying oven and kept at 105°C until they can be processed further.

(6) An appropriate number of crucibles, still containing the ash, are then transferred to a desiccator and from this moved one-by-one onto an analytic scale. The crucibles are weighed as quickly as possible, as the moisture in the air will immediately tend to change the weight of the dry ash. As a test for possible errors originating from humidity, some crucibles are moved back to the drying oven and the procedure started again at stage (5). No error larger than 0.2 mg can be accepted.

(7) The ash is removed from each crucible using a suitable brush or similar device, and the empty crucibles weighed again. To check that they have not changed their original weights (see paragraph (2), it is important that each empty crucible be weighed every time it is used. The weight varies almost continuously, due to humidity changes.

(8) The gross and net weight of the crucibles as well as the weight of the ash are plotted on a form or in a suitable table in the laboratory diary. From the information about the original volume of the water sample, the sediment concentration (in mg/litre) is calculated. From the information about the river discharge at the time of sampling, the sediment transport (in g/sec) is also calculated. Both the sediment concentration and the sediment transport are given in the final report from the laboratory.

NOTE: if the oven temperature rises above the above-mentioned temperature, carbonates will easily start to decompose and a too small sediment content may be obtained. On the other hand, if the temperature is too low, some organic components will not be completely removed from the samples. However, when samples are taken close to a glacier, there should be no risk of having too much organic material in the river water.

CHAPTER 11. SURVEYING TECHNIQUES AND INSTRUMENTATION

11.1. General

Glacier maps, particularly constructed for glaciological studies, are needed for all basins as a base for plotting results, stake locations and other data, etc. Initially provisional maps can be made by enlarging existing small-scale topographic maps, but these should be superseded with more detailed maps constructed from air photographs or satellite remote-sensing images. Regardless of which are available, affordable and of sufficient accuracy, it will normally be necessary to survey the glacier several times using conventional methods. This is not a task for just anyone in the field party, since specific training, practice and proven proficiency in surveying techniques is required. However, crew members should become familiar with the topic and make preparations for assisting in later surveys.

Vantage points overlooking large parts of the glacier should be marked so that they can be identified on vertical photographs or remote-sensing images. Furthermore, if the required satellite or aircraft overpass is expected soon, additional key positions on the glacier should be marked (see below). Remote sensing methods are briefly covered in Appendix VIII, but can best be understood by referring to summary reference manuals and reports written for remote sensing analysis (e.g., Canada Centre for Remote Sensing, 1991; Franklin *et al.*, 1991; RADARSAT International Inc., 1990; Rott *et al.*, 1988; Werle, 1988).

11.2. Ground Control and Marking Points

11.2.1. Selecting Fixed Points

Points on bedrock, or on stable ground, overlooking large parts of the glacier should be selected. At these locations, crew members should build a cairn at the first possible occasion and mark it with a flag on a vertical pole. If a mountain peak is very steep and undoubtedly the highest point within several hundred metres' radius, it is <u>not</u> necessary to mark it further with a cairn or flag. For all other points, however, it is necessary to mark them so that they will be clearly visible on air photographs, and if possible also satellite images. They must also be easily identifiable for ground triangulation purposes.

11.2.2. Marking Fixed Points

Pieces of white cloth about one metre wide and at least 3 m long should be placed in an L with the inner corner of the L at the selected point. White paint is better than cloth, and can be applied in a similar pattern on the ground. If bedrock is not exposed, it is acceptable to move boulders into some suitable pattern. Note however, that when the painted area is seen from above it should form a continuous white surface. Approximately 2 litres of white paint are required to make one such mark. Large, bright white cloth may suffice if properly secured. When the ground is marked for aerial photography it is also advisable to paint the top of the cairn so that it can be readily recognized. Where space does not permit an L to be marked on the ground another pattern, such as a triangle or a square, might be used. Note however, that in the air photographs a markers can easily be mistaken for a natural

spot so any shape selected should not be "natural". (The L-shaped mark described above is probably the least natural shape.)

11.2.3. Marking Glaciers for Air Photography or Satellite Imagery

It is of great value if the main stakes or at least the most important ones are marked so that their position can be directly recognized and plotted from air photographs. Prior to air photography the following procedures will make stakes visible on the photographs:

11.2.3.1. Glacier Ice

Stakes on the glacier ice will normally not be visible on the air photographs unless taken from a low altitude. Large flags however, might be visible on photographs and it is recommended that large pieces of cloth be attached to each main stake. If the glacier is very dirty a white or fluorescent flag can be used; if the glacier ice is comparatively clean a dark colour should be used. Either the flag itself or its shadow (or both) might then be recognized on the photographs. In Canada, bright orange and yellow fluorescent flags, of woven, plasticized cloth, are preferred. Yellow is best for surveying at great distances, but orange is also very easy to see.

11.2.3.2. Accumulation Area

The location of stakes in the firn area may be marked by powdered dye, lampblack, or fine-grained, dark sediment, distributed on the snow surface in a circle around the stake. A circle is created by means of a 10-metre rope attached to the stake. The marker material is sprinkled in the circle making a very thin layer approximately 1 m broad. Two kilograms of lampblack or sediment, or about 3 kg of powdered dye, should be sufficient to make a complete ring. If time is short or only limited amounts of dye are available a half circle may be sufficient.

The rings should be inspected and reinforced until it is certain that air photographs have been taken.

11.2.3.3. Supplementary Ground Control

As a horizontal check for the map compilation, at least two distances between outstanding points should be measured with a tape. The distances can be measured between two stakes that are marked with dye in the firn area, or between two points near the glacier tongue. (Large, single rocks on the glacier, a hut or similar outstanding features on the ground might be used). The horizontal distance, at least 200 m, should be measured as accurately as possible and all information about the selected point should be recorded. This information is vital for map compilation.

11.3. Surveying Instruments and Methods

11.3.1. Compass and Altimeter

In most field situations a compass and altimeter are the most basic surveying instruments that should be carried by the field party at all times. Not only are they useful for basic navigation, but they can also be used for measuring pole tilt and general pole location in addition to the more elaborate surveying techniques described

below. Quite often with simply a map, compass and altimeter one can locate poles with sufficient accuracy that their position can be verified for mass balance computations. These data also help orient the local surveying coordinate system to true north, if no other method is available. At each stake the compass should be used to measure local surface slope, and to aid in accurately sketching and recording the shape and tilt of the pole for future reference if it looks crooked.

Throughout the day, altimeter readings and time of day should be recorded for several reference points of known elevation, and then at the end of the day recorded again at the known altitude of the starting point. The altimeter should not be read in the direct sunlight, and should be checked for reliability under changing temperature conditions. Barometric pressure and/or altimeter readings should be taken at the beginning and the end of each survey, if laser distomats are used then the distomat distance can be properly corrected for changes in atmospheric pressure using the manufacturers PPM (parts per million) correction tables.

The usefulness of the compass and altimeter should not be underestimated.

11.3.2. Plane-Table and Alidade Surveys

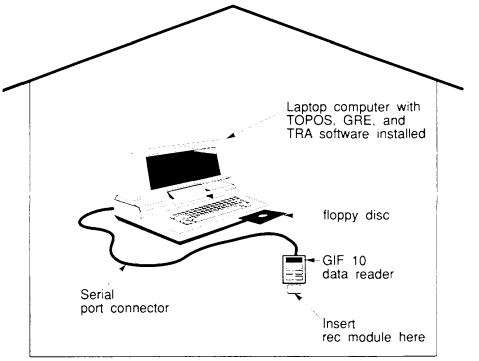
Plane-table surveying differs from theodolite surveying in that the map is drawn as the field work is in progress. Procedures are described in basic geodetic surveying texts (Maslov *et al.*, 1980). A telescopic alidade is used to sight and measure angles that are then plotted on the plane table board upon which the alidade is mounted. This method of surveying is only used when other methods are not available, but can be very useful for detailed mapping if the staff are sufficiently well trained.

11.3.3. Theodolite Measurements

A theodolite is a highly accurate optical device that can be used to measure horizontal and vertical angles in the field. In order to obtain useful data using this instrument, field personnel must be trained in survey techniques that are beyond the scope of this book. Use of the theodolite involves proper setting up of the tripod and levelling the instrument, shading the instrument from the effects of irregular heating due to solar radiation, reference mark sighting, angle measurement and reference mark closing techniques, as well as proper methods for transporting and caring for these delicate instruments. The height of the instrument above the bench mark is called the "H.I." and is normally defined as the vertical distance from the top of the bench mark to the optic centre of the theodolite; the height of the reflector is "H.R.", and the top-of-stake to ice is called "TTI" (Fig. 11.1).

Many older theodolites can read angles to a higher degree of accuracy than the newer electronic theodolites, and some such as the early Wild models, are still considered some of the most accurate instruments ever built. For example the Wild T2 theodolite can read to an accuracy of ½ second of arc (0.5'') in a 360 degree circle. In addition, the features of the T2 include magnification of 30X, minimum focusing distance of 2.2 metres, 29 metre field of view at 1 kilometre and a weight of 6 kg.

Some of the older WILD instruments still used in Canadian glacier studies are capable of taking equally accurate readings but weigh significantly less. The models



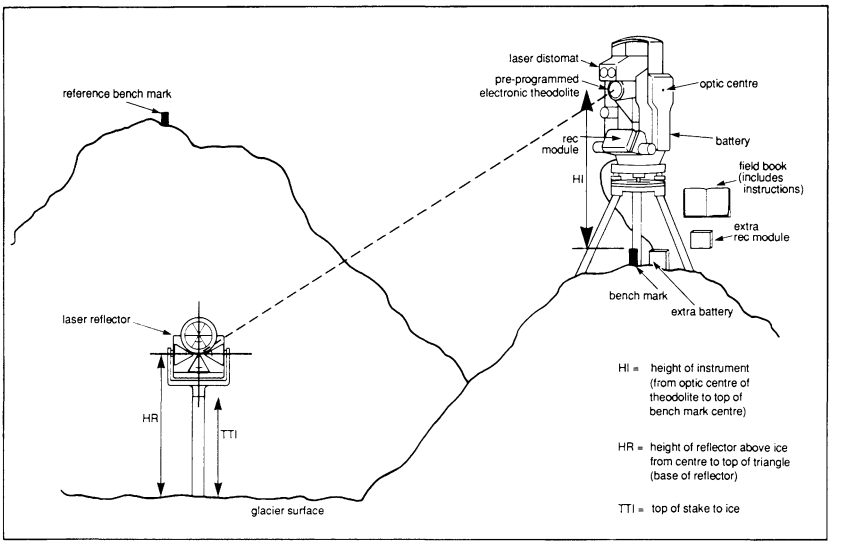


Figure 11.1: Surveying Instruments and Measurements
Wild electronic theodolite and distomat that are used for surveying the glacier and locating stakes. Two sketches are showing how the instrument is used to survey the coordinates of a stake, TTI distance, bench marks, and how data is retrieved.

are more cumbersome for the unpractised user because the scope images are inverted from their actual orientations, and repeated bubble levelling is required for the vertical readings; also the horizontal level is sometimes more sensitive. With the older instruments, it is often easy to accidentally turn a levelling knob when you may intend to just adjust the horizontal position of the telescope, thus easily destroying the entire set of readings you just took.

Most newer theodolites are able to automatically relevel for vertical readings either using internal surface reflection techniques, for non-electronic theodolites in addition to the electronic capability of the theodolite.

Theodolites may be used together with a known baseline distance to compute the coordinates of points on a glacier by triangulation from two or three fixed-reference markers, or by resection from the glacier surface to reference markers surrounding the glacier margin. If used properly and if done using a number of reference marks, triangulation and resection allow accurate computation of surface coordinates.

11.3.4. Using Stadia Method to Measure Distances

If other methods are not available for measuring distance, then a simple one to use is called the stadia method (Maslov *et al.*, 1980, p.149). This involves measuring the vertical angle subtended by a stadia rod of known length, and then also knowing the focal length characteristics of your theodolite. Alternatively, if the angle subtended by a known length l_{rod} is read to a high degree of accuracy, then the distance to that object may be estimated using basic trigonometric relationships. For small angles the angle subtended, expressed in radians, is approximately equal to the tangent of that angle, and therefore the distance may be quickly estimated without a distomat, provided l_{rod} is accurately known.

Using this method the slope distance to an object may be computed using only the angle subtended of a known length of a rod. The accuracy of these reading will depend upon primarily upon the accuracy of reading angle subtended and the distance of the rod; it is possible to locate an object to less than 10 metres, depending upon the total distance to the object, the accuracy of each reading involved, and local atmospheric refraction effects. Of course, if other methods are available such as direct taping of distances and/or distomat measurements, then stadia or angle subtended methods should not be used.

11.3.5. Electronic Theodolite and Distomat

The electronic theodolite and distomat combination allow survey data to be obtained very rapidly and are the most convenient instruments to-date for surveying. The combination used in Canada includes a Wild TC1600 theodolite with rec-module storage capability and a DI1600 medium range electronic distance meter (EDM), as shown in Fig. 11.1. It takes 0.9 second to take an angle reading and the values are recorded to an accuracy of 0.5''. If the coordinates of the reference markers (bench marks) are programmed into the theodolite prior to starting the field survey, then the coordinates of the stakes surveyed, terminus position or other targets are immediately computed by the theodolite and recorded together with the raw field data on angles measured and whatever comments and labels that are input. The distomat DI1600,

for example, measures distance to a reflector target (for highest accuracy and distance capabilities, normally a high-quality glass corner reflector) using an infra-red laser that is accurate to within 3 mm, and has a range of 1 to 3 kilometres on a single reflector, and a range of about 7 km on 11 reflectors. The distance readings must be corrected for atmospheric pressure, temperature and humidity (i.e., air density) along the path length measured. Normally it is sufficient to calculate this PPM (parts per million) correction using just temperature and atmospheric pressure (or elevation) at the instrument location, but if highly accurate surveys are required, then temperature, atmospheric pressure and humidity at both ends of the path length should at least be measured.

The steps used for using the electronic theodolite (Fig. 11.1) are as follows:

1. Charge batteries and check for all equipment and connecting cables before going to field. Including an extra small 9V battery for the GIF 10.

2. Pre-program the electronic theodolite and EDM to record what you want, in the order you want it.

3. Dump data from the rec modules and erase all data on them. Then put in coordinates of the reference marks you will use on to the rec module, and record their labels in your notebook; include a sketch of all the marks you wish to survey and the location of the reference marks to speed their identification in the field.

4. Survey the points in the field and record the date, time, air temperature and pressure, height of instrument, height and position of reflector, location surveyed from and to, persons surveying and holding the reflector, type of reflector, location surveyed (ie. top of pole, base of pole, base centre of reflector), make sketches of the glacier and field situation and take photos as appropriate.

5. Particular emphasis should be placed on repeated measurement of known reference points to ensure proper atmospheric corrections and data reliability.

6. Check data regularly using the data key, so that you can be sure it is recording. Keep an extra rec module because you don't have much room once it becomes filled. You can always display the angles and distances and record them in your field notebook if necessary.

7. Keep track of the battery voltage for the same reason, and turn off the instrument when you are not using it. If you do not immediately get a distance reading (within about 3 to 5 seconds) then turn it off, clear the reading with the CE key and display the vertical and horizontal angles and record those, otherwise you will waste battery strength.

8. Bring the rec module back to the hut and dump the data each night using the GIF10 reader. Use the GRE software to dump the data and the TRA software to translate the files and to check the data. Then use a file editor of your choice to edit the file and prepare it for use on TOPOS. If all the data have been entered correctly, and the reference marker coordinates are included, then

TOPOS may be used directly after GRE and TRA. The TOPOS manual is some help in this regard, but the steps involved really only become clear after some practice. Always save the downloaded GRE file in an unedited format so that the original data are maintained untouched for future reference.

9. The data may be plotted and tabulated using TOPOS software and output in a coordinate file.

10. This coordinate file may then be sent to program such as Surfer® or Lotus-123 for volume computations, topographic mapping, positioning of markers or whatever the task is desired.

With time these instruments will doubtless be replaced with newer and better models. For the time being these surveying instruments represent the top-of-the-line in quality that is most useful for glacier studies. Such ground surveys will probably always be necessary if accuracies in the order of millimetres to metres are required in horizontal and vertical positioning. These instruments are durable but expensive; the cost of the electronic theodolite and distomat in Fig. 11.1 is about $30,000. The instruments may be rented for significantly less, and similar instruments built by Sokkisha (Leitz-Red1A-types in USA), Geodimeter, are also of high quality.

11.4. Radio Echo Sounding of Ice Depth

Both scientists and engineers may be interested in glacier ice thickness. For calculations of "ice discharge", e.g. from an ice cap, knowledge of the thickness of the ice stream is, of course, of vital concern.

For hydrological calculations of water yield from glacierized basins, where the glacier is hiding a water divide, it is necessary to make soundings to define the exact location of the water divide. Only then can the correct area of the basin be determined.

Several attempts have been made to develop a reliable method to determine ice thickness. Both gravity measurements and the conventional seismic methods have been used, but radio-echo sounders seems to give the best results (Fig. 11.3), they are more accurate and easier to use than the other methods.

A sketch showing how soundings are made from the glacier surface is shown in Fig. 11.3, where also the resulting records are shown. Radio-echo equipment for use from airplanes and helicopters has also been developed.

11.5. Topographic and Mass Balance Change

Topographic change together with glacier density allows one to compare mass balance to topographic change and check for how representative of the actual mass balance is sampling network on the glacier and to check for possible errors. An example of topographic change is shown in Fig. 11.4, and may be compared to the balance change measured. Repeated, detailed glacier mapping has shown that systematic errors in annual mass balance may occur (Haakensen, 1986). Such errors were recently discovered for Sentinel Glacier and subsequently required adjustment of the earlier balance values. This study underscores the importance of regular re-mapping of glacier topography and snow, firn and ice distribution to calibrate the balance values obtained for each glacier and evaluate errors.

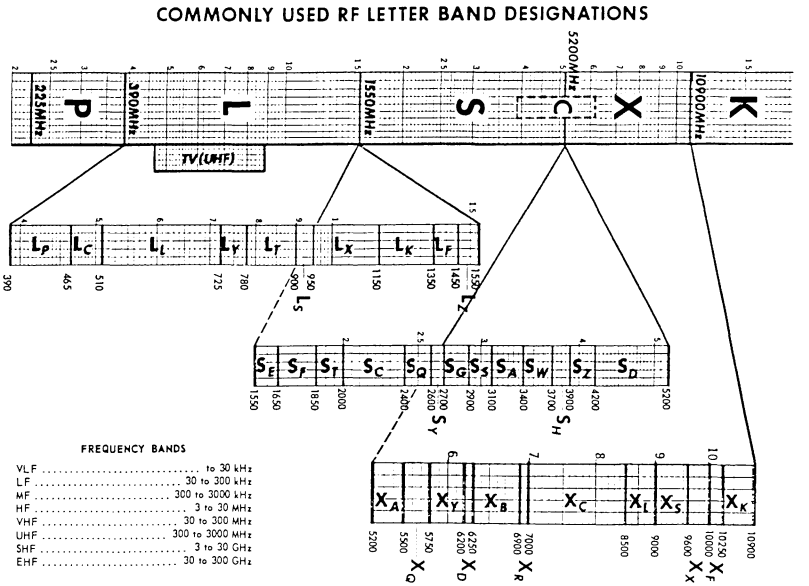
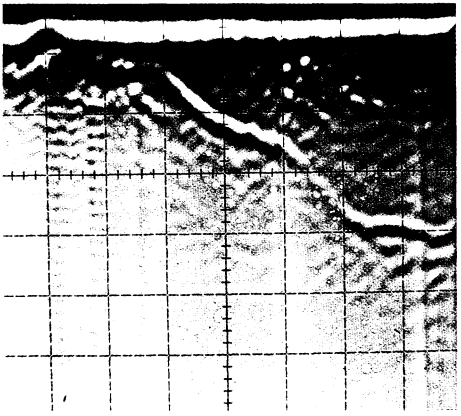


Figure 11.2: Frequency Chart
Frequency bands that are commonly used and their lettter designations. Radio communications and remote-site data telemetry is done with either UHF or VHF rrequencies, although it is feasible to use other frequencies. The FMCW radar (snow depth sounder) built by NHRI operates on a center frequency of 5.2 GHz (5200 MHz),and is directly in the middle of the "C" band for radar; this is the same frequency that the Canadian RadarSat SAR (Synthetic Aperature Radar) will have when it is launched within the next few years. Other radar frequencies are used for microwave remote sensing from aircraft and satellites. Frequencies used for sounding glacier ice depth on polar glaciers operate at about 35 - 400 MHz (Paterson, 1981), while a mono-pulse radar system described in the text operates at much lower frequencies of about 10 MHz. (See Fig. 11.3).



RADIO-ECHO EQUIPMENT

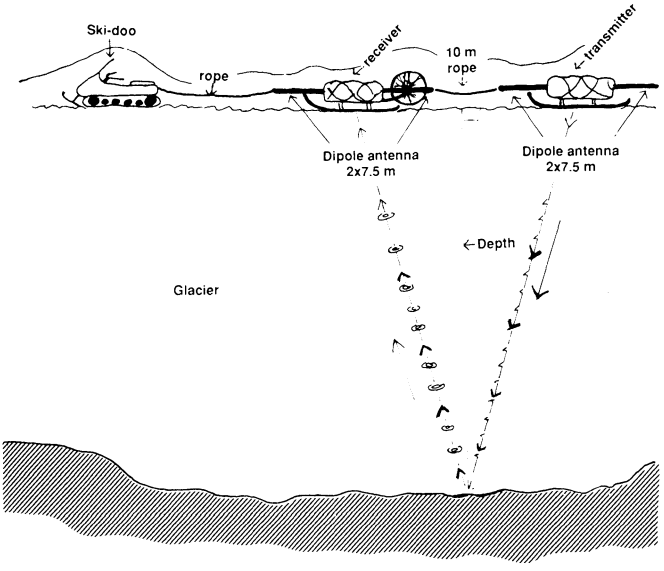
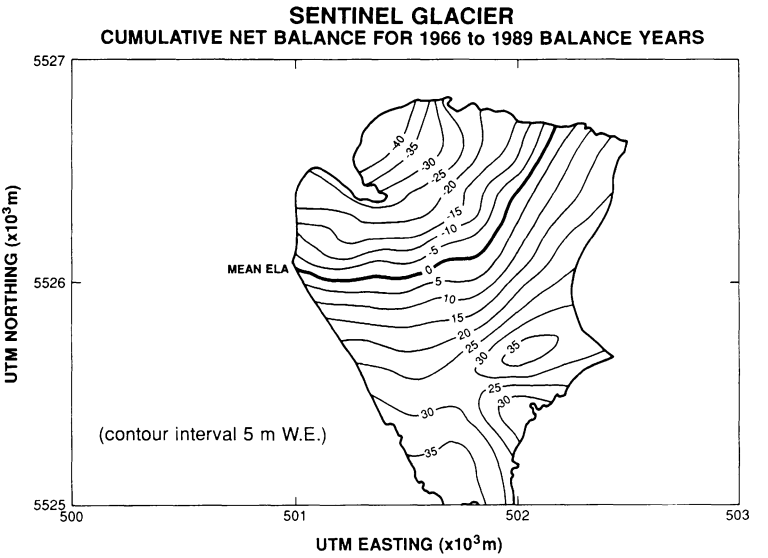


Figure 11.3: Radio-Echo Equipment
Various methods have been used to determine the ice thickness of a glacier. On Canadian glaciers a small radio echo sounder is used (can be back-packed) whereas slightly larger equipment is used in Norway (see sketch). The echogram (top) may look like this example from Svartisen, northern Norway. Horizontal scale is 100 m per square. Maximum depth on this echogram is about 130 m (right-hand side).



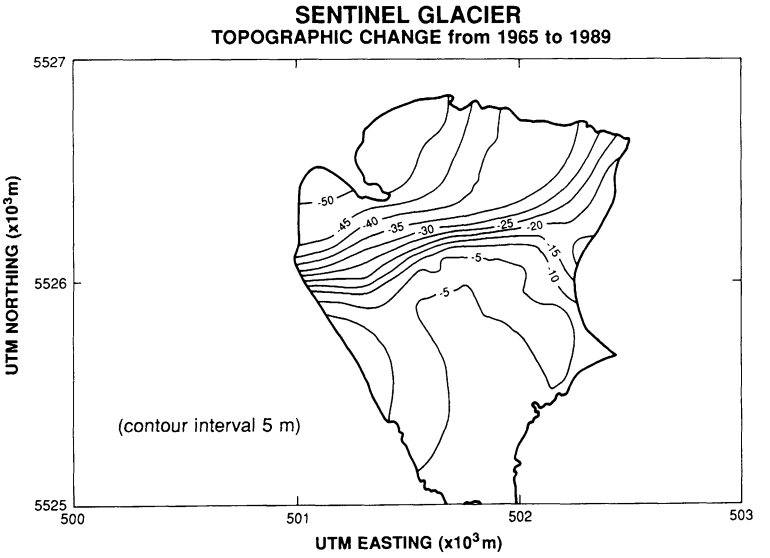


Figure 11.4: Sentinel Glacier Topographic and Balance Changes
A map of topographic change (lower) measured using aerial photography and ground based surveys, may be compared to a map of cumulative mass balance change (upper) during this same interval at Sentinel Glacier measured using Stratigraphic method.

CHAPTER 12. FIELD ORGANIZATION

12.1. General

Many different glaciers will be investigated in the coming years and a large volume of data will be accumulated. Most of these data should be processed in the field, so that results of mass-balance measurements, meteorological data, etc. can be published without delay.

Staff will handle many data sheets so to avoid confusion it is essential that all sheets of paper are marked with the name of the glacier and the year. Each sheet must have a title and should be initialled in the bottom right-hand corner. The senior crew member will be responsible for marking the sheets.

Example: Place Glacier 1991
Snow Pit Measurements

At the end of the field season the senior crew member will:

(a) Check that all data are adequately tabulated and the summary forms completed.

(b) Ensure that all records reach the Head Office safely (not sent by mail or included with equipment sent as luggage).

(c) At the glacier, leave (in the hut) a copy of a map showing all stake locations, together with a list of the last readings (those made before leaving the glacier).

For most of the field observations and for the results of the data processing done in the field, special forms have been developed and should be used.

A complete inventory of the equipment, etc. left in the hut at the end of the field season it is vital for future operations. Standard inventory lists have been developed for this purpose and the responsible senior crew member must ensure that the forms are carefully and correctly completed.

To maintain an atmosphere conducive to efficient work, the field crew should pay particular attention to keeping all equipment inside and outside the houses in good order. Anything damaged should be repaired or, if irreparable, properly discarded and removed from the field area; and a report of discards sent to the Head Office.

So as not to attract animals (such as mice, squirrels, bears, etc.) garbage should either be taken away, stored in animal-proof containers or burnt. For the latter, the best method is to build an incinerator from rocks or from an old gasoline drum. The ash, unburned tins, etc. should then be buried in the ground or removed from the site later. The toilet can be a pit dug in the ground. A small amount of chlorinated water or sanitary chemical should be sprinkled in the pit after use. Chemical toilets or specially-designed outhouses with removable barrels are preferable for responsible disposal of human wastes. Garbage must not be disposed of on the glacier, even in the firn area or a crevasse!

At the end of the field season the station must be closed. Full details are given below.

12.2. Data, Summaries and Forms

All observed field data must be listed on standard forms. However, if data are in field note-books they should be transferred to the standard forms immediately after return to the camp. Then, if the note-book is lost, only one day's observations will be missing.

NOTE: The following details apply to glacier stations where a crew is based all summer or for most of the summer. For glaciers where only short visits are made, please select only the applicable parts.

To facilitate office procedures and speed up publication of the mass balance results, summaries of certain data should be made in the field. These can be plotted as graphs but are generally presented in tables. The stake diagram is an example of a "graphical" summary (although it is used mainly to check the stake readings). Data to be summarized and tabulated are: daily values of precipitation, mean temperature (corrected thermograph readings), maximum and minimum temperatures, relative humidity, hours of sunshine, run of wind, mean cloud cover, and water discharge. Although most of these data will already be listed on other forms, such as the temperature correction chart, the daily meteorological observation form, etc., is it extremely helpful to compile these data on the summary forms. From them meteorological and other results can be plotted directly for reproduction. (See Chapter 13) A collection of sample forms is included in Appendix VI.

