GLACIER MASS BALANCE MEASUREMENTS

A MANUAL FOR FIELD WORK

by

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A guide to field officers and assistants
with limited background in Glaciology

DEPARTMENT OF MINES AND TECHNICAL SURVEYS

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FOREWORD

During the International Hydrological Decade it is anticipated that glaciological data will be collected at numerous glaciers. In order that these data can be compared directly it is essential that they are collected in a consistent manner and that the results presented in a standardized form. Field procedures followed at the Department of Mines and Technical Surveys in Canada are described in this manual. They were made in order to ensure, as far as possible, uniform accuracy and to obtain results that can be directly comparable.

The manual:

1. describes standard field techniques
2. outlines practical difficulties and indicates how to overcome them
3. gives some hints of practical use for the field work
4. suggests how the data can be recorded and tabulated
5. shows a suitable form for summary of data to be made in the field
6. describes the construction of an A-frame hut

Most of the detailed instructions are directly concerned with the Canadian glaciological program which started during 1965 in southern British Columbia and Alberta, but they could probably be used for similar field programs elsewhere - with minor adjustments in each particular case.

Final revisions in the text were made at a Field Seminar at South Cascade Glacier, March 1966, in close cooperation with glaciologists of the Water Resources Division in Tacoma, Washington.

Ottawa, March 1966
Gunnar Østrem, Alan Stanley

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SELECTION OF SUITABLE GLACIERS

It is not physically possible to examine all glaciers in a mountain system or within the catchment area of large streams. Therefore, it will be necessary to select one or more glaciers which are considered representative of the whole area under study. However, the results obtained from one or more glaciers can probably be applied to a large glacierized area. It is therefore extremely important that the choice of the representative basin be made very carefully, but practical conditions (mainly accessibility) might influence the choice of glaciers for this kind of study. It is therefore probably necessary to make a compromise in most studies.

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

a) The glacier must have a well-defined catchment area and the degree of glacierization must be as high as possible so that the melt water stream depicts conditions on the glacier rather than conditions on the surrounding terrain.

b) The size of glacier should be comparable with all glaciers in the area of study but small enough to be fully examined by a 2-3 man party. (The upper limit of such an area is probably 10-15 km^2). In special cases, when great economic interests are involved it might be possible to have more people involved in the field measurements and thus a larger glacier area could be examined.

c) The range in altitude between the glacier tongue and the upper firn area should be as large as possible, or at least cover the main part of the range for the glaciers in the area under study.

d) The glacier should be drained by one single melt water stream with local conditions favourable for discharge measurements close to the glacier snout.

e) The glacier should have relatively easy access so that it will be feasible to visit it throughout the year without extensive 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. This question, however, must be decided for each particular glacier depending on available resources.

f) The glacier should have few crevasses as they make the work unnecessarily risky for observers and may restrict proper observations to only a small area. However, if a representative glacier within an area has a great number of crevasses the value of this point must also be considered in each particular case.

g) The glacier should be situated in an area for which reliable maps and good air photographs are available or can be readily obtainable shortly after investigations have started. All accumulation and ablation measurements must be plotted on maps, and the scale of 1:10,000 is generally most suitable for this purpose. A contour interval of 10 metres will be appropriate for the glacier surface, 50 m will be sufficient for the surrounding area. The map must cover the entire catchment area above the site of river observations.

BRIEF DESCRIPTION OF THE GLACIOLOGICAL PROGRAM IN WESTERN CANADA

As a part of Canada's contribution to the International Hydrological Decade glaciological studies will be conducted at a number of glaciers. These studies will include measurements of mass balance, meteorological observations on or near the glacier, measurements of discharge and silt content in outflow streams. Besides these subjects which are within the scope of the International Hydrological Decade program, studies of the ice movement (i.e. "ice discharge" in a glacierized valley), ice formation in the firn area, ice crystallography and related problems will be carried out. In some cases however the limited sources of trained personnel will restrict studies to the first mentioned subjects.

The primary purposes of the glaciological investigations on the selected glaciers will be:

1. To determine the mass balance on the glaciers. The winter accumulation will be measured as accurately as possible and the total amount of ablation during the summer season will be observed by a network of stakes drilled into the ice. Variations in snow density in the firn area will be observed by pit studies throughout the ablation season.

2. To study the accumulation pattern and, if possible, follow its variation throughout the accumulation season. Furthermore, to make a comparison between the total accumulation on the glacier up to certain dates during the winter and the precipitation records kept by meteorological stations and snow courses in the area.

3. To study the ablation throughout the summer and correlate variations with meteorological parameters obtained at the glacier and/or deduced from observations at distant meteorological stations.

Measurements will be continued for a period of at least ten years. Accumulation will be measured at the end of the accumulation season (in April or May), but in addition, it will be necessary to make winter visits to glaciers in areas of heavy accumulation to extend the main stakes in the firn areas. Because all accumulation measurements in the spring must be referred to known points on the glacier surface it is vital to keep them visible throughout the winter, and inspection is anticipated in November and February each year. Ablation and river discharge will be measured during the entire melt season by parties of 2-3 men who will also keep records of meteorological conditions. They will make summaries of all their observations so that the processing of data can be performed immediately after their return from the field in September.

A base camp will be established at all glaciers comprising at least an insulated hut for accommodation, a shelter for a snow vehicle and/or storage of supplies, one or more Stevenson screens for meteorological observations, and probably a shelter for an automatic stream gauge.

STAKE NETS

As measurements of both accumulation and ablation are referred to stakes placed on the glacier surface it is advantageous to plan carefully the pattern of the stakes. Ideally, the stakes 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 practical and it is suggested that stakes be arranged in one or another geometrical pattern to facilitate the daily work on the glacier. It is impossible to make a rigid recommendation for stake locations which would fit all different shaped glaciers, but for valley glaciers the most useful is a long line up the centre with transverse lines at regular intervals.

1. Stake location

One longitudinal profile is approximately along the centre line of the glacier (for numbering of these stakes, see below) and several transverse profiles are located at suitable intervals across the glacier from the snout to the firn area. The transverse profiles should be placed at right angles to the longitudinal profile. 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.

2. Numbering system

If stakes disappear or bad weather conditions make navigation difficult on the glacier a good system makes it easier for the crew to decide their location. In order that each stake can be easily identified it is necessary to have a logical system of numbering. There are several systems but the following has proved to be very useful for a valley glacier.

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 side of the glacier and even numbers, 12, 14, 16 etc., on the right 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 side of the glacier; 22, 24, 26, etc. on the right side. If it is necessary to insert more stakes in the longitudinal profile they could be numbered with figures not already used in the transverse profiles, as 18, 19, 28, 29, etc. For most valley glaciers there will be less than 10 stakes in the transverse profiles and sufficient numbers will be available for intermediate stakes in the longitudinal profile. An example is shown among the illustrations.

3. Replacement of missing stakes

If it is necessary to replace a stake which has disappeared a new stake can be inserted as close as possible to the "original" stake's position. The new stake important. If very accurate measurements are applied, special precuations must be taken to ensure accurate calculation of the new position.

A hand operated ice drill consists of a seamless steel tube with 4-8 teeth cut into the lower end. The drilling equipment is shown among the illustrations.* 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 inside the tube and hinder further drilling. Normally 50 cm can be drilled before the tube 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 by two men in 1/2 - 2 hours depending upon ice conditions, air temperature and the skill of the drillers.**

It is always advisable to drill holes for the stakes when the ice is cold and there is no melt water to percolate down into the hole. However, if the air temperature is above $0^{o}C$ or there is strong sunshine the drill warms up and might freeze into the hole if the ice is very cold. Under such conditions it might be necessary to drill during the night. To loosen a drill frozen to a hole, alcohol or antifreeze can be poured into the hole immediately. Denaturated alcohol should therefore always be carried by the ice drillers.

To insert a stake in the firn area, it can be pushed down to the desired position or a hole can be drilled to facilitate the insertion. Metal stakes tend to sink in the firn and it is important to support the lower end before they are used to measure any variation in the snow or firn surface. To prevent sinking, the stake could be:

(1) placed on the previous summer crust, this is a relatively hard surface and will support the stake more efficiently than any snow

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*This equipment was developed in Scandinavia during the last 15 years, and can be obtained from: Institute of Physics (Verksmester R. Holm), University of Oslo, Blindern, Norway. Approximate cost is $150.00 for a complete set.

**Other kinds of drills have been developed, many have a horizontal cutting knife and a long spiral along which fragments are raised. In cases when glacier ice is very wet this type of drill could have some advantages, although raising ice crumbs to the surface might still be difficult.

layer. However, when melt water percolates through the crust, the mechanical strength decreases and the stake will start to sink anyway.

(2) placed on a small "platform" made of any cheap material plugged into its lower end. The simplest is to insert a cork or a wooden plug before the stake is put in position. If, furthermore, the stake is placed so that it rests on the summer crust; it is likely that it will be held in correct position for most of the summer.

(3) placed on a plate that is larger than the stake diameter. This can be done by drilling a large diameter hole (SIPRE-type coring auger) and fixing a circular plate to the stake before it is inserted. This method has proven satisfactory under various conditions, provided the plate is strong enough.

If a pit is dug, a large plate can be laid at the summer surface, and the stake placed on it before the pit is filled up again with snow. This is a very satisfactory method, but it requires much labor.

In remote areas where glaciers will be visited only 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 not be necessary until the ice has melted approximately 20 metres vertically. No description or explanation of the hot point drill is given here as this is beyond the scope of this manual, but assistants who are occasionally working on glaciers where such stake chains have been inserted previously must be aware of the special technique involved in the observation of glacier melt at these stake chains (or wires frozen vertically into the ice). (See under the description of ablation measurements below).

A complete equipment for hand drilling comprises:

a) a seamless steel tube 1 metre long with 4-8 teeth cut in the lower end and a 5/8" thread in the upper end.

b) aluminum extensions 1 metre long with brass couplings fitting the above mentioned thread.

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.

e) 2 open end wrenches or pipe wrenches to dismantle the drill and extensions.

f) a bottle containing denaturated alcohol to free the drill if it freezes into the ice.

ACCUMULATION MEASUREMENTS

1. General

The total thickness of snow that accumulates over the entire glacier surface must be measured at the end of the accumulation season. (For most glaciers in southern Canada this will be during the month of April or May.) Snow will then start to disappear 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 total accumulation as measured in April/May.

