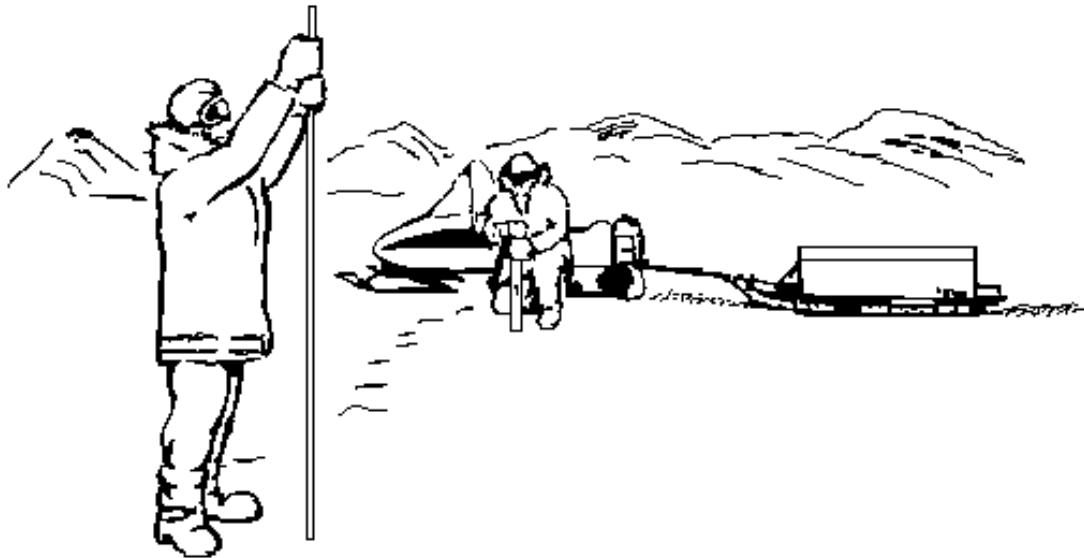


# **A GUIDE FOR GROUND BASED MEASUREMENT OF THE ARCTIC SNOW COVER**



**Ming-ko Woo, Ph.D., PH (A.I.H.)**

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# A GUIDE FOR GROUND-BASED MEASUREMENT OF THE ARCTIC SNOW COVER<sup>1</sup>

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## INTRODUCTION

Snow is a major land cover of the Arctic for a large part of each year. Observations of the arctic snow conditions can be made at the ground level, or from an airborne or space platform. Ground level observations offer the conventional and most direct measurement of snow conditions at single points or within limited areas, though they cannot provide snow cover information on a regional scale. Much advances have been made in the application of remote sensing to the surveillance of the snow cover, but ground truthing remains an important task. Regardless of the scale of investigation, it appears that ground-based measurements will be needed in the foreseeable future.

This document draws mainly upon the arctic field work of the author and his associates. Many snow survey problems were encountered and many lessons were learned through field investigations. Although existing literature contains numerous references to snow measurement results, most of them do not dwell upon details of the field techniques or on the pitfalls to be avoided. The purpose of this field guide is to present the author's experience of snow surveying in the Arctic conducted over the past 20 years.

## SNOWFALL DATA

### Snow gauge measurements

#### *Considerations:*

A precipitation gauge which is essentially a container into which snow, rain or other forms of precipitation is deposited, is employed to collect the solid and liquid deposits of atmospheric moisture. Several problems have been identified for snowfall measurements:

- (1) For historical reasons strongly tied to the weather stations being formerly administered under the Department of Transport, many snow gauge sites are located close to runways where the open sites with blowing snow conditions are common. Snow particles may travel along trajectories at as low as 4° from the horizontal. The presence of an object in an open area interrupts the path of the snow and causes local deposition and scour. Thus, shields are set up around the mouths of the snow gauges to create zones of relative calmness to encourage snow deposition.