The following records and summaries should be handed in as soon as possible after return from the field:

1. Brief diary showing date and work accomplished.

   Example: June 6 Arrive Lake Louse.
   June 7 Arrive glacier, ferry supplies, helicopter two hours. (Flight report to be enclosed.)
   June 8 Read all stakes on lower part of glacier, sorted supplies.

2. Summaries of daily meteorological observations (to supplement data logger files) including:

   a) Daily mean temperature
   b) Positive degree days
   c) Rainfall
   d) Mean cloudiness
   e) Hours of sunshine, if recorded
   f) Run of wind
   g) Other data according to given instructions

   NOTE: The standard forms should be used and the columns between those with headings left blank for they will be used in later calculations of sub-totals for selected periods, etc.

3. Dates when each stake was read throughout the season. (Use standard forms, see Appendix VI)

4. Stake diagram completed in all respects. See example among the illustrations.

5. Table of river discharge - to show daily discharge and, where requested, sub-totals for periods from 0000 to 0600 hrs; 0600 to 1200, 1200 to 1800, and 1800 to 2400 hrs.

6. Snow pit measurements - completed standard forms - and, for each pit, graphs showing density and water equivalent vs. depth (Fig. 5.5).

7. A list of all equipment and supplies remaining at the hut (standard list).

8. A list of all equipment and supplies returned to the Head Office (standard list).

9. When applicable: Report of losses or disposal of equipment (Departmental form).

10. Any remaining statement of financial disbursements (on printed forms) together with all receipts arranged chronologically, neatly glued or stapled on 8½ x 11" (or standard A4) sheets of blank paper.

The leader of the project must ensure that the summer assistants are given complete instructions so that completion of the appropriate forms can be carried out continuously during the field season. The senior crew member must check, before leaving the Head Office, that sufficient forms are sent to the field. If data loggers and computers are in use, data should be transferred directly into the computer database files whilst in the field. Some output, screen display or plot, should be generated before leaving the field to verify that the required data have been obtained.

12.3. Closing the Station

The base camp must be left tidy and in good order. All personal belongings that are not brought back must be burned or buried with all other garbage. The remaining food supplies should be checked for items that might deteriorate during the fall and winter, and such items must be removed. If propane is left at the site, the regulator should be removed and secured to prevent others from depleting the fuel supply.

A list of supplies and a sketch showing the location of gasoline drums etc. must be left in the hut. Stakes, stake extensions (2-m pieces), and extension tubes must be placed so that they will be readily accessible during the winter.

In case of an emergency, a stove and limited supplies of fuel and food should be left in the garage. It will normally not be locked.

Batteries that have been used (or partly used) must be removed for proper disposal or recycling. Only unused batteries should be left and placed in a plastic bag: never left in radios, flashlights or other equipment! Such batteries should be marked with the year when they were brought to the stations. Example: "New 1991 unused".

A shovel must be placed outside above the doors of all houses, and fuel for lighting, cooking and vehicles left in handy containers inside.

To facilitate any winter surveys, it is essential to leave in the hut a map of the stake locations and a list of the last stake reading. Then, if the stakes are being buried in the snow, the winter crew can concentrate on finding the longest stakes first. By comparing their present lengths with the last stake reading, the crew can deduce which stakes may be completely buried and not worth searching for.

12.4. Inventory of Essential Equipment

In general there is a standard set of equipment that is absolutely necessary on each station. Shovels, ice drills, snow samplers, balances, etc. must be present to ensure the work can be done. In most cases it is also necessary to have a reasonable supply of spare parts. Some stations may need more of certain items than others, or the number of spare parts must be larger for logistic reasons. It is obvious that a detailed record must be kept of the equipment at each station. A special inventory form, has been developed. It should be completed at least by the end of the field season so that replacements can be ordered in good time for the next season. Sometimes a complete inventory should also be made in the middle of the summer, to make efficient use of a helicopter when the crew is taken out at the end of the season. Replacements and supplies such as gas may then be brought up to the glacier when personnel, damaged equipment, etc. are taken out.

All equipment should be stored in suitable boxes under beds or on shelves, in such an order that it can be found easily. A duplicate sketch showing the location of various boxes should be made; one copy left in the hut (fixed to the wall, if visitors are not expected) and another copy returned to the Head Office at the end of the field season.

12.5. Some Statistical Considerations (by W. J. Campbell, U.S. Geological Survey, Tacoma, Washington [reproduced from 1969 edition])

The observations of accumulation and ablation are some of the most fundamental in glaciology, yet considerable disagreement concerning the accuracy of these measurements exists in the literature. Some investigators feel that a certain number of stakes per given area must be fixed, as a kind of statistical constant, in order to obtain measurements of sufficient accuracy but such a concept fails to allow for the vast topographic variations that occur on glaciers. For example, one stake in central Greenland might be representative for hundreds of square kilometres, whereas a stake on a valley glacier might be representative for a few square metres. Other investigators feel that the individual glacier under consideration must determine the number and array of stakes used. Although more pleasing in an intuitive physical sense than the fixed stake per area concept, this philosophy of measurement confronts the investigator with the great problems of determining the density of this observation network.

Any practical method of field measurement of accumulation and ablation must be composed of an intuitive as well as a statistical methodology. The intuitive skill is obtained only by much experience with the glaciers being measured, thus we cannot talk about it. The statistical aspects can be discussed, but one must bear in

mind that in reality they must be combined with intuition in order to yield valid results.

The enclosed graph (Fig. 12.1) allows one to determine the number of observations necessary to obtain a representative mean, if the individual observations fit a normal probability distribution. First, the standard deviation of a number of observations, for example the ablation measurement of a number of stakes in a certain area of uniform ablation on a glacier, is computed. Alternatively, if an experiment is being planned, some information on the expected standard deviation might be obtained from other experiments. The standard deviation is defined:

$$\delta = \sqrt{\frac{\Sigma(a-\bar{a})^2}{N}}$$

where a is the individual measurement value, $\bar{a}$ is the arithmetic mean of the observations, and N is the number of observations, or in this case the number of stakes.

The arithmetic mean is considered to be representative if it differs, with a predetermined probability P, not more than x from the true mean. Generally x and P are fixed according to the requirements of the study, and δ may be fixed by the inherent dispersion of point-values on the glacier.

With a given δ and a chosen x the point on the chosen probability curve whose ordinate is x/δ can be found, and the abscissa of this point is then the number of observations, or stakes, necessary. Of course, this says nothing about the array of observations, but in order for the statistics to be valid it is necessary that the area in question on the glacier be covered. The array design demands intuitive insight, since it is probable that δ will not only vary considerably from glacier to glacier but will vary from one part of the glacier to another.

The graph may be used in two ways. As above it can be used to estimate the density of an observational network necessary for a desired accuracy. The graph can also be used to find the accuracy for a given set of observations.

For example, suppose 30 ablation stakes gave measurements with a standard deviation of 2.0. Suppose also that one desired a probability of 99 percent that the arithmetic mean was representative of the true mean. The point on the 99 percent P-curve whose abscissa is 30 is then located and the ordinate is read as 0,5. The accuracy of the determination of the mean value is then

$$x = \delta(0{,}5) = 2(0{,}5) = 1 \text{ centimetre}$$

This method affords an objective way of estimating the accuracy of one's measurements as well as a check on the density of the observation network. Of course, it is useful only after some observations have been made, thus it is of little help in the initial design of an observational network. However, it can be most helpful in the modification of existing networks to make these more accurate.

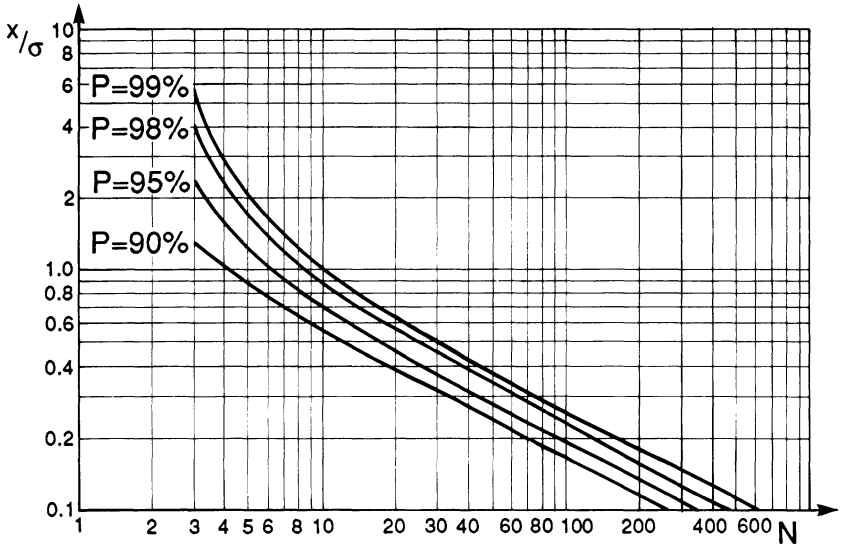


Figure 12.1: Probability Diagram
Graph for determination of number of single values (N) necessary to obtain a representative arithmetic mean.

CHAPTER 13. DATA REDUCTION

13.1. General

To allow for direct comparison between glaciological results from various glaciers, all data should be tabulated, plotted and presented in a uniform manner. Standard units should also be used when results are published. However, experience has shown that, even when the same units are used by different authors, their graphs cannot necessarily be directly compared as they may use different units for the axes affecting the slope of curves and the visual impressions of the graphs. In the following sections, standard graphs and tables are proposed for data presentation. The formats have been used for several years in Canada, Norway, Sweden and other countries. See, for example, Østrem (1966a, Schytt (1968), Liestøl (1967), Pytte (1967), Kasser (1967), or Kjeldsen (1987). Recommendations from a Workshop on Glacier Mass Balance Standards (held in Seattle 28-29 November 1990) are incorporated in the following sections.

13.2. Data Presentation

Glaciological results may be used by other scientists for further analysis, etc. and others may be used directly in calculations of practical importance for planning, etc. If the data are to be used thus the figures must be tabulated, but many results are more readily understood if they are graphed or plotted on maps. Therefore all pertinent data (generally not the rough field data) should be published in tables and selected results plotted on maps and in graphs. What has actually been measured must be clearly distinguished from that which has been computed. Those data selected will generally be chosen for their particular relevance to the main goal of the investigation. A waterpower institution will likely be more interested in the hydrological applications of mass balance studies than meteorologists, who will certainly be more interested in climatic parameters. The suggestions that follow must therefore be regarded only as a guide.

13.2.1. Stake and Pit Location

The glacier outline and the locations of the stakes and pits are best shown on a map (refer to Figs. 1.2 and 7.2). However, for digital computations a system of co-ordinates can also be used for all stake and pit locations. Such systems have been developed in connection with computer programs and will be described below.

A map showing the pit and stake locations can be relatively simple with only the glacier outline, a few contour lines (every 50 or 100 m) and some reference points, such as the main triangulation points, etc.

When accumulation is measured in the field many soundings are made. It will be practically impossible to plot all of them on a map. Therefore, only the lines along which soundings were performed should be plotted on the map as "sounding profiles". A sample map showing stake and pit locations and sounding profiles is shown in Fig. 4.1.

13.2.2. Accumulation Results

The "true" winter accumulation on a glacier can seldom be measured because some ablation normally occurs also in wintertime. When the accumulation measurements are made in late-spring, one obtains the final result of the "true" winter accumulation minus the material lost through evaporation, wind removal, etc. during the winter. This measured result is termed "winter balance", and will be slightly smaller than the "true" accumulation (see Introduction and Fig. 1.1).

The water equivalent of the winter balance is obtained by sounding the snow pack at many points (mostly along sounding profiles) and making several density measurements in pits dug down to the previous summer surface. Snow-depth measurements should, at least for valley glaciers, be made with a density greater than 10 points/km^2. Thus, it is not practical to present all depth measurements, in cm or in cm of water equivalent. The original snow depths are plotted on a working map along the sounding profiles. The location of each sounding profile must therefore be known. On this working map, with all single field data plotted, isolines are constructed for selected water equivalent intervals. Example: Contours may be drawn for 50, 100, 150, etc. cm of water equivalent (see for example Fig. 7.1). The total amount of accumulation can be obtained by planimetering the areas between contours. The area between 50 and 100 cm would be given the mean value of 75 cm of water equivalent etc. When this planimetering is completed for the whole glacier, the total winter balance can be calculated. However, we want information about variations in winter balance in relation to altitude. Thus, the planimetering must be done separately for each elevation interval, using the working map with 50-m or 100-m contours. The results should be presented in a table showing the winter balance within each height interval, expressed in 10^6 m^3 of water. A sample table is shown in Fig. 13.1. The mean specific values (i.e. the mean figure for each elevation interval) can be presented in the same table in cm of water equivalent.

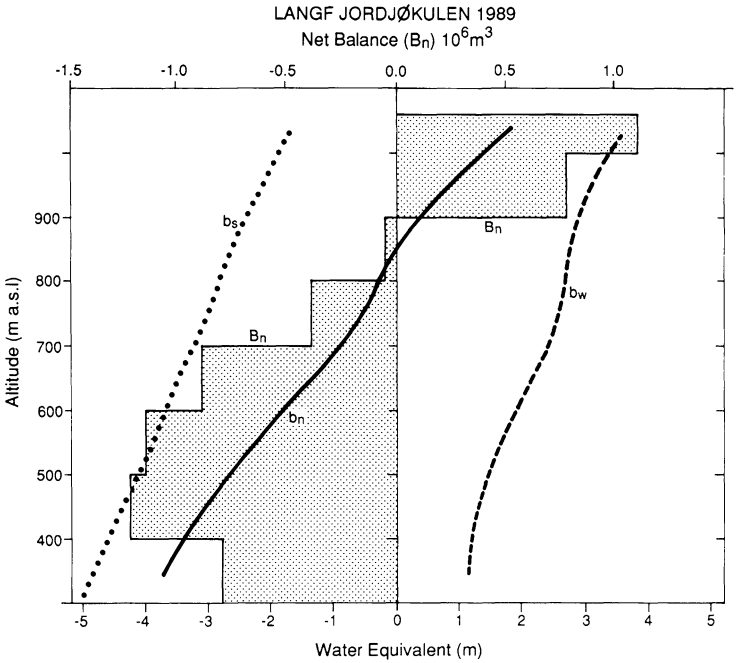
This table and a reduced map showing the contour lines and isolines of water equivalent, should be published. The various areas on the map can be emphasized with different colours or shading (Fig. 7.1). With the recent advent of affordable colour printers,even computer-generated plots can be produced in the standard colours for easy referencing and comparison of data sets.

Information on snow densities is generally used for data processing in the office (converting snow depth figures to water equivalent values) and will normally not be published. Only for unusual snow conditions will it be of interest to publish a diagram showing the density variations with depths.

13.2.3. Ablation Results

As in winter season, the glacier may receive material during the summer. This so-called "summer accumulation" has previously been handled differently by different glaciologists. Under "summer balance" the "ablation" measurements might also include summer snowfalls, so the final result represents a difference between the ablation and the accumulation during the summer.

NOTE: If detailed studies are being made of climatological parameters vs. glacier melt, the amount of summer snowfall should definitely be recorded, because an "extra" amount of heat is needed to melt this snow before the "normal" ablation can



LANGFJORDJØKULEN 1989

Height	Area	Winter balance			Summer balance			Net balance		
		Bw		bw	Bs		bs	Bn		bn
m a.s.l.	km*2	10x6m*3	m	l/s km*2	10x6m*3	m	l/s km*2	10x6m*3	m	l/s km*2
1000-1062	0.668	2.30	3.45	109	1.24	1.85	59	1.07	1.60	59
900-1000	1.005	3.02	3.00	95	2.26	2.25	71	0.75	0.75	28
800-900	0.691	1.83	2.65	84	1.90	2.75	87	-0.07	-0.10	-4
700-800	0.691	1.73	2.50	79	2.14	3.10	98	-0.41	-0.60	-22
600-700	0.628	1.32	2.10	67	2.23	3.55	113	-0.91	-1.45	-54
500-600	0.503	0.83	1.65	52	1.99	3.95	125	-1.16	-2.30	-85
400-500	0.396	0.51	1.30	41	1.74	4.40	140	-1.23	-3.10	-115
300-400	0.215	0.25	1.15	36	1.04	4.85	154	-0.80	-3.70	-137
300-1062	4.797	11.79	2.46	78	14.54	3.03	96	-2.75	-0.57	-18

Figure 13.1: Langfjordjøkulen 1989
The Norwegian annual reports on glacier mass balance are produced and distributed to interested agencies and individuals. To save time and labour, a standard diagram and a table are given for each observed glacier. Both show winter, summer and net balance for selected height intervals; totals are given at the bottom of the table. In addition, maps of winter balance may also be published.

Note that the ratio between units on the axes is 1:100, thus making possible a visual appreciation of certain glaciological properties; the slope of the mass balance curve is of particular interest. The height of the equilibrium line is where the net balance curve cuts the y-axis, in this case at about 850 m a.s.l.

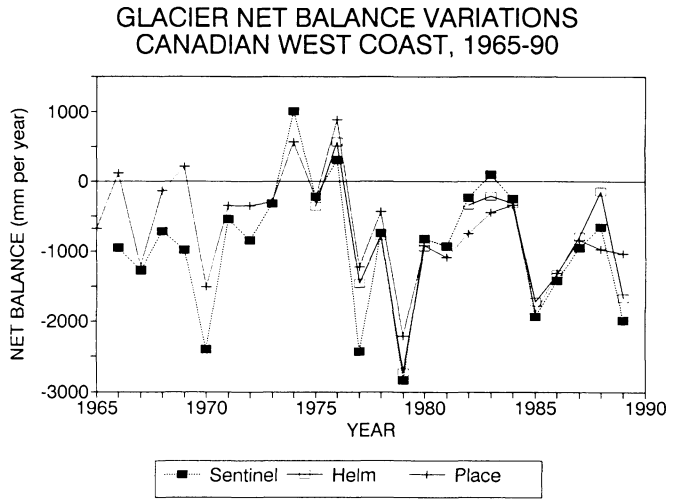
continue. The surface albedo (reflectance) of the ablation area may change dramatically during the summer, thus affecting the amount of solar energy available for surface melting. In most cases, ablation is far larger than the summer snowfalls and the glacier will normally lose material during the entire melt season.

Ablation measurements are made at stakes on the glacier. The stakes are far fewer than the number of soundings made at the end of the accumulation season. Thus, total ablation (or more correctly, the summer balance) is calculated from a limited number of stake readings. Generally, glacier melt decreases fairly regularly with increasing altitude, so isolines of equal melt will more-or-less parallel the contour lines on the glacier, with some local deviations from this general rule. For a particular glacier these deviations will normally occur in the same areas from year-to-year. It is thought that they are due to local topography, winter snow distribution, etc.

For the figures of the total summer balance at each stake, a summer balance map can be constructed, showing isolines for selected ablation intervals. Example: Lines may be drawn for 100, 200, 300, etc. cm of water equivalent and the areas between these lines coloured or shadowed (Fig. 7.1). Similar to the accumulation map (see above), these areas should be planimetered or digitized. The total summer balance is obtained by simple multiplication. However, as we need to know the variations in summer balance with height, each elevation interval (preferably every 100 m) must be processed separately and the results given in a table similar to that described previously. The specific values, i.e. the mean ablation in cm of water equivalent, may be given in the same table.

After several years' observation on Norwegian glaciers a slightly simplified method has been used: Based on stake observations, the average ablation is plotted against altitude. The resulting smooth curve is the b_s-curve (as shown in mass balance diagrams, see below). The shape of this curve is similar from summer-to-summer, so a skilled person can produce a reliable graph, particularly when well acquainted with the glacier.

Ideally, stakes should be evenly distributed on the glacier surface so that observations are obtained from all parts. As a rule-of-thumb one should have at least two stakes within each height interval (50 m or 100 m, according to glacier size). It is, however, difficult to insert and observe stakes in heavily-crevassed areas. It may even be impossible, or at least very dangerous, to travel across the crevassed areas and then glaciological information cannot be obtained. Some kind of interpolation must then be made, based upon the measurements made below and above the crevassed area. Assuming a linear variation, this can easily be done. However, more ice is exposed to the atmosphere per km^2 in crevasses than in other parts of the glacier. Thus, a higher ablation rate is likely in a highly-crevassed area. A study by Karlén (1965) indicated as much as 17% more ablation in the crevasses than on adjacent horizontal ice surfaces. Recent results from Sentinel Glacier indicate that this effect may be even more pronounced at other glaciers and can only be corrected for if regular surveys of topographic change and vertical velocity are done together with surface balance measurements (see Chapter 14). Compare for example Figs. 1.2 and 4.4; the final adjusted data are plotted in Fig. 13.2.



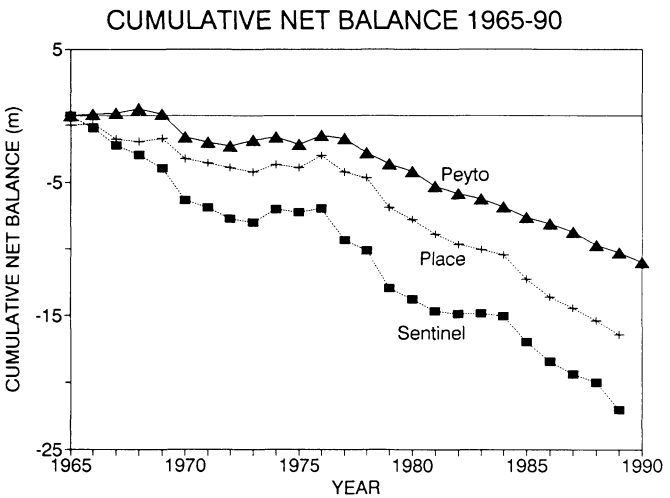


Figure 13.2: Net Balance Fluctuations in Western Canada
Net balance of Canadian west coast glaciers (Sentinel, Helm and Place) versus time from 1965 to 1989 is shown on the supper diagram. Note the strong coherence in the net balance fluctuations of these three glaciers. The Sentinel Glacier data has been corrected for measured topographic change; Place glacier mass balance data needed no adjustment since surface balance was consistent with topographic change. The negative cumulative net balance trends for Peyto, Place and Sentinel Glaciers (shown on lower diagram) are consistent with with measured thinning and dramatic terminus retreats measured during this same time period.

13.2.4. The Mass Balance

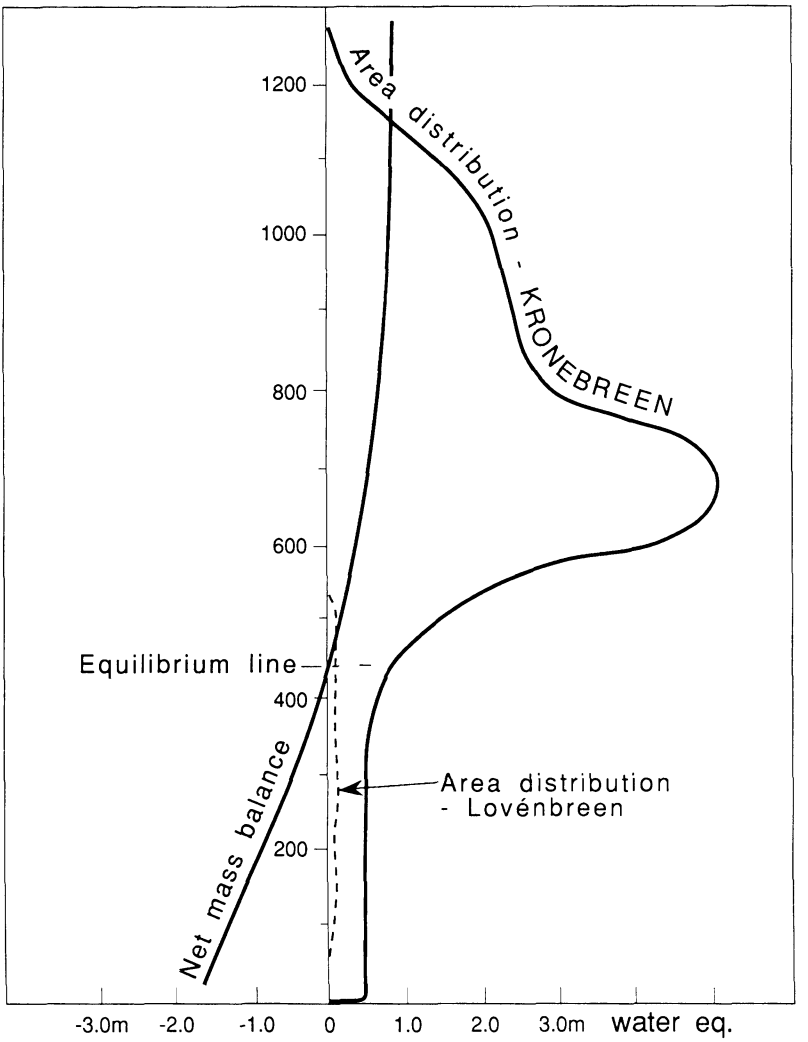
The difference between the glacier "income" (winter balance) and "expenditure" (summer balance) gives the net balance for one year. If this difference is positive, the glacier has increased its total mass; if negative, it has decreased. In hydrological terms this means that the glacier stream has received less water or more water, respectively, than it would have if all the winter snow had melted in the basin and there had been no influence from the glacier. It is therefore of practical importance to obtain good information about the mass balance of glaciers in areas where the river water is used by man. In a wider sense, mass balance studies are of scientific interest for several reasons. The result of mass balance studies should therefore be published in a form that will satisfy both the engineering hydrologists, glaciologists and climatologists.

The tables described in the two previous sections (see Tables with Fig. 7.1) show the winter balance and the summer balance for each elevation interval (generally 50 or 100 m), both as a total water volume in 10^6 m^3 and as specific figures in cm of water equivalent. The mass balance for each elevation interval can thus easily be obtained as a difference between corresponding figures. Such a table should always be published for glaciers where mass balance studies have been performed. It should include, for each elevation interval, the area, the winter and summer balance (both total and specific) as well as the mass balance. Figures for the entire glacier can be obtained by adding the corresponding data in the table.

A mass balance diagram should also be constructed. In this, the specific winter balance, summer balance and net mass balance are plotted vs. elevation (Fig. 13.1).

In the same diagram the area distribution can also be plotted (Fig. 13.3). Finally, the total net mass balance can be shown in a histogram. If the histograms are shadowed, they will give a good impression of the conditions on the glacier for that year (Fig. 13.1).

To make the diagrams easily comparable and to ensure that the slopes of curves will always be the same for the same conditions, the following rule should be used: the X-axis is divided into metres of water equivalent. The length of the axis representing 1 m is arbitrary, but should equal the length of the Y-axis representing 100 m of elevation. In other words, the divisions on the coordinate axes should be at a ratio of 1:100. When the diagram is reduced for publication, the slopes and general appearance of the curves will remain the same and diagrams from various glaciers (especially net balance curves) can be compared directly. It is important to present the slope of the net balance curve at the equilibrium line, originally termed the "energy of glacierization" by Shumskiy (1947), in a standardized manner. Shumskiy's term was later "translated" by Meier (1961) into an "activity index". Haefeli (1962) introduced the term "ablation gradient", which is also discussed by Schytt (1967). See, for example, the slope of the net balance curve for glaciers on Spitsbergen (Fig. 13.3); because these glaciers are arctic, the slope of elevation vs. local net balance (b_n) is very steep. This can be compared with the corresponding b_n curve in Fig. 13.1 which is less steep because the glacier is temperate and maritime. Similarly, in Fig. 13.4, compare the slope of the curves for the temperate and maritime Sentinel Glacier (Fig. 3.1); the activity index for the same glacier does not change much from year-to-year.