Due to practical difficulties in visiting all glaciers at the right time it will be necessary, at least for some glaciers, to measure the accumulation prior to the actual end of the accumulation season. For such glaciers additional accumulation after the snow survey must be recognized and recorded.

To study the rate of accumulation during the winter it will be necessary to make several visits to each glacier and to make a complete accumulation measurement at each visit. However, the method will be similar to those used at the end of the accumulation season and they are described in this chapter.

As the accumulation is expressed in water equivalent it is necessary to measure snow depth and use a snow density factor to calculate the water equivalent in 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 will be necessary to make a great number of 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 snow pack to previous summer's crust (or the ice surface). The snow density is measured

*The swiss snow probe is made by Dr. P. Kasser, Abt. für Glaziologie, Voltastr. 24, Zürich 7/44, Switzerland.

by weighing a known volume of snow obtained from the snow pack between the existing snow surface and previous summer's crust (or the glacier ice surface).

Results of water equivalent determinations at numerous places are plotted on a map and lines of equal accumulation drawn. From this accumulation map the total accumulation, expressed in millions of m^3 of water equivalent can be calculated.

2. Snow depth soundings

Snow depth can be highly variable as deposition is greatly affected by topography and wind action. Prevailing winds will probably produce a deposition pattern of the winter snow cover which is similar from year to year for any particular glacier. However, great variations might occur even in two consecutive years and before the snow accumulation pattern can be anticipated it will be necessary to measure the snow depth at a large number of points. A density of 100 points per km^2 will probably be desirable for a valley glacier whereas a less dense network might be sufficient for a large ice cap.

Ideally, the measuring points should be uniform 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 50 metres) should be laid in a pattern which will cover the entire glacier. If snow conditions are more or less known from previous experience, a skeleton network could be placed in areas of even snow distribution and a denser network in areas where large local variations are expected. Even distribution generally occurs on the tongue or on the intermediate part of the glacier, whereas wide variations are commonly expected in the upper firn areas, that also tend to have greater thicknesses of snow.

The easiest method is to locate sounding profiles between the "main" stakes down the length of the glacier and extend other lines at right angles to this center profile. At 50 metre intervals along all profiles, snow depth should be sounded to the nearest cm.

It is advisable to plot all field measurements the day they are obtained. In this preliminary plotting all figures will express snow depth only and not water equivalent, but they will show any irregularity in distribution and determine the position of additional sounding profiles.

It is advantageous to first sound the snow depth on the glacier tongue for two good 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 become difficult to locate the lower boundary of the winter snow pack. During a warm summer a rigid "summer crust" will be developed and its location can be detected with a probe. However, during a cold summer, no real "summer crust" develops, and summer snow falls may give a number of poor developed crusts. It becomes difficult to decide which of them should be defined as the previous summer's surface. *

Generally the greatest variations in snow depth can be expected in the upper part of the glacier which also has the heaviest accumulation. It is important to spend more time in this area and have more sounding profiles than on the tongue. Generally travel becomes difficult and each sounding takes more time so work may take 2-3 times longer than on an equal area on the glacier tongue.

Before the soundings are completed on the glacier, make sure that all data are plotted on a map and contours are drawn to show areas of equal accumulation.

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*If such conditions are observed during the ablation season in a particular year, special measures should be taken by the crew to <u>mark</u> a surface which could be defined as that summer's crust (see later).

Additional soundings might then be necessary in areas where it seems difficult or impossible to interpolate the data to obtain a reasonable pattern.

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

3. Pit studies

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. If time is very short it would be advisable to dig at least 3 pits, one on the tongue, another in the middle part, and one high up in the firn area. Intervening pits should be dug according to the time available.

Before digging a pit, first make a number of snow depth soundings to determine the depth which will be necessary for the pit 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 in the old snow (firn) below the previous summer's crust. Normally the pit will have a square or a rectangular cross section and before starting one must decide which of the four sides should remain untouched. Otherwise it will be impossible to determine the original upper surface of the snow pack. To avoid changes in snow conditions due to direct sunlight, it is advisable to select the southern pit wall for sampling.

If a pit is dug near an existing stake it should as a rule be dug at a standard distance downstream from the stake. A distance of 5 or 10 m is recommended. The same distance should be maintained for all pits dug on the same glacier. If there is no stake at the pit location it is advisable to place a stake there, because if repeated pit studies are necessary, the exact location can be easily recognized at each visit.

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, its length being normally determined by the physical condition of the snow, presence of ice layers, etc.

To obtain the sample: push 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 vertical distance between the surface and plate to the nearest 0.5 cm. This is the length of the sample and although snow may settle inside the tube it will not effect the density measurement.

Remove some of the snow from the pit wall to release the sample tube and transfer the content of the tube to a suitable bag. Weigh the bag and contents with a 1,000 gram spring balance* to the nearest 5 gram. 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 below). From these figures the snow density and water equivalent can be easily calculated and a diagram of their variations with depth constructed.

If sampling is performed in warm weather or during a day with strong radiation the sampling tube might become warm and snow may stick to it. Then it will be difficult to transfer the snow sample from the steel tube to the plastic 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 might also help .

A series of temperature observations should be carried out at regular intervals in the snow pack to determine if melting has occured. If freezing temperatures are present in the lower part of the snow pack no substantial amount of melt water has disappeared and the water equivalent observations would be reliable except for surface evaporation. The amount of evaporated snow is difficult to determine but for most

*A suitable balance can be obtained from Thorolf Gregersen, Tollbugt. 24, Oslo ,Norway, for approx. $9.00.

purposes it may be neglected.

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 datum of powdered dye will make it easier to recognize the actual summer surface later in the season because percolating melt water will form ice layers in the snow pack and, eventually, loosen the summer crust. The boundary between last winter's snow and firn from previous years will gradually be obscured. Pits that are 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 is not made, it will be necessary to dig pits at the end of the ablation season to measure the remaining part of last winter's accumulation. For further details, see chapter on ablation measurements.

4. Density determinations performed from the snow surface

Many attempts have been made to avoid time-consuming pit digging to obtain snow density values, but one of the main difficulties in all these methods is to recognize the previous summer's surface, i.e. to what depth the sampling should continue. Another problem is the accuracy of these methods (Williams, 1964).

a) The coring drill

With a SIPRE type coring drill it is possible to obtain snow samples similar to those taken with a cylindrical snow sampler. However, due to variations in physical conditions (degree of packing, crystal size, density), almost each time the auger is raised the snow core breaks and a part of the sample core is lost before a density measurement can be made. Special precautions must be taken to ensure that measured densities are valid for the whole snow pack. Example: The coring auger has been lowered 50 cm in the hole and a 50 cm cylindrical snow sample should have been obtained. When the auger is raised the length of the sample is only 45 cm. The water equivalent of this sample will therefore be approx. 10 per cent less than expected and a correction must be made accordingly. To make the correction a special form has been developed for field use, and it is described in a following section. It is advisable to check at least some of the results obtained by the coring auger with pit studies at the same location. In loose snow such check is vital, as the coring auger has shown a tendency to over-register the density of light snow.

b) A radioactive method

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 is determined for snow within a radius of 12-40 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. The total weight of necessary equipment is higher than the weight of a complet SIPRE coring auger, and is not yet practical for fielduse.

5. Additional Accumulation

Snow that falls after spring accumulation measurements have been made must be accounted for before the total accumulation is computed. This 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 accumulation season can be used in connection with a correlation coefficient and calculations of prevailing temperatures on the glacier, see below. In the latter case a simple measurement is made of the actual snow cover 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 existing snow surface at the time of the snow survey with masonite sheets anchored to the stakes or scattering sawdust or powdered dye near the stakes.

During a short period in the spring some additional accumulation can result from rain falling on snow that remains well below 0°C. The rain water will freeze within the snow pack and form layers that increase the total amount of accumulation. This kind of additional accumulation, however, will be negligible in temperate areas. To check the amount of additional accumulation pits should be dug at the beginning of the ablation season (especially in the firn area) and the total water equivalent measured in the snow pack. A comparison with figures obtained by the snow survey in April/May will indicate if a correction is necessary.

A meteorological method using precipitation data from a meteorological station is complicated for it is necessary to decide if precipitation will fall as snow or rain at the glacier on each occasion and, furthermore, to decide if rain water will freeze within the snow pack or not. If it does not freeze it is assumed that the rain water drains completely off the glacier, and does not increase the amount of accumulation. This statement is based on the assumption that the temperature of the firn is at 0°C. Such conditions are assumed to be valid for glaciers in temperate areas. (The conditions of additional accumulation are however completely different for a "cold" glacier in the Arctic.)

A direct measurement of additional accumulation should be made immediately after arrival at the glaciers in June.

6. Recording data and completion of forms

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

b) The coring drill form

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

1. Column 1 shows the depth as measured 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 shows the distance of the drill between each sample, and is calculated as the difference between the depth of each sample.

3. Column 3 shows the actual length of the sample measured when it is removed from the auger. This length will normally be slightly less than the distance between sample depths. It can also happen that the sample has to be trimmed at the ends to make a proper cylinder.

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

5. Column 5 shows the volume of sample. This figure can be obtained by multiplication of the cross sectional area with length of sample. There is no standard size coring auger and consequently no standard table has been constructed to calculate the sample volume.

6. Column 6 shows the density of the snow sample. Note that 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 (the depths taken from column 1).

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

   Any decision is difficult to make, but when using a drill the operator may feel when he is drilling in heavier snow and when he is penetrating loose snow. 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 expresses the water equivalent assumed to be present in the area indicated in column 7. Note that this figure is the adjusted water equivalent and not the actually measured value for the individual snow sample.

9. Figures in column 9 are the cumulative values of figures in column 8, and can be directly plotted in the diagram.

ABLATION MEASUREMENTS

1. General

Glacier ablation comprises all material which is removed from the glacier by melting, calving , evaporation or wind action (Ahlmann, 1948, p. 26). The most important factor on mountain glaciers is melt, most of which occurs on the surface. Wind action is negligible and evaporation is dominant only for short time periods during the spring. The amount of material lost by evaporation is commonly only a fraction of the material which is removed from the glacier by melting. Investigations of the relationship between the many factors, the influence of meteorological parametres (air temperature, wind speed, humidity, radiation etc.) is extensively described in the literature and is not dealt with in this manual. (See, par example, Wallén, 1948 or Hubley, 1957).