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- (2) Trace precipitation events (<0.2 mm) are not recorded by the gauges because of their limited precision level.
- (3) Snow may accumulate on the rim of the gauge without falling into the container, part of it being blown off some time after the snowfall events. Automated and non-attended gauges are particularly prone to such error since there are no observers to check the snow on the gauges.
- (4) After snowfall events and before manual observations are made, precipitation collected in the gauge may lose an unknown amount to evaporation and sublimation. Heated gauges are especially problematic as they increase the evaporation losses from the gauge catch.
- (5) Every time an observer empties the gauge for measurement, some moisture may adhere to the container and is lost to evaporation. This is known as wetting loss and is not accounted for in the record.

#### *Operations:*

The Canadian MSC Nipher Shielded Snow Gauge System is the standard instrument for measuring winter precipitation. The snow gauge is a hollow metal cylinder, 560 mm long and 127 mm in diameter, surrounded by a solid shield with the shape of an inverted bell. The Nipher shield was originally of spun aluminium but since 1981, a fibreglass shield replacement is employed. (Goodison *et al.* 1981) Manual measurements of snowfall are made by an observer once every six hours by melting the content in the gauge, pouring it into a graduated cylinder and recording the amount. The performance of the Canadian Nipher gauge was first reported by Goodison (1978a). Subsequently, the Nipher gauge was compared with the Double Fence Intercomparison Reference (DFIR) which consists of octagonal vertical double fences surrounding a shielded Russian Tretyakov gauge (Yang *et al.* 1995). The results can be used to correct the snowfall record obtained using the Nipher system (Goodison and Metcalfe 1992).

#### *Correction of snowfall records:*

Metcalfe *et al.* (1994) proposed the following corrections to the data obtained by the Canadian Nipher Shielded Snow Gauge System:

- (1) Each 6-hour recorded trace precipitation event for an Arctic station is assigned a value of 0.03 mm.
- (2) If the 24-hour snowfall accounts for >50% of daily precipitation, a wetting loss of 0.15 mm is added, otherwise no correction is applied.
- (3) If the 24-hour snowfall exceeds 50% of daily precipitation, the undercatch by the Nipher gauge is adjusted by a gauge catch ratio expressed as a function of wind speed at 2 m height.

#### *An experimental study:*

Wyoming shielded precipitation gauges were set up by the Meteorological Service of Canada (now the Atmospheric Environment Service) and data acquired for several years in the 1970's to 1980's but the results have not been reported. Figure 1 shows the snow distribution pattern on the ground

around a Wyoming gauge set up in Resolute, Cornwallis Island. This type of gauge when used in arctic Alaska, was found to increase the NWS 8" gauge catch by a ratio of 3.5 (Benson 1982) though the NWS gauge records were not adjusted for wetting loss nor trace events.