Area distribution and net mass balance with height of Kronebreen and Midre Lovénbreen (1989).

Figure 13.3: Spitsbergen Diagram
The Norsk Polarinstitutt (Norwegian Polar Research Institute) publishes results for 2-3 glaciers on Spitsbergen in their annual "Årbok" (e.g., Liestøl, 1989)

The net mass balance diagrams for Kronebreen and M. Lovénbreen are different from most other Norwegian glaciers because they are sub-arctic. Note the steep slope of the net balance curve, and compare it to similar graphs shown elsewhere in this manual.

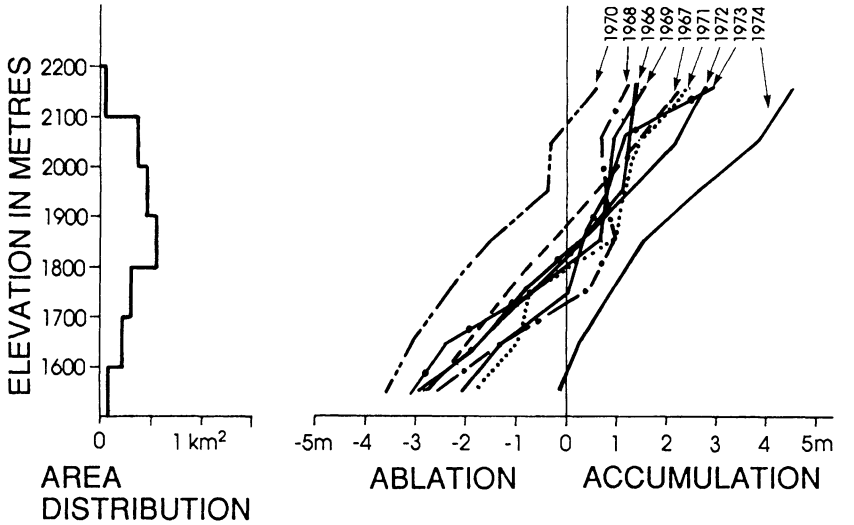


Figure 13.4: Elevation versus Local Balance (b_n)
The net balance versus elevation (left) and the distribution of glacier surface area with elevation are shown for the maritime Sentinel Glacier for 1968-74. The activity index of the glacier is the slope of the line at the ELA (the elevation on a glacier where the net annual balance is zero), and is relatively constant for each glacier, but varies markedly between glaciers.

Sometimes it is interesting to follow the variations in mass balance continuously throughout the season. For this a special stake form has been designed on which all observed data can be plotted for each stake and the mass balance calculated for any time of observation (Appendix VI). If this form is completed for each stake on the entire glacier, one can calculate the ablation (e.g., variations in summer balance) for any given period, provided that complete stake readings have been made at least at the beginning and at the end of it. The stake form is also useful for general mass-balance studies, as it allows a check of all observations made during the summer. A disadvantage is that the form looks formidable and may be difficult to complete properly. The following rules should be used as a guide when the Canadian form is used. (The Norwegian form is slightly different).

a) Fill in all details requested at the top: one form for each stake. If duplicate stakes or replacement stakes are used, measurements must be recorded on separate forms.

b) Column 1 is for the date of the readings.

c) Column 3 and 4 show the visible length of the stake. If ice is exposed, only Column 4 is completed; if the spot is still snow-covered, only Column 3 should be used.

d) Columns 5-9 are for recording snow depths at stakes which still have some of the last winter's snow present. Consequently, if the stake length was placed in Column 4 (see c) above) nothing should be put in Columns 5-9, as no snow exists at that location.

   If the snow depth is actually sounded (see Section 5.2), the mean value of the three soundings should be placed in Column 6. From the snow density in Column 5 (obtained by pit studies at the stake or in the same part of the glacier) the water equivalent of the snow cover is calculated and the figure placed in Column 7. Column 8 is used only when soundings are not taken and the snow depth is calculated from the stake reading alone. This may happen when there is insufficient time available for the measurement or when a snow probe is not available, so that only stake readings can be made. The use of Column 8 should therefore be restricted as far as possible.

e) Columns 10-20 are used for calculations and should not contain any observations. The thickness of superimposed ice, found by variations in stake length above the ice surface, is put in Column 12 and its water equivalent in Column 13 (assume a density of 0.7 - 0.8). Superimposed ice is regarded as accumulation, so this figure should be marked as positive.

   The variation in water equivalent of the snow pack between two readings (compare Column 7) should be placed in Column 11. Strictly speaking, this will normally be a negative figure, as snow disappears during the melt season, but any observed additional snowfall in the summer is considered positive.

   The actual melting of glacier ice is recorded in Column 18. This figure will always be negative. The difference in stake reading between the last two

observations should be noted, and the water equivalent calculated and placed in Column 19 (assuming a density of 0,9).

f) Column 22 shows the total ablation between the previous two readings. The figure in this column will be the algebraic sum of figures shown in Columns 10, 13 and 16. For practical reasons however, it can be shown without an algebraic sign (it is always negative).

g) The cumulative value of figures in Column 22 is noted in Column 25. If it appears that accumulation has occurred (generally summer snowfall) between the two readings, Column 24 should be used.

Column 26 shows the present situation at the stake, starting with the amount of snow accumulation (the winter balance), as observed in the spring (being a positive value). During the melt season this value diminishes according to the figures shown in Column 25. At the end of the season, the figures in Column 26 might be very small or even negative (on the lower part of the glacier) if those in Column 25 exceed the original accumulation (i.e., all the winter snowcover and some of the ice has melted). At the end of the season there will always be negative figures in Column 26 for those stakes where glacier ice is exposed. At the equilibrium line, however, the final figure approaches zero, indicating zero net accumulation and zero net ablation.

13.2.5. Movement Studies

Although movement studies are not required to obtain the mass balance of a glacier, they may be of general interest. Because stakes are fixed on the glacier surface, they serve as good reference points for movement studies. Difficulties of identification can be overcome by using various markers on the stakes. A combination of small and large flags helps identification from a distance. Stake positions are determined by conventional triangulation from fixed points on the adjacent ground, or by use of modern survey equipment, such as geodimeters, etc.

If the stake has been relocated ("redrilled") between the two surveys, this "artificial" movement of the stake must be noted. Distance and direction of the new position relative to the previous location is recorded.

The movement studies can be presented either in a table, in which all movements are indicated by direction and distance, or on a map (Fig. 13.5). The movement is shown as arrows, pointing in the direction of movement with the length proportional to the displacement between surveys. Ideally a map of both horizontal (Fig. 13.5) and vertical velocities will be constructed.

The vertical component of velocity must be measured with particular care because it allows comparison between topographic changes surveyed and surface balance measured during the same time interval. A careful record must be kept of the length, tilt, orientation, and shape (if bent) of the pole. Any pole resetting information is vitally important, since the vertical velocity component is normally smaller than the changes imposed by pole resets or pole extensions. The measured vertical component of ice velocity is, of course, a combination of the vertical component due to the glacier flowing downhill, plus the motion due to convergence or divergence of the glacier flow field. It is the latter portion of the velocity vector

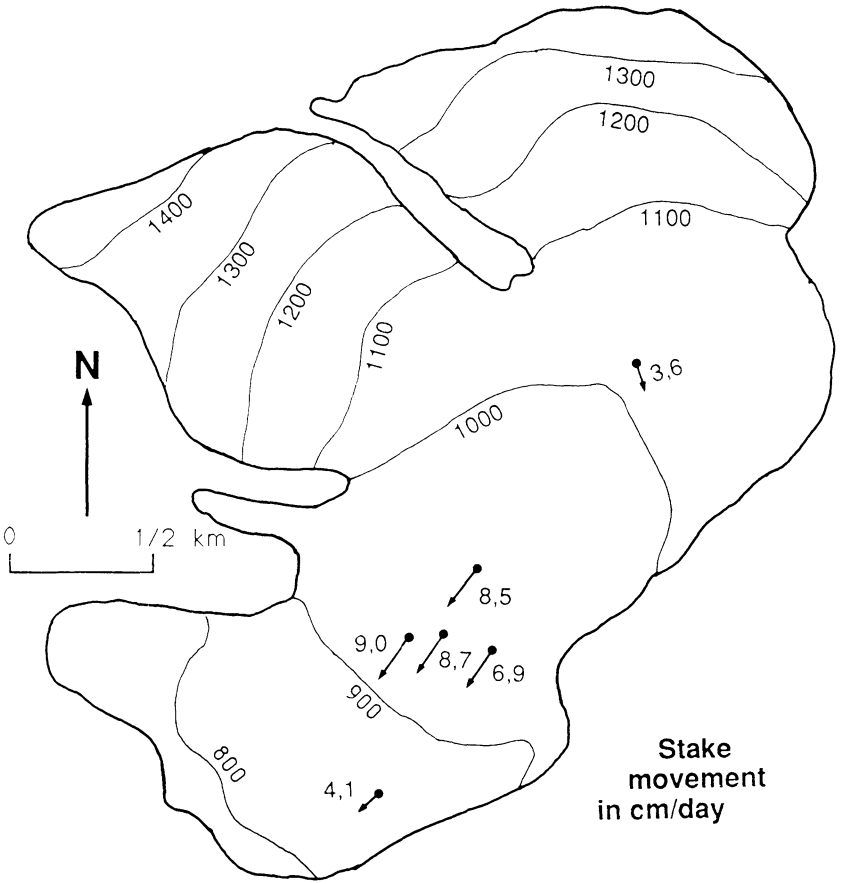


Figure 13.5: Svartisheibreen Ice Velocity
An example of how ice velocity results may be reported. The length of arrows is proportional to the surface ice velocity. Heights are in metres above sea-level.

that must be used for determining whether changes can be explained by the vertical component of velocity or maybe due to changes in near-surface glacier density, or perhaps measurement error. If the topographic change observed is consistent with convergence or divergence of the local flow field then, if density changes are properly accounted for, the topographic change observed must be consistent with the measured surface balance (melt and accumulation). This method allows identification of areas on the glacier where ablation stakes are not representative of the areally averaged balance value. This is particularly important where the surface is crevassed.

13.2.6. Meteorological Results

The meteorological data obtained at each glacier will normally be presented or published in tables or diagrams showing the daily variations in the various parameters. If precipitation is measured at many locations the observations are better plotted on maps. The summary diagram normally contains observations made at the base station and maybe for some other locations on the glacier. To make the results easily comparable, the format shown used in Fig. 13.6 should be followed or the data presented in a similar manner. The recommended graph consists of four (or more) separate diagrams, all of them having a common X-axis with divisions for each day during the entire observation period. Each curve in the diagram has its own Y-axis; the divisions are selected for each variable with regard to the ultimate size of the diagram (Fig. 13.6).

If additional meteorological parameters are observed they can be shown in the same large diagram, but for ease of further scientific data processing it is advisable to present all data in tables. The preparation of these tables is not dealt with here.

13.2.7. Stream Discharge

The water discharge in glacier streams is observed for three main reasons:

(1) To check ablation measurements and for statistical study of the relationship between discharge variations and meteorological parameters (rainfall, radiation, air temperature, wind, etc.).

(2) As a basis for sediment transport and stream water quality studies. Sediment and water samples are taken at various intervals, so for total sediment transport (per hour, per day or for the whole season) it is necessary to know the discharge variations. For this purpose daily values are insufficient, because short-term variations have a great influence on the transport.

(3) To provide general hydrological information about discharge conditions in glacierized catchment areas.

Provided a rating curve is established for the measuring site, the stream discharge can be calculated for selected periods during each day. The field crew should have calculated daily values in 10^6 m^3 of water volume on the summary forms. The office work is then limited to a simple plotting of the daily discharges in the form of a histogram. This histogram can be presented separately or included

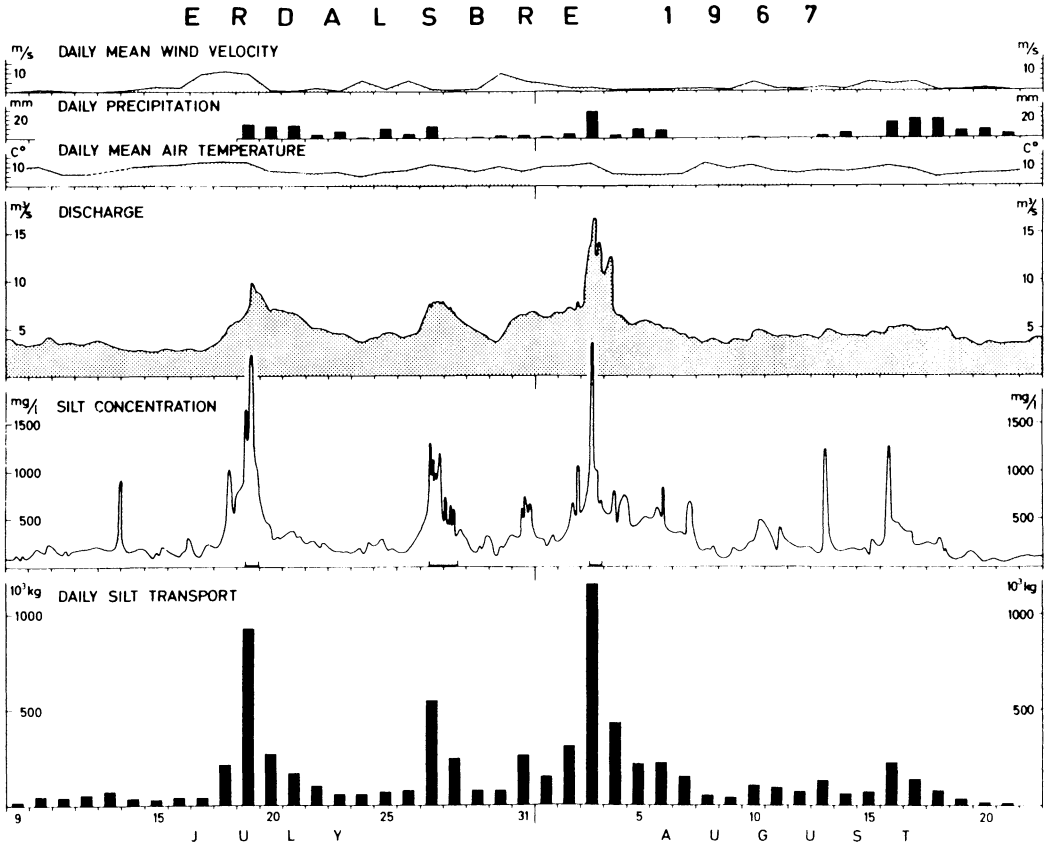


Figure 13.6: Erdalsbre 1976
An example of publishing one summers Field data at a glacier where daily met. observations and run-off data are recorded. Sediment concentrations are based upon frequent water sampling by a field-based crew, and subsequent laboratory analysis. Daily suspended sediment transport (bottom bars) is calculated from data on concentration and discharge.

This kind of diagram gives a good visual impression of conditions at the glacier. But mass balance data must be shown separately, see for example, Figures 7.1 and 13.1.

with the diagram of the various meteorological observations. If the data are needed for numerical modelling, the daily figures should also be tabulated.

13.2.8. Suspended Sediment Transport

The study of the sediment transport is based upon a number of relatively small samples (generally 1 litre) taken at regular intervals in the glacier stream. The laboratory analysis of each sample gives the sediment concentration at the time of sampling. To calculate the amount of transported sediment in a given time interval it is also necessary to know the discharge. If the sample is regarded as representative for a given interval, the figure for the sediment concentration should be multiplied by the total discharge in this interval.

If discharge variations are very small, it may be sufficient to take two samples a day, each being representative of a 12-hour period. However, if rapid or large discharge variations occur, samples must be taken more frequently; each of them representing a relatively short time period. Particularly when the water stage is rising it is important to take samples frequently. When the results are published it will be of interest to show not only the size of the daily sediment transport, but also showing variations in sediment concentration and water discharge.

Three graphs should therefore be constructed:

(1) The water discharge variations, as detailed as possible, during the entire melt season.

(2) The results of all sediment sample analyses in the form of a sediment concentration graph.

(3) The total sediment transport for each day plotted as a histogram or as single vertical columns for each day of the observation period.

To help explain the main reasons for variations in river discharge, it may be of interest to plot daily precipitation, air temperature, etc. in the same diagram as well (Fig. 13.6).

13.3. Computer Programs

During recent years many computer programs have been developed to facilitate complex calculations and office procedures. As this field is developing rapidly and continuously, it is impossible to give a comprehensive review of all such programs or procedures suitable for glaciological work. The following sections only indicate some possibilities that should be checked by the leader of a mass balance project before starting time-consuming calculations are started.

13.3.1. Water Discharge

In the chapter on water discharge measurements, it was mentioned how to calculate the discharged water volume from gauge readings and the rating curve. Recently computer programs have been developed both to construct the rating curve from a number of discharge measurements (and simultaneous gauge readings) and to

"read" charts from automatic gauges and transform the information directly into water volumes. The rating curve is anticipated to be a linear function in a logarithmic system. Its mathematical expression is given by the formula $Q = k (h + \Delta h)^n$ in which:

Q	is the water discharge (m^3/sec),
k	is a constant,
h	is the gauge reading (on a vertical scale),
Δh	is a constant directly connected with the vertical scale. It will be 0 if zero of the scale has exactly the same elevation as the lowest part in the river profile that controls the water level at the measuring site. In all other cases it will be a positive or negative figure showing the difference in height.
n	is an exponent

The computer input will be a series of observations of water discharge (Q), the corresponding gauge readings (h) and information about the zero point of the gauge relative to the lowest point of the "controlling profile". The computer calculates k and n. Regardless, the rating curve must be regularly checked and updated by qualified personnel, since its reliability depends on the state of the weir and instrumentation.

Due to topographical conditions at each measuring site, a rating curve may be divided in several sections, each of them being a straight line in a logarithmic system. The computer program will indicate which sections provide the best possible fit to the initial water discharge observations. It will also print a complete table so that any later gauge reading can be transformed directly into discharge.

Records from automatic recording gauges and data loggers can be "read" by various machines (coordinatographs, or more-or-less automatic tracing instruments and computers) that will digitalize them and allow data to be entered directly into data-base files (such as Lotus 1-2-3 or QuattroPro®). The stream stage record files can be also combined with the rating curve so that actual water discharge figures are tabulated.

13.3.2. Mass Balance

The construction of accumulation and ablation maps and the measurement of areas to obtain the total winter and summer balance are very time consuming. Computer programs have been developed by the Glaciology Section of the Norwegian Water and Energy Administration to calculate the winter balance directly from the snow depth soundings and the density information obtained by pit studies. The computer can construct accumulation and ablation maps and give a complete table of balance variations vs. height. In practice, at some point the computerized contouring routines fail to reproduce nature unless many poles are available each year. Consequently, knowledge of local conditions on the glacier and consistency with previous years must be either programmed into the models or must be directly applied by the human user.

A program for computing mass balances and generating balance plots has been developed by NHRI. The original version was written by G.J. Young (1974) and optimized for Peyto Glacier. It has now been updated and further refined for general application to the glaciers of western Canada by Dave Peters. It calculates a regression equation that describes the relationship between an elevation map of the glacier and the changes in mass balance over a period of time. Once the relationship has been established the program then applies the equation to the glacier to produce a tabulation of the changes in mass balance. The output can be used to produce graphs of the expected changes in mass balance over the surface of the glacier. A schematic of the basic program is shown in Fig. 13.7. More details on the routines and a sample output are given in Appendix VII.

Programs such as Surfer® or SigmaPlot® allow plotting of contour values, mapping, and three-dimensional diagrams of any parameter or perspective desired. Spreadsheet program, such as Lotus 1-2-3®, QuattroPro® or D-Base®, allow easy plotting of tabulated data. The graphics quality of QuattroPro® preferred for this book and was used to produce the plots shown in Figs. 6.4 and 13.2. The added benefit of using standard format data-base spreadsheet files is the ease of statistical analysis. For example, in Fig. 6.4, computation of linear regression parameters, correlation coefficients, and standard error estimates are given directly. Final plots are easily adjusted using the spreadsheets. If more detailed statistics are desired, such as testing the significance of various correlations, then these tests can be programmed in or the data exported for analysis using a standard statistical package. Computer software is a rapidly developing field so more powerful analytical routines can be expected to be made available in the future.

13.3.3. Movement

The movement of a stake can be calculated with a computer program that determines the co-ordinates of a stake directly from the angle observations made in the field. The field triangulation can be made from fixed points with known co-ordinates or by resection using known stations. The movement of the stake is computed directly when two sets of field data are given. The distance and the direction of movement is printed out for each stake.

This program is a modification of programs used in terrestrial triangulation. Stake measurements may also be conveniently computed using TOPOS® software (available from WILD). Either triangulation, resection or distance and angle measurement modes may be used to compute coordinates and from these the velocity vectors.

13.3.4. Correlation and Error Calculations

The discharge in a glacier stream and glacier mass balance can be correlated with various independent variables (precipitation, wind, air temperature, etc.). A detailed inspection of diagrams showing daily mean air temperature, precipitation, etc. and water discharge from a glacier may give an impression of the relationship between discharge and various meteorological parameters. Such a study was done for Canadian glaciers (Østrem 1966a) and later discussed by Paterson (1966) and

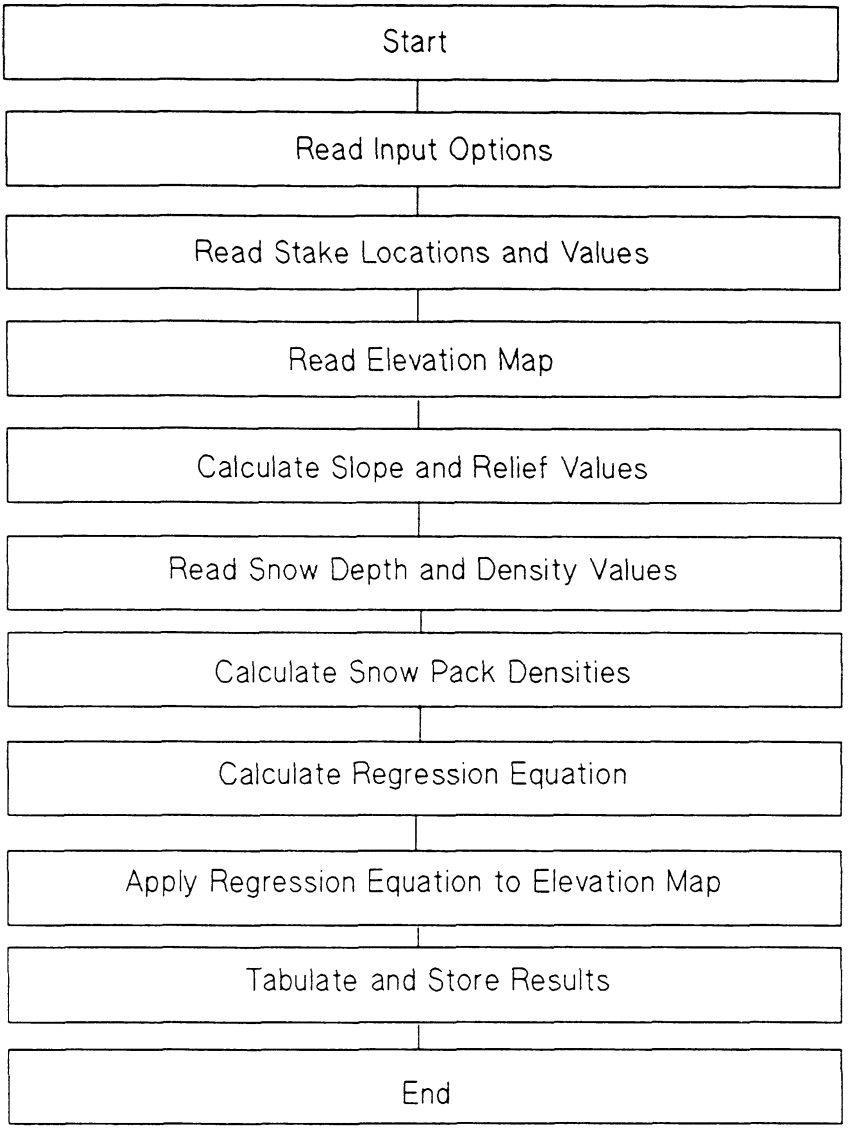


Figure 13.7: Glacier Mass Balance Computation Model
Glacier mass balance computations may be simplified using a computer model that is calibrated for the particular glacier under study. The model inputs include maps of: 1. Glacier topography (for computation of slope, aspect, elevation, relief), 2. Glacier albedo, 3. Snow/firn/ice density, 4. Intensity of crevassing and, 5. Mean solar radiation incident on the glacier surface.

Østrem (1966b). See also discussions at the Banff meetings in 1972, for example Jensen & Lang, 1973.

There is certainly a correlation between daily water discharge in the glacier stream and the energy balance (e.g., daily mean air temperature, radiation, precipitation and wind speed on the same day or one or two days before). A stepwise regression analysis (details of the special program used are given in Wøien 1966) selects the most significant parameters to describe the variation in discharge, and separate equations are given for the one, two, or more independent variables included in the regression. The program will give correlation coefficients between the variables, their significance, and finally, the resulting regression equations with partial and multiple coefficients.

It is assumed that studies carried out for the same glacier for a number of years with variable meteorological conditions will provide a basis for future discharge prediction, and will become vital in understanding the relationship between glacier variations and climate.

A number of computer programs are available commercially for performing statistical computations on data and should be used if possible. However, care must be taken to ensure that the methods used in these program are actually appropriate for the data being analyzed. Thus the program should be capable of differentiating between significance testing for small data sets (less than 30 points), where a students-t or chi^2 test is most appropriate, versus a large data set (greater than 30 points), where a z-test or other methods may be applied instead. The students-t test is best for all data set sizes since it approaches the z-test results for large data files anyhow. The method of computation of regression lines and standard deviations differs between programs, so it is best to check independently and document all statistical programs and methods used, as well as the manner in which the degrees of freedom are computed. The data set should be tested for normality, skewness and kurtosis, and properly transformed before any of the standard tests are applied.

CHAPTER 14. MASS BALANCE METHODOLOGIES AND REPORTING SYSTEMS

14.1. Overview

A techniques described in this manual allow us to measure mass balance parameters that may conform to one or more reporting systems (such as "Fixed-date", "Stratigraphic" systems; Unesco, 1970).

Commonly, it is not possible, nor desirable to obtain a complete net balance in the form required to report under these two systems. That is why a number of other methods have been used throughout the years to obtain a measure of snow, firn and ice balance parameters that can be used in a meaningful way for climate, water supply studies and a variety of other applications. In this section the methods used to obtain data reported under the "Stratigraphic" system of reporting mass balance is compared to the other mass-balance methodologies currently used in North America and Norway.

Some are worthwhile, but others involve too many extrapolations about the real world, that it leads one to completely distrust such reported data. In this section emphasis is placed on evaluating the other methods in light of the variables used in the "Stratigraphic" system and described in the previous sections. It is crucial that the personnel making measurement in the field and computing balance values in the office clearly understand the methods and mass-balance reporting system that they are using, and that data is presented in a form that is usable to a wide variety of researchers including meteorologists, climate change modellers, geographers, water planning and mining engineers, glaciologists, recreation and ski area planners and numerous others. To accomplish this, data are required in a form that allows inter-comparisons between different glaciers, and throughout time at one glacier, with all actually measured data clearly separated from derived data.

Eleven different methods used for measuring glacier mass balance are summarized on Figure 14.1a and the primary reporting systems are shown on Fig. 14.1b. It is often impossible to perform data inter-comparisons because they tend to provide completely different measured parameters. If spatial net balance integrations for the **entire glacier** are considered (i.e. "Traditional" Method), then comparisons between measurement methods may be made (i.e. methods indicated for "entire" glacier in 2nd column of Fig. 14.1a). To avoid misuse of mass-balance data obtained in past years and to improve the usefulness of data obtained in the future, a discussion of how mass balance measured using the "Traditional" method and reported using the "Stratigraphic" system for b_n, b_s, b_w compares with data obtained using other methods, primarily balance Fixed-Date, Floating-Date (or equivalently "Known-Date"), Combined and Index Methods for particular locations on a glacier. Further information on Hydrological and Geodetic mass-balance measurements are briefly summarized on Fig. 14.1, although the techniques are also discussed in the surveying, stream-gauging and data reduction sections of this manual.