The total amount of material lost from the glacier during the summer is called total ablation and it can best be obtained from observing the relative lowering of a large number of 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 be measured by photogrammetric means and this method is still used to measure the volume change at a large number of glaciers in Europe and in North America.*

*For a number of Canadian glaciers terrestrial photogrammetry has been used to determine the glacier shrinkage or, more correct, the shrinkage of the tongue, by the Water Resources Branch of the Dept. of Northern Affairs. However, as this method only comprises the lower part of the glacier a figure for the total budget is not obtained.

The variation in total glacier volume from year to year can be obtained by photogrammetric means if the glacier is photographed at the end of each ablation season. This yearly variation in mass results from both accumulation and ablation and is defined as the glacier net budget. (A negative budget means that the glacier volume has decreased, a positive budget that it has increased). Terms used in this kind of investigation have been defined in a discussion of glaciological mass balance terms by Meier (1962). However, some modification of these terms were suggested as a result of further discussion at a field seminar at South Cascade Glacier, March 1966.

"Net budget total" is redefined as "Total budget"
"Mean specific budget" is redefined as "Mean budget"
"Cumulative mass flux" is redefined as "Transient budget"

Other glaciological terms were considered and the most useful for attention are: Firn edge, summer surface and snow line (which represents the final position of the transient snow line).

Information of ablation can be obtained from the position of the snow line (the lower border of last winter's snow cover) at the end of the ablation season. However, under equal melting conditions it will be situated higher in a year of less accumulation and calculations of total ablation are difficult to base entirely on this concept. But a series of photographs showing the position of the transient snow line throughout the summer will be extremely valuable support in the construction of ablation maps. Such photographs should therefore be taken by the field crew at 5-10 days's intervals from suitable fixed points.

2. Stake readings

Lowering of the ice surface can be measured directly by comparing the visible length of a stake in a given time 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 and this 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" must be followed:

a) For 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.

b) For stakes drilled in ice which is still covered by snow:

A measurement must include the visible length of stake (i.e. from the top to the snow surface defined similar to the ice surface above) and the snow depth. The snow depth is measured with a snow probe as outlined in the previous chapter. The probe is pushed down vertically in at least three places within 1-2 m of the stake. The arithmetic mean of these soundings is used for the snow depth figure at this location* and is noted on the stake form. (See further below under description of completion of forms).

At the beginning of the ablation season the glacier ice is relatively cold and percolating melt water will refreeze at the ice surface to form superimposed ice (Schytt, 1949). Superimposed ice will disappear later in the summer, at least on lower parts of the glacier. It must, however, be taken into account when short-term

*As snow depth alone does not give information of the water equivalent it will be necessary to determine the snow density from time to time. See previous section about pit studies.

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.

c) For stakes in the firn area:

Stakes in the firn area are not normally supported in a solid mass similar to stakes drilled into glacier ice, some artificial support must be used so that the stake does not sink into snow or firn. See previous section describing techniques of inserting stakes ! If a stake is not supported it must be expected that it will suddently start to sink at any time during the summer and all subsequent readings will be false.

If a stake has an efficient 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 by a snow sounding stick and the summer crust identified by feeling a hard layer at or near the expected depth, based upon previously made observations. (Compare accumulation measurements in the area). However, formation of numerous ice layers within the snow pack might confuse measurements of snow depth. An ice layer can easily be taken for the previous summer's crust and the measurement would be worthless. To overcome this difficulty it is generally possible to make a snow depth measurement to a plate previously placed on the summer surface. The stake form will give information whether a plate is present or not.

Variations in snow density already mentioned in section b above will also apply to the snow cover in the firn area and consequently the snow dentiy must be determined several times during the summer so that the water equivalent of the snow pack can be calculated.

d) Special stake chains or wires inserted in a hot point drill hole:

As mentioned previously, in areas of great ablation stakes may be replaced by a stake chain (or a wire) frozen vertically in the ice in a very deep hole made by a hot point drill. These stake chains or wires will not be visible until the snow has disappeared and readings will give information of ice ablation only. Reading a stake chain or a wire is basically identical to reading a normal stake. The length of the stake chain or wire 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 if the stake chain or wire is several metres long.

To locate a stake chain or a wire on the glacier surface, it is advisable to drill in a normal stake and mark it with a flag.

3. Completing stake forms

To calculate variations of ablation throughout the melting season special stake forms have been constructed so that they account for all possible conditions. The form looks formidible and it might be difficult to complete it properly, but the following rules should be used as a guide:

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

b) Column 1 shows the date of the readings.

c) Column 2 shows the time difference between two observations and gives number of days between each reading.

d) Column 3 and 4 show the visible length of the stake. If ice is exposed, only column 4 is filled in; if the spot is still snow covered only column 3 should be used.

e) Columns 5-8 are to record 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 (d) above) nothing should be put in columns 5-8 as no snow exists at the location.

Elev. of stake: 2,121 m.a.s.l.
Total length of stake (m): 4.0 m

STAKE OBSERVATIONS

on glacier Peyto

Al.:)
Steel:)
Wire:) Stake No. 48
Bamboo:)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Date	Time diff.	Top to snow	Top to ice	Snow Depth					Difference					Abl.	Cumulative w. eq.		Net w.eq. (±)	Remarks
				Sounded		Computed			Super imp. ice		Snow	Ice			Acc.	Abl.		
		cm	cm	cm snow	cm w.eq.	cm snow	cm w.eq		cm	cm w.eq.	cm w.eq	cm	cm w.eq		cm	cm	cm	
9/4		180		120	40			(300)									+40	stake inserted
25/4		190		110	36			(300)			4			4		4	+36	
3/5		225		(88)		75	30				6			6		10	+30	
12/5		240		50	20			(290)	10	8	10			2		12	+28	
24/5		270		21	9			(291)			11			11		23	+17	
10/6		-	303							8	9	3	3	20		43	-3	Bare ice
13/6			307									4	3	3		46	-6	Stake reset
"			105															
30/6			135									30	27	27		73	-33	

Sample of a stake form partly completed. The sample figures were chosen so as many different situations as possible could be demonstrated.

w. eq.= water equivalent

If the snow depth is actually sounded (see description of stake readings in section (b), the mean value of the three soundings should be put in column 5. From knowledge of the snow density (obtained by pit studies at the stake or in the same part of the glacier) the water equivalent of the snow cover can be calculated and the figure placed in column 6. Columns 7 and 8 are used only when soundings were not taken and the snow depth calculated from the stake reading alone. This might occur when time is very short or when a snow sounding stick is not available so that only stake readings can be made. The use of columns 7 and 8 should therefore be restricted as far as possible.

f) Column 9 is used for incidental notations, for example for a check of totals of figures shown in columns 3 and 5. This sum should be a constant but if great variations occur it is necessary to investigate more closely conditions at the stake to determine whether the depth to the summer surface has been miscalculated or the stake has sunk.

g) Columns 10-14 are used for calculations and should not contain any observed figures. The thickness of superimposed ice found by variations in stake length above the ice surface should be put in column 10 and its water equivalent placed in column 11 (assume a density of 0.8). Superimposed ice is regarded as accumulation, and this figure should be marked as positive.

The variation in water equivalent of the snow pack between two readings (compare column 6 or in extreme cases column 8) should be placed in column 12. Strictly, this will normally be a negative figure as snow disappears during the melting season but any additional snowfall in the summer should be considered positive.

The actual melting of glacier ice is recorded in column 13. This figure will always be negative. The difference in stake reading between the last two observation occasions should be noted, and the water equivalent calculated and placed in column 14 (assuming a density of 0.9).

h) Column 15 shows the total ablation between the previous two readings. The figure in this column will be the algebraic sum of figures shown in columns 11, 12 and 14. For practical reasons however, it can be shown without any prefix.

i) The cumulative value of figures in column 15 should be noted in column 17. If, however, it appears that accumulation has occurred (generally summer snow fall) between the two readings, column 16 will be used.

Column 18 shows the present situation at the stake, starting with the amount of accumulation as observed in the spring (being a positive value). During the melt season this value will diminish according to figures shown in column 17. At the end of the season the figures in column 18 might be very small or even negative (on the lower part of the glacier)if figures in column 17 exceed the original accumulation (i.e. all winter snow cover and some of the ice has melted). At the end of the season there will always be negative figures in column 18 where the glacier ice proper is exposed. At the equilibrium line, however, the final figure will be zero, indicating zero net accumulation and zero net ablation.

4. Pit studies at the end of ablation season

The total ablation must be determined at the end of the ablation season. On the glacier tongue this is easily determined from stakes where the entire winter accumulation has disappeared and glacier ice exposed. In the upper part of a glacier, normally, only a 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 if the boundary between the winter's snow cover and previous year's firn has been obliterated or obscured during the summer. However, recognition of the summer surface can probably be made in pits, and this work 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 on accumulation measurements.

PLOTTING AND CONTOURING

Most of the data from glaciological mass balance studies are processed graphically and some of the basic methods should be mentioned briefly in this manual. It is desirable that most of the preliminary data processing is done in the field, in order to obtain the final results as quickly as possible, so they can be readily published.

1. General

All accumulation and ablation measurements as well as some meteorological results (see below) 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 must therefore be supplied before the field work starts.

For the accumulation map the positions of the main stakes should be marked together with all sounding profiles showing the location of all snow depth soundings, which are given in actual snow depths and their water equivalents. Isolines should then be sketched to divide the glacier into areas of selected 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 must be selected for each particular glacier as it might be necessary to decrease or increase the intervals if the accumulation is unusually small or large. An example of a

2. Air temperature measurements

The thermohygrograph should be placed in the Stevenson screen immediately after the crew's arrival at the base camp. Charts are normally changed each Monday morning when the clock is wound and the pen filled with recording ink. The thermohygrograph registration is checked every morning and evening by simultaneous observation of the pen and the standard mercury thermometer placed in the screen. These two figures are noted on a form. Furthermore, a check of the clock is made by making a "time mark" every morning. Discrepancies between the time mark and the correct time are used when the chart is processed (see below). The calibration screw on the instrument could be used to adjust the instrument to as correct a temperature as possible at the beginning of the season but the adjusting screw should then not be touched during the season.

3. Cloud cover

To estimate the amount of incoming and outgoing radiation it is valuable to know the total amount of cloud cover (expressed in tenths). The daily mean cloud cover should be estimated for each day and if the cloud cover changes considerably during the day this should be mentioned on the form, and also whether the clouds are low, medium or high altitude. It is, however, not expected that the observer should have a complete knowledge of different kinds of clouds, but in case he has such knowledge a sufficient space is available for notation on the meteorological forms.