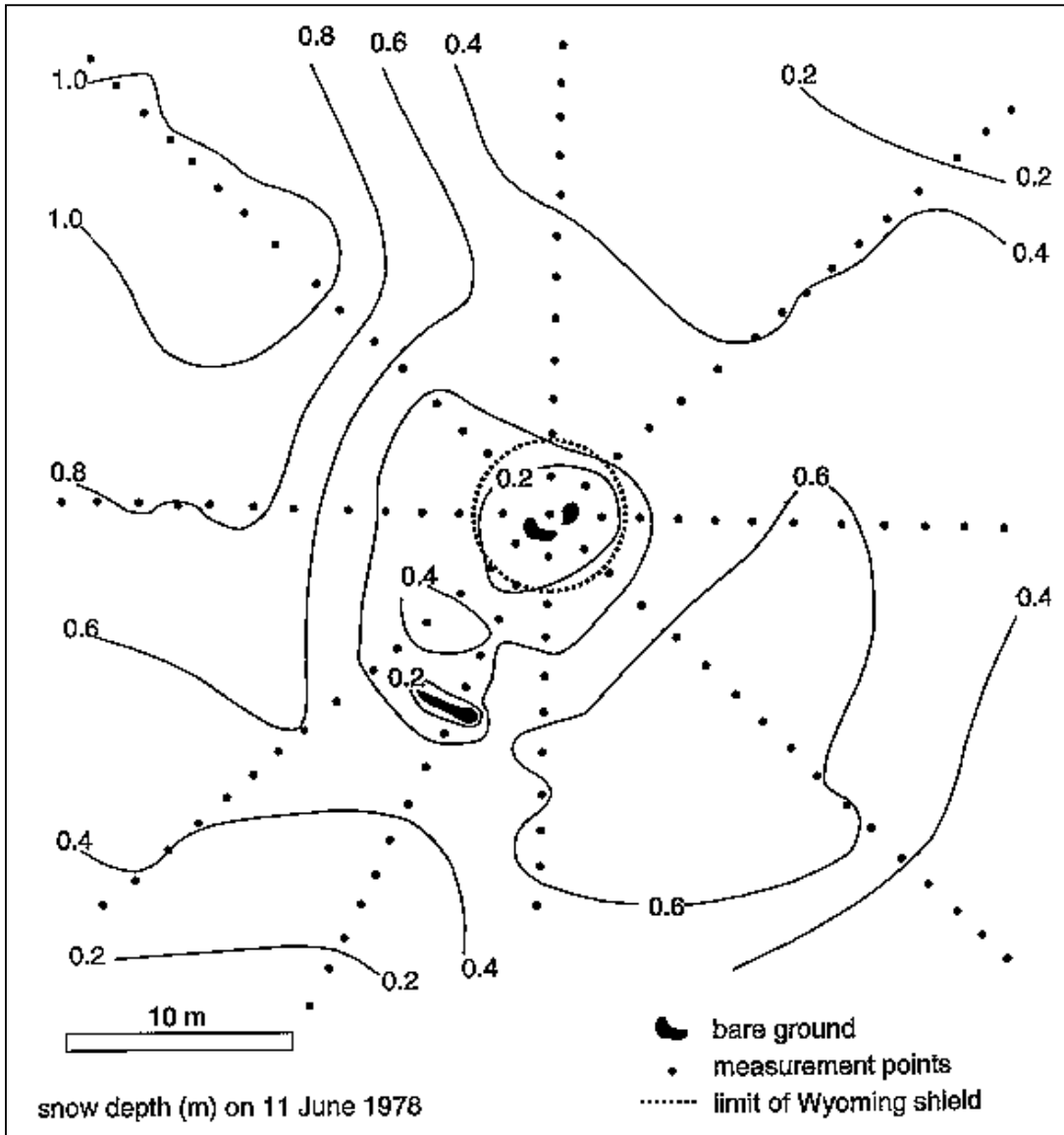


Fig. 1. Pattern of snow drift around a Wyoming gauge, Resolute, Cornwallis Island.

### Snow depth measurements

#### *Operations:*

Before 1960, all weather stations used snowboards to capture the amount of snow falling within a specified time period (Potter 1965). The thickness of snow on the board was measured by a ruler,

the board was reset on the new surface of the snow to await the next period of snowfall. The depth of snow measured on the board was multiplied by an assumed density of  $100 \text{ kg m}^{-3}$  to convert it into snow water equivalent. To improve the assumed density, Metcalfe *et al.* (1994) calculated average densities based on the ratio of corrected Nipher gauge measurement to snowfall measurement for storms of  $\geq 5 \text{ mm}$ . They obtained different densities of freshly fallen snow for different regions. For the High Arctic, a mean density of  $108 \text{ kg m}^{-3}$  can be used to convert the snowboard data into snowfall in water equivalent unit. One modification in snow depth measurement is the use of automatic snow depth sensors to record continuously the changes of snow depth at a point. The instrument (Goodison *et al.* 1988) is mounted at a fixed distance above the ground and sends acoustic pulses downward. The time required for a pulse to reach the target and back to the sensor is used to determine the distance between the sensor and the snow surface. The root-mean-square error is reported to be  $<20 \text{ mm}$ .