For net surface balance methods for the entire glacier (Fig. 14.1, I.A.), the main goal is to obtain detailed measurements of summer, winter and net balance (b_s, b_w, b_n respectively) for all elevations and spatial locations on the glacier; the time scales chosen differ, as described below. It is important not to mix variables obtained

GLACIER MASS BALANCE MEASUREMENT METHODS			
MEASUREMENT METHODS	GLACIER MEASURED	DETAILS	REFERENCE
A. TRADITIONAL	entire	surface stakes, snow probing, snow pit methods, snow coring, survey locations	Østrem & Stanley (1966)
B. SNOW-COVER	entire	same as A (above) except measure only ablation less snow cover remaining at end of summer	Zubok (1975)
C. INDEX STAKE 1. Balance/Elevation Integration	entire or portion	longitudinal profile of surface stakes, snow pit, coring, surveying locations	Koerner (1986)
2. Stake Farm	portion	localized high density network of surface stakes; snow pit and ice core methods	Koerner (1986); Reynaud (1991)
3. Single Stake	portion	one stake; snow pit and ice core methods	Meier (1961)
D. STATISTICAL MODELS 1. Linear Balance Model	entire or portion	multivariate/statistical methods employed using data obtained from A & C based on site and year	Lliboutry (1974); Letréguilly (1984)
2. Parameter Correlation Model	entire/ portion	similar to above (D-1) but with additional correlations based upon model of most important melt parameters expected (i.e., topography, roughness, slope, aspect, etc.)	Young (1976)
E. RECONNAISSANCE 1. AAR	entire	remote sensing using microwave to visible wavelengths, aerial photogrammetry, ground surveys of snow line & surface roughness, runoff/refreezing features, mapping of superimposed ice zones	UNESCO (1970); Glen (1963)
2. ELA			Østrem & Stanley (1966)
3. Runoff Line			Koerner (1986)
F. GEODETIC	entire	photogrammetry, remote sensing imagery, ground theodelite & EDM surveys and/or GPS, radar and laser altimetry	Krimmel (1989); Meier & Tangborn (1965); Meier *et al.* (1961)
G. HYDROLOGIC	entire	basin wide precipitation, evaporation and runoff	Meier *et al.* (1961)
H. TERMINUS POSITION	entire	ground surveys, remote sensing or aerial photographs, glacier flow response model; often called the "inverse problem"	Paterson (1981)
I. CROSS-SECTION	entire or portion	mass continuity using successive glacier cross-sections; especially across ELA	Lliboutry (1971); Letréguilly (1984)
J. VELOCITY VECTOR	entire or portion	ice flow in vertical & horizontal directions; topographic change	Meier & Tangborn (1965)
K. CLIMATE PARAMETER MODEL	entire or portion	energy balance at surface; precipitation	Greuelland & Oerlemans (1986)
		temperature/precipitation at nearby locations	Kotlyakov & Krenke (1982); Tangborn (1980)

Figure 14.1a. Glacier mass balance measurement methods used in Canada, Norway, USA and worldwide.

for different reporting systems ("Stratigraphic", "Fixed-Date", "Floating-Date") unless it is explicitly stated (such as "Combined"). In addition, it is important to report data so that all actual and derived data and sampling dates may be compared in an unbiased manner, between the different net balance methods.

For the index stake methods (Fig. 14.1a, C), the goal is usually to obtain the net balance at certain locations (C.2. and 3.) or at along certain profiles as an index of the entire glacier (Fig. 14.1a, C.1.). Alternatively, the reconnaissance methods employ another variable such as ELA and AAR described below (Fig. 14.1a, E.). Sometimes the summer, winter and net balance obtained at a certain stake (or a nominal number of well-studied index stake locations) is used to determine the net balance of the entire glacier (Fig. 14.1a, D.1. and 2.), or to calculate: the AAR (ratio of accumulation area to the total area of the glacier: Fig. 14.1a, E.1.); or the ELA (equilibrium line altitude, which is equal to the end-of-summer snowline where the ice is temperate throughout the year and/or internal accumulation is insignificant: Fig. 14.1a, E.2.); or the Runoff-Line (for cold glaciers with superimposed ice and extensive internal accumulation: Fig. 14.1a, E.3.).

The Geodetic (and/or photogrammetric) (Fig. 14.1a, F.), Hydrologic (Fig. 14.1a, G) and other methods (Fig. 14.1a, H.- K.) may be used to check data obtained using the first five techniques (Fig. 14.1a, A.- E.) and help in analysis of the accuracy of the other methods. Of these two, the Geodetic Method is the most useful; the Hydrological Method is subject to numerous unknowns that often make the measurement of net balance impossible.

In this manual we have discussed to some extent the methods used by Dr. R.M. Koerner in the Canadian High Arctic (Fig. 14.1a, C.1.- 3.), and these are covered further in Appendix IV. The Koerner methods are included because they clearly show how high-quality data can be obtained, under adverse conditions and extreme logistical constraints, where entire-glacier or entire-ice-cap measurements are not possible. For these index methods, the spatially-integrated summer, winter and net balance parameters of the entire glacier are, in general, not known, nor are they needed.

It can not be overemphasized that for relating data obtained by the different methods outlined in Fig. 14.1a, one must clearly understand the differences in methodologies and measurement reporting systems (Fig. 14.1b). Otherwise, completely incorrect conclusions may be reached on climate and global ice volume change.

Other methods are not discussed because they are not advocated, although they may be useful under certain circumstances; they often involve too much guesswork and not enough direct measurement. The glacier mass-balance parameters reported for most of these methods are closely related, but often not directly. The Geodetic and Hydrological Methods may be used to check data obtained using the first four techniques (Fig. 14.1a) and help in analysis of the accuracy of the other methods.

14.2. Stratigraphic System

The first "stratigraphic" system involves measuring the minimum and maximum balance each year and from these computing the net balance. This technique is described in Fig. 14.2, and is the primary method that has been advocated throughout this manual. Unfortunately this is difficult to accomplish in practice. If dates of minimum and maximum balance are not known precisely then

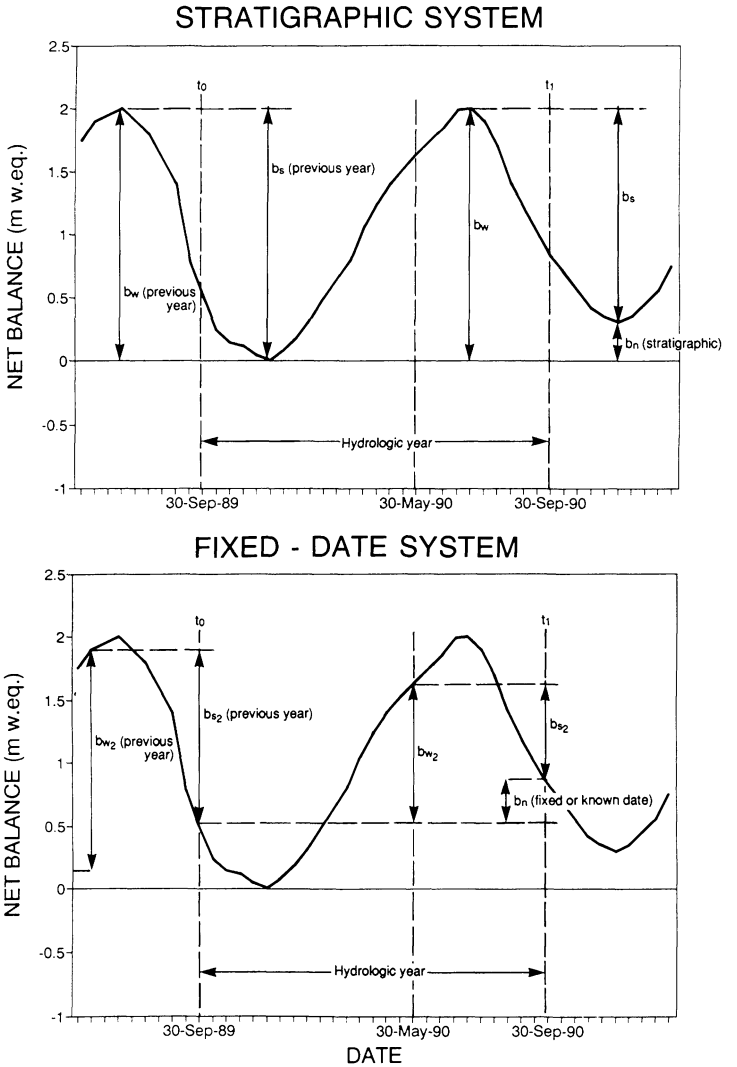


Figure 14.2: Comparison of "Stratigraphic" and "Fixed Date" Systems
The upper sketch is similar to Figure 1, and shows basically how the "Stratigraphic" system defined and a simplified view of the three basic measurements (b_w, b_s, b_n) that are defined. Other important measurements obtained using this method include AAR and ELA, and this is the standard method as outlined by Østrem and Stanley (1966).

This may be compared to the "Fixed-Date" (or "Known-Date") system shown in the lower sketch where quite different variables are measured and reported (b_{w2}, b_{s2}, $b_{n\ annual}$). For simplicity it is assumed that the known and fixed dates coincide, but this is rarely the case in practice.

it is virtually impossible to relate balance records to climate variables. The summer balance is computed using the following equation:

Stratigraphic System

summer: $b_s = b_{s1} + b_{s2} + b_{s3} - b_{w1}$

winter: $b_w = b_{w1} + b_{w2} + b_{w3} - b_{s3(\text{previous year})}$

If the winter measurement is made BEFORE the peak in winter snow accumulation (when $b_{w3} = - b_{s1}$),

or: $b_w = b_{w1} + b_{w2} - b_{s1} - b_{s3(\text{previous year})}$

If the winter measurement is made AFTER the peak in winter snow accumulation (when $b_{w3} = 0$),

net: $b_n = b_w + b_s = b_{n(\text{stratigraphic})}$

The variable b_{w1} is the early-winter accumulation that had accumulated on the glacier by the time of the previous fall measurement, and $b_{s3(\text{previous year})}$ (= $b_{\text{late-fall}}$) is the late-fall ablation that occurred after the fall measurement the previous year, as shown in Figs. 14.3 and 14.4. For simplicity, b_{w2} and b_{s2} are assumed to be the winter and summer balances measured at a known (or fixed) date; this variable is identical to the b_m described by Mayo and others (1972) and is dramatically different from the b_w or b_s reported using the Stratigraphic System.

The time transgressive nature of the glacier stratigraphic record (Unesco, 1970) on each glacier, also complicates detailed comparisons between monthly climate parameters and net glacier balance. If data are reported for each measurement location (each stake with coordinates known) on the glacier, then detailed comparisons with monthly meteorological variables can be made more accurately.

If field personnel cannot remain at the glacier until the time of minimum or maximum balance, then the precise dates of minimum and maximum balance must be extrapolated from temperature and precipitation records or remotely-sensed accumulation and ablation variables. It is unlikely that the time of minimum and maximum balance will coincide with field visits unless the personnel remained through the entire season, or reliable remote sensing of snowpack water equivalent and ablation was available (which it is not at the present time). Consequently, other methods (e.g., the other six, Fig. 4.1) have been used over the years at various glaciers.

In Canada and Norway the Stratigraphic is the principal system used and advocated (in conjuction with the Combined System when necessary). The Fixed-Date System might help solve the time-transgressive problem mentioned earlier. One drawback to using the stratigraphic system arises in part because glacier thinning and thickening and retreat complicates its use. The Canadian and Norwegian date have been obtained since the mid-1960s in this way and there appear to be no compelling arguments for changing. However, there must be clearer reporting of these data so

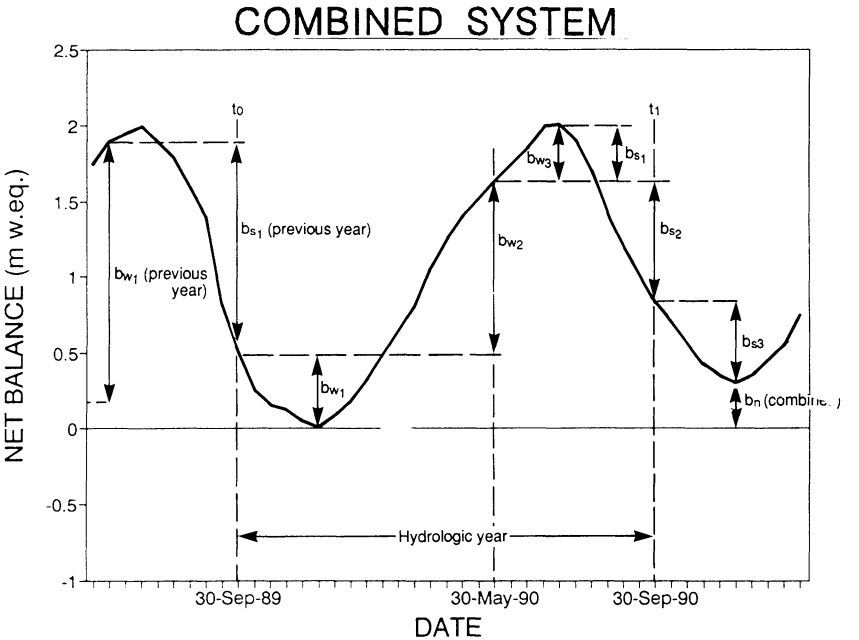


Figure 14.3: Combined System
The "Combined" System is often used in practice although not all of the measured variables are reported at present to the WGMS, they are published as in-house proceedings. The mass balance variables b_{w1}, b_{w3}, b_{s1}, b_{s3} are the early- and late-winter and early- and late-summer balances, respectively. The Combined method allows for complete reporting of information that is directly measured as compared to that which is calculated. A more detailed description of how each of these balance terms may be obtained is given by Mayo, Meier and Tangborn (1972).

Glacier Mass Balance Reporting Systems			
System	Reported Dates	Comments	Reference
A. Stratigraphic	annual melt horizon (b_s, b_0); max. snow accumulation (b_w)	balance values directly measured; dates often extrapolated; time transgressive nature often averaged out	Østrem & Stanley (1966); UNESCO (1970)
B. Time 1. Floating Date	field visit(s)	reference to stratigraphic horizons normally necessary; practical	
2. Fixed Date	calendar year or hydrologic year	same but with balance values extrapolated to pre-specified fixed-dates	UNESCO (1970)
C. Combined	all or mixture of above	allows flexible & accurate reporting but may not give complete balance	Higuchi (1991)

Figure 14.1b. Glacier mass balance reporting systems used in Canada, Norway, USA and worldwide.

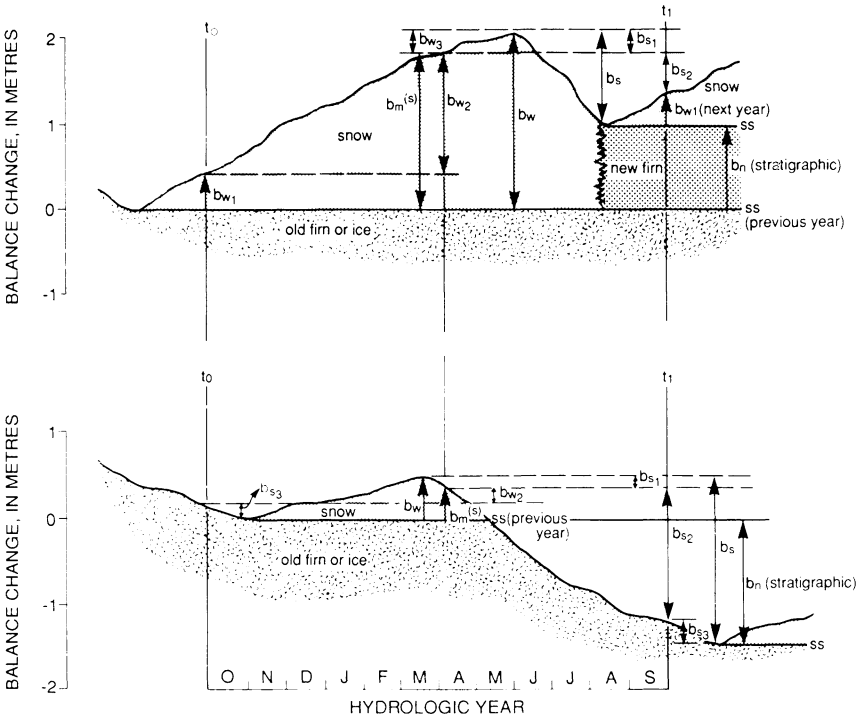


Figure 14.4: Combined System
The "Combined" System involves obtaining the variables as indicated on these two diagrams (upper for the accumulation area and lower for the ablation zone). The measured winter balance, $b_m(s)$, as defined by Mayo and others (1972) is the snow depth sampled during the spring visit to the glacier which is directly measured; $b_m(s)$ is may be used together with the late fall melt b_{s3} and the late winter snowfall, b_{w3} , to obtain the parameters b_{w2} and b_w. The glacier mass balance definitions as described here are included in the appendix section for reference.

that all extrapolated data can be distinguished from those directly-measured. Because of the volume of data obtained for each of these programs, this can best be accomplished using a well-planned data base; unfortunately not yet in place. Data must be in a form that can be directly verified using topographic-change and ice-flow information, related to terminus position and runoff measurements. They must be clearly separated from "algorithm-deduced" data IF correlations with meteorological variables are to hold up to scientific scrutiny. Like any variable, glacier mass balance must be carefully understood in terms of what it is recording and the errors involved before reliable statistical correlations can be made. This manual should ensure the field personnel provide the high-quality data required, or their efforts will be wasted.

14.3. Floating-Date versus Fixed-Date Systems

To rectify some of the limitations of reporting data using the Stratigraphic System, the Fixed-Date System was suggested by the International Association of Hydrological Sciences, but has not been used in Canada or Norway. For the Fixed-Date System the following simple balance relationships hold:

Fixed-Date System

summer: b_{s2}

winter: b_{w2}

net: $b_{n(fixed\text{-}date)} = b_{w2} + b_{s2}$

The Floating-Date System is actually used by all researchers whether or not they are aware of it, whenever they record a glacier mass-balance observation. All mass-balance data can be converted to this reporting scheme, but in practice this is not done. This manual recommends that such reporting be done, as well as for the net balance. Thus if someone wants to convert data collected according to the Floating-Date and Stratigraphic Systems then they have the information available to do so. Forms are included in Appendix VI for recording this type of information. There are a number of limitations to the Fixed-Date System so Norwegian and Canadian scientists have avoided using it. These are discussed in more detail below in describing how the Fixed-Date System differs from the Floating-Date System. The Floating-Date System is identical to the Fixed-Date System, except when the known measurement and fixed reporting dates do not coincide. The observation dates defined for the Fixed-Date System are often chosen to coincide with the end of the hydrological year (Oct. 1 to Sept. 30), but include an arbitrary date in the spring (such as May 30) for end-of-winter measurement as shown in Fig. 14.2. It must be emphasized that normally the <u>known</u> measurement and <u>fixed</u> reporting dates do <u>NOT</u> coincide, consequently normally

$$b_{n(fixed\text{-}date)} \neq b_{n(floating\text{-}date)} \neq b_{n(stratigraphic)}$$

For the Floating-Date System, there are no adjustments necessary for reporting the balance data measured at a particular (x,y,z) coordinate on a glacier. To report data for a prescribed Fixed-Date at the same (x,y,z) location, the reported values from Floating-Date results must extrapolated.

Often adjustments are made to obtain data that are not measurable at the fixed dates when b_{w2} and b_{s2}. These adjustments are not always reported or possible to check. Then we must believe in the algorithms used to adjust the balance measurement year adjust to the required fixed date (or stream survey "hydrological") year. The data used to make these extrapolations may be questionable so in Canada and Norway other systems are used for reporting glacier mass balance data.

Of course, it is of critical importance to clearly separate "extrapolated data" from directly measured data. As there are definite advantages in using Floating-Date and Fixed-Date Systems, it is important to understand the differences between their different measurement, computation and reporting techniques.

14.4. Combined System

In this system a combination of both Fixed-Date, Known-Date and Stratigraphic Systems is used to arrive at a measure of glacier summer, winter and net balance. It may be necessary because of logistics, or to eliminate the need for deriving balance parameters, such as b_{w3} (late-winter snowfall), b_{s1} (early-summer melt), which are sometimes impossible to measure directly.

Normally b_{s3} (late-fall melt) is simple to determine directly, but usually this is not possible until the poles melt out during the summer; quite often it is more difficult to measure accurately in the accumulation zone of a glacier than at lower elevations in the ablation zone. The early-fall snow accumulation, b_{w1}, is measured directly at the end of the season. If careful measurements are made each spring, when poles melt out or poles can be completely dug out, and each fall, when winter accumulation has already started, then both variables may be determined.

The fall measurement of balance, b_{s2} , is usually made at a flexible date during mid-September to mid-October in southwestern Canada and Norway. The Floating-Date parameters, b_{w2} and b_{s2} are needed to determine the Stratigraphic parameters b_s and b_w, and to compute the Fixed-Date parameters if the field and fixed dates do not coincide.

These Floating-Date parameters, b_{w2} and b_{s2} , are normally obtained during the late-winter (April, May, June) and early-fall months (August, September, October). The time of measurement has changed over the years, and in western Canada now is early- to late-May, for b_{w2}, and in mid-September to early-October, b_{s2} at Sentinel, Place, Helm and Peyto Glaciers. The snow water equivalent probed, and reported for most previous years, at these four glaciers is:

Spring snow depth probed each year (m w.eq.) = $b_{m\,(spring)}$

$$b_{m\,(spring)} = b_{w1} + b_{w2} - b_{s3(previous\ year)} = b_w - b_{w3}$$

If the winter measurement is made BEFORE the peak in winter snow accumulation (when $b_{w3} = - b_{s1}$),

$$b_{m\ (spring)} = b_{w1} + b_{w2} - b_{s3(previous\ year)} = b_w + b_{s1}$$

If the winter measurement is made AFTER the peak in winter snow accumulation (when $b_{w3} = 0$),

where either b_{w1} or $b_{s3(previous\ year)}$) are equal to zero, and where b_{s1} is negative; b_w and b_{w3} are positive. The winter balance b_w as reported to the WGMS is most accurately reported using this method, since normally b_{w3} (late-spring accumulation) and b_{s1} (early- or late-spring ablation) were not measured.

For simplicity and logistical considerations, it has often been assumed that b_{w3} is negligible; this is not unreasonable since often $b_{w3} << (b_{w1} + b_{w2})$, but it should be clearly stated when the data are reported. Actually, b_{w3} normally constitutes a measurement error for c_{annual} (annual accumulation) that may be compensated for by an equal and opposite error in a_{summer} (annual ablation) represented by b_{s1}, thereby not affecting the accuracy of b_n. When b_{w3} is significant, and not measured, then summer balance parameters (b_{s2} or b_s) will not properly correlate to known temperature and precipitation.

Reporting of measurement dates for each balance parameter will facilitate more effective use of the data for climate variability analyses. Likewise, extrapolated dates for maximum and minimum balance in the Stratigraphic System, and extrapolated balance values in the Fixed-Date System for minimum and maximum balance must be clearly indicated and separated from actual measurement dates and values.

14.5. ELA and AAR

Both the equilibrium line altitude (ELA) and the accumulation area ratio (AAR) are useful parameters for monitoring glacier mass balance provided their relationship to it is known. The former, represents the line dividing the areas of net accumulation and net ablation, the latter is the ration of the area of accumulation to the total area of the glacier. Fig. 6.4 shows the close linear relationship between ELA and AAR.

For glaciers with negligible internal accumulation, the ELA corresponds to the mean annual snowline. For situations when the snowline and lower limit of superimposed ice is readily apparent on images (e.g. aerial photography, LANDSAT Thematic Mapper, Synthetic Aperture Radar, etc.), it may be quite easy to obtain the AAR values. They can be measured with a planimeter, digitized or processed with an image analysis system such as PCI. Ground-based surveys of the areal extent of the ELA provide the most accurate assessment, but are often time consuming and cannot cover large areas. The ELA and AAR are "parameters" or "index" terms that indicate certain balance values. They are unreliable or difficult to use when there are complicating factors such as internal accumulation, or early snowfalls obscuring the limits. Although they may seem to be convenient tools providing for easy monitoring of glacier mass balance, they are much less reliable than the surface stake, probing and snow-pit methods discussed previously. They work well in conjunction with these methods in extending the results spatially.

14.6. Koerner Index-Methods: Stake-Farm and Stake-Profile

The two index methods included on Fig. 14.1 are referred to here as the "Koerner" Methods and they include the "Stake-Farm" and "Stake-Profile" Methods, described in Appendix IV. These are alternative forms of Stratigraphic, Fixed-Date, Known-Date and Combined Systems. In recent years the latter two methods have been used in the Canadian High Arctic. The Koerner Methods were not intended to give the net balance of an entire glacier, but rather a useful "index" balance measurement.

In contrast to some other index methods not mentioned, the Koerner Method is supplemented by isotopic and snow-chemistry studies, careful evaluation of internal accumulation, snow-temperature studies, ice-motion and ice-depth studies and topographic surveys whenever possible. Future plans include the use of laser altimetry and remote sensing. They can be used when a climate-change index site is desired on a large glacier or ice cap that is difficult or impossible to measure using the Stratigraphic, Fixed-Date or Combined System.

The Koerner Methods primarily obtain just $b_{n\ annual}$ each year in August (at a "known" but not a "fixed" date); usually b_{s2} and b_{w2} are not determined. Measurement dates are closely linked to the measurements reported, so it is a type of Known-Date System since it is related to the net balance of the glacier (the minimum of which occurs at some unknown date, but the precise value of which is recorded clearly at each site by stakes placed on the glacier).

Overall, the Combined Method is recommended, despite the difficulty of determining b_{w3} and b_{s1} without either direct measurements or additional extrapolations based on nearby temperature and precipitation records. In practice the Koerner Methods are a form of the Traditional Method that has proved to be particularly useful in the Canadian High Arctic. In annual terms, the Koerner Methods differ little from the Traditional Method advocated by Østrem and Stanley (1966) except in how the overall balance of the glacier is computed and reported. In the Koerner Method the net balance of the entire glacier is considered relatively useless compared to the net balance at one location, or along one longitudinal profile of the glacier; for a more detailed description see Appendix IV.

14.7. Geodetic Method

The Geodetic Method involves determining the topographic change of the glacier surface from the beginning to the end of the measurement period, and integrating it across the entire glacier to deduce the net balance. This method is only applicable if the entire glacier is examined for thickness change, due to the complicating effects of flow convergence and divergence. If thickness change is used as a local indicator of balance then the vertical change due to accumulation and ablation must be much larger than that due to the vertical component of glacier flow, or alternatively the vertical flow velocities must be known. In addition, the mean density change of the glacier at that site must be known if the changes are to be related to water equivalent values. If this is negligible, or small, then it is a relatively simple task to compute the net balance of a glacier using the Geodetic Method. Normally the mean density of a glacier is unknown, but can be estimated

(Paterson, 1980); ideally one should take vertical profiles of glacier density change, but this is impractical.

If photogrammetry is used in the accumulation area of the glacier,or where ground control is poor, then the quality of the topographic base map may also be poor. It must be checked using ground surveys, otherwise vertical position error of up to tens of metres may result (apparently the problem with the 1965 base map of upper Peyto Glacier). This re-emphasizes the need for all data to be reported in a form that can be understood clearly by the people using them for climate and other comparisons. It is suggested that data be reported as outlined in the tables (Appendix VI) so the data will be accompanied by information on such problems and/or if any of the data or dates reported were extrapolated from known measurement points.