4. Precipitation

Precipitation is collected in a simple rain gauge (type Pluvius)* placed on the ground anchored to a rock. The rain gauge is reliable for observation of liquid precipitation and probably for wet snow as well. Snow must be melted before the measurements are made. Dry snow will generally be moved by wind and readings will not be reliable. Most of the precipitation, however, will probably be in the form

*Manufactured by Nyströms Bläckkärls-fabrik, Torshälla, Sweden, for less than $2.00 each.

of rain so it is anticipated that the observed values will be reliable. One single rain gauge may not give representative results so a number of rain gauges must be placed in the catchment area and observations of the collected rain made by visits at suitable intervals. Daily precipitation observations will normally be made only at the camp or in its vicinity, but precipitation for several days might be collected in more distant gauges.* It is advisable, however, to visit all rain gauges as regularly as possible to facilitate calculations connected with comparisons between the run-off, ablation, and precipitation. Ideally, all rain gauges (and all stakes on the glacier) should be read at 5 day intervals. (If heavy precipitation has occurred, the rain gauge might overflow and intermediate readings are necessary). The total amount of rain water must be calculated for the whole catchment area by plotting all single gauge observations on a map. Assuming each gauge is representing a certain area, the total amount of water can be found graphically. The result is to be listed.

5. Wind direction and speed

Observation of wind direction should be made every morning and evening, most easily in connection with the temperature readings in the screen. The direction from which the wind travels is noted as well as the estimated speed in m/sec. To facilitate this estimation a feather or a small piece of paper could be allowed to travel a known distance in the wind and its speed calculated roughly.

6. Field processing of meteorological data

Meteorological observations must be summarized for each week, and the field crew will process all temperature charts and calculate daily mean temperatures as well as number of positive degree days. It is also desirable that the total amount of rain water is calculated as indicated in previous section, but the temperature summaries are the most important and must have priority.

*During cold periods it is necessary to use glycerin or antifreeze to prevent freezing of collected rainwater in the gauge. A known amount (corresponding to a few mm of rain) should be placed in the gauge, and corrections in readings made accordingly.

As soon as a chart is completed and taken off the thermohydrograph the air temperature for each hour is read from the chart (corrected for errors in the clock mechanism and for temperature discrepancies, as found by the two daily comparisons with the mercury thermometer). A special form has been developed for this work. When the form is completed the daily mean temperatures should be calculated and the chart attached to the form and filed. At the end of the season both the form and the chart must be returned to Ottawa for further processing.

The number of positive degree days is calculated as follows: All the figures for positive temperatures is noted for each hour and totalled (negative temperatures omitted); the sum divided by 24 to give the number of "positive degree days" for that day. Such calculations must be made for each day throughout the summer. The resulting figure will coincide with the daily mean temperature if the air temperatures are above $0^{\circ}C$.

WATER DISCHARGE MEASUREMENTS

1. General

Water discharge and suspended load must be measured for the melt water stream at all glaciers in order to substantiate ablation calculations for each glacier. The discharge will mainly be the sum of ablation and summer rainfall. The silt content measurements can be used to estimate the amount of material eroded beneath the glaciers for different conditions. See further next chapter.

Discharge calculations are based upon water level readings on a vertical gauge or data from an automatic water level recorder. The relation between the level of water at a site and actual discharge (expressed in m^3/sec) must be determined by numerous direct measurements of the river flow for different gauge readings to obtain a graph of levels vs. discharge, the rating curve, for each measuring site.

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 highly turbulent. Turbulent streams can be measured using colourimetric methods but this is not recommended if the silt content is high. It is preferable to use a method which is independent of the silt content in the water, such as the "salt method". In this method (or in a similar method using soluble radioactive compounds), an agent is poured in the river in one point and at another point downstream the dilution will be a measure of the water discharge.

All direct discharge measurements are difficult to perform without training and specialized equipment. Therefore the methods will not be described in detail in this manual. For a closer description, see Østrem 1964.

As soon as 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 sinks 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.

2. Stream 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 on it. The gauge should be placed at a location in the river where the water is as tranquil as possible. A pool in bedrock may be the best site to erect a gauge and the gauge must be located so that both a small discharge and a very large discharge can be measured directly. In some streams, however, it may be necessary to use one gauge for very high levels and another gauge

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

4. 24 hour periods

To obtain information about the normal diurnal variations in water level and to construct a curve showing these variations it is necessary to obtain readings throughout a 24 hour period and assume that they are "normal". The curve can then be used as a standard to obtain daily variations estimated from three or four daily readings. The crew must therefore decide when "normal" conditions exist and select a period of 24 (or 36) hours and record the water level every hour and take water samples (see below). At least two or three periods must be selected during the summer. Ideally, the period should include times of low water discharge and high water discharge.

Furthermore, when it is obvious that an extremely high water discharge is expected it is necessary to make additional periods of similar measurements. They might be longer or shorter than 24 hours depending upon the discharge pattern. Any series of observations should always be combined with silt sampling for the amount of silt will vary according to the type of discharge. Under extreme conditions the readings and the water samples may be taken at shorter interval and if the river tends to rise to an extraordinary peak, all efforts must be concentrated on taking frequent readings and water samples. Periods of rising water level are more important for silt sampling than periods of constant or falling level.

5. Preliminary processing of results

To obtain discharge figures, all gauge readings must be plotted initially on millimeter graph paper using the vertical axis for gauge readings. When time is plotted on the horizontal axis, one day might be represented by 12 centimetres, so that 2 (or 4) days can be portrayed on one paper sheet. For periods of small variations in discharge shorter units could be used on the x-axis.

Using the "standard" variations obtained from a 24 hour series, a curve can be estimated to show the daily variations in water level. It is advisable to construct this curve as soon as possible and the results should be plotted at least every week. Forms for notations of water level etc. have been developed and the daily notations must be transferred to these forms. All data connected with river observations must be kept in a separate binder.

6. Calculation of water volume

Calculations of the water volume discharged in a given time interval can only be calculated if a rating curve has been established. From the estimated curves that show water levels at the gauge it will be possible to calculate the water discharge for any given time. For rapid variations within short time intervals (compare charts from a thermograph) it may be necessary to calculate the discharged water volume for each hour or even shorter intervals. Experience has shown that a 6 hour period will generally be sufficient.

The volume of water discharge should be calculated for the following 6 hour periods: 0000-0600, 0600-1200, 1200-1800 and 1800-2400 (midnight). The greatest discharge will probably occur in the last two periods and special attention should therefore be given to possible variations within them (see above concerning number of gauge readings). Results of these calculations must be recorded on summary forms (sample forms are included in the appendix). It is anticipated that rating curves will be established during the latter part of the summer 1966 for most glacier streams and it must be expected that calculations of water volume for periods earlier in the summer must be done towards the end of the season.

MEASUREMENTS OF SUSPENDED MATERIAL

1. General

Glacier streams carry a great load of silt, sand, gravel and boulders that result from glacier erosion. To obtain information about this erosion it is necessary to take samples of the river water, analyze it for its content of suspended material and calculate the total transport The bottom transport of fragments including boulders is difficult to observe and until methods for their determination have been developed it will be necessary to estimate the size of this transport. The amount of fine material suspended in water is easier to determine and the total amount transported daily can be calculated from known water discharge and anslysis of silt samples. The results of these investigations will give not only valuable information for a study of glacier erosion under different conditions but also indicate possible rates of sedimentation that can be expected in reservoirs and lakes along rivers that drain from glaciers.

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 that originate from the glacier. Sampling site should be selected anywhere the water is turbulent so that the sample can be regarded as representative for the total water volume discharge past the site at the time of sampling. This means generally that the sample should be taken just below a small waterfall or in a section of extremely turbulent water.

3. Sampling method

Numerous water samplers have been designed but most of them are developed for use in streams of laminar flow and are not suitable for highly turbulent streams. Experience has shown that a simple method - a bottle is lowered into the turbulent water and raised immediately after filling - is probably as good as using any complicated water sampler. It is important that the bottle is raised immediately after it has been filled with the river water, otherwise additional silt will enter the bottle (Hjulström, 1935, p. 386). The size of each sample should be 1 litre, but most bottles readily available are not calibrated to this volume when completely filled so it is necessary to measure the exact volume of the sample bottle. The volume of the water sample must be noted on the form where all silt sample data are collected.

4. Filtering

The bottle and contents must be carried back to camp or to a suitable place where no additional material can blow into the sample or filtrating equipment. A tent without a floor could be erected near the river for this purpose. A filtrating stand can be made by drilling holes in wooden planks. All water in the bottle should be poured into the funnel and passed through a filter paper that collects all suspended material. The filtered water (leaving the funnels after passing the filter paper) is normally not collected unless it is not clear. Then it has to be refiltered through a denser filter paper.

For all normal water samples a quick filtrating paper (Munktell No. 00) must be used. If very fine fractions are present a denser paper (No. 0A) is necessary, but as this paper is slower filtering it should be used only in exceptional cases.

The bottle generally contains more water than can be placed directly in the funnel. It is therefore necessary to pour water in the funnel in small amounts with a result that for a sample the complete process might take one half to one hour depending upon the amount of silt. A sample with much silt may take even longer due to sealing effects of the silt on the upper surface of the paper.

After filtering (ensure that all silt which might have settled in the bottle is poured out) the paper is left to dry in air and it is then wrapped and placed in a small plastic bag within an envelope marked with the sample number and other pertinent data.

Only one filter paper must be placed in each envelope but all envelopes from one day's sampling could be collected and transferred to a larger plastic bag.

At the end of the season all silt samples must be packed together with the list giving all details (sample number, water volume, date, etc., see special form in appendix) and taken to Ottawa for laboratory analysis. The samples must not be sent by mail or freight but brought personally by a member of the crew as his hand luggage.

5. Numbering of samples

Samples should be numbered consecutively during the whole season. A record must be kept showing when the different samples were taken (time and date), the size of the sample (compare previous section) as well as information about unusual conditions at the time of sampling. Samples taken during the 24 hour periods could be regarded as a distinct set to separate them from ordinary daily samples, but to avoid any confusion it is strongly recommended that all samples be kept in strict consecutive order.