#### *Considerations:*

- (1) Some of the snow falling on the snowboard may be blown away or some snow may be blown onto the board between the end of snowfall and the time of measurement. This is also a problem for the acoustic snow depth sensor which cannot distinguish between true snowfall or snow drifted to the site.
- (2) The snow board is a most inexpensive device and can be deployed at many field camps. However, an observer is needed to record the snow depth and then reset the snowboard. The acoustic snow depth sensor can be attached to an automatic weather station and left unattended throughout the winter.
- (3) The mean density of  $100 \text{ kg m}^{-3}$  or  $108 \text{ kg m}^{-3}$  may not be a suitable value for the fresh snowfall in different parts of the Arctic.

## **SNOW ON THE GROUND DATA**

The net amount of snow lying on the ground at a particular time of the year is determined by snow-pit measurements or snow surveys. The arctic snow cover is often hard packed and denser than the snow of the subarctic (Williams 1957). The snow stratigraphy generally follows Benson *et al.* (1975) description derived from observations in Greenland, Antarctica and northern Alaska. Four major varieties of snow are recognized, including:

- (1) fresh snow at the surface with variable crystal forms and a density between  $150$  and  $200 \text{ kg m}^{-3}$ ,
- (2) hard and fine-grained windslab with a density between  $350$  and  $450 \text{ kg m}^{-3}$ ,
- (3) medium-grained snow at a density between  $230$  and  $350 \text{ kg m}^{-3}$ ,
- (4) depth hoar consisting of coarse, loosely-bonded crystals yielding an average density between  $200$  and  $300 \text{ kg m}^{-3}$ . The stratigraphic consideration has a bearing upon the gathering of the snow cover data.

## Snow-pit measurements

Data from snow pits provide the most accurate information of the snow cover against which other techniques of measurements can be compared. The 'stratigraphic method' for depth and density observations is given below.

### *Operations:*

- (1) A snow pit is dug large enough for the observer to move about within the pit. Steps may be cut in the snow leading down to the bottom of deep pits. A saw is the best tool to clean the face to be examined.
- (2) Before sampling, the stratigraphy of the snow is recorded by recognizing the layers, measuring their thickness and noting the mean grain size for each layer (Fig. 2). The most expedient way to obtain the grain size is to spread the snow grains on a small (pocket size) piece of metric graph paper, laminated in plastic, and estimate the diameter of several grains.
- (3) For each layer, at least two snow samples should be taken using small snow tubes of known volume. If the tubes are made of metal, make sure that they are handled with gloves; otherwise the heat from the hands may cause some snow to stick to the tubes.
- (4) The tube is inserted horizontally and the snow sample is broken off after full insertion. A pen knife trims the snow that protrudes from both ends of the tube to ensure that the sample volume matches the known volume of the tube. Care should be taken when sampling loose snow layers such as the depth hoar as their snow crumples in the tubes.
- (5) The samples are weighed by an accurate scale in the field, or bagged, labelled and melted in the laboratory to obtain the volumetric water equivalent.
- (6) It is difficult to cut through ice layers to obtain a proper sample using the snow tube. In this case, ice samples have to be broken from the layer and brought back to the laboratory for weighing and then emersed in cold ( $<0^{\circ}\text{C}$ ) oil or diesel to determine the sample volume by displacement.
- (1) Density is then calculated for each layer. It is found that the density does not vary greatly within individual layers that are visually distinguishable (Fig. 3). The snow water equivalent of the entire profile ( $S$ ) can be obtained by summing the products of the densities ( $\rho$ ) and the thicknesses ( $d$ ) of the various layers:

$$S = \sum_{k=1}^m \rho_k d_k$$

with  $m$  being the number of distinguishable layers in the snow.