14.8. Hydrological Method

The Hydrological Method (Fig 14.1a;G.) is used to compute the values using a water-balance approach, where the net precipitation in the basin is subtracted from the net runoff to compute the amount that is stored or released from the glacier. This method sounds great but unfortunately it is influenced by numerous parameters that are either very difficult or impossible to measure correctly (such as basin-wide precipitation and evaporation, outside surface water input, terminus stream discharge, ground-water inflow and outflow, seasonal storage and release of englacial water).

14.9. Summary and Comparison of Methodologies

Rarely is measurement at a prescribed "fixed-date" actually possible due to weather, budgetary and logistical constraints; for similar reasons it is rarely possible to measure the "stratigraphic" balance variables at precisely the minimum and maximum balance times. Consequently, adjustments must be made to either the Stratigraphic or the Fixed-Date Systems, and there are advantages and disadvantages to both.

For all methods, data reported on accumulation and ablation is sometimes not directly measured, but is computed from a derived algorithm using nearby air temperature and precipitation records to estimate the actual dates and data values to be reported to the WGMS (e.g., the Alaskan studies, Appendix V). The actual dates for minimum and maximum balance under the Stratigraphic System, or the adjusted balance values of the Fixed-Date System, can only be determined by extrapolation unless detailed remote-sensing measurements are made continuously at each site to obtain ablation and accumulation parameters in terms of water equivalent values. Normally, in both Canada and Norway, the Traditional Method is used to obtain the Stratigraphic System variables. Where budgetary and logistic constraints are most severe (e.g., the Arctic) the annual and net balance of the glaciers and ice caps are determined once a year at particular elevations or profiles.

With careful and clear data documentation the mass balance records can become valuable tools for deciphering climate change. They can then be related to meteorological parameters such as cloud thickness and type, short and long-wave radiation, temperature, wind and precipitation.

CHAPTER 15. REFERENCES AND RECOMMENDED LITERATURE

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APPENDIX I

TERMS AND DEFINITIONS

I.1. **STRATIGRAPHIC** (terms in *italics* are from Mayo *et al.*, 1972)

$b_{n\ Stratigraphic}$ = net mass balance (net change in glacier mass expressed in metres water equivalent, m w.eq., during one balance year as defined by stratigraphy not calendar dates; normally easy to observed location in stratigraphic record, but exact dates of minimum and maximum balance are often difficult to obtain accurately)

$b_w = b_{w\ Stratigraphic}$ = $b_w(s)$ = *maximum snow balance* = winter balance (maximum net snow and ice accumulation during winter months or equivalently during accumulation season)

$b_s = b_{s\ Stratigraphic}$ = (minimum summer balance) = summer balance (maximum net mass loss by sublimation, evaporation or melt-water runoff during summer months or ablation season)

b_{w1} = $b_0(s)$ = *initial snow balance* = $b_l(ls)$ = *late summer snow previous year* = winter balance (net accumulation) after summer has ended but before fall measurement (early fall snow)

b_{w2} = $b_m(s)$ = *measured winter snow balance* = winter balance (net accumulation) between measurement times in fall and spring

b_{w3} = winter balance (net accumulation) after spring measurement time (snow probing) but before summer ablation season starts.

b_{s1} = early summer balance (net ablation) after winter balance has reached a maximum value (end of winter measurement period) but before spring measurement; spring or early summer ablation).

b_{s2} = main summer balance (net ablation) between measurement times in spring and fall.

b_{s3} = $b_0(i)$ = *initial ice balance = firn and ice loss after the start of the hydrological year and before ablation ceases in winter* = late summer balance (net ablation) after fall measurement time (snow probing) but before time winter measurement period starts; same as late fall melt.

$t_{minimum}$ = time of minimum balance (end of b_s measurement period)

$t_{maximum}$ = time of maximum balance (end of b_w measurement period)

$t_{meas.\ spring}$ = time of measurement in spring

$t_{meas.\ fall}$ = time of measurement in fall

$t_{meas.}$ = time of measurement at other times of the year

I.2. FIXED-DATE

$b_{n\ Fixed\text{-}date}$ = net mass balance (net change in glacier mass expressed in metres water equivalent, m w.eq., during one calendar year as defined by fixed-dates of measurement and/or balance computation; often taken to be the hydrologic year defined as Oct. 1 to Sept 30; exact balance is difficult to obtain because stratigraphic record can not be used directly)

$b_{w\ Fixed\text{-}date}$ = winter balance (net snow and ice accumulation during winter months as defined by fixed-dates minus net loss by ablation during this time period; period often taken to be from Oct. 1 to May 30, or at the exact time of field measurement if possible)

$b_{s\ Fixed\text{-}date}$ = summer balance (net mass loss by sublimation, evaporation or meltwater runoff minus net gain by accumulation during summer months or ablation season; period often taken to be May 30 to Sept 30 or as defined by the researcher)

$t_{meas.\ spring}$ = time of measurement in spring

$t_{meas.\ fall}$ = time of measurement in fall

$t_{meas.}$ = time of measurement at other times of the year

$t_{fixed\ spring} = t_{fixed\text{-}date\ start\ summer}$ = pre-defined beginning of summer for reporting purposes

$t_{fixed\ fall} = t_{fixed\text{-}date\ start\ winter}$ = pre-defined time of winter for reporting purposes

I.3. FLOATING-DATE

$b_{n\ Floating\text{-}date}$ = net mass balance (net change in glacier mass expressed in metres water equivalent, m w.eq., between known measurement dates that are separated by approximately one calendar year as defined by actual times of measurement only; NO computed balance values or computed dates are reported; often taken to roughly coincide with hydrologic year defined as Oct. 1 to Sept 30 or as necessary for field-logistical reasons; exact balance is difficult to obtain because stratigraphic record can not be used directly)

$b_{w\ Floating\text{-}date} = b_{w2}$ = winter balance (net snow and ice accumulation during winter months as defined by known-dates of field measurement only)

$b_{s\ Floating\text{-}date} = b_{s2}$ = summer balance (net mass loss by sublimation, evaporation or melt-water runoff during summer months or ablation season as defined by known-dates of field measurements only)

$t_{meas.\ spring}$ = time of measurement in spring

$t_{meas.\ fall}$ = time of measurement in fall

$t_{meas.}$ = time of measurement at other times of the year

I.4. COMBINED

$b_{n\ Combined}$ = net mass balance (net change in glacier mass expressed in metres water equivalent, m w.eq., during one balance year as defined by the researcher and his dates of measurement and/or computed for reporting purposes; normally a mix between floating-date and stratigraphic systems, but could be also a combination with fixed-date systems; must be reported precisely in terms of what was measured and what was computed if any sense it to be made of the data)

b_w = winter balance (net snow and ice accumulation during winter months as defined by researcher and dates given below)

b_s = summer balance (net mass loss by sublimation, evaporation or melt-water runoff during summer months or ablation season as defined by researcher and dates given below)

b_{w1} = winter balance (net accumulation) after summer has ended but before fall measurement (early fall snow)

b_{w2} = winter balance (net accumulation) between measurement times in fall and spring

b_{w3} = winter balance (net accumulation) after spring measurement time (snow probing) but before summer ablation season starts.

b_{s1} = early summer balance (net ablation) after winter balance has reached a maximum value (end of winter measurement period) but before spring measurement (early summer or spring melt snow).

b_{s2} = main summer balance (net ablation) between measurement times in spring and fall.

b_{s3} = late summer balance (net ablation) after fall measurement time (snow probing) but before minimum summer balance and time winter measurement period starts; same as late fall melt.

$t_{minimum}$ = time of minimum balance (end of b_s measurement period)

$t_{maximum}$ = time of maximum balance (end of b_w measurement period)

$t_{meas.\ spring}$ = time of measurement in spring

$t_{meas.\ fall}$ = time of measurement in fall

$t_{meas.}$ = time of measurement at other times of the year

$t_{fixed\ spring}$ = $t_{fixed\text{-}date\ start\ summer}$ = pre-defined beginning of summer for reporting purposes

$t_{fixed\ fall}$ = $t_{fixed\text{-}date\ start\ winter}$ = pre-defined time of winter for reporting purposes

I.5. OTHER DEFINITIONS

a_t = ablation at time, t, since beginning of balance year

c_t = total accumulation at time, t, since beginning of balance year

$\bar{b}_w$ = areally-averaged mean winter balance

$\bar{b}_s$ = areally-averaged mean summer balance

$\bar{b}_n$ = areally-averaged mean net balance

A = surface area of glacier

$B_w = A\ \bar{b}_w$

$B_s = A\ \bar{b}_s$

$B_n = A\ \bar{b}_n$

ELA = Equilibrium Line Altitude = line between net accumulation and net ablation on a glacier = location where net annual balance is zero

AAR = Accumulation Area Ratio = ratio of accumulation area of a glacier to total area in any one year

activity index = slope of the net balance curve with elevation at the equilibrium line

runoff line = line below which meltwater does not refreeze with the snowpack, glacier firn or ice, and instead runs off as meltwater

superimposed ice = part of glacier where surface runoff or percolating meltwater has refrozen due to the fact that the glacier surface is subfreezing at that location.

APPENDIX II

UNITS AND CONVERSION TABLES

Conversion Tables

Glaciological data are measured and reported in the metric system. For the benefit of people who are not sufficiently familiar with the metric system or who feel a need to convert to or from other units, we include some frequently used definitions and conversions:

QUANTITY	MEASURE OF UNIT	SYMBOL	EQUIVALENT
Length	kilometre	km	1000 m
	metre	m	100 cm
	centimetre	cm	10^{-2} m
Mass	kilogram	kg	1000 g
	gram	g	10^{-3} kg
	tonne	t	1000 kg
Time	hour	h*	3600 s
	second	s	0.278×10^{-3} h
Frequency	hertz	Hz	s^{-1}
Temperature	degree celsius	°C	
	degree kelvin	°K	°C + 273.15
Volume	cubic metre	m^3	10^6 cm^3
	litre	ℓ	10^{-3} m^3
Force	newton	N	Kg m/s^2
Pressure	bar	b	10^5 Pa
	millibar	mb	10^2 Pa = 10^{-3} b
	pascal	Pa	N/m^2
Energy	joule	J	Nm
Velocity	metre per second	m/s	3.6 km/h
Acceleration	metre per sec^2	m/s^2	
Density	kilogram per cubic metre	kg/m^3	10^{-3} g/cm^3

* often in practice, the symbol "hr" is used instead.

Non-SI Units Commonly Used			
Quantity	Measure of Unit	Symbol	Additional Units & Conversions
Area	are	a	1 a = 100 m^2
	hectare	ha	1 ha = 10000 m^2
Energy	calorie	cal	1 cal = 4.187 J
Velocity	mile per hour	mi/h	1 mi/h = 0.4470 m/s = 1.609 km/h
	knot	kn	1 kn = 0.5144 m/s
Distance	nautical mile	n mi	1852 m
	micron	μ	1μ = 1μm = 10^{-6}m
	nanometre	nm	10^{-9} m
	ångström	Å	10^{-10} m = 10 nm

English Units/Equivalents	
1 inch	0.0254 m 2.54 cm
1 foot	0.3048 m 30.48 cm
1 mile	1609.344 m
1 yard	0.9114 m
1 acre	4046.856 m^2 43560 ft^2
1 acre foot	1233.48 m^3
1 square foot	0.0929 m^2
1 square inch	6.4516 $10^{-4}m^2$
1 square mile	2.5899 km^2
1 square yard	0.8361 m^2
1 U.S. gallon	3.785 ℓ*
1 U.K. gallon	4.546 ℓ*

*In Canada, the symbol "L" is normally used to represent litre.

Multiples of Ten		
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

APPENDIX III

WORLD-WIDE OVERVIEW

GLACIER MASS-BALANCE OBSERVATIONS

C.S.L. Ommanney
National Hydrology Research Institute
Saskatoon, Saskatchewan

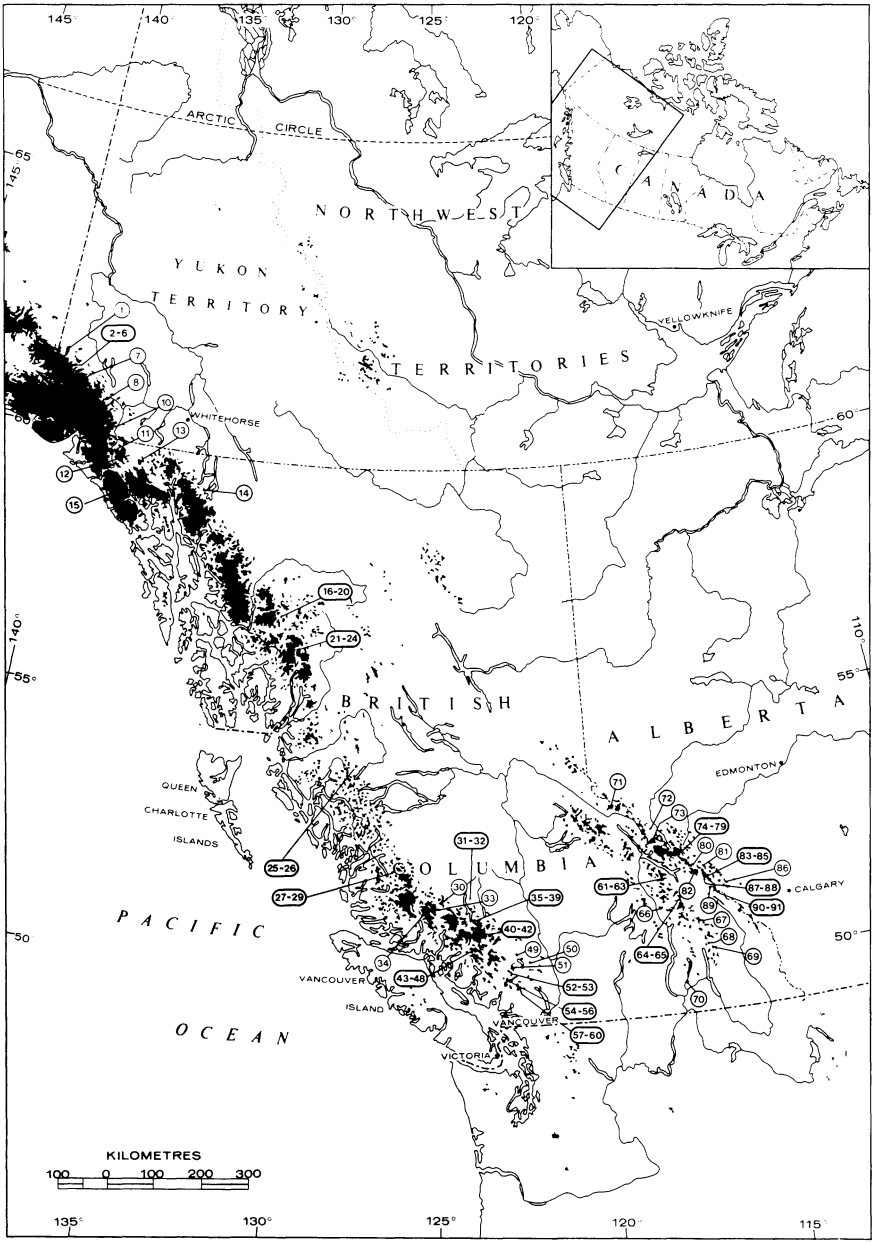


Figure III.1. Glaciers of Western Canada (see Table)

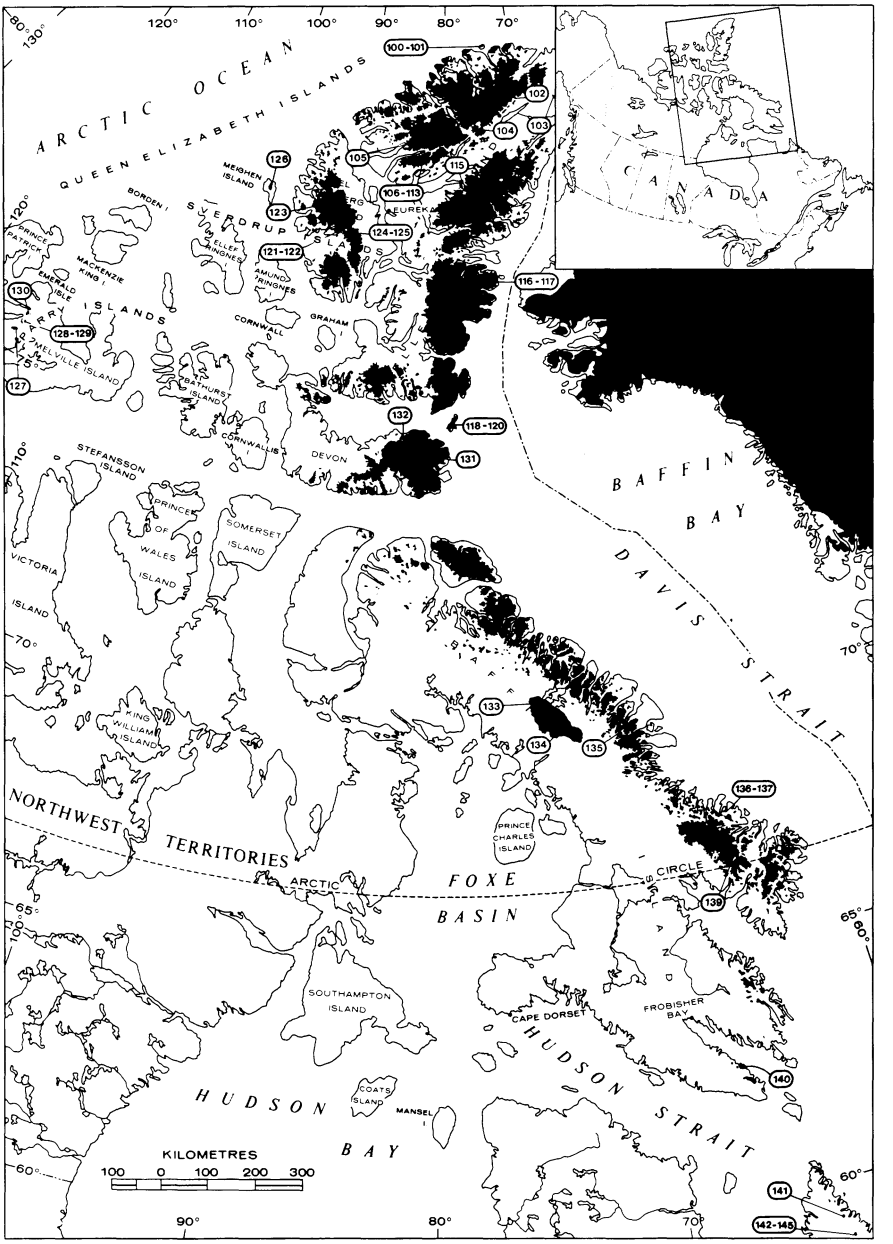


Figure III.2. Glaciers of Arctic and Eastern Canada (see Table)

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
CANADA, MAINLAND	DETERMINATION OF GLACIER MASS BALANCE												
16. Alexander Glacier	57 06.4	130 49.1	5.8	.....	.....	.....	.....	.....	.....	.....	.....	.....********...**	
18. Yuri Glacier	56 58.0	130 42.2	3.6	.....	.....	.....	.....	.....	.....	.....	.....	.....**********...**	
19. Andrei Glacier	56 55.7	130 55.6	92	.....	.....	.....	.....	.....	.....	.....	.....	.....**********...**	
23. Berendon Glacier	56 14.8	130 05.0	33.4	.....	.....	.....	.....	.....	.....	.....	....******..*****..	.....	
30. Bench Glacier	51 27.0	124 56.0	10	.....	.....	.....	.....	.....	.....	.....	.....	.....******...**	
33. Tiedemann Glacier	51 19.5	125 00.0	63	.....	.....	.....	.....	.....	.....	.....	.....	.....******...**	
40. Sykora Glacier	50 52.7	123 33.8	4.2	.....	.....	.....	.....	.....	.....	.....	.....	.....******....	
41. Bridge Glacier	50 49.4	123 33.0	21.4	.....	.....	.....	.....	.....	.....	.....	.....	....**********	
42. Zavisha Glacier	50 48.4	123 25.3	25	.....	.....	.....	.....	.....	.....	.....	.....	....**********	
49. Place Glacier	50 25.3	122 36.0	3.8	.....	.....	.....	.....	.....	.....	.....	.....	...**********	
54. Helm Glacier	49 57.8	123 00.0	3.1	.....	.....	.....	.....	.....	.....	.....	.....	....**********	
56. Sentinel Glacier	49 53.6	122 58.9	1.8	.....	.....	.....	.....	.....	.....	.....	.....	.....**********	
66. Woolsey Glacier	51 07.5	118 02.5	3.9	.....	.....	.....	.....	.....	.....	.....	....**********	.....	
81. Ram River Glacier	51 51.0	116 11.5	1.8	.....	.....	.....	.....	.....	.....	.....	....**********	.....	
83. Peyto Glacier	51 40.6	116 32.8	13	.....	.....	.....	.....	.....	.....	.....	....**********	.....	
142. Superguksoak Glacier	58 57.0	63 47.0	1.8	.....	.....	.....	.....	.....	.....	.....	.....	.....	****.....
143. Abraham Glacier	58 56.2	63 31.9	0.8	.....	.....	.....	.....	.....	.....	.....	.....	.....	****.....
144. Hidden Glacier	58 55.7	63 32.7	0.7	.....	.....	.....	.....	.....	.....	.....	.....	.....	****.....
145. Minaret Glacier	58 53.1	63 41.2	0.9	.....	.....	.....	.....	.....	.....	.....	.....	.....	****.....
CANADA, ARCTIC	DETERMINATION OF GLACIER MASS BALANCE												
100. Ward Hunt Ice Shelf	83 7.2	73 30.3	660	.....	.....	.....	.....	.....	.....	.....	**********...******	....	
101. Ward Hunt Ice Rise (Ell)	83 7.0	74 10.0	32	.....	.....	.....	.....	.....	.....	.....	**********...******	....	
102. Gilman Glacier (Elles)	82 5.8	70 36.9	480	.....	.....	.....	.....	.....	.....	.....	**********	.....	
103. Unnamed Ice Cap (Elles)	81 57.3	64 12.0	7.5	.....	.....	.....	.....	.....	.....	.....	.....**..	******	.....
104. Per Ardua Gl. (Elles)	81 31.0	76 27.0	4.34	.....	.....	.....	.....	.....	.....	.....	...*******	.....	.....
114. Agassiz Ice Cap (Elles)	80 25.0	75 00.0	17326	.....	.....	.....	.....	.....	.....	.....	.....	.....**********	
116. Leffert Glacier (Elles)	78 41.3	75 1.4	593	.....	.....	.....	.....	.....	.....	.....	.....	....**	.....
117. Unnamed Glacier (Elles)	78 39.1	74 55.0	50	.....	.....	.....	.....	.....	.....	.....	.....	....**	.....
118. Laika Glacier (Coburg)	75 53.5	79 5.2	.3	.....	.....	.....	.....	.....	.....	.....	.....	..***...	.....
119. Laika Ice Cap (Coburg)	75 53.0	79 9.1	10	.....	.....	.....	.....	.....	.....	.....	.....	...**...	.....
120. Wolf Glacier (Coburg)	75 54.2	79 12.2	2.0	.....	.....	.....	.....	.....	.....	.....	.....	....**	.....
121. Baby Glacier (Axel)	79 26.4	90 58.0	0.6	.....	.....	.....	.....	.....	.....	.....	**********.****..	.....	**
125. White Glacier (Axel)	79 26.7	90 40.0	39	.....	.....	.....	.....	.....	.....	.....	**********	.....	****
126. Meighen Ice Cap	79 57.2	99 8.0	90	.....	.....	.....	.....	.....	.....	.....	**********	.....	**********
127. South Ice Cap (Melville)	75 25.4	115 1.1	66	.....	.....	.....	.....	.....	.....	.....	.*****.***.***.....	*.....	****
128. West Ice Cap (Melville)	75 37.8	114 45.0	36.4	.....	.....	.....	.....	.....	.....	.....	..****.****.*.....	.....	
129. East Ice Cap (Melville)	75 39.3	114 28.6	16.0	.....	.....	.....	.....	.....	.....	.....	..****.****.*.....	.....	
130. Leopold Gl. (Melville)	75 49.0	114 45.0	27.7	.....	.....	.....	.....	.....	.....	.....	..****.****.*.....	.....	
131. Devon Ice Cap (Devon)	75 20.0	82 30.0	12825	.....	.....	.....	.....	.....	.....	.....	**********	.....	**********
132. Sverdrup Glacier (Devon)	75 40.6	83 15.5	672	.....	.....	.....	.....	.....	.....	.....	***.....	.....	.....
133. Lewis Glacier (Baffin)	70 25.9	74 46.0	182	.....	.....	.....	.....	.....	.....	.....	..***....	.....	.....
134. Barnes Ice Cap (Baffin)	70 10.0	73 30.0	6200	.....	.....	.....	.....	.....	.....	.....	..**********	.....	.....
135. Decade Glacier (Baffin)	69 38.2	69 49.5	8.7	.....	.....	.....	.....	.....	.....	.....	....*******.*.....	.....	.....
136. Akudnirmuit Gl.(Baffin)	67 34.6	65 14.5	0.6	.....	.....	.....	.....	.....	.....	.....	.....	**.....	.....
137. Boas Glacier (Baffin)	67 34.1	65 15.6	1.4	.....	.....	.....	.....	.....	.....	.....	.....	*******....	.....
GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980

Appendix III. Years During Which Observations Made on Glacier Mass Balance

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
GREENLAND	DETERMINATION OF GLACIER MASS BALANCE												
Narssaq Brae	60°15′N	45°55′W	1.30										****
Valhaltindegl.	61°26′N	45°21′W	0.90										******
Qapiarfiup S.													******

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
NORWAY	DETERMINATION OF GLACIER MASS BALANCE												
Bondhusbreen	60° 2′N	6°20′E	23.26										*******
Hardangerjøkull	60°32′N	7°22′E	18.52										**********
Storbreen	61°34′N	8°08′E	5.16										**********
Hellstugubreen	61°34′N	8°26′E	3.13										**********
Supphellebreen	61°31′N	6°48′E	11.81										** **********
Gråsubreen	61°39′N	8°36′E	3.03										**********
Nigardsbreen	61°43′N	7°08′E	48.20										**********
Ålfotbreen	61°45′N	5°39′E	4.82										**********
Blaisen													*******
Storsteinfjellbreen													******
Cainhavarre													*****
Vesledalsbreen													*******
Omnsbreen													***
Hoegtuvbreen	66°27′N	13°39′E	2.60										********
Engabreen	66°39′N	13°51′E	32.02										**********
Storglombreen	66°40′N	14°00′E	59.16										**
Tretten-Null-To	66°43′N	14°01′E	4.92										**
Werenskioldbreen	77°05′N	15°24′E	28.00										**
Vesledalsbreen													***
Tungbergsdalsbreen													******
Trollbergsdalsbreen													******
Memurubre													******
Folgefonni													*********
Grabreen													***
Blomsterskardbre													******

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
SPITSBERGEN	DETERMINATION OF GLACIER MASS BALANCE												
Austre Brøggerbreen	78°53′N	11°50′E	6.10								*****	**********	
M. Lovenbreen	78°53′N	12°04′E	5.80								****	**********	

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
GERMANY	DETERMINATION OF GLACIER MASS BALANCE												
Schneeferner	47°25′N	10°59′E	0.57								*******		

Appendix III (cont'd). Years During Which Observations Made on Glacier Mass Balance

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
SWEDEN	DETERMINATION OF GLACIER MASS BALANCE												
Rabots Glaciären	67°54'N	18°33'E	4.22									******	
Storglaciären	67°54'N	18°34'E	3.12						****				
Karsojietna	68°21'N	18°19'E	1.48									*****	
Mikkajökeln											*.*..		
Ruotesglaciären											*.*..		
Suotasglaciären											*.*..		
Vartasglaciären											*.*..		
Hyllglaciären											*.*..		
Salajekna											*.*..		