SURVEYING - HINTS FOR FIELD CREW

1. General

Glacier maps are being constructed for all the investigated areas as a base for plotting results, indicating stake locations and other data. For initial studies the provisional maps were enlargements of existing small scale topographic maps, but it is planned to replace them with more accurate maps constructed from air photographs. Where air photographs have not been taken it will be necessary to survey the glacier by conventional methods, but this will not be a task of a field party based at the glacier. However, it is desirable for crew members to become familiar with the area to help in surveys carried out by a visiting party. Vantage points overlooking large parts of a glacier should be marked in a manner so that they can be identified on vertical photographs. Furthermore, if photography is expected during the same summer an additional number of key positions on the glacier should be marked (see below).

2. Selecting fixed points

Points on bedrock or on stable ground overlooking large parts of a glacier and a number of other points should be selected. Access to these fixed points should not be too difficult but in special cases it will be necessary to locate a fixed point on a mountain peak. If crew members visit such a point they should build a cairn on the first possible occasion and mark it with a flag mounted on a vertical pole (aluminum poles for this purpose will be available at the camp). If the mountain peak is very steep and undoubtedly the highest point within an area of several hundred metres' radius, it is not necessary to mark this point further with cairn or flag. For all other points, however, it is necessary to mark them so that they will be clearly visible on air photographs (see below) and can be easily identified and used for ground triangulation.

3. Marking fixed points

Pieces of white cloth one yard in width and at least 5 yards in length should be placed in an L with the inner corner of the L at the selected point. White paint is better than cloth, and it could 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 quarts of white paint are required to make one such mark.* In places where space does not allow an L to be marked on the ground another pattern might be used such as a triangle or a square. Note however, that in the air photographs a painted mark can easily be mistaken for a natural spot so any shape

*When the ground is painted for aerial photography it is advisable also to paint the top of the cairn so that it can be more easily recognized.

selected should not be natural. (The L shaped mark described above is probably the least natural shape).

4. Marking points on the glacier

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

a) On the 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 therefore it is recommended that large pieces of cloth be attached to each main stake. If the glacier is very dirty a white flag should 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.

To facilitate recognition of stakes their locations might be indicated by two rows of boulders placed at the glacier ice radiating in straight lines out from the stake. The directions should be chosen so that they do not coincide with the natural ice pattern (cracks, crevasses, bluebands, surface streams, etc.).

Due to surface melt it will be difficult to keep all the rocks in the right position for a long time and adjustments must be made frequently. It is therefore advisable not to try and mark too many stakes in the ablation area. It is better to mark one or two and keep the markings in good shape throughout the summer.

b) In the accumulation area:

Locations of stakes in the firn area are marked by powdered dye or lampblack distributed on the snow surface in a circle around the stake. A circle is established by means of a 10-metre rope attached to the stake. The dye powder is sprinkled in the circle making a very thin layer approximately 1 m broad. Two to three pounds of lampblack or about 5 pounds of powdered dye will 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.

During the summer dye will increase the snow melt but it will still be clearly visible from above except when it is covered by new snow. The rings must therefore be inspected and reinforced during the summer and kept visible until it is certain that air photographs have been taken. No dye should be sprinkled near the stake as this will disturb the normal rate of ablation at the stake.

5. Supplementary ground control

As a horizontal check for the scale in the map construction at least two distances between outstanding points should be measured with a tape. The distance 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 points and the results of the measured distance should be recorded.

ERECTING AN A-FRAME HUT

1. General

At glaciers where a series of long-term observations is anticipated, small semi-permanent buildings will be erected. These buildings will be of two types:

1) houses for accommodation

2) garages, or buildings for storage etc.

Experience has shown that this simple A-frame hut can be erected by 2 men in less than 2 days. The total weight of all necessary materials amounts to approximately 2,500 pounds.

DUTIES AT THE END OF THE SUMMER FIELD SEASON

1. General

Many different glaciers will be investigated throughout the coming years and it is obvious that a large volume of data will be accumulated in these investigations. Some of the data has to be processed in the field so that results of mass balance, meteorological data etc. can be published without delay.

The staff at the Glaciology Section in Ottawa will handle many lists of data and to avoid confusion it is essential that all sheets of paper are marked with the name of the glacier and the year. In addition each individual sheet must have some sort of title and the work initialed in the bottom right hand corner.

e.g. Place Glacier 1966
Snow Pit Measurements

The senior crew member will be held responsible for marking sheets with the full title.

At the end of the field season he will:

a) Leave at the glacier (in the hut) a copy of a map showing all stake locations together with a list of the last readings (as made before leaving the glacier)

b) Check that all data are adequatel, tabulated and summary forms are completed.

c) Ensure that all records reach Ottawa safely (not sent by mail or included with equipment that is sent as luggage).

2. List of data sheets and summaries

The following records and summaries must 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 Louise
   June 7 Arrive glacier, ferry supplies, helicopter 2 hours. (Flight report to be enclosed).
   June 8 Read all stakes, on lower part of glacier, sorted supplies.

2. Summaries of daily meteorological observations including:

   a) Daily mean temp. (centigrade)
   b) Positive degree days (centigrade)
   c) Rainfall (in mm's)
   d) Mean cloudiness (in 10ths)

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

3. A table to show dates when each stake has been read throughout the whole season. (Use standard form).

4. Stake forms completed in all respects. The cumulative ablation must be clearly indicated for each single stake.

5. Table of river discharge - to show daily discharge in sub-totals. Total water volume to be calculated from 0000 to 0600 hrs; 0600 to 1200, 1200 to 1800, and 1800 to 2400 hrs; as well as each day's total water discharge.

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

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

8. A list of all equipment and supplies returned to Ottawa (standard list).

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

10. Statement of disbursements (on printed forms) together with all receipts arranged chronologically, neatly glued or stapled on 8 1/2" x 11" size sheets of blank paper.

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 dug down as all other garbage. Remaining food supply should be checked for items that could deteriorate during the fall and winter, and such items removed.

A list of supplies and a sketch showing location of gas barrels etc. must be left in the house. Stakes, stake extensions (2 m pieces), extension tubes (steel) and masonite plates must be placed so that they will be readily accessible during the winter.

All batteries that have been used (or partly used) must be thrown away. Only unused batteries should be left, and must, always be placed in a plastic bag - never left in radios, flashlights or in other equipment ! Such batteries should be marked "New 1966 - unused".

The station will probably be visited several times during the winter, and as an emergency measure a stove and limited supplies of fuel and food must be left in the garage. The garage will normally not be locked.

A shovel must be placed on the outside wall above the door on all houses, and fuel for lightning, cooking and for the ski-doo be left in handy containers inside.

APPENDIX

a) Standard Forms

The following sample collection consists of standard forms for:

Winter stake readings and stake extensions
Snow pit measurements
Representative core drill measurements
Stake observations
Daily meteorological observations
Daily temperature corrections and daily means
Summary of daily meteorological observations
Stream gauge recordings
Stream discharge calculations
Silt sample data
Altimeter readings and corrections
Air temperature correction tables for altimeter.

b) Short description of ashing procedure

This ashing procedure has been tried out in the Geographical Institutions at the Universities of Uppsala and Stockholm, Sweden. During the last several years many thousands of silt samples from glacier streams etc., have been processed according to the points mentioned below. Comparisons have also been done with other methods such as filtrating and drying the material in the field by means of membrane filter and suction pumps. As the material in that particular case was obviously free from organic matter the comparison showed good agreement with the ashing procedure.

The water samples should be taken either with a specially designed water sampler (in case of laminary streaming water) or with a simple bottle of known volume (in cases of extremely turbulent water). If river is low, a larger sample should be taken. The following procedure should then be followed.

1. 1 litre (or another known volume) of the river water should be filtrated by means of a quick filtrating funnel and filtrating paper Munktell No. 00. In cases when very fine particles are expected the denser paper, Munktell No. OA should be used.

2. The filtrating paper should be removed from the funnel and partly dried in the air. Observe however that no dust adds to the content.

3. The filtrating paper should be folded and put in a plastic bag and then placed into an envelope for transportation. The number of the sample as well as the particulars concerning sampling time etc., should be noted on the outside of the envelope.

4. The laboratory work starts with weighing a number of empty porcelaine crucibles together with their lids. The filtrating papers should be placed one in each cup.

5. By means of a Bunsen burner the crucible should be heated carefully so that the paper starts burning. To facilitate the smoke to escape the lid should be placed so that it only partly covers the crucible.

6. After this procesure, i.e. when the smoke has nearly completely ceased to form, the crucibles should be placed in the ashing oven, the lids covering the crucibles completely. The optimal temperature of the oven is approximately 550°C.

7. After 2 hours the crucibles should be transferred to a drying oven and kept at 100°C for half an hour.

8. The crucibles should then be placed in a dessicator for half an hour and from this they are moved one by one onto the scale and weighed as quickly as possible as the moisture in the air will immediately change the weight of the dry ash. As a test for possible errors originating from humidity some of the crucibles could be moved back to the drying oven and the procedure should start again according to point 7. An error no larger than 0.2 mg could be accepted. It is important that each empty crucible should be weighed each time it is used, as the weight varies almost continuously due to humidity changes.

9. The ash should then be removed from the crucible which is then weighed empty in order to check that it has not changed its original weight. (see point 4). The removal of the ash can easily be done with a dry brush.

   Note: It is advisable always to "burn" all new crucibles before they are used in this analysis as they will normally change their original weight.

   If the oven temperature rises above the mentioned temperature carbonates will easily start to decompose and a too small silt content might be obtained by this analysis. On the other hand if the temperature is too low some organic components will not be removed from the samples. However, in the case of samples taken close to a glacier there should not be large risks of having too much organic material in the sample.

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SOME STATISTICAL CONSIDERATIONS

by

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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 kilometers, whereas a stake on a valley glacier might be representative for a few square meters. 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 problem of determining the density of his 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 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

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

Winter Stake Readings and Stake Extensions

Glacier ....

Day ....
Month ....
Year ....

Stake No.	Measured length above snow surface	Stake extended to (cm above snow surface	Extension tube marked with no.	Sounded snow depth at stake (cm)	Remarks (flag etc.)

Pit Location:
Cross Sectional area
of snow sampler:
(cm^2)

SNOW PIT MEASUREMENTS
on glacier ....

Date .... 19....
Elev .... m

1 Depth (cm)	2 Length of Sample (cm)	3 Weight of Sample (grams)	4 Water eq. Weight/area (grams/cm^2)	5 Cumulative Water Equivalent (g/cm^2)	Density (grams/cm^3)	Remarks

Mean Density:

REPRESENTATIVE
CORE DRILL MEASUREMENTS

Glacier:
Location:
Cross sectional area of core (cm^2)

Date .... 19....
Elev ....m
Type of Coring drill ....