- (8) If required, dial thermometers may be inserted into the snow to obtain its temperature profile. Such thermometers are easy to use and robust (while electronic devices may have problems due to the poor performance of the batteries at extremely low temperatures and the digital read-out may be hard to read under strong sunlight). The depth at which temperatures are obtained need not correspond with the snow samples and it may be regularly spaced down the profile.
- (9) Sometimes, a photographic record is needed for the snow profile. The best result for thin snowpacks is to cut a vertical slab (about 10 cm wide) using a saw, remove the snow in front and behind this slab, trim the face carefully and photograph it with backlighting by the sun.

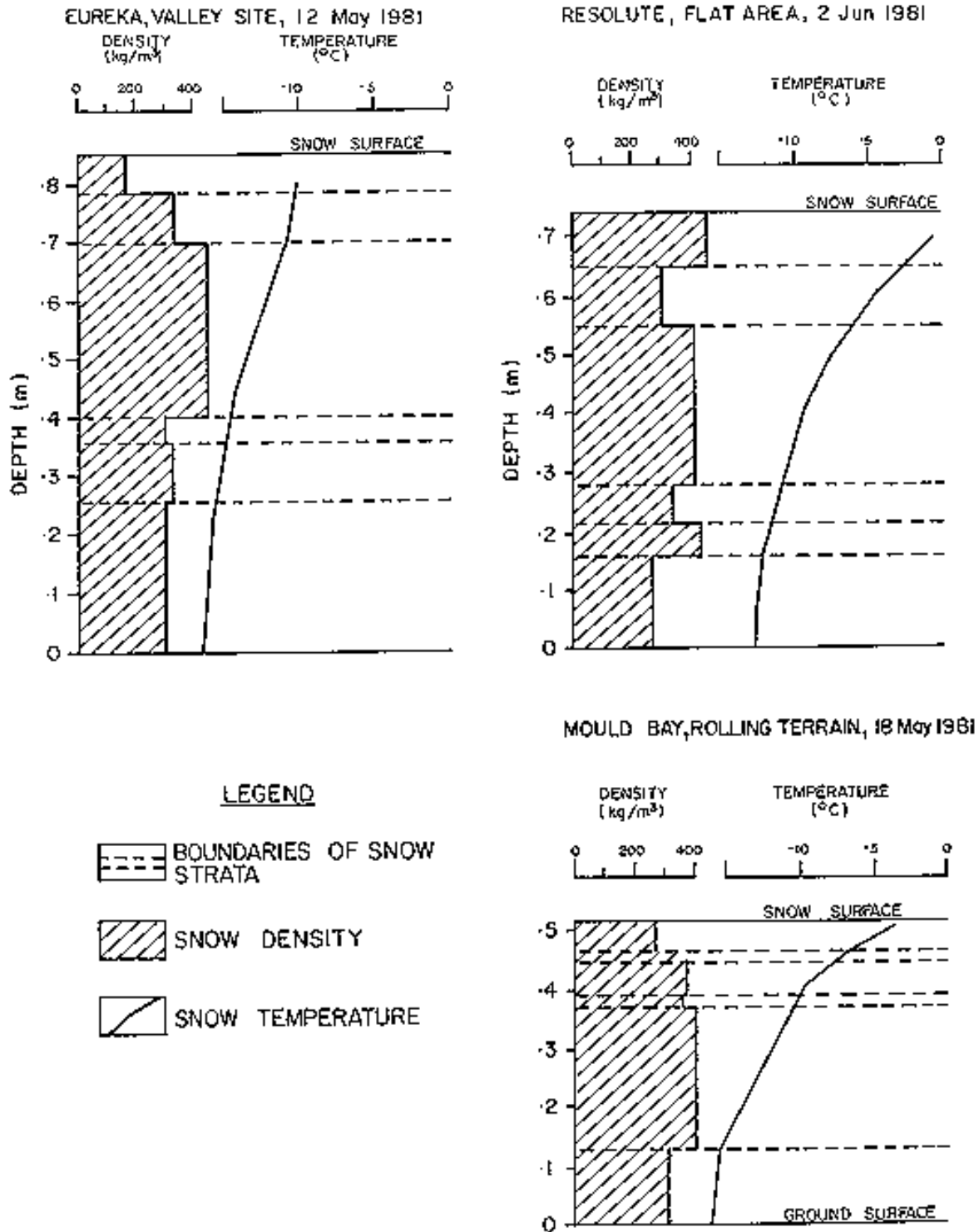
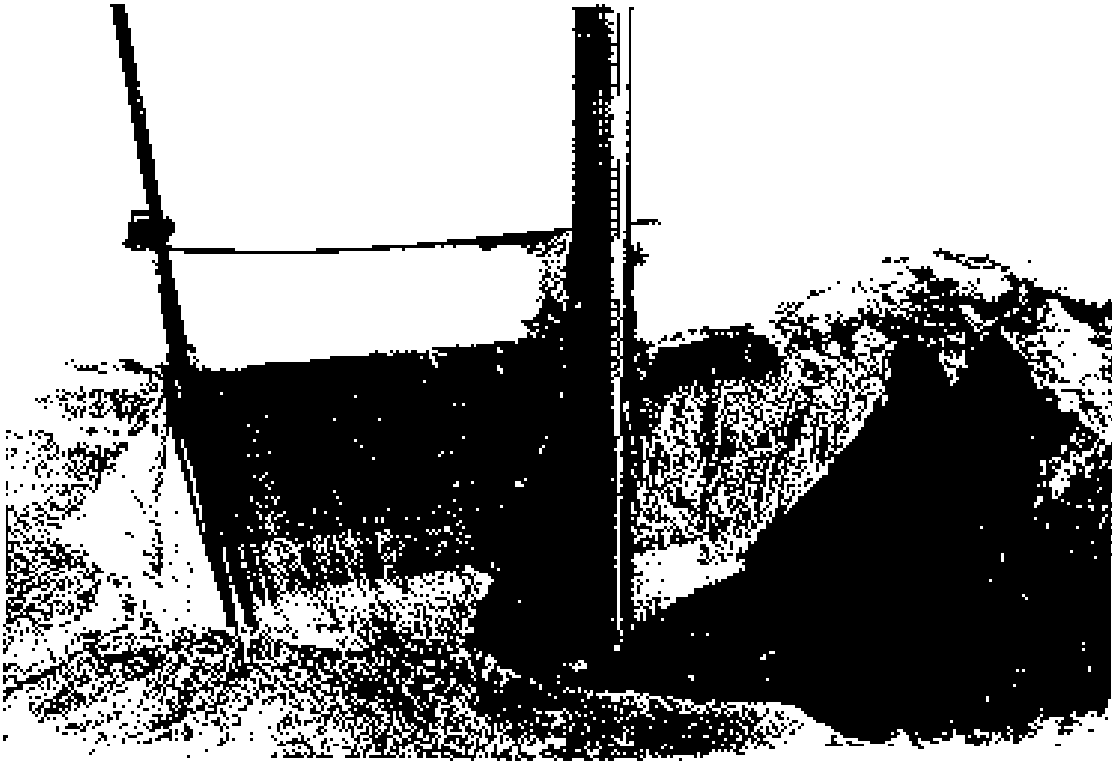


Fig. 2. Three snow profiles from different parts of the High Arctic showing density changes associated with stratigraphy.



**Fig. 3. Face of a snowpit, Hot Weather Creek, Ellesmere Island, with layering accentuated by the incorporation of various amounts of aeolian dust. Left is a steel snow rod with a measuring tape lying on the snow, and centre is a Meteorological Service of Canada snow sampler.**

### **Snow surveys**

Snow surveys are conducted to acquire snow depth and snow density data for a particular transect or an area so that the snow water equivalent can be calculated.