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
FRANCE	DETERMINATION OF GLACIER MASS BALANCE												
Sarennes	45°07'N	6°10'E	0.80						********				
Saint Sorlin	45°11'N	6°10'E	3.00								**********		
Argentiere	45°58'N	6°56'E	15.60									******	
Mer de Glace	45°53'E	6°56'E	33.00								*********		

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
SWITZERLAND	DETERMINATION OF GLACIER MASS BALANCE												
Rhône	46°37'N	8°24'E	17.38									*****	
Gries (Aegina)	46°26'N	8°20'E	6.28							**********			
Grosser Aletsch	46°30'N	8°02'E	86.76						**********				
Limmern	46°49'N	8°59'E	2.39						***.**********				
Plattalva	46°50'N	8°59'E	0.73								**********		
Silvretta	46°51'N	10°05'E	3.25							**********			

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
AUSTRIA	DETERMINATION OF GLACIER MASS BALANCE												
Hintereis F.	46°48'N	10°46'E	9.70							**********			
Vernagt F.	46°53'N	10°49'E	9.55								**********		
Langtaler F.	46°48'N	11°01'E	3.52								*********		
Kesselwand F.	46°50'N	10°48'E	4.24							**********			
Sonnblick K.	47°08'N	12°36'E	1.77								**********		
Filleck K.	47°08'N	12°36'E	0.16								**********		

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
ITALY	DETERMINATION OF GLACIER MASS BALANCE												
Caresèr	46°27'N	10°42'E	4.83								**********		

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980

Appendix III (cont'd). Years During Which Observations Made on Glacier Mass Balance

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
U.S.S.R.													
Kupol Vavilova			1805.80									..********	
IGAN			0.69							**********	**********		
Obrucheva			0.30							**********	**********	.*	
Marukhskiy			3.30								**********		
Khakel			2.70									..********	
Bezengi			36.20							**********			
Dzhankuat			3.13								**********	**********	.....
Yunom			3.34									.....**..	
Tbilisa			3.75								**********		
Abramova			26.21								**********		
No.314			1.46										****....
Golubina			6.21								**********	**********	.....
Tuyuksu Tsentralnyy			3.02							**********	**********	**********	....
Igli Tuyuksu			1.72							**********	**********	**********	....
Karabaktak			4.56							**********	**********	**********	....
Molodezhniy			1.43							**********	**********	**********	....
Korzhenevskogo			37.50								...*.*...		
Mametovoy			0.35							**********	**********	**********	....
Shokalskogo			10.80							****.***	.....		
Kosmodemyanskoy			0.36								**********	**********	....
Ordzhonikidze			0.31								**********	**********	....
Mayakovskogo			0.18								**********	**********	....
Partizan			0.14								**********	**********	....
Visyachiy 1 & 2			0.29								**********	**********	....
Sari-Tor			3.61										...**....
Davidova			11.43										..***....
Bolshoy Berelskiy			9.50								*....*..		
Malyi Berelskiy			6.80								*....*..		
Maliy Aktru			3.80								**********	**********	....
Leviy Aktru			6.50									******	....
Grechishkina			14.20									..**	
Koryto			8.80								...*******		**.....
Kozelskiy			1.78									**********	
Kropotkina			0.60										...**....
Mutnovskiy NE			1.37										*******....
Mutnovskiy SW			1.09										******....
Novaya Zemlya										***.....			
Kelbashi											******..		
Zeiskiy										**********			
Teu-Northern											.***.....		
Teu-Southern											.***.....		

Appendix III (cont'd). Years During Which Observations Made on Glacier Mass Balance

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
CHINA													
Shuiguanhe No.4	37°33′N	101°45′E	1.86	.....	.....	.....	.....	.....	.....	.....	.....	....***..	.....
Yanglonghe No.5	39°14′N	98°34′E	1.46	.....	.....	.....	.....	.....	.....	.....	.....	....****	.....
Qiyi	39°14′N	97°54′E	2.78	.....	.....	.....	.....	.....	.....	.....	.....	....***..	..***....
Laohugou	39°26′N	96°33′E	21.91	.....	.....	.....	.....	.....	.....	.....	.....	....**...	.....
Urumqi S. No.1	43°05′N	86°49′E	1.84	.....	.....	.....	.....	.....	.....	.....	**********	**********	....*

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
JAPAN	DETERMINATION OF GLACIER MASS BALANCE												
Hamaguri Yuki	36°36′N	137°37′E	0.01	.....	.....	.....	.....	.....	.....	.....	.....	.....	*****....

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
KENYA	DETERMINATION OF GLACIER MASS BALANCE												
Lewis	9°S	37°18′E	0.25	.....	.....	.....	.....	.....	.....	.....	.....	.....	********....

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
INDONESIA	DETERMINATION OF GLACIER MASS BALANCE												
Meren	4°5′S	137°10′E	1.95	.....	.....	.....	.....	.....	.....	.....	.....	.**.....	.....
Carstensz	4°6′S	137°10′E	0.89	.....	.....	.....	.....	.....	.....	.....	.....	.**.....	.....

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
NEW ZEALAND	DETERMINATION OF GLACIER MASS BALANCE												
Tasman	43°31′S	170°19′E	100.90	.....	.....	.....	.....	.....	.....	.....	.....******	.....	.....
Ivory	43°08′S	170°55′E	0.80	.....	.....	.....	.....	.....	.....	.....	.....**********	.....	.....

GLACIERS	Latitude	Longitude	km²	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980
ANTARCTICA	DETERMINATION OF GLACIER MASS BALANCE												
Deception Is. G-1	63°S	60°36′W	-	.....	.....	.....	.....	.....	.....	.....	.....****	.....	.....
Alberich	77°35′S	161°37′E	1.36	.....	.....	.....	.....	.....	.....	.....	.....	*****....	.....
Heimdall	77°35′S	162°52′E	7.96	.....	.....	.....	.....	.....	.....	.....	.....	*****....	.....
Jeremy Sykes	77°36′S	161°33′E	9.92	.....	.....	.....	.....	.....	.....	.....	.....	*****....	.....
Byrd Station	80°S	120°W	480.00	.....	.....	.....	.....	.....	.....	.....	....*..*.*.*.*.....		.....

Appendix III (cont'd). Years During Which Observations Made on Glacier Mass Balance

APPENDIX IV

OVERVIEW OF CANADIAN ARCTIC PROGRAM

R.M. Koerner
Geological Survey of Canada
Ottawa, Ontario

REPRINTED FROM

Novyy metod ispol'zovaniya lednikov dlya monitoringa izmeneniy klimata.
A new method for using glaciers as monitors of climate
Proceedings of the International Symposium "Glacier Mass-balance, Fluctuations and Runoff"
Almaatinskii Simpozium, , 30 September - 5 October 1986, Alma-Ata

Materialy Glyatsiologicheskiy Issledovanii No.57, Mezhduvedomstvenni Geoficheskii Komitet
pri Prezidiume Akademii Nauk SSSR, Moskva, 47-52; (English, 175-179), 1986

Note: The figures cited in this text are contained in the Russian portion of the text (p. 47-52). They have not been reproduced here.

A NEW METHOD FOR USING GLACIERS AS MONITORS OF CLIMATE

Two new methods of glacier mass balance measurements are advanced: by plotting balance-altitudinal profile and with the help of separate stakes' network, fixed on the limited site on the glacier.

Glacier mass balance has usually been measured as part of glacier dynamics or climate studies, or, more often, for hydrological purpose. This paper is concerned with using mass balance measurements to monitor the present-day climatic trend in the High Arctic. This is partly to improve our understanding of surface-to bedrock ice core results in a paleoclimatic sense. It is also to determine what the climate is doing at a time when the continuously increasing level of anthropogenic CO_2 in the atmosphere is considered capable of bringing to the area the warmest climate of the last several thousand years.

Areal changes of glaciers, such as snout retreat, have been the traditional method of using glaciers to determine historic changes of climate. Thickness changes may also be interpreted climatically. However, the glaciers that are studied are usually dynamic and show a lag response to climate change which is proportional to the activity index and size of the glacier. On large ice masses the response is so poorly known that area changes may give very limited information on climatic change. Thickness changes may only relate the accumulation/ablation rate between the time of thickness measurements to a preceding period of unknown length.

Glacier mass balance is measured each year on several glaciers throughout the world so that mass balance records might provide a good way of monitoring climate. However, the glacier mass balance method has its own drawbacks. The entire glacier must be sampled and this may include hazardous areas. It will also mean the measurement network will take a lot of time to cover in an area which is prone to poor weather. Compromises are inevitably made for safety and logistical purpose so that many mass balance results are compromise approximations. In addition to these problems the final calculated balance results can not be directly related to climate. Because area is a variable in the glacier mass balance equation, advance and retreat of the glacier, which may be determined by past climatic changes, affects the current mass balance by increasing or decreasing the area of the glacier in parts with the most negative balance. The mass balance may then bear no relationship to current climate trends.

With these limitations in mind, a new approach to the use of glaciers as climate monitors was undertaken. This paper considers the first results and conclusions of the study.

IV.1. Alternative Methods for Monitoring Climate from Glacier Measurements

IV.1.1. Balance/Elevation Integration

At present the Polar Continental Shelf Project of the Federal Government Department of Energy, Mines and Resources maintains stake networks on Devon, Meighen, Melville and Agassiz ice caps. The logistical problems involved in measuring these networks means that an occasional year is missed on Meighen or

Melville Ice Caps. Every year, on all four ice caps, some poles do not get measured because they have melted out, been broken by animals or strong winds, or cannot be found in poor weather. These problems can be partially solved using the appropriate statistical approach to the data.

On Agassiz Ice Cap the existing map is not accurate enough to compute the mass balance. However, the purpose of that network is to understand the balance/elevation relationship and improve the interpretation of three surface-to-bedrock ice cores, drilled in 1977, 1979 and 1984. From this work it became clear that there is no need to include the area variable if we are to use mass balance networks only to monitor climatic trends. In this case the only boundary of importance is what may be termed the "Runoff-line". This line separates the area where all melt refreezes within the firn from that where some part, or all, of the meltwater leaves the ice cap. If the pole measurements are integrated against elevation we have a set of accumulation values above the run-off line and a set of melt values below it. However, the run-off line altitude is a function of both summer warmth and annual snow accumulation. This means that the accumulation value is affected by the amount of summer melt. To separate out this effect an arbitrary line is chosen as the lower boundary of the accumulation pole series. Above this line meltwater always refreezes within the firn. The time series is then solely of accumulation.

With appropriate methods (see below) the set of melt values can be extended above the firn line to the dry snow line. On Devon Island this data sub-set from above the firn line has been shown to bear not only a good relationship with the total mass balance but also with other proxy climate indicators such as sea ice extent. So, while this sub-set may itself form only a small part of the total integrated melt value, it is valuable if the time series is to be extended back in time from a study of deep cores.

Accumulation and melt time series have been calculated using data from the mass balance networks on the northwest side of Devon Ice Cap (Fig. 2). They may be compared with the mass balance results in the same diagram. However, further refinement of both time series in Fig. 2B is planned as proper statistical methods have not yet been used to account for the discontinuity of various pole records.

IV.1.2. Discrete Pole Networks of Limited Extent

An alternate, a simpler method than the one just described is the use of a "stake-farm" in one small area of an ice cap or glacier. A time series is developed either of accumulation or melt depending on the location of the stake-farm. Several such series have, of course, already been developed at permanent stations in the Antarctic and similar networks have been used for the past 20 years on the Ward Hunt Ice Shelf and Ice Rise on northern Ellesmere Island. The number of stakes in the farm must be sufficient to eliminate statistical noise in the data due to "mobile" features. For example, a pole that at some stage is located on a migrating hummock or stream bed will introduce a non-climatic trend into the data unless compensated by others that move out of that situation.

To test the applicability of this method sub-sets of pole measurements have been extracted from White Glacier on Axel Heiberg Island, and from Meighen and

Devon Ice Caps (Table IV.1). Very few poles are used for each glacier in this test. The poles were chosen firstly, for continuity of record, and secondly, from the 100-200 m altitude part of each network to ensure negative balances in most years. Only on Meighen Ice Cap, where over the last 25 years every pole has had a positive balance in one or more years, is the record of negative balance discontinuous.

Location	Number of Poles	Altitude m	Mass Balance Network
Sverdrup Glacier	4	100-300	Northwest side, Devon Ice Cap
White Glacier	5	100-200	Axel Heiberg
North Edge	2	100-200	Meighen Ice Cap

Table IV.1. Data, using for mass balance calculation

The results are shown in Fig. 3 along with the normalised July/August mean temperatures from Resolute Bay for the period 1948-1984 and the normalised and summed July/August temperatures for the 1960-1982 period for 3 High Arctic weather stations. The Northern hemisphere record for the area north of 65 N is also shown for comparison. The degree of agreement between the combined temperature record for 3 weather stations and the combined record for three glaciers (a total of 11 poles) is encouraging (r = 0.86) when one realises that there should not be a 1:1 relationship anyway. As one of the criteria was to choose only those poles at the lowest elevations it is likely that a more sophisticated and objective selection of pole records would yield a substantially better record. This is planned for the future using appropriate computer techniques.

There is no reliable time series with which to compare the accumulation time series. The weather station records are prone to a variety of errors which have been discussed elsewhere.

IV.2. Field Methods

In general the same field techniques apply to the two proposed methods and the traditional mass balance one. However, some points need emphasizing. Logistics make "fixed-date" measuring impossible in the High Arctic so that the balance-year method is used. However, only one measurement for each pole is needed each year. The best time for this is in the spring when the balance at each pole for the previous year (August to August) is measured.

For method-A a single line of poles should run from the top of the ice cap or glacier to near its edge. Two poles should be drilled into the ice or firn at each measuring location. They are drilled to different depths and extend to different heights above the glacier. This ensures that at least one will not melt out or get buried.

On sub-polar glaciers melt-water above the firn line refreezes within the firn-pack. To measure mass balance in this situation a device is used to collect the

meltwater before it percolates too deep. We have used trays measuring 0.3 m square and 0.1 m deep. The tray is buried sufficiently deep to prevent it ending up too close to the surface by the close of the melt season. In the Canadian High Arctic a depth of about 0.5 m is suitable. Snow density measurement to the tray depth at both the time of placement and of retrieval give the mass balance to the end of the melt season in the previous year (August, year n) and also to the time of retrieval (April or May, year n+1). The previous summer's firn must be differentiated from the overlying winter snow to do this. The two data-sets give time series of both annual and summer balance. To measure total melt near each pole above the firn line the amount of ice in each tray and the thickness and number of ice layers above it must be measured.

The problem area for balance measurement is between the firn and long-period equilibrium lines where conditions are very variable from year to year (the shaded area in Fig. 1B). Trays buried to catch percolating melt water may overflow or end up at the surface. In other years new firn is added to the surface but buried under superimposed ice in subsequent years. The new firn layer will eventually be soaked by percolating meltwater to form ice. Shallow cores must be taken each year to follow the highly variable process of percolation and refreezing. Variability of the percolation process, even within an area as small as 1 m^2, means several cores must be drilled. There is seldom time to do this. Often the values for this area are based on extrapolations from the accumulation areas above and the melt area below. Straight forward pole height changes help in the extrapolations.

IV.3. Advantages of the Alternative Methods

In glacier/climate terms the two methods just described have several advantages over the traditional mass balance one.

1. The stake network for both methods is much simpler to design and measure. In the case of method-A a single line from the top of the ice cap or glacier to its edge is adequate. Thus regions of difficulty or danger may be avoided and travelling reduced.

2. Because area does not enter the calculations, accurate surveys are unnecessary. This is particularly advantageous in the High Arctic where photogrammetric methods are difficult to apply, especially over the vast, poorly defined, surfaces of snow covered ice caps.

3. Method A may be applied to existing data sets where the total glacier balance is inaccurate due to inadequate sampling of the whole glacier. Small sub-sets can also be extracted as in the test illustrated above.

4. The results are not affected by changing glacier area. On a retreating ice cap or glacier the lowermost poles represent smaller and smaller areas each year. Some poles will eventually disappear from the network. In the traditional mass balance method there is then a retreat area term that reduces the negative term of the balance in a way that is completely unrelated to the

present trend of climate. The same effect also occurs on a stagnant ice cap. For example, with a stable climate and an equilibrium line between the edge and the top of the ice cap, the central regions of the ice cap thicken while the lower parts grow thinner and the edge retreats. This pattern has occurred on Meighen Ice Cap where, between 1960 and 1982, the central parts have thickened at a rate of 90-100 mm/a and the lower parts thinned by 100 mm/a.

5. The mass balance of a glacier is the sum of the ablation and accumulation terms. Relating the final value to climate means separating and evaluating each term. This is already done with method A. Method B only considers the melt variable.

IV.4. Conclusions

In many countries today financial restrictions on research are forcing a need for programme reviews. Routine mass balance measurements can be very time-consuming and therefore, expensive. While some programmes may be retained others, threatened by budgetary constraints, could be continued in one of the modified forms described in this paper. The most effective of the two methods may prove to be suitably located "stake-farms" in the ablation regions of several glaciers, all of which may be measured in one or two days with fixed-wing air support. Each stake-farm should be measurable in one hour either on foot or on skis. This approach to monitoring climate could be important. A preliminary and brief review of 20 years of records from some of the Canadian High Arctic glaciers shows that melting rates lowered during the early 1960s but have shown no consistent trend since. Accumulation rates show no significant changes for the entire 1961-1982 period. These glaciers do not yet show any evidence for an anthropogenically induced climatic warming.

APPENDIX V

OVERVIEW OF ALASKAN PROGRAM

SPECIAL CONSIDERATIONS REGARDING COLD GLACIERS

Larry Mayo
U.S. Geological Survey
Fairbanks, Alaska

V.1. Alaskan Glacier Mass Balance Studies

Gulkana Glacier (continental) and Wolverine Glacier (maritime) are the primary sites of the U.S. Geological Survey for mass balance studies in Alaska (locations shown on Fig. 3.1). Observations have been maintained at these glaciers since 1966 to study mountain climate, glacier growth and shrinkage, glacier flow, and glacier runoff. Recording instruments monitor air temperature, precipitation, and streamflow. Detailed mass balance mapping was carried out on each glacier twice each year from 1966 to 1974. Since 1975, mass balance, glacier flow, and ice thickness changes are measured three or four times a year at three index sites on each glacier. Discontinuous records of glacier mass balance are available in Alaska at about 15 other glaciers (Mayo, 1984).

Mass balances of Gulkana and Wolverine Glaciers are measured by glaciological methods using stakes, snow depth soundings, snow pits, and photographs. The spatial and temporal distribution of the components of mass balance — snow, new firn, old firn and ice, and internal accumulation, are determined independently to avoid cancellation where units with different signs are found in the same altitude zone. Differences of mass balances between summer surfaces, which are time-transgressive with altitude, and corresponding mass balances found at the beginning and ending of fixed-date hydrologic years (Oct. 1 to Sept. 30), are estimated from air temperature and precipitation data to improve analyses of the mass balance information with climate and runoff data. Concepts of the combined mass balance system for reporting data are given by Mayo, Meier, and Tangborn (1972).

Stakes used for mass balance measurements at Gulkana and Wolverine Glaciers are also surveyed to measure glacier flow. Ice volume changes are monitored regularly at three horizontally fixed locations. Points along longitudinal and transverse profiles are surveyed at approximately 10-year intervals as an independent check on cumulative mass balance calculations. The precision of these surveys is improved by determining the actual atmospheric refraction coefficient at the time of each survey. Concepts of these methods are beyond the scope of this manual, but are available in publications (Meier, 1960; Meier and Tangborn, 1965; Mayo, Trabant, March, and Haeberli, 1979; and Mayo and Trabant, 1982).

Many similarities are found among the methods presented in the body of this manual and the methods used in Alaska. The purposes of appendixes 4 and 5 are to supplement the manual with a few additional methods that have been used successfully in Alaska, and may be useful elsewhere. Some of the additional methods require lengthy explanation. In these cases, the reader is referred to the literature.

V.2. Relocating Oversnowed Stakes, Alaskan Experience

The location of a buried stake may become obvious a few days after fresh snowfall by a tell-tale small hump in the surface. The hump forms over the stake as the snow settles. The location of more deeply buried stakes can be found by surveying, detecting a magnetic field, listening to a radio beacon, or by probing to a large board. The likelihood of finding a buried stake increases if more than one method is used.

In the surveying method, the x,y,z coordinates of the stake position are predicted using previous flow measurements. With a theodolite in a known location, such as at a resection location near the stake, the horizontal angle, vertical angle, and slope distance to the stake's predicted coordinates can be calculated using a programmable calculator (Mayo, and others, 1979). A pit can then be dug to find the stake. Of course, an unanticipated change in glacier flow can produce disappointing results. Methods of using magnets to identity locations on glaciers and estimate snow depths were pioneered by Harrison, MacKeith, and Ferguson (1978) of the University of Alaska. An Alnico V magnet (about 25 mm diameter, 250 mm long, and having a magnetic dipole moment of 8,000 gamma m_3) can be placed upright at the summer surface in the fall. Its location and depth can be determined at a later date by mapping the magnetic anomaly at the snow surface. For snow depths of about 2-10 m, a sensitive (+1 gamma) magnetometer is needed to detect the background and perturbed magnetic fields. The observations are complex and subject to many errors. The results, simply stated, are that the peak of the magnetic anomaly is located directly over the buried magnet and the snow depth can be calculated from the magnetic field geometry. Calculations for this require a programmable calculator, and formulas are given by Harrison, MacKeith, and Ferguson (1978). These same type of magnets can also be placed inside the top of a metal stake. When digging a pit to find the stake, a small compass can be used to detect the magnet over a distance of about 1-2 m. Metal stakes having iron can have sufficient magnetism to find them with a sensitive magnetometer.

Small radio beacons are available for tracking wildlife and these can be used as location indicators on glaciers. They can operate for several years and can transmit through wet snow of any depth. Such beacons can be fitted with circuits that control the transmit pulse period to report temperature. Directional antennas and signal strength meters are used to locate a beacon and pulse-width meters used to read its temperature. If such a beacon is placed at the summer surface in the glacier's accumulation area, and at least 10 m from a metal stake, temperature information obtained during winter is useful for estimating a glacier's internal accumulation.

A board of about 1 m^2 in size with a hole in it's center can be placed over a stake in the fall to assist in relocating the stake and also to mark the summer surface. If the stake is buried, diligent probing or repeated drilling with a steam drill can be done to find the board. This method is made easier if the approximate location has been determined by surveying. A wire mesh can also be used for the same purpose and is easier to carry than a board. Because a sounding rod can penetrate a wire mesh, a steam drill is required to find it. Markers at summer surfaces are also very helpful for "calibrating" the interpretations of sounding with a probe rod.

V.3. Freezing of Water in Glaciers

V.3.1. Introduction

Part of the water originating from melting, condensation, and rainfall at the surface of a glacier freezes (1) during spring and summer as it passes into cold snow,

porous firn, and englacial cavities; and (2) during the following winter when the freezing front penetrates through wet firn where water is held at grain contacts and in cavities (Trabant and Mayo, 1985). Water that freezes in snow, firn, and cavities in glacier ice produces recognizable deposits. Heat released by this freezing in glaciers warms the surrounding snow, firn, or ice. As a result, "temperate" glaciers are found where the annual average air temperature is a few degrees colder than 0°C. Some knowledge of temperatures fluctuations in ice and firn (Fig. V.1) is essential for understanding freezing of water in glaciers.

V.3.2. Water, Ice Glands, and Ice Pipes in Snow and New Firn

Water that percolates into and freezes in snow and new firn produces grain rounding, void fillings, vertical ice pipes, and horizontal ice glands. That redistributed ice is normally included in surface mass balance measurements because it is part of the snow and annual new firn. The remaining liquid water in snow and new firn, including any slush layers, is also part of the surface mass balance measurements for a year. Most of that liquid water in new firn probably freezes during the following winter, so it is correct to consider it as part of the year's net accumulation.

V.3.3. Superimposed Ice

Slush that freezes at the base of a snowpack is sometimes missed in glacier mass balance measurements because the top of this "superimposed ice" can be mistaken for the summer surface; that is, superimposed ice can produce a "false" surface above the "true" initial summer surface, ss_o. Superimposed ice generally appears smoother and finer grained than glacier ice, and lacks the foliation structures found in glacier ice. During the summer melt season, superimposed ice is commonly overlain by bubbly slush. When superimposed ice is exposed at the surface between wet snow (or slush) and glacier ice, its surface appears smoother (smaller crystals and no foliation) and its colour whiter (less dirt) than glacier ice. A dirty summer surface horizon can usually be found at the bottom of superimposed ice by chopping through it with an ice axe. Slush and superimposed ice tend to be thickest where the surface gradient of a glacier is relatively flat and where the underlying ice had been chilled most during the preceding winter. Superimposed ice that survives a summer season becomes part of the glacier's net accumulation.

When the ice surface at a stake appears to be higher than a previous reading, this is usually insufficient evidence for identifying superimposed ice because such observations can also be caused by probing to an irregular surface; by anomalous vertical stake motion due to stake sinking, firn compaction; or by vertical deformation of the ice as it changes shape in a horizontally compressive stress field. Superimposed ice is correctly identified by observing a summer surface at its base. It may be helpful to note that superimposed ice, including frozen rain layers, is typically widespread, whereas ice glands have a horizontal extent of only a few meters. Furthermore, superimposed ice and frozen rain deposits can accumulate off the glacier on cold rock and in vegetated areas.

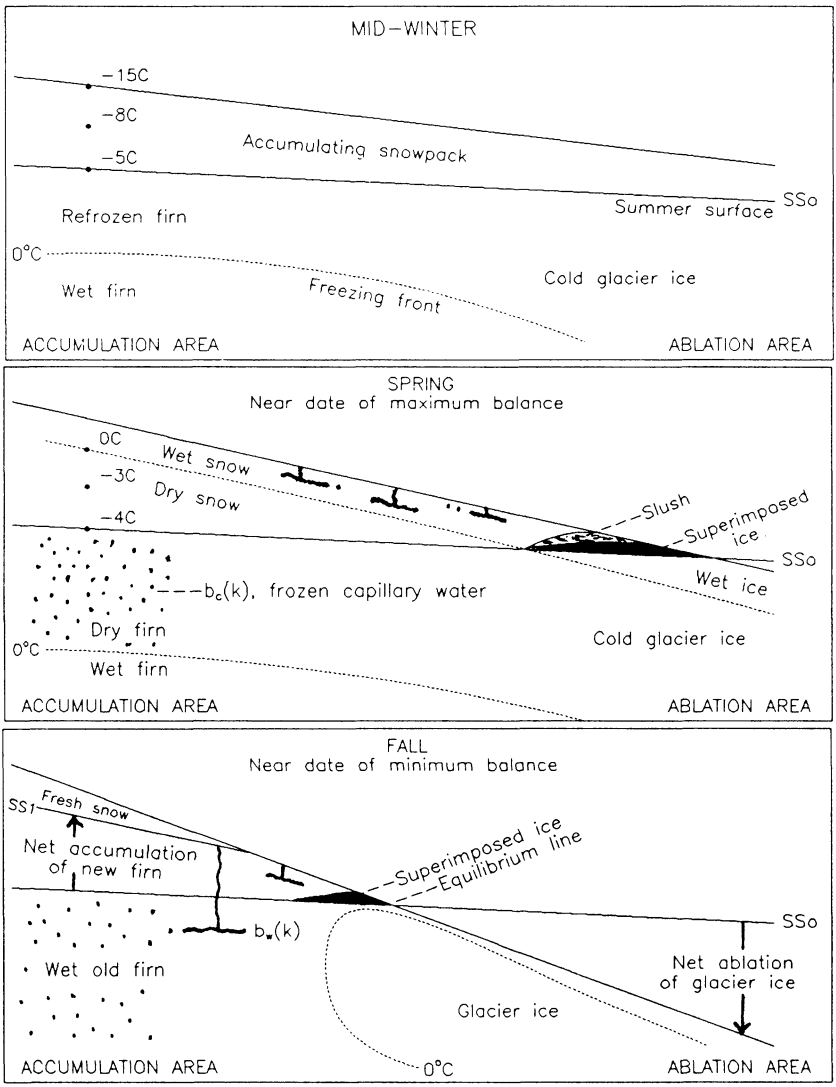


Figure V.1: Superimposed-Ice Formation and Temperature Conditions Schematic cross-section of a glacier showing mass balance and temperature conditions at different times of a year.