1	2	3	4	5	6	7	8	9	10
Depth (cm)	Penetration, calculated (cm)	Length of sample (cm)	Weight of sample (grams)	Volume of sample (cm^3)	Sample density (g/cm^3)	Length repr. by sample	Water equivalent	Cumulative water equivalent	Remarks

Mean density: (g/cm^3)

Elev. of stake:
Total length
of stake (m):

STAKE OBSERVATIONS

on glacier ....

Al.:)
Steel:)
Wire:) Stake No...............
Bamboo:)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Date	Time diff.	Top to snow	Top to ice	Snow Depth					Difference					Abl.	Cumulative w. eq.		Net w.eq. (±)	Remarks
				Sounded		Computed			Super imp. ice		Snow	Ice			Acc.	Abl.		
		cm	cm	cm snow	cm w.eq.	cm snow	cm w.eq.		cm	cm w.eq.	cm w.eq.	cm	cm w.eq.		cm	cm	cm	

w. eq.= water equivalent

TEMPERATURE CORRECTION CHART

....................GLACIER 196....

....................Station .... Elevation Time Zone GMT Central Mountain Pacific

Date	Temp. (T)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Sum	Tm	Rem
	T chart																											
	T merc.																											
	T corr. ±																											
	T calc.																											
	T chart																											
	T merc.																											
	T corr. ±																											
	T calc.																											
	T chart																											
	T merc.																											
	T corr. ±																											
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	T calc.																											
	T chart																											
	T merc.																											
	T corr. ±																											
	T calc.																											
	T chart																											
	T merc.																											
	T corr. ±																											
	T calc.																											
Total																												

..................GLACIER 19....... TIME ZONE...............

DAILY METEOROLOGICAL OBSERVATIONS

Location of screen ....

Date		Hour	T°C		Ppt in m.m.	Wind		Weather	Visibility in km.	Cloud low		Cloud med.		Cloud high		Cloud total	Remarks and time marks
day	date		Hg	graph		m/s	dir'n.			tenths	type	tenths	type	tenths	type	tenths	

............................GLACIER 19..... MONTH..........

SUMMARY OF DAILY METEOROLOGICAL OBSERVATIONS

Location of met. screen........................ Elevation............

Day	Date	Temp °C	Sub Totals	Degree Days	Sub Totals	Cloudiness in 10's	Rainfall m.m.	Sub Totals
	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							
	29							
	30							
	31							

SIGNATURE...............................

..........................GLACIER 19..... TIME ZONE............

STREAM GAUGE RECORDINGS

Gauge type:...................... Location:...................... Drainage Area:...............

Day	Date	Hour	Water Level	Discharge cu. m/sec	Day	Date	Hour	Water Level	Discharge cu. m/sec.	Day	Date	Hour	Water Level	Discharge cu. m/sec.

..............................GLACIER 19.... MONTH..................

STREAM DISCHARGE CALCULATIONS

Day	Date	Discharge in $m^3 \times 10^3$				Daily Total
		0006-0600	0600-1200	1200-1800	1800-2400	

SIGNATURE.............................

..........................GLACIER 19...... MONTH................

SILT SAMPLE DATA

Day	Date	Hour	Sample No.	Volume	Location etc.		

SIGNATURE..............................

ALTIMETER READINGS AND CORRECTIONS

GLACIER -　　　　　　　　YEAR - 19　　　DATE -　　　　　OBSERVER -

	OBSERVED									
Station	Time	Altimeter Reading (ft)	Tempera-ture (°C)	Altimeter Reading Corrected from Graph (col 2 vs col 3)	Air Temp. in °F (Converted from col. 4)	Difference between Corrected Readings (ft) (See col 5)	Average Air Temperature (°F)	Altitude Corr-ection for Air Temp. (ft)	Actual Difference in Alt. (ft) (col 7 + col 9)	Actual Elevation (m)
1	2	3	4	5	6	7	8	9	10	11

Average Air Temperature Correction in Feet

For temperatures above 50° F. the values are to be added
For temperatures below 50° F. the values are to be subtracted

Average air temp. °F.		Difference of readings in feet: 0	20	40	60	80	100	120	140	160	180	200	220	240	260	Average air temp. °F.	
	+50°	0	0	0	0	0	0	0	0	0	0	0	0	0	0	+50°	
+48°	+52°	0	0.1	0.2	0.2	0.3	0.4	0.5	0.5	0.6	0.7	0.8	0.9	0.9	1.0	+52°	+48°
+46°	+54°	0	0.2	0.3	0.5	0.6	0.8	0.9	1.1	1.3	1.4	1.6	1.7	1.9	2.0	+54°	+46°
+44°	+56°	0	0.2	0.5	0.7	0.9	1.2	1.4	1.6	1.9	2.1	2.4	2.6	2.8	3.1	+56°	+44°
+42°	+58°	0	0.3	0.6	0.9	1.3	1.6	1.9	2.2	2.5	2.8	3.1	3.5	3.8	4.1	+58°	+42°
+40°	+60°	0	0.4	0.8	1.2	1.6	2.0	2.4	2.7	3.1	3.5	3.9	4.3	4.7	5.1	+60°	+40°
+38°	+62°	0	0.5	0.9	1.4	1.9	2.4	2.8	3.3	3.8	4.2	4.7	5.2	5.7	6.1	+62°	+38°
+36°	+64°	0	0.5	1.1	1.6	2.2	2.7	3.3	3.8	4.4	4.9	5.5	6.0	6.6	7.1	+64°	+36°
+34°	+66°	0	0.6	1.3	1.9	2.5	3.1	3.8	4.4	5.0	5.7	6.3	6.9	7.5	8.2	+66°	+34°
+32°	+68°	0	0.7	1.4	2.1	2.8	3.5	4.2	4.9	5.7	6.4	7.1	7.8	8.5	9.2	+68°	+32°
+30°	+70°	0	0.8	1.6	2.4	3.1	3.9	4.7	5.5	6.3	7.1	7.9	8.6	9.4	10.2	+70°	+30°
+28°	+72°	0	0.9	1.7	2.6	3.5	4.3	5.2	6.0	6.9	7.8	8.6	9.5	10.4	11.2	+72°	+28°
+26°	+74°	0	0.9	1.9	2.8	3.8	4.7	5.7	6.6	7.5	8.5	9.4	10.4	11.3	12.3	+74°	+26°
+24°	+76°	0	1.0	2.0	3.1	4.1	5.1	6.1	7.1	8.2	9.2	10.2	11.2	12.2	13.3	+76°	+24°
+22°	+78°	0	1.1	2.2	3.3	4.4	5.5	6.6	7.7	8.8	9.9	11.0	12.1	13.2	14.3	+78°	+22°
+20°	+80°	0	1.2	2.4	3.5	4.7	5.9	7.1	8.2	9.4	10.6	11.8	13.0	14.1	15.3	+80°	+20°
+18°	+82°	0	1.3	2.5	3.8	5.0	6.3	7.5	8.8	10.0	11.3	12.6	13.8	15.1	16.3	+82°	+18°
+16°	+84°	0	1.3	2.7	4.0	5.3	6.7	8.0	9.4	10.7	12.0	13.4	14.7	16.0	17.4	+84°	+16°
+14°	+86°	0	1.4	2.8	4.2	5.7	7.1	8.5	9.9	11.3	12.7	14.1	15.6	17.0	18.4	+86°	+14°
+12°	+88°	0	1.5	3.0	4.5	6.0	7.5	9.0	10.4	11.9	13.4	14.9	16.4	17.9	19.4	+88°	+12°
+10°	+ 90°	0	1.6	3.1	4.7	6.3	7.9	9.4	11.0	12.6	14.1	15.7	17.3	18.9	20.4	+ 90°	+10°
+ 8°	+ 92°	0	1.6	3.3	4.9	6.6	8.2	9.9	11.5	13.2	14.8	16.5	18.1	19.8	21.4	+ 92°	+ 8°
+ 6°	+ 94°	0	1.7	3.5	5.2	6.9	8.6	10.4	12.1	13.8	15.6	17.3	19.0	20.7	22.5	+ 94°	+ 6°
+ 4°	+ 96°	0	1.8	3.6	5.4	7.2	9.0	10.8	12.6	14.5	16.3	18.1	19.9	21.7	23.5	+ 96°	+ 4°
+ 2°	+ 98°	0	1.9	3.8	5.7	7.5	9.4	11.3	13.2	15.1	17.0	18.9	20.7	22.6	24.5	+ 98°	+ 2°
0°	+100°	0	2.0	3.9	5.9	7.9	9.8	11.8	13.7	15.7	17.7	19.6	21.6	23.6	25.5	+100°	0°
— 2°	+102°	0	2.0	4.1	6.1	8.2	10.2	12.3	14.3	16.3	18.4	20.4	22.5	24.5	26.6	+102°	— 2°
— 4°	+104°	0	2.1	4.2	6.4	8.5	10.6	12.7	14.8	17.0	19.1	21.2	23.3	25.5	27.6	+104°	— 4°
— 6°	+106°	0	2.2	4.4	6.6	8.8	11.0	13.2	15.4	17.6	19.8	22.0	24.2	26.4	28.6	+106°	— 6°
— 8°	+108°	0	2.3	4.6	6.8	9.1	11.4	13.7	15.9	18.2	20.5	22.8	25.1	27.3	29.6	+108°	— 8°
—10°	+110°	0	2.4	4.7	7.1	9.4	11.8	14.1	16.5	18.9	21.2	23.6	25.9	28.3	30.6	+110°	—10°
—12°	+112°	0	2.4	4.9	7.3	9.7	12.2	14.6	17.0	19.5	21.9	21.4	26.8	29.2	31.7	+112°	—12°
—14°	+114°	0	2.5	5.0	7.5	10.1	12.6	15.1	17.6	20.1	22.6	25.1	27.7	30.2	32.7	+114°	—14°
—16°	+116°	0	2.6	5.2	7.8	10.4	13.0	15.6	18.1	20.7	23.3	25.9	28.5	31.1	33.7	+116°	—16°
—18°	+118°	0	2.7	5.3	8.0	10.7	13.4	16.0	18.7	21.4	24.0	26.7	29.4	32.1	34.7	+118°	—18°
—20°	+120°	0	2.7	5.5	8.2	11.0	13.7	16.5	19.2	22.0	24.7	27.5	30.2	33.0	35.7	+120°	—20°
—22°	+122°	0	2.8	5.7	8.5	11.3	14.1	17.0	19.8	22.6	25.4	28.3	31.1	33.9	36.8	+122°	—22°
—24°	+124°	0	2.9	5.8	8.7	11.6	14.5	17.4	20.3	23.3	26.2	29.1	32.0	34.9	37.8	+124°	—24°
—26°	+126°	0	3.0	6.0	9.0	11.9	14.9	17.9	20.9	23.9	26.9	29.9	32.8	35.8	38.8	+126°	—26°