#### *Weather station operations:*

Canadian weather stations conduct 10-point snow surveys, usually at the beginning and the middle of each month between the period when the initial winter snow cover is established and when this cover is depleted. Each survey point is marked by a snow stake, sometimes arranged in a line and sometimes along two perpendicular lines. At each point, snow depth is measured, a snow core is obtained, bagged and melted at the weather station to determine the snow density and water equivalent. The depth, density and water equivalent were published in the *Snow Cover Data*, currently being transferred into digital format.

*Non-routine snow surveys:*

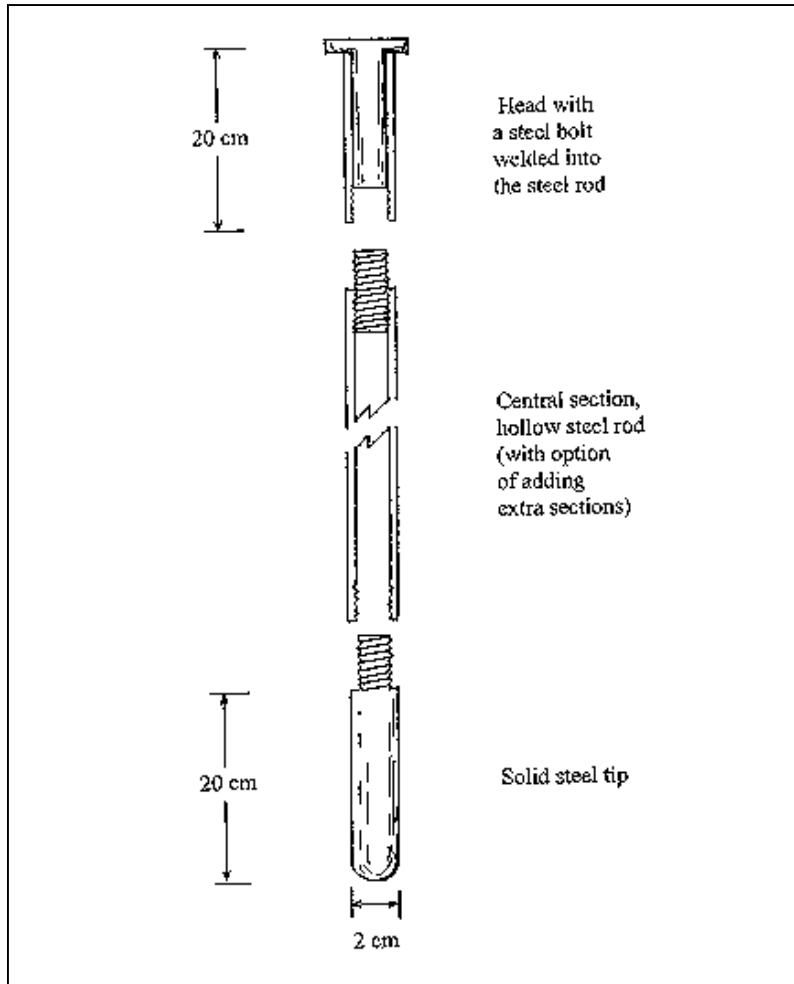
(1) Depth measurements

Snow stakes provide markers to show the exact spots where repeated measurements can be made. However, blowing snow and stake-enhanced snowmelt creates scour or melt hollows around the stakes. Such localized irregularities in snow depth can represent a significant percentage error for shallow snow covers commonly encountered in the Arctic. Care should be exercised to avoid taking depth readings that are affected by the presence of the stakes.

For sampling snow depth at unmarked (i.e. without a pre-set snow stake) sites, a metal ruler can be plunged vertically into shallow snow that is not hard packed, and the depth read directly on the ruler.