***Editors Note: As shown on this diagram, the equilibrium line altitude (ELA) is located at the lower end of the super-imposed-ice-zone. For a glacier that has internal temperatures below the freezing point, the ELA which is computed (and shown) is located at a lower elevation than the observed snow-line. The actual ELA position does not necessarily lie exactly at the base of the superimposed ice zone, but rather somewhere between the lower limit of the super-imposed ice zone (as shown) and the snow-line depending upon spatial distribution of internal snow, firn and ice temperatures.**

V.3.4. Internal Accumulation

Water that passes through the initial summer surface each year and freezes before it can run off is termed the annual internal accumulation, $b_a(k)$. This component of glacier accumulation is missed in surface mass balance measurements because it is distributed deeply below the initial summer surface, ss_o, in permeable firn; yet, it can be significant. If ignored for many years, it can cause a significant cumulative mass balance error; or worse, it can mask a systematic error of opposite sign in some other component of mass balance measurement.

Contrary to general expectations, glaciers in relatively warm climates, as well as those in cold climates, can have significant amounts of internal accumulation. Temperature observations by LaChapelle (1961) at Blue Glacier, Washington, showed that the firn below the winter snow was wetted by rain and refroze three times during one winter. Trabant and Mayo (1985) used those observations to estimate that 0.2-0.3 m water equivalent of ice had accumulated internally in Blue Glacier's firn during that winter. Detection of this process would be possible by overwintering an automatic temperature recorder at the summer surface in a glacier's firn area, or by monitoring a vertical string of thermocouples in the snow and underlying firn. Attempts to measure internal accumulation directly have not been successful because it is unevenly distributed through a large thickness of old firn. For that reason, Trabant and Mayo (1985) developed an indirect and relatively simple method to estimate internal accumulation by measuring the temperature in late winter at the summer surface in areas of old firn. The temperature observations can be made anytime from about January through March, because the summer surface temperature varies little during that season. Rewarming of the summer surface takes place in the spring during the onset of significant surface melting. Methods for measuring summer surface temperatures include installing thermocouple systems (most accurate method), inserting a thermometer in the walls of a snow pits, inserting a thermometer into fresh core samples, lowering a thermometer into core holes, or operating temperature-sensing radio beacons at the summer surface (fastest method).

Ice that accumulates in old firn during spring and summer causes warming of the firn, and is thus called the firn warming component of internal accumulation, $b_w(k)$. Capillary water that freezes during fall and winter as the freezing front moves downward is the capillary component of internal accumulation, $b_c(k)$, and is generally the larger of the two. Water that had been trapped in crevasses or englacial conduits and frozen there can be observed in the ablation zone of many glaciers as crevasse fillings of blue (bubble-free) ice crossing ice foliation structures, or as concentric layers of oriented ice crystals (conduit fillings). Thus, internal accumulation is small, but not zero, below the equilibrium line of most glaciers. Annual internal accumulation, $b_a(k)$, is the sum of all internal accumulation processes. The potential for internal accumulation at any site can be estimated using summer surface temperature data by referring to the internal accumulation diagram (Fig. V.2).

For example, if the measured summer surface temperature in late winter is -6°C, then about 0.22 m/yr of water can freeze below the summer surface. For this to happen, at least this amount of water must pass through the summer surface. Thus, two criteria must be met for the "potential" $b_a(k)$ to be reported as "actual" $b_a(k)$. First, the underlying firn must be permeable. Second, sufficient water must pass through the summer surface to warm it to 0°C. If these conditions are not met,

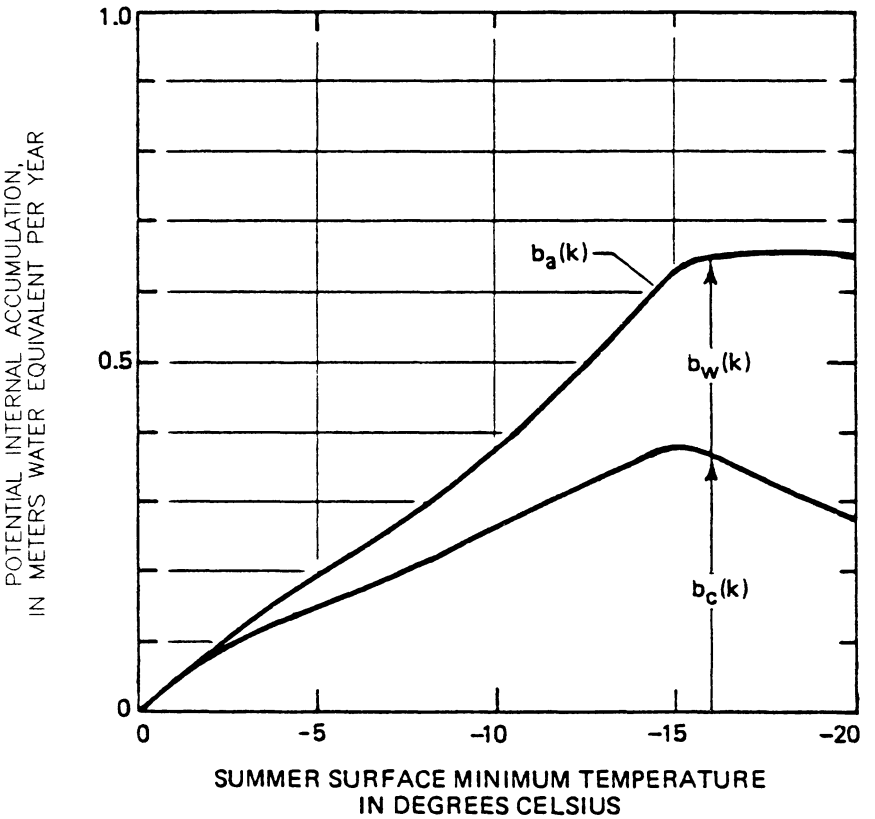


Figure V.2: Annual Internal Accumulation versus Surface Temperature Graph of estimated internal accumulation as a function of the minimum snow-firn interface temperature showing the relative contribution of the firn-warming component $b_w(k)$ and the capillary component $b_c(k)$.

then $b_a(k)$ is equal to the amount of water that percolates through ss_o and no runoff can happen, even though surface melting and snowpack saturation have been observed. Internal accumulation can take place both up-glacier and down-glacier from a surface mass balance equilibrium line, so it is determined separately and added to the other mass balance components to obtain a glacier's change in ice storage. Internal accumulation is estimated even though for one year it may be smaller than the reported error estimate of mass balance. Internal accumulation, $b_a(k)$, is always positive and affects the cumulative mass balance from year to year; thus, it is not part of the randomly-distributed uncertainty that is reported for other mass balance measurements.

APPENDIX VI

STANDARD FORMS

This appendix contains a sample collection of forms used by Canadian and Norwegian field parties in their work at the glaciers. This set is provided to demonstrate the various approaches and designs that have been adopted. Several other solutions are, of course, possible.

The following forms are included:

Snow Pit Measurements
Snow Stratigraphy
Core Auger Measurements
Snow Wetness and Dielectric Measurement
Norwegian Stake Reading Form (Stakemåling)
Norwegian Stake Redrilling Form (Omboring av staker)
Norwegian Stake Form (Stakeprotokoll, mainly for office work)
Canadian Stake Observations
Late-fall Melt Observation and Computation
Date Schedule for Net Mass Balance Measurements
Net Mass Balance Summary Sheet
Norwegian Sediment Sample Data Form (Slamprøver)

SNOW PIT MEASUREMENTS

.....GLACIER

.....LOCATION OF PIT

.....ELEVATION OF PIT

.....SNOW SAMPLER VOLUME

.....SNOW SAMPLER LENGTH AND DIAMETER

.....DATE .....SIGNATURE

1	2	3	4	5	6	7	8	9
PIT DEPTH (cm)	SAMPLE				TEMP (C°)	SNOW WET-NESS (%)	DENSITY (gcm^{-3})	REMARKS
	Length (cm)	Tot wt (g)	Tare wt (g)	Snow wt (g)				

MEAN DENSITY.....gcm^{-3}

TOTAL WATER EQUIVALENT.....cm

SNOW STRATIGRAPHY

.....GLACIER

.....LOCATION OF PIT

.....ELEVATION OF PIT

.....DATE .....SIGNATURE

1	2	3	4
DEPTH (cm)	HARDNESS	GRAIN SIZE (mm)	REMARK

CORE AUGER MEASUREMENTS

.....GLACIER

.....LOCATION

.....ELEVATION

..... AUGER TYPE

.....DATE .....SIGNATURE

1	2	3	4	5	6	7	8	9	10
DEPTH (cm)	CALC PENETR-ATION (cm)	SAMPLE			DENSITY (gcm^{-3})	LENGTH REPR BY SAMPLE (cm)	WATER EQUIV (cm)	CUMUL WATER EQUIV (cm)	REMARKS
		LENGTH (cm)	WEIGHT (g)	VOLUME (cm^3)					

MEAN DENSITY.....gcm^{-3}

TOTAL WATER EQUIVALENT.....cm

A = value of the LCD with the sensor in air;
S = value of the LCD with the sensor in snow;
K = constant (full or halfspace value);
$K_{fullspace} = 7.48$
$K_{halfspace} = 12.20$
ε_s = dielectric constant of snow;
ρ = snow density (gcm^{-3});
W = percent water by volume;

The dielectric constant can be calculated from the LCD value of snow and air;

$$\varepsilon_s = 1 + K\log_{10}\left(\frac{S}{A}\right)$$

The snow liquid water content of the snow can be calculated with the equation;

$$\varepsilon_s = 1 + 1.92\rho - 0.44\rho^2 - 0.187W + 0.0046W^2$$

or;

$$0.0046W^2 + 0.187W + (1 + 1.92\rho + 0.44\rho^2 - \varepsilon_s) = 0$$

which allows us to calculate the percentage of water in the snow by using the equation;

$$W = \frac{-18.7 \pm \sqrt{170 - 353\rho - 81\rho^2 + 184\varepsilon_s}}{0.92}$$

SNOW WETNESS MEASUREMENTS

.....GLACIER

.....LOCATION

.....ELEVATION

.....TYPE OF MEASUREMENT DEVICE

.....DATE .....SIGNATURE

1	2	3	4	5	6	7	8
DEPTH (cm)	K	ε_s	A	S	ρ (gcm^{-3})	W (%)	REMARKS

MEAN SNOW WETNESS.....%

Dato-år

NVE Vassdragsdirektoratet

STAKEMÅLING

Bre				Observatør			
Stake nr.	Lengde cm	Sond. cm	Merknader	Stake nr.	Lengde cm	Sond. cm	Merknader

BI. M-6058

NVE-Vassdragsdirektoratet

OMBORING AV STAKER

Bre

Dato	Kl.	Stake nr.	Gammel stake				Ny stake				Ny stake sett fra gammel stake		Årsak til omboring	Merknader
			Al.	Wire	Stål	Total lengde	Al.	Wire	Stål	Total lengde	Avstand	Retning		

BL. M-6065

STAKEPROTOKOLL

BRE: Stake Al stål wire Dim.: Nr.: Utsatt: H.O.H.:

Dato	Tid	Topp til is cm	Topp til snö cm	Topp til s.o. cm	Snö-tett-het g/cm³	Snödyp sondert snö cm	Snödyp sondert v.v. cm	Snödyp beregnet snö cm	Snödyp beregnet v.v. cm	pål. is is cm	pål. is v.v. cm	Differens mellom fortløp. mål. snö v.v. cm	Differens mellom fortløp. mål. is is cm	Differens mellom fortløp. mål. is v.v. cm	abl. v.v. cm	Sommer-akk. snö cm	Sommer-akk. ρ g/cm³	Sommer-akk. vv cm	Sommer-akk. Σvv cm	Sum Akk v.v. cm	Sum Abl v.v. cm	Sum Bal. v.v. cm	St. tot lengd cm	Anm

STAKE OBSERVATIONS

.....GLACIER

.....LOCATION OF STAKE

.....TOTAL LENGTH OF STAKE

.....TYPE OF STAKE

KEY

"ρ" = DENSITY (gcm^{-3})
" w.eq" = WATER EQUVIALENT (cm)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
DATE	TIME DIFF	TOP TO SNOW	TOP TO ICE		SNOW DEPTH cm				DIFFERENCE											ACCUMUL ATION	ABLATION	NET MASS BALANCE	CUMULATIVE w.eq			POLE TILT	BEARING AND REMARKS
				ρ	SOUNDED		COMPUTED		SNOW	SUPER IMPOSED ICE			FIRN			ICE			INTERNAL ACC IN FIRN								
		cm	cm	gcm^{-3}	SNOW	w.eq	SNOW	w.eq	w.eq.	ρ	cm	w.eq.	ρ	cm	w.eq.	ρ	cm	w.eq.	w.eq.	c	a	b_n	Σc cm	Σa cm	Σb_n cm		
																				w.eq.	w.eq.	w.eq.					

LATE FALL MELT

.....GLACIER

.....STAKE #

.....TOTAL LENGTH OF STAKE

.....LOCATION

.....ELEVATION

"w.eq"= WATER EQUIVIALENT
"ρ" = DENSITY
"ss" = SUMMER SURFACE

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
FALL					SPRING						LATE FALL MELT			REMARKS
DATE	TOP TO SS (cm)	TILT	VERTICAL DISTANCE ABOVE SS (cm)		DATE	TOP TO SNOW (cm)	SNOW TO SS (cm)	TILT	VERTICAL DISTANCE ABOVE SS (cm)		ρ (gcm^{-3})	cm	w.eq (cm)	
			measured	computed					measured	computed				

DATE SCHEDULE FOR NET MASS BALANCE

.....GLACIER

.....YEAR

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
STAKE #	b_{s3} (PREVIOUS YEAR) DATE		b_m (SPRING) DATE		WINTER BALANCE								SUMMER BALANCE								FIXED OR KNOWN b_n DATE		STRATI-GRAPHIC b_n DATE	
					b_{w1} DATE		b_{w2} DATE		b_{w3} DATE		b_w DATE		b_{s1} DATE		b_{s2} DATE		b_{s3} DATE		b_s DATE					
	fr	to	fr	to	fr	to	fr	to	fr	to	fr	to	fr	to	fr	to	fr	to	fr	to	fr	to	fr	to

NET MASS BALANCE

.....GLACIER

.....YEAR

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
STAKE #	STAKE POSITION				b_{s3}	b_m	WINTER BALANCE						SUMMER BALANCE						TIME b_n	STRATI-GRAPHIC b_n
	DATE	X	Y	Z	PREVIOUS YEAR	SPRING	b_{w1}	b_{w2}	b_{w3}	b_w	DATE		b_{s1}	b_{s2}	b_{s3}	b_s	DATE			
											fr	to					fr	to		

NVE - Vassdragsdirektoratet

SLAMPRØVER

År

Sted for prøvetagningen

Nr. (dato - tid)	Prøvens volum (ml)	Vann-stand (cm)	Vass-føring (m^3/s)	Været da prøven ble tatt	Prøvetakerens navn	Filter	Merknader

BL M-6071

APPENDIX VII

SAMPLE PROGRAMS

VII.1. Peyto Glacier Programs (D. Peters)

As discussed in Section 13.3.2, a program to determine mass balance values was developed at NHRI by Young (1974). A schematic of the basic program is shown in Fig. 13.7.

The program requires as input, a uniformly spaced, rectangular grid of data points describing the glacier's elevation. This grid must describe the entire glacier, giving an elevation value for each point. The accumulation or ablation for each point on the map grid is calculated by the program. The grid interval is determined by the data but the program does not enforce any minimum or maximum grid interval, although the smaller the grid interval the better the results.

As well as the map grid, the program requires the snow depth and bulk density values at as many locations on the glacier as feasible. This information must correspond the map grid so the program knows at which points on the map the values where measured. It is not necessary to have the same number of depth values as density values. In the ideal case, there would be a depth and density value for each grid location. As these points are used as the data values in determining the regression equation the better the distribution of these points across the glacier surface the more accurately the results describe the real mass-balance changes. Some of the results obtained are shown in Fig. VII.1. The program is followed by a sample data-logger program used at the same glacier and the a copy of the prompt used used by those who program the loggers in the field (see Figs. VII.2 and VII.3).

The first step the program takes is to calculate a slope indicator and a convexity/concavity (relief) indicator for each grid point. These indicators are determined by examining the elevations surrounding each point. The second step the is to ensure there is a density value assigned to each point for which depth values are supplied. The current version of the program assumes density varies linearly with elevation, future versions of the program will use a more accurate model to relate elevation to pack density.

The third step is to calculate the water equivalent values for each point at which the snow density was calculated. Once the water equivalent values have been determined the program generates the regression equation relating the selected predictor variables to the snow depth/water equivalent. The operator can have the regression equation based on elevation alone or, elevation, slope angle and relief. As well, a third option in which the operator directly specifies the coefficients for slope angle and relief is available. Once the equation has been calculated, the program applies it to each point on the map grid. The results are then written to a disk file and the operator can examine the results in tabular format or use the values to create maps of the predicted changes.

The program, now being refined, was used during the early years of the Peyto Glacier mass-balance program and then discontinued as personnel and computer formats changed. Recent tests have shown that it still holds great promise, especially once additional parameters are added to simulate other natural conditions, such as albedo, total incident radiation, crevasse distribution, etc.

ALTITUDE INFORMATION

WHOLE AREA ZONE	MEAN	STD	MAX	MIN	RANGE	NO. OF GRID PTS
	2625.68	190.95	3122.91	2152.36	970.55	3308
2100 - 2200	2184.09	13.23	2199.85	2152.36	47.49	35
2200 - 2300	2255.64	31.01	2299.79	2200.00	99.79	246
2300 - 2400	2346.91	32.86	2398.76	2300.00	98.76	127
2400 - 2500	2460.08	28.29	2499.91	2400.46	99.45	359
2500 - 2600	2548.32	29.50	2599.81	2500.00	99.81	667
2600 - 2700	2650.71	28.82	2699.93	2600.00	99.93	647
2700 - 2800	2745.24	29.45	2799.87	2700.00	99.87	555
2800 - 2900	2846.79	29.78	2899.76	2800.00	99.76	480
2900 - 3000	2942.16	30.52	2998.55	2900.00	98.55	153
3000 - 3100	3022.22	25.78	3093.59	3000.00	93.59	35
3100 - 3200	3112.76	7.15	3122.91	3107.57	15.34	4

LOCAL RELIEF INFORMATION WITHIN ALTITUDE ZONES

WHOLE AREA ZONE	MEAN	STD	MAX	MIN	RANGE	NO. OF GRID PTS
	-.01	2.02	17.84	-29.59	47.43	3308
2100 - 2200	-.43	1.04	.66	-3.54	4.20	35
2200 - 2300	.00	.63	2.40	-1.76	4.16	246
2300 - 2400	-.31	.80	4.78	-2.70	7.48	127
2400 - 2500	-.13	.62	2.23	-3.07	5.30	359
2500 - 2600	-.29	.94	5.65	-8.32	13.97	667
2600 - 2700	-.13	1.70	13.58	-11.22	24.80	647
2700 - 2800	.05	2.23	17.84	-29.59	47.43	555
2800 - 2900	.08	2.54	15.64	-13.58	29.22	480
2900 - 3000	.43	4.13	13.75	-14.72	28.47	153
3000 - 3100	4.78	5.50	17.71	-5.74	23.45	35
3100 - 3200	8.28	1.42	9.81	6.65	3.16	4

SLOPE ANGLE INFORMATION WITHIN ALTITUDE ZONES

WHOLE AREA ZONE	MEAN	STD	MAX	MIN	RANGE	NO. OF GRID PTS
	7.77	4.56	32.72	.00	32.72	3308
2100 - 2200	4.24	1.65	6.79	1.19	5.61	35
2200 - 2300	3.53	1.17	7.30	.14	7.15	246
2300 - 2400	7.00	2.82	14.34	1.14	13.20	127
2400 - 2500	5.34	1.74	12.73	1.66	11.07	359
2500 - 2600	6.53	2.74	16.97	1.42	15.55	667
2600 - 2700	8.28	4.40	32.13	1.54	30.58	647
2700 - 2800	8.38	4.99	29.80	1.08	28.73	555
2800 - 2900	9.63	3.56	21.00	.00	21.00	480
2900 - 3000	15.51	6.12	32.72	.00	32.72	153
3000 - 3100	13.80	8.41	26.74	.00	26.74	35
3100 - 3200	11.99	.63	12.84	11.34	1.50	4

STAKE	ALTITUDE	RELIEF	SLOPE	SNOW DEPTH
30	2186.60	-.43	4.24	424.00
40	2211.60	-.01	3.53	487.00
41	2212.50	-.02	3.54	437.00
42	2216.50	-.01	3.73	443.00
50	2239.80	-.05	3.25	457.00
511	2236.70	-.01	3.97	486.00
52	2238.00	-.08	3.18	457.00
512	2226.20	-.10	3.01	474.00
60	2259.40	-.78	3.42	443.00
61	2239.60	-.03	3.28	433.00
62	2264.50	-.88	3.66	460.00
80	2280.90	-.90	3.13	454.00
81	2280.00	-.91	3.78	493.00
82	2283.90	-.77	3.88	424.00
180	2520.00	-.30	6.77	166.00
190	2640.00	-.40	8.88	121.00
160	2330.00	-.25	3.55	289.00
193	2640.00	-.38	8.79	97.00

Figure VII.1. Peyto Glacier Program Output

```
  X,Y            ALTITUDE       RELIEF         SLOPE          SNOW DEPTH
NO ADDITIONAL X,Y POINTS PROVIDED


NUMBER OF POINTS BEING USED :          18

  MEANS           2305.90          -.35           4.31          391.39
  STD DEV          141.35           .35           1.84          129.43
  MINS            2186.60          -.91           3.01           97.00
  MAXS            2640.00          -.01           8.88          493.00
METHOD =           1 OBERVATIONS =          18 INDEPENDENT VARIABLES = 3

        ALTITUDE  RELIEF    SLOPE     SNOW
ALTITUDE   1.000     -.144      .951     -.952
RELIEF     -.144     1.000     -.052      .004
SLOPE       .951     -.052     1.000     -.922
SNOW       -.952      .004     -.922     1.000

                                INTERCEPT   ALTITUDE    RELIEF     SLOPE
                   AMOUNT =      2311.1510    -.8312  -48.3100   -4.6482
STANDARD DEVIATION OF REGRESSION COEFFS          .2283   28.7299   17.3936
T-VALUES                                      -3.6405   -1.6815    -.2672
STANDARD PARTIAL REGRESSION COEFFICIENTS       -.9077    -.1301    -.0660
MULITPLE CORRELATION COEFFICIENT                                   .9614
STANDARD ERROR OF ESTIMATE                                       39.2391
SUM OF SQUARES ATTRIBUTABLE TO REGRESSION                     263248.4000
DEGRESS OF FREEDOM ASSOCIATED WITH SSAR                            3.0000
MEAN SQUARE OF SSAR                                            87749.4600
SUM OF SQUARES OF DEVIATIONS FROM REGRESSION                   21555.9100
DEGREES OF FREEDOM ASSOCIATED WITH SSDR                           14.0000
MEAN SQUARE OF SSDR                                             1539.7080
F-VALUE                                                           56.9910


 RANGE IN ALTITUDE OF STAKES
TOTAL NO. OF GRID CELLS = 3308. ABOVE LIMIT = 1622. ( 49.03  PERCENT OF AREA)
                              WITHIN LIMITS=  1670. ( 50.48  PERCENT OF AREA)
                              BELOW LIMIT  =    16. (   .48  PERCENT OF AREA)
 RANGE IN LOCAL RELIEF OF STAKES
TOTAL NO. OF GRID CELLS = 3308. ABOVE LIMIT = 1253. ( 37.88  PERCENT OF AREA)
                              WITHIN LIMITS=  1604. ( 48.49  PERCENT OF AREA)
                              BELOW LIMIT  =   451. ( 13.63  PERCENT OF AREA)
 RANGE IN SLOPE ANGLES OF STAKES
TOTAL NO. OF GRID CELLS = 3308. ABOVE LIMIT =  936. ( 28.30  PERCENT OF AREA)
                              WITHIN LIMITS=  2161. ( 65.33  PERCENT OF AREA)
                              BELOW LIMIT  =   211. (  6.38  PERCENT OF AREA)
TEST GLACIER

                   MEAN       STD        MAX        MIN      RANGE    NO. OF GRID PTS

 WHOLE AREA       111.76     163.91     549.12   -325.40     874.52       3308
     ZONE

2100  -  2200     492.89      29.15     549.12     462.36      86.76         35
2200  -  2300     427.78      27.93     512.38     386.09     126.28        246
2300  -  2400     346.66      40.52     427.93     281.92     146.01        127
2400  -  2500     251.59      26.05     329.13     205.49     123.65        359
2500  -  2600     179.87      33.58     257.19     109.82     147.38        667
2600  -  2700      88.40      30.50     169.55      28.52     141.03        647
2700  -  2800       9.05      30.90      88.29     -56.16     144.45        555
2800  -  2900     -75.44      31.95       -.43    -138.43     138.00        480
2900  -  3000    -154.94      37.35     -82.83    -221.79     138.96        153
3000  -  3100    -232.60      29.14    -194.71    -301.03     106.32         35
3100  -  3200    -316.96       5.94    -312.65    -325.40      12.75          4
```

Figure VII.1. Peyto Glacier Program Output (cont'd)

```
Program:  PEYTOSTR.DOC
Flag Usage:
Input Channel Usage: 1:AirT-107, 2:UDG01, 3:WaterT-107F
Excitation Channel Usage: 1:Air Temp and UDG01, 2:107F
Continuous Analog Output Usage:
Control Port Usage:
Pulse Input Channel Usage: none
Output Array Definitions: 1:AirTemp,3:WaterT,7:Distance


 *      1        Table 1 Programs
   01: 10        Sec. Execution Interval

 01:  P4         Excite,Delay,Volt(SE)
   01: 1         Rep
   02: 4         500 mV slow Range
   03: 3         IN Chan
   04: 2         Excite all reps w/EXchan 2
   05: 0         Delay (units .01sec)
   06: 500       mV Excitation
   07: 9         Loc : Water Temp 107F
   08: 0.001     Mult
   09: 0.0       Offset

 02:  P55        Polynomial
   01: 1         Rep
   02: 9         X Loc
   03: 9         F(X) Loc : Water Temp 107F Centigrade
   04: -74.143   C0
   05: 645.21    C1
   06: -3835.8   C2
   07: 16025.    C3
   08: -33996.   C4
   09: 29763.    C5

 03:  P34        Z=X+F
   01: 9         X Loc
   02: 273.15    F
   03: 10        Z Loc : Water Temp 107F Kelvin

 04:  P11        Temp 107 Probe
   01: 01        Rep
   02: 01        IN Chan
   03: 01        Excite all reps w/EXchan 1
   04: 0001      Loc : Air Temp 107 probe (oK)
   05: 1.0000    Mult
   06: 273.15    Offset

 05:  P20        Set Port
   01: 01        Set high
   02: 03        Port Number

 06:  P20        Set Port
   01: 00        Set low
   02: 01        Port Number
```