Average Air Temperature Correction in Feet

For temperatures above 50° F. the values are to be added
For temperatures below 50° F. the values are to be subtracted

Average air temp. °F.		Difference of readings in feet: 280	300	320	340	360	380	400	420	440	460	480	500	Average air temp. °F.	
	+50°	0	0	0	0	0	0	0	0	0	0	0	0	+50°	
+48°	+52°	1.1	1.2	1.3	1.3	1.4	1.5	1.6	1.6	1.7	1.8	1.9	2.0	+52°	+48°
+46°	+54°	2.2	2.4	2.5	2.7	2.8	3.0	3.1	3.3	3.5	3.6	3.8	3.9	+54°	+46°
+44°	+56°	3.3	3.5	3.8	4.0	4.2	4.5	4.7	4.9	5.2	5.4	5.7	5.9	+56°	+44°
+42°	+58°	4.4	4.7	5.0	5.3	5.7	6.0	6.3	6.6	6.9	7.2	7.5	7.9	+58°	+42°
+40°	+60°	5.5	5.9	6.3	6.7	7.1	7.5	7.9	8.2	8.6	9.0	9.4	9.8	+60°	+40°
+38°	+62°	6.6	7.1	7.5	8.0	8.5	9.0	9.4	9.9	10.4	10.8	11.3	11.8	+62°	+38°
+36°	+64°	7.7	8.2	8.8	9.3	9.9	10.4	11.0	11.5	12.1	12.6	13.2	13.7	+64°	+36°
+34°	+66°	8.8	9.4	10.1	10.7	11.3	11.9	12.6	13.2	13.8	14.5	15.1	15.7	+66°	+34°
+32°	+68°	9.9	10.6	11.3	12.0	12.7	13.4	14.1	14.8	15.6	16.3	17.0	17.7	+68°	+32°
+30°	+70°	11.0	11.8	12.6	13.4	14.1	14.9	15.7	16.5	17.3	18.1	18.9	19.6	+70°	+30°
+28°	+72°	12.1	13.0	13.8	14.7	15.6	16.4	17.3	18.2	19.0	19.9	20.7	21.6	+72°	+28°
+26°	+74°	13.2	14.1	15.1	16.0	17.0	17.9	18.9	19.8	20.7	21.7	22.6	23.6	+74°	+26°
+24°	+76°	14.3	15.3	16.3	17.4	18.4	19.4	20.4	21.4	22.5	23.5	24.5	25.5	+76°	+24°
+22°	+78°	15.4	16.5	17.6	18.7	19.8	20.9	22.0	23.1	24.2	25.3	26.4	27.5	+78°	+22°
+20°	+80°	16.5	17.7	18.8	20.0	21.2	22.4	23.6	24.7	25.9	27.1	28.3	29.5	+80°	+20°

+18°	+82°	17.6	18.8	20.1	21.4	22.6	23.9	25.1	26.4	27.7	28.9	30.2	31.4	+82°	+18°
+16°	+84°	18.7	20.0	21.4	22.7	24.0	25.4	26.7	28.0	29.4	30.7	32.1	33.4	+84°	+16°
+14°	+86°	19.8	21.2	22.6	24.0	25.5	26.9	28.3	29.7	31.1	32.5	33.9	35.3	+86°	+14°
+12°	+88°	20.9	22.4	23.9	25.4	26.9	28.4	29.9	31.3	32.8	34.3	35.8	37.3	+88°	+12°
+10°	+ 90°	22.0	23.6	25.1	26.7	28.3	29.9	31.4	33.0	34.6	36.1	37.7	39.3	+ 90°	+10°
+ 8°	+ 92°	23.1	24.7	26.4	28.0	29.7	31.3	33.0	34.6	36.3	37.9	39.6	41.2	+ 92°	+ 8°
+ 6°	+ 94°	24.2	25.9	27.7	29.4	31.1	32.8	34.6	36.3	38.0	39.8	41.5	43.2	+ 94°	+ 6°
+ 4°	+ 96°	25.3	27.1	28.9	30.7	32.5	34.3	36.1	37.9	39.8	41.6	43.4	45.2	+ 96°	+ 4°
+ 2°	+ 98°	26.4	28.3	30.2	32.1	33.9	35.8	37.7	39.6	41.5	43.4	45.2	47.1	+ 98°	+ 2°
0°	+100°	27.5	29.5	31.4	33.4	35.4	37.3	39.3	41.2	43.2	45.2	47.1	49.1	+100°	0°
— 2°	+102°	28.6	30.6	32.7	34.7	36.8	38.8	40.9	42.9	44.9	47.0	49.0	51.1	+102°	— 2°
— 4°	+104°	29.7	31.8	33.9	36.1	38.2	40.3	42.4	44.5	46.7	48.8	50.9	53.0	+104°	— 4°
— 6°	+106°	30.8	33.0	35.2	37.4	39.6	41.8	44.0	46.2	48.4	50.6	52.8	55.0	+106°	— 6°
— 8°	+108°	31.9	34.2	36.5	38.7	41.0	43.3	45.6	47.8	50.1	52.4	54.7	57.0	+108°	— 8°
—10°	+110°	33.0	35.4	37.7	40.1	42.4	44.8	47.1	49.5	51.8	54.2	56.6	58.9	+110°	—10°
—12°	+112°	34.1	36.5	39.0	41.4	43.8	46.3	48.7	51.1	53.6	56.0	58.4	60.9	+112°	—12°
—14°	+114°	35.2	37.7	40.2	42.7	45.3	47.8	50.3	52.8	55.3	57.8	60.3	62.8	+114°	—14°
—16°	+116°	36.3	38.9	41.5	44.1	46.7	49.3	51.9	54.4	57.0	59.6	62.2	64.8	+116°	—16°
—18°	+118°	37.4	40.1	42.7	45.4	48.1	50.8	53.4	56.1	58.8	61.4	64.1	66.8	+118°	—18°
—20°	+120°	38.5	41.2	44.0	46.7	49.5	52.2	55.0	57.7	60.5	63.2	66.0	68.7	+120°	—20°
—22°	+122°	39.6	42.4	45.2	48.1	50.9	53.7	56.6	59.4	62.2	65.1	67.9	70.7	+122°	—22°
—24°	+124°	40.7	43.6	46.5	49.4	52.3	55.2	58.1	61.0	64.0	66.9	69.8	72.7	+124°	—24°
—26°	+126°	41.8	44.8	47.8	50.8	53.7	56.7	59.7	62.7	65.7	68.7	71.7	74.6	+126°	—26°

Average Air Temperature Correction in Feet

For temperatures above 50° F. the values are to be added
For temperatures below 50° F. the values are to be subtracted

Average air temp. °F.		500	520	540	560	580	600	620	640	660	680	700	720	740	760	Average air temp. °F.	
	+50°	0	0	0	0	0	0	0	0	0	0	0	0	0	0	+50°	
+48°	+52°	2.0	2.0	2.1	2.2	2.3	2.4	2.4	2.5	2.6	2.7	2.7	2.8	2.9	3.0	+52°	+48°
+46°	+54°	3.9	4.1	4.2	4.4	4.6	4.7	4.9	5.0	5.2	5.3	5.5	5.7	5.8	6.0	+54°	+46°
+44°	+56°	5.9	6.1	6.4	6.6	6.8	7.1	7.3	7.5	7.8	8.0	8.2	8.5	8.7	9.0	+56°	+44°
+42°	+58°	7.9	8.2	8.5	8.8	9.1	9.4	9.7	10.1	10.4	10.7	11.0	11.3	11.6	11.9	+58°	+42°
+40°	+60°	9.8	10.2	10.6	11.0	11.4	11.8	12.2	12.6	13.0	13.4	13.7	14.1	14.5	14.9	+60°	+40°
+38°	+62°	11.8	12.3	12.7	13.2	13.7	14.1	14.6	15.1	15.5	16.0	16.5	17.0	17.4	17.9	+62°	+38°
+36°	+64°	13.7	14.3	14.8	15.4	15.9	16.5	17.0	17.6	18.1	18.7	19.2	19.8	20.3	20.9	+64°	+36°
+34°	+66°	15.7	16.3	17.0	17.6	18.2	18.9	19.5	20.1	20.7	21.4	22.0	22.6	23.3	23.9	+66°	+34°
+32°	+68°	17.7	18.4	19.1	19.8	20.5	21.2	21.9	22.6	23.3	24.0	24.7	25.5	26.2	26.9	+68°	+32°
+30°	+70°	19.6	20.4	21.2	22.0	22.8	23.6	24.4	25.1	25.9	26.7	27.5	28.3	29.1	29.9	+70°	+30°
+28°	+72°	21.6	22.5	23.3	24.2	25.1	25.9	26.8	27.7	28.5	29.4	30.2	31.1	32.0	32.8	+72°	+28°
+26°	+74°	23.6	24.5	25.5	26.4	27.3	28.3	29.2	30.2	31.1	32.1	33.0	33.9	34.9	35.8	+74°	+26°
+24°	+76°	25.5	26.6	27.6	28.6	29.6	30.6	31.7	32.7	33.7	34.7	35.7	36.8	37.8	38.8	+76°	+24°
+22°	+78°	27.5	28.6	29.7	30.8	31.9	33.0	34.1	35.2	36.3	37.4	38.5	39.6	40.7	41.8	+78°	+22°
+20°	+80°	29.5	30.6	31.8	33.0	34.2	35.4	36.5	37.7	38.9	40.1	41.2	42.4	43.6	44.8	+80°	+20°

+18°	+82°	31.4	32.7	33.9	35.2	36.5	37.7	39.0	40.2	41.5	42.7	44.0	45.3	46.5	47.8	+82°	+18°
+16°	+84°	33.4	34.7	36.1	37.4	38.7	40.1	41.4	42.7	44.1	45.4	46.7	48.1	49.4	50.8	+84°	+16°
+14°	+86°	35.3	36.8	38.2	39.6	41.0	42.4	43.8	45.2	46.7	48.1	49.5	50.9	52.3	53.7	+86°	+14°
+12°	+88°	37.3	38.8	40.3	41.8	43.3	44.8	46.3	47.8	49.3	50.7	52.2	53.7	55.2	56.7	+88°	+12°
+10°	+ 90°	39.3	40.9	42.4	44.0	45.6	47.1	48.7	50.3	51.8	53.4	55.0	56.6	58.1	59.7	+ 90°	+10°
+ 8°	+ 92°	41.2	42.9	44.5	46.2	47.8	49.5	51.1	52.8	54.4	56.1	57.7	59.4	61.0	62.7	+ 92°	+ 8°
+ 6°	+ 94°	43.2	44.9	46.7	48.4	50.1	51.9	53.6	55.3	57.0	58.8	60.5	62.2	64.0	65.7	+ 94°	+ 6°
+ 4°	+ 96°	45.2	47.0	48.8	50.6	52.4	54.2	56.0	57.8	59.6	61.4	63.2	65.1	66.9	68.7	+ 96°	+ 4°
+ 2°	+ 98°	47.1	49.0	50.9	52.8	54.7	56.6	58.4	60.3	62.2	64.1	66.0	67.9	69.8	71.6	+ 98°	+ 2°
0°	+100°	49.1	51.1	53.0	55.0	57.0	58.9	60.9	62.8	64.8	66.8	68.7	70.7	72.7	74.6	+100°	0°
— 2°	+102°	51.1	53.1	55.1	57.2	59.2	61.3	63.3	65.4	67.4	69.4	71.5	73.5	75.6	77.6	+102°	— 2°
— 4°	+104°	53.0	55.2	57.3	59.4	61.5	63.6	65.8	67.9	70.0	72.1	74.2	76.4	78.5	80.6	+104°	— 4°
— 6°	+106°	55.0	57.2	59.4	61.6	63.8	66.0	68.2	70.4	72.6	74.8	77.0	79.2	81.4	83.6	+106°	— 6°
— 8°	+108°	57.0	59.2	61.5	63.8	66.1	68.3	70.6	72.9	75.2	77.5	79.7	82.0	84.3	86.6	+108°	— 8°
—10°	+110°	58.9	61.3	63.6	66.0	68.3	70.7	73.1	75.4	77.8	80.1	82.5	84.8	87.2	89.6	+110°	—10°
—12°	+112°	60.9	63.3	65.8	68.2	70.6	73.1	75.5	77.9	80.4	82.8	85.2	87.7	90.1	92.5	+112°	—12°
—14°	+114°	62.8	65.4	67.9	70.4	72.9	75.4	77.9	80.4	83.0	85.5	88.0	90.5	93.0	95.5	+114°	—14°
—16°	+116°	64.8	67.4	70.0	72.6	75.2	77.8	80.4	83.0	85.6	88.1	90.7	93.3	95.9	98.5	+116°	—16°
—18°	+118°	66.8	69.5	72.1	74.8	77.5	80.1	82.8	85.5	88.1	90.8	93.5	96.2	98.8	101.5	+118°	—18°
—20°	+120°	68.7	71.5	74.2	77.0	79.7	82.5	85.2	88.0	90.7	93.5	96.2	99.0	101.7	104.5	+120°	—20°
—22°	+122°	70.7	73.6	76.4	79.2	82.0	84.9	87.7	90.5	93.3	96.2	99.0	101.8	104.7	107.5	+122°	—22°
—24°	+124°	72.7	75.6	78.5	81.4	84.3	87.2	90.1	93.0	95.9	98.8	101.7	104.7	107.6	110.5	+124°	—24°
—26°	+126°	74.6	77.6	80.6	83.6	86.6	89.6	92.6	95.5	98.5	101.5	104.5	107.5	110.5	113.5	+126°	—26°

Average Air Temperature Correction in Feet

For temperatures above 50° F. the values are to be added
For temperatures below 50° F. the values are to be subtracted

Average air temp. °F.		Difference of readings in feet 780	800	820	840	860	880	900	920	940	960	980	1000	Average air temp. °F.	
	+50°	0	0	0	0	0	0	0	0	0	0	0	0	+50°	
+48°	+52°	3.1	3.1	3.2	3.3	3.4	3.5	3.5	3.6	3.7	3.8	3.8	3.9	+52°	+48°
+46°	+54°	6.1	6.3	6.4	6.6	6.8	6.9	7.1	7.2	7.4	7.5	7.7	7.9	+54°	+46°
+44°	+56°	9.2	9.4	9.7	9.9	10.1	10.4	10.6	10.8	11.1	11.3	11.5	11.8	+56°	+44°
+42°	+58°	12.3	12.6	12.9	13.2	13.5	13.8	14.1	14.5	14.8	15.1	15.4	15.7	+58°	+42°
+40°	+60°	15.3	15.7	16.1	16.5	16.9	17.3	17.7	18.1	18.5	18.8	19.2	19.6	+60°	+40°
+38°	+62°	18.4	18.8	19.3	19.8	20.3	20.7	21.2	21.7	22.1	22.6	23.1	23.6	+62°	+38°
+36°	+64°	21.4	22.0	22.5	23.1	23.6	24.2	24.7	25.3	25.8	26.4	26.9	27.5	+64°	+36°
+34°	+66°	24.5	25.1	25.8	26.4	27.0	27.6	28.3	28.9	29.5	30.2	30.8	31.4	+66°	+34°
+32°	+68°	27.6	28.3	29.0	29.7	30.4	31.1	31.8	32.5	33.2	33.9	34.6	35.4	+68°	+32°
+30°	+70°	30.6	31.4	32.2	33.0	33.8	34.6	35.4	36.1	36.9	37.7	38.5	39.3	+70°	+30°
+28°	+72°	33.7	34.6	35.4	36.3	37.2	38.0	38.9	39.8	40.6	41.5	42.3	43.2	+72°	+28°
+26°	+74°	36.8	37.7	38.7	39.6	40.5	41.5	42.4	43.4	44.3	45.3	46.2	47.1	+74°	+26°
+24°	+76°	39.8	40.9	41.9	42.9	43.9	44.9	46.0	47.0	48.0	49.0	50.0	51.1	+76°	+24°
+22°	+78°	42.9	44.0	45.1	46.2	47.3	48.4	49.5	50.6	51.7	52.8	53.9	55.0	+78°	+22°
+20°	+80°	46.0	47.1	48.3	49.5	50.7	51.8	53.0	54.2	55.4	56.6	57.7	58.9	+80°	+20°

+18°	+82°	49.0	50.3	51.5	52.8	54.1	55.3	56.6	57.8	59.1	60.3	61.6	62.8	+82°	+18°
+16°	+84°	52.1	53.4	54.8	56.1	57.4	58.8	60.1	61.4	62.8	64.1	65.4	66.8	+84°	+16°
+14°	+86°	55.1	56.6	58.0	59.4	60.8	62.2	63.6	65.0	66.5	67.9	69.3	70.7	+86°	+14°
+12°	+88°	58.2	59.7	61.2	62.7	64.2	65.7	67.2	68.7	70.2	71.6	73.1	74.6	+88°	+12°
+10°	+ 90°	61.3	62.8	64.4	66.0	67.6	69.1	70.7	72.3	73.8	75.4	77.0	78.6	+ 90°	+10°
+ 8°	+ 92°	64.3	66.0	67.6	69.3	70.9	72.6	74.2	75.9	77.5	79.2	80.8	82.5	+ 92°	+ 8°
+ 6°	+ 94°	67.4	69.1	70.9	72.6	74.3	76.0	77.8	79.5	81.2	83.0	84.7	86.4	+ 94°	+ 6°
+ 4°	+ 96°	70.5	72.3	74.1	75.9	77.7	79.5	81.3	83.1	84.9	86.7	88.5	90.3	+ 96°	+ 4°
+ 2°	+ 98°	73.5	75.4	77.3	79.2	81.1	83.0	84.8	86.7	88.6	90.5	92.4	94.3	+ 98°	+ 2°
0°	+100°	76.6	78.6	80.5	82.5	84.5	86.4	88.4	90.3	92.3	94.3	96.2	98.2	+100°	0°
— 2°	+102°	79.7	81.7	83.7	85.8	87.8	89.9	91.9	94.0	96.0	98.0	100.1	102.1	+102°	— 2°
— 4°	+104°	82.7	84.8	87.0	89.1	91.2	93.3	95.5	97.6	99.7	101.8	103.9	106.1	+104°	— 4°
— 6°	+106°	85.8	88.0	90.2	92.4	94.6	96.8	99.0	101.2	103.4	105.6	107.8	110.0	+106°	— 6°
— 8°	+108°	88.8	91.1	93.4	95.7	98.0	100.2	102.5	104.8	107.1	109.4	111.6	113.9	+108°	— 8°
—10°	+110°	91.9	94.3	96.6	99.0	101.3	103.7	106.1	108.4	110.8	113.1	115.5	117.8	+110°	—10°
—12°	+112°	95.0	97.4	99.9	102.3	104.7	107.2	109.6	112.0	114.5	116.9	119.3	121.8	+112°	—12°
—14°	+114°	98.0	100.6	103.1	105.6	108.1	110.6	113.1	115.6	118.2	120.7	123.2	125.7	+114°	—14°
—16°	+116°	101.1	103.7	106.3	108.9	111.5	114.1	116.7	119.3	121.9	124.4	127.0	129.6	+116°	—16°
—18°	+118°	104.2	106.8	109.5	112.2	114.9	117.5	120.2	122.9	125.5	128.2	130.9	133.6	+118°	—18°
—20°	+120°	107.2	110.0	112.7	115.5	118.2	121.0	123.7	126.5	129.2	132.0	134.7	137.5	+120°	—20°
—22°	+122°	110.3	113.1	116.0	118.8	121.6	124.4	127.3	130.1	132.9	135.8	138.6	141.4	+122°	—22°
—24°	+124°	113.4	116.3	119.2	122.1	125.0	127.9	130.8	133.7	136.6	139.5	142.4	145.3	+124°	—24°
—26°	+126°	116.4	119.4	122.4	125.4	128.4	131.4	134.4	137.3	140.3	143.3	146.3	149.3	+126°	—26°