Figure VII.2. Data Logger Program, Peyto Glacier Site

```
07:  P20        Set Port
  01: 01        Set high
  02: 02        Port Number

08:  P20        Set Port
  01: 00        Set low
  02: 02        Port Number

09:  P20        Set Port
  01: 01        Set high
  02: 01        Port Number

10:  P20        Set Port
  01: 01        Set high
  02: 02        Port Number

11:  P20        Set Port
  01: 00        Set low
  02: 02        Port Number

12:  P20        Set Port
  01: 00        Set low
  02: 01        Port Number

13:  P87        Beginning of Loop
  01: 00        Delay
  02: 0006      Loop Count

14:  P20        Set Port
  01: 01        Set high
  02: 02        Port Number

15:  P20        Set Port
  01: 00        Set low
  02: 02        Port Number

16:  P95        End

17:  P20        Set Port
  01: 01        Set high
  02: 02        Port Number

18:  P22        Excitation with Delay
  01: 01        EX Chan
  02: 0001      Delay w/EX (units=.01sec)
  03: 0000      Delay after EX (units=.01sec)
  04: 0.0000    mV Excitation

19:  P20        Set Port
  01: 00        Set low
  02: 03        Port Number

20:  P20        Set Port
  01: 01        Set high
  02: 03        Port Number
```

Figure VII.2. Data Logger Program, Peyto Glacier Site (cont'd)

```
21:  P22        Excitation with Delay
  01: 01        EX Chan
  02: 0008      Delay w/EX (units=.01sec)
  03: 0000      Delay after EX (units=.01sec)
  04: 0.0000    mV Excitation

22:  P20        Set Port
  01: 00        Set low
  02: 02        Port Number

23:  P30        Z=F
  01: 1.0000    F
  02: 0003      Z Loc : F=1

24:  P30        Z=F
  01: 0.0000    F
  02: 0004      Z Loc : F=1

25:  P87        Beginning of Loop
  01: 00        Delay
  02: 0016      Loop Count

26:  P20        Set Port
  01: 01        Set high
  02: 02        Port Number

27:  P20        Set Port
  01: 00        Set low
  02: 02        Port Number

28:  P1         Volt (SE)
  01: 01        Rep
  02: 05        5000 mV slow Range
  03: 02        IN Chan
  04: 0008      Loc : Raw UDG01 Depth Input Chan2
  05: 1.0000    Mult
  06: 0.0000    Offset

29:  P89        If X<=>F
  01: 0008      X Loc
  02: 03        >=
  03: 3000.0    F
  04: 30        Then Do

30:  P33        Z=X+Y
  01: 0003      X Loc
  02: 0004      Y Loc
  03: 0004      Z Loc : F x UDG01-ch2raw

31:  P95        End

32:  P37        Z=X*F
  01: 0003      X Loc
  02: 2.0000    F
  03: 0003      Z Loc : F x UDG01-ch2raw
33:  P95        End
```

Figure VII.2. Data Logger Program, Peyto Glacier Site (cont'd)

```
34:  P30        Z=F
  01: 291.00    F
  02: 0002      Z Loc : F=291.0

35:  P38        Z=X/Y
  01: 0001      X Loc
  02: 0002      Y Loc
  03: 0005      Z Loc : Z=X/Y

36:  P39        Z=SQRT(X)
  01: 0005      X Loc
  02: 0006      Z Loc : Z=SQRT(X)

37:  P36        Z=X*Y
  01: 0004      X Loc
  02: 0006      Y Loc
  03: 0007      Z Loc : Z=X * Y

38:  P37        Z=X*F
  01: 0007      X Loc
  02: .52176    F
  03: 0007      Z Loc : Z= X * F

39:  P34        Z=X+F
  01: 0007      X Loc
  02: -16.000   F
  03: 0007      Z Loc : Z= X + F

40:  P20        Set Port
  01: 00        Set low
  02: 01        Port Number

41:  P20        Set Port
  01: 00        Set low
  02: 02        Port Number

42:  P20        Set Port
  01: 00        Set low
  02: 03        Port Number

43:  P92        If time is
  01: 0000      minutes into a
  02: 0015      minute interval
  03: 10        Set flag 0 (output)

44:  P77        Real Time
  01: 0110      Day,Hour-Minute

45:  P10        Battery Voltage
  01: 11        Loc : Battery Voltage

46:  P71        Average
  01: 01        Rep
  02: 0001      Loc Air Temp 107 (oK)
```

Figure VII.2. Data Logger Program, Peyto Glacier Site (cont'd)

```
47:  P71        Average
  01: 1         Rep
  02: 10        Loc Water Temp 107F (oK)

48:  P71        Average
  01: 01        Rep
  02: 0007      Loc Distance to Water (mm)

49:  P71        Average
  01: 1         Rep
  02: 11        Loc Battery Voltage

51:  P92        If time is
  01: 0         minutes into a
  02: 1440      minute interval
  03: 10        Set flag 0 (output)

52:  P77        Real Time
  01: 0110      Day,Hour-Minute

53:  P73        Maximize
  01: 1         Rep
  02: 10        Value with Hr-Min
  03: 7         Loc minimum water level

54:  P74        Minimize
  01: 1         Rep
  02: 10        Value with Hr-Min
  03: 7         Loc maximum water level

56:  P          End Table 1


*     2         Table 2 Programs
  01: 0.0000    Sec. Execution Interval

01:  P          End Table 2


*     3         Table 3 Subroutines

01:  P          End Table 3


*     4         Mode 4 Output Options
  01: 01        (Tape OFF) (Printer ON)
  02: 2         Printer 9600 Baud
```

Figure VII.2. Data Logger Program, Peyto Glacier Site (cont'd)

```
Mode A

*      A        Mode 10 Memory Allocation
  01:  0028     Input Locations
  02:  0064     Intermediate Locations


*      C        Mode 12 Security (OSX-0)
  01:  00       Security Option
  02:  0000     Security Code



Input Location Assignments (with comments):


Key:
T=Table Number
E=Entry Number
L=Location Number

T:   E:   L:
1:   4:   1:   Loc : Air Temp 107 probe (oK)
1:  34:   2:   Z Loc : F=291.0
1:  23:   3:   Z Loc : F=1
1:  32:   3:   Z Loc : F x UDG01-ch2raw
1:  24:   4:   Z Loc : F=1
1:  30:   4:   Z Loc : F x UDG01-ch2raw
1:  35:   5:   Z Loc : Z=X/Y
1:  36:   6:   Z Loc : Z=SQRT(X)
1:  37:   7:   Z Loc : Z=X * Y
1:  38:   7:   Z Loc : Z= X * F
1:  39:   7:   Z Loc : Z= X + F
1:  28:   8:   Loc : Raw UDG01 Depth Input Chan2
1:   1:   9:   Loc : Water Temp 107F
1:   2:   9:   F(X) Loc : Water Temp 107F Centigrade
1:   3:  10:   Z Loc : Water Temp 107F Kelvin
1:  45:  11:   Loc : Battery Voltage
```

Figure VII.2. Data Logger Program, Peyto Glacier Site (cont'd)

CR10 PROMPT SHEET

—— *MODES ——

*0 — Compile/log data

*1,*2,*3 — User program

*5 — Set/display time
:HH:MM:SS

05:xx	Year
05:xxxx	Day
05:HH:MM:	Hours:Minutes

*6 — Display/alter Input Storage/flags/ports
06:0000 Location to advance to
Commands while viewing location:
Display loc No./enter loc to jump to
C Change value
D Display flags 1-8, toggle flag w/1-8
0 Display ports 8-1, toggle port w/1-8

NOTE: x represents a digit

*7 — Display Final Storage

07:00	Select area 1 or 2 (skipped if 2 not allocated)
07:xxxxx	DSP loc./location to advance to
Commands:	# Display FS loc. No./enter loc to jump to
	#A Advance to some pt in next array w/same ID
	#B Backup to same pt in preveious array w/same ID

*8 — Manual data dump

08:00	Select Storage Area 1 or 2 (skipped if 2 not allocated)
01:xx	Output Device Code (see inst. 96 options)
02:xxxxx	Current/start F.S. loc
03:xxxxx	DSP/end F.S. loc
04:00	Enter any No. to start dump

*9 — Storage Module Commands.
see SM prompt sheet

*A — Memory Allocation

01:xxxx	Input Storage loc.
02:xxxx	Intermediate Storage loc.
03:xxxxx	Final Storage loc. Area 2
04:xxxxx	Final Storage loc. Area 1
04:xxxx	Remaining program mem. (bytes)

*B — Signatures / Status

01:xxxxx	Program memory
02:xxxxx	EPROM signature
03:xx	K memory RAM + ROM
04:xx	No. of E08 (key 88 to reset)
05:xx	No. of table overruns (88 to reset)

*C — Security

12:0000	Enter password xxxx
01:xxxx	Lock *1,*2,*3,*4,*A,*D
02:xxxx	Lock *5 & *6 display only
03:xxxx	Lock *7,*8,*9,*B; tele.cmds. except A,L,N, and E

*D — Save/load program
Commands 1 & 2 require baud rate code
1 — Print program (ASCII)
2 — Load program (ASCII)
3 — Save program on tape
4 — Load program from tape
7N — Save/Load/Clear program in Stor. Mod. N
1x Save program x (x = 1-8)
2x Load program x
3x Clear program x

Figure VII.3. CR10 Data Logger Prompt Sheet

APPENDIX VIII

REMOTE SENSING TECHNIQUES AND COSTS

VIII.1. Introduction

In Canada, remote-sensing data are obtained from satellites at two main receiving stations and then processed in Ottawa. In Norway, the Tromsø receiving station will deliver NOAA and ERS-1 data. Data from SPOT, NOAA, EXOS-D, LANDSAT and MOS are current acquired in Canada (Canadian Users Guide to ERS-1, 1991) and will be obtained from ERS-1, RADARSAT and various other satellites as they are launched, the sensors calibrated, and the products distributed. Passive-microwave sensors are only useful if spatial rsolutions of the order of 1 km are acceptable, which is not normally the case for most of the glaciers studied for mass balance in Canada and Norway.

Presently data may be purchased through a private company called RADARSAT International, "RSI", (not to be confused with the Canadian Space Agencies C-Band RADARSAT Satellite to be launched in by 1994). The cost of images (active or passive microwave as well as visual to infra-red wavelengths) depends upon what type of georeferencing is required by the user, the spatial resolution desired, and the spatial coverage needed.

VIII.2. Active Radar Remote Sensing from Satellites

ERS-1 (C-Band side-looking active-microwave instrument) was launched in mid-1991 by the European Space Agency and is expected to have a lifespan of two to three years; this will be followed by ERS-2, adding another two to three years to the project. A similar satellite will be launched by Japan in early 1992, called "J-ERS"; it will differ in polarization and will have both C and L-band capabilities.

In 1994, Canada plans to launch a satellite that will image the entire earth once every six days, north of 48° latitude, once every 4 days, and daily north of 70° latitude (see technical data provided by RadarSat International, 1991). The RADARSAT-SAR Radar operates at 5.3 GHz C-band, 5.6 cm wavelength, see Fig. 11.2, with a single HH polarizations, images are available in product forms that range in mode (Standard to fine, or ScanSAR 2 or 4 beam mode), resolution (10 to 100 metres), looks (1 to 16), swath-width (45 to 500 km), and incidence angle (20 to 59 degrees). The final ERS-SAR data products are available in digital and hard-copy formats that range from what is called "raw data", which is largely unprocessed, to "georeferenced fine resolution" (ERS-1 SAR georeferenced by longitude and latitude but not projected on a map) to even what is called a "systematically geocoded product" (ERS-1 SAR geocoded to a find resolution of between 7 to 40 metres). The Canada Centre for Remote Sensing in Ottawa (CCRS) has contracted for RSI to distribute RADARSAT data for the world, that is once it becomes operational, during or after 1994.

VIII.3. LANDSAT MSS and SPOT Satellite Data

Similar, but slightly different terminologies are used to describe the products sold for LANDSAT and SPOT data. LANDSAT Multi Spectral Scanner (MSS 4 bands), and the Thematic Mapper (TM 7 bands) sense the electromagnetic radiation from the surface of the earth at a number of selected wavelength bands. The spatial resolution of MSS data is 80 metres while the spatial resolution of TM data is 30 metres, except for the thermal infra-red TM band #7 (operating at 10.5 to 12.5

nanometres) which has a spatial resolution of 120 metres. The wavelengths covered by the other bands available range from 0.45 nanometres (blue) to 2.5 nanometres (short-wave infrared). LANDSAT data is usually used with three wavelength bands overlain in a false-colour composite that is designed to best bring out the surface features under study, such as snow, ice, lakes, roads, vegetation, bare-rock, cold or warm surfaces.

The horizontal positioning of all portions of the images cannot be guaranteed to be better than 1 km, although the resolution is much smaller at 30 meters. The cost (in 1991) of obtaining a product commercially that can be used readily (such as Geocoded or Precision Geocoded Quad 95 x 88 km subscene) ranges from $1,000 Canadian for 3-Band digital TM data, to $2,300 (for 7-band digital TM data). SPOT data is considerably more expensive (from $2,000 to $3,000) Canadian). The software necessary to analyze these digital image products is available from PCI, and other companies, and costs in the order of $10,000 or more, depending upon the image processing system desired. Once the costs of all the hardware, software and data products and training are combined and the limitations of the data are considered, standard aerial photography seems incomparably good and must still be utilized.

VIII.4. Other Satellite Instruments

Radar altimetry and laser altimetry, as well as a host of other instruments will be used in future years (e.g. Earth Observing System; EOS; NASA, 1991).

VIII.5. Application of Radar Remote-Sensing to Glaciers

It is possible that we can improve the accuracy of glacier mass-balance results and decrease the amount of field measurement required by more effectively utilizing remotely-sensed data, especially using active microwave methods. Excessive cloud cover often makes visual data unreliable in coastal and mountainous areas, and accuracies of about 10 meters are needed to properly map glacier surface features. Thus far, the resolution of such visual satellite data has been insufficient for most annual monitoring studies.

Synthetic Aperture Radar (SAR) is a tool that may be useful in glacier mass-balance studies but these techniques are still in development.

There is strong reason to believe that the L-band will penetrate quite far into the snowpack, even if wet, while the C-band will only penetrate dry snow. Although the polarizations available are limited, the data should still provide a useful test of the utility of satellite SAR methods in glaciology.

Detailed knowledge of the surface wetness and roughness beneath the snowpack, in addition to the snowpack wetness, density, crystal size and stratigraphy, is necessary in order to determine information about the spatial distribution of snow water equivalent, snow and ice extents, surface roughness and wetness characteristics from SAR images.

An active radar calibrator should be used on the ground and data analysis done in conjunction with SAR related studies. The calibrator must be chosen so that it is optimized for the wavelength and polarization of the incoming radar beam under study, such as HH polarization C-Band Radar for RADARSAT. If corner reflectors are used they must be very large, and the costs are prohibitive; on the order of $9,000 Canadian for a single instrument!

APPENDIX IX

ACCOMMODATION

IX.1. General

At glaciers where long-term observations are planned, small semi-permanent buildings, instead of tents, can be erected to accommodate the field crew. This chapter deals with two types of simple and easily constructed buildings:

1) houses for accommodation and
2) garages or buildings for storage etc.

Both types have the same original design - a wooden framework (2" x 4"), nailed together as triangles with almost equal sides and covered with planks and roofing paper on the outside; in the case of the living house it is insulated and covered with panelling on the inside. The design is as simple as possible, to make it easy for unskilled personnel to erect the buildings, and to make them rugged. A sketch of a simple hut and construction layout is shown in Fig. IX.1 and photographs show construction details in Fig. IX.2.

IX.2. Building Site and Foundation

The huts should preferably be placed on bedrock that is exposed throughout the winter or sited where only small amounts of snow collect. This is to avoid an unnecessary snow load on the construction and to allow easy access to the huts all year round. On the other hand, if a snow vehicle is to be used in summertime, it is an advantage if the garage is placed close to an area where snow remains all summer. Then the vehicle can be driven easily to and from the garage. (Note, the use of snowmobiles by field crews in Canada's national parks is not permitted).

The 4" x 4" foundation beams should be placed parallel to each other and levelled. The floor joists (2" x 4") joined to the roof rafters (thus forming a wooden triangle; see sketch) should then be raised vertically, resting on the foundation at right angles.

IX.3. The Framework, Roof and End Walls

The 2" x 4" framework is joined together as follows. One floor joist is placed horizontally on the ground. Two roof rafters are also placed horizontally so that they form a triangle together with the floor joist. The corners of the rafters are cut so that they can easily be nailed to the floor joists at their lower ends and nailed together at their other (upper) ends. The lengths of the rafters may be equal to the lengths of the floor joists, thus forming a triangle with 60° angles. If a higher house is desired, the rafters must be longer. It is not recommended to build a too high house, unless it is sheltered.

Two of the completed triangles are selected to carry the end walls. Vertical supports for window and door should then be nailed in their proper places in these triangles before they are erected. Pieces of 2" x 4" lumber can be used for these supports. The space between them and between the horizontal supports for the window will be determined from the size of the window and the door, respectively.

A-FRAME HUT

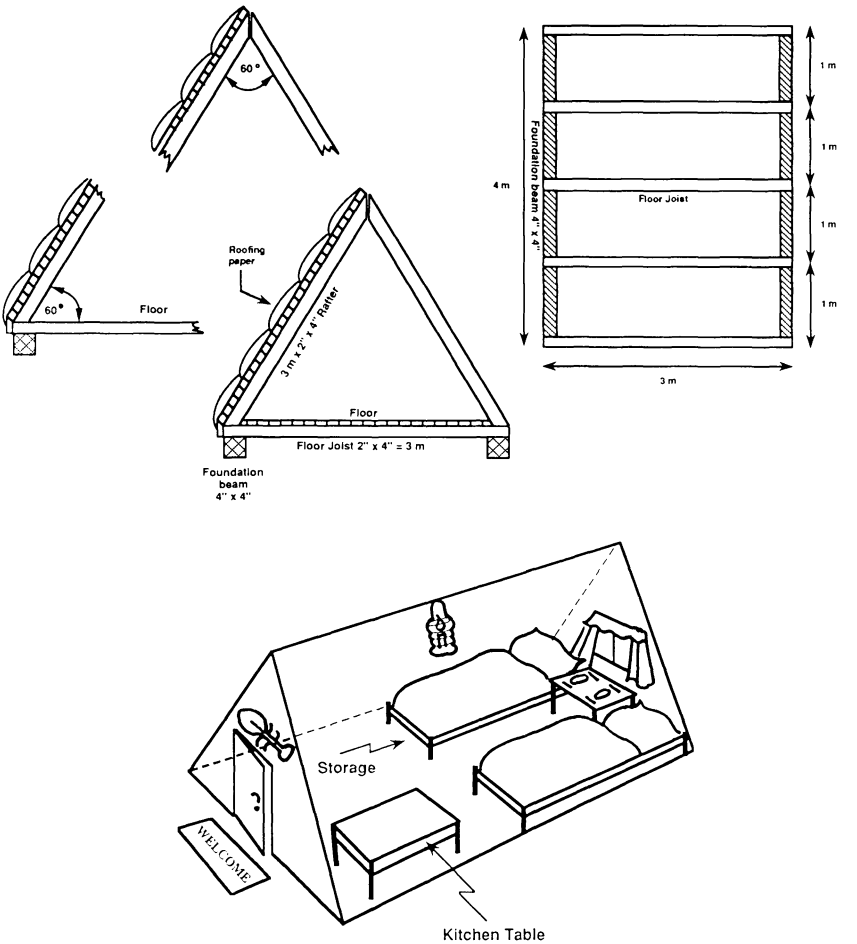
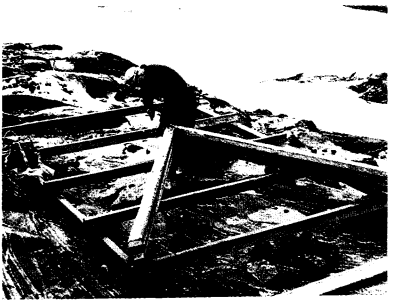
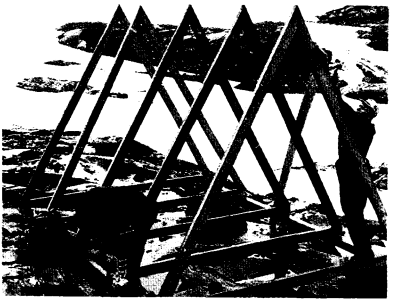


Figure IX.1: Diagram of A-frame Construction
An A-frame construction is sturdy and well suited to withstand harsh conditions in high-mountain areas. Prof. W. Karlen has built several "glacier-huts" in Canada and Norway. The roof angle, 60°, makes the hut slightly lower than some people like, so many Canadian huts are higher(roof rafters = 4 m or more) but they catch more wind. The door may also be made higher than shown here.

This sketch does not show insulation or inner panel, which is advisable is the huts will be used for longer periods of stay.





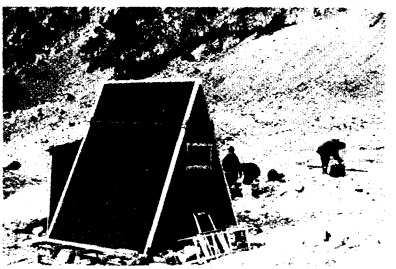


Figure IX.2: Building an A-frame Shelter
The two upper pictures show how to start the building. After the foundation of 4" x 4" beams is laid and levelled, the roof rafters are cut and nailed together at the correct angle and then raised. They are nailed to the floor joists and temporarily held in place with a diagonal plank. Bolt holes for the guy wires are drilled into bedrock with a power drill. This hut was built at Erdalsbreen, Norway.

The lower left picture shows how a guy-wire support is made when no bedrock is exposed. Steel wires are tied to a boulder placed in the bottom of a pit. The picture shows a loop of this wire before the pit is completely filled with gravel. The guy wire will be attached to this loop and tightened with a turnbuckle.

The lower right picture show the A-frame at Place Glacier, Canada. Note the guy-wires and the steeper roof on this hut.

The roof consists of planks of rough lumber, or heavy plywood, preferably precut to fit the distance between the end walls or 30-40 cm longer. In the latter case the house will have a better appearance and the vertical end walls will be better protected. When the woodwork is completed, the whole roof is covered with heavy roofing paper (Grade A).

The side walls are made in a similar manner as the roof, but each plank must be cut at the correct angle to make a good join with the roof. It is recommended that the end walls should also be covered with heavy roofing paper. It is advisable to precut planks for the end walls to save transportation costs and time when the house is erected.

The floor is made from 1" to 1½" planks with tongue and groove, to ensure a draft-free surface and to allow the planks to support each other when a heavy load is applied. These planks also may be precut to equal lengths, but, owing to the framework construction, it will be necessary to adjust the lengths of some of them so that they fit properly inside the house.

For an insulated house, a support for the floor insulation and the insulation itself must be placed in position before the floor is laid.

IX.4. Door, Window, Outside Cover, Insulation

The storage building will be used as a shelter for supplies or as a garage for a snowmobile so it is not necessary to make it completely airtight. Thus the door can be made of a sheet of heavy plywood or a number of planks nailed together. To ensure a sturdy construction, it should be mounted on three hinges. Two ordinary hooks can be used to close the door, one on each side. For the house, however, a conventional door is preferred to avoid drafts and to keep the inside free of drifting snow.

The window can be any kind of wooden frame window which can be squeezed into the opening provided in the end wall. To obtain tight joints between the window-frame and the wall, use a caulking compound or sheets of aluminum cut into suitable strips. A simple outside protection of the glass is recommended when the house is not in use.

To waterproof a hut, both roof and end walls should be covered with roofing paper of the best quality. The manufacturers' instruction for application should be followed to prevent the roofing paper being torn off by high winds. To strengthen the edge along the top of the roof and to protect the roofing paper from damage caused by the guy wires, it is advisable to fit a strip of aluminum or galvanized steel along the edge. At the outside corners, between the end walls and the roof, it is recommended that 1" x 1" (either square or quarter-round) flashing material should be applied to make the joints as tight as possible.

Insulation is placed between the outer roof (and the end walls) and the inner panel. Rockwool, foamed plastic sheets or similar materials are well suited for insulation. The thickness of the sheets should be 4" at the maximum, as this will be the width between the roof and the inner panel corresponding to the size of the roof rafters. As panelling, 3/4" planed boards can be used; plywood can also serve for this purpose, but lumber will normally have a better appearance and needs no painting.

IX.5. Guy Wires

The house must be anchored to the ground with steel wire cables or guy lines. Ideally, the cables should be fastened to steel bolts drilled into bedrock near the corners of the house. However, if it is impossible to drill holes, or the ground consists of moraine material with no exposed bed-rock, dig a hole, attach a wire to a boulder and drop it into the hole. Fill up the hole with gravel and pile large rocks on top. The wire attached to the buried boulder should be long enough to form a loop 20-50 cm above the ground. One guy wire across each end of the roof will normally be sufficient. But if strong winds are expected against the end walls, additional guy wires could be fixed at the top of the end walls. To tie these wires to the roof rafters, a small hole is made in the wall.

IX.6. Materials Necessary for One Complete Hut

The size of the hut depends on its purpose. As a shelter for a snowmobile, a 3 x 4 m floor surface will be sufficient, and this size has been selected for some A-frame huts constructed at glaciers in western Canada. This size may be also sufficient for occasional use as accommodation for two people, but in Norway most A-frames have 3 x 5 m floor size.

The materials necessary for a complete garage are given in the list below, but paint and materials for shelves, etc. have not been included. NOTE: For a house, the inner panel, materials for tables and beds etc., a conventional door, and the insulation must be added. The length of the guys will depend on local conditions, but 50 m in total will probably be sufficient for most huts.

For roof: 1" planks, rough wood (grade 2 or 3) 26 m^2
For front and end walls: 1" planks rough wood (grade 2 or 3)
10 m^2 = total ca 40 m^2
For floor: 1" or 1½" tongue and groove (grade 2 or 3), 12 m^2
Floor joists 5 lengths, 2" x 4" x 3 m
Rafters 10 lengths, 2" x 4" x 3 m (or longer for a higher hut)
Door and window supports 4 lengths, 2" x 4" x 2,5 m
Door, plain 3/4" plywood (for garage only) approx. 1,2 x 1,2 m
Finishing rod 1/4 round 12 linear m
Roofing paper 5 rolls (26 m^2)
Roofing nails 7/8" galvanized 4 kg box
Nails (1000) 2" (gum nails, box coated) 2½ kg
Nails (300) 2½" (gum nails, box coated) 1½ kg
Hinges for door 3 pieces + screws
Door hooks and eyes 2 sets
Foundation 4 lengths, 4" x 4" x 4 m or 5 m (see text)
Guy wire, turnbuckles, cable clamps: quantity to be decided in each case, according to local conditions

Experience has shown that this simple A-frame hut can be erected by two people in less than 2 days. The total weight of all necessary materials amounts to approximately 1200 kg. In addition there would be material for the indoor construction, mentioned above. For an insulated hut, allow some 400 kg more.

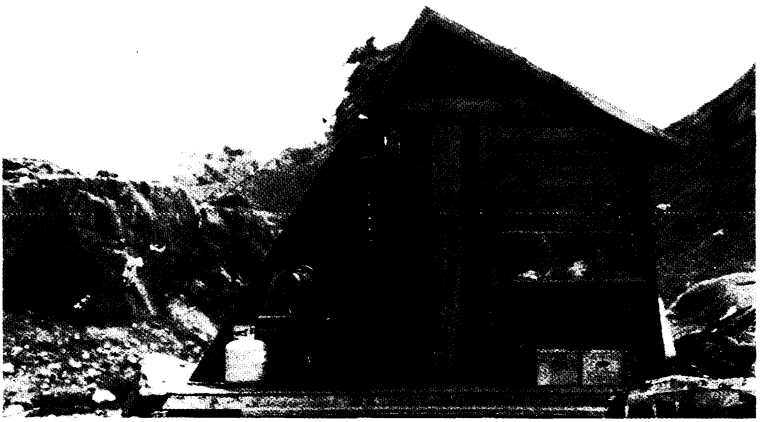


Figure IX.3: Sentinel Glacier Hut Rebuilt after Avalanche
The original A-frame at Sentinel Glacier, built in 1963, was flattened by an avalanche in the spring of 1975. It was rebuilt and extended the same summer, then in 1990 it was further remodelled and repaired. It serves as an example of how useful and durable this type of hut can be, while maintaining the heritage character of the original glacier hut, first constructed by Wibjörn Karlén.