Where the snow is deep or hard-packed or contains ice layers, a steel snow rod is needed. It is recommended that the rod consist of a rounded, solid, steel tip, attached to a hollow rod with threads at the opposite end. The threaded end allows a steel top section to be screwed on or for extension rods to be added (Fig. 4).

The steel top section can measure 20 to 50 cm and is made of hard steel with a flat top-end that can withstand the blows of a steel mallet. The extension rods may conveniently be at 1.5 or 2.0 m length so that for deep snow, depth can be measured by a pocket tape from the rod junction upward and added to the length of the known rod segments. It is futile to paint a scale on the rods as the paint wears off very quickly during the first survey; though it may be useful to engrave the rods at half-metre intervals to facilitate reading.



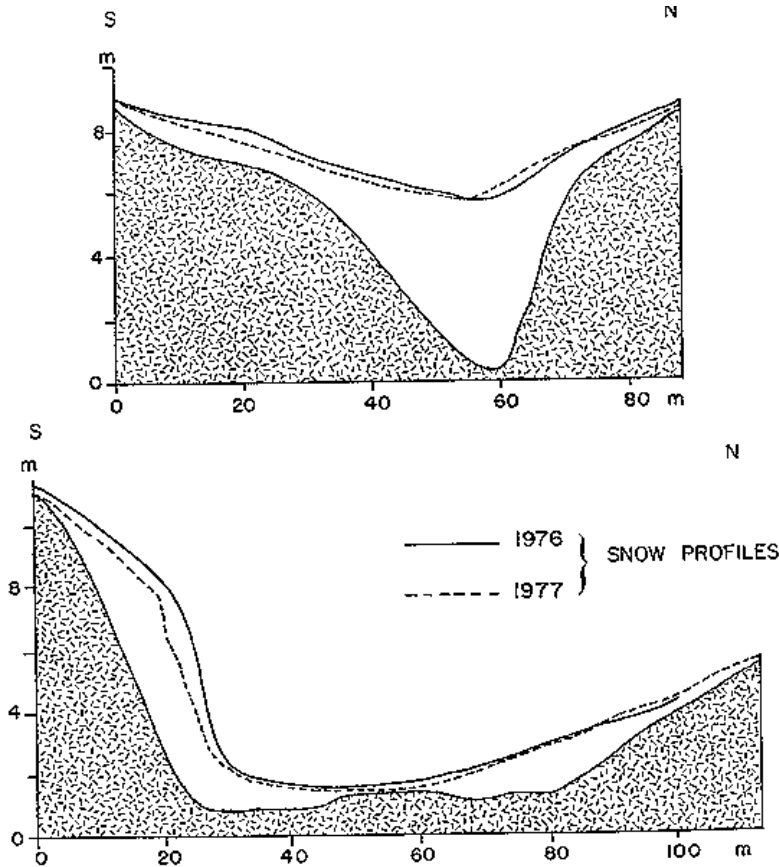
**Fig. 4. Steel rod used for probing snow depth, including a solid steel tip, a hollow rod with threads to couple with the tip and with the top section into which is welded a solid steel bolt. Extension sections may be added.**

To secure correct depth measurements, the tip of the rod should reach but not penetrate the ground

surface. Where the snow is hard, repeated jabbing motion is needed to push the rod through. Sometimes, pounding by a steel mallet is necessary to penetrate ice lenses or very fine-grained layers. Once broken through, the rod may be jammed in the snow and has to be twisted out using a wrench. Note that (1) that the direction of wrenching is the same as the threads that couple the extension rods, otherwise, the lower rod segments will be detached and have to be dagged out, (2) after retrieving the rod, the extensions will be so tightly attached that two wrenches are needed to separate them.

For very deep snow or steep cornices, direct probing may be too dangerous or non-feasible. An alternative is to select a transect, mark out the end points, and survey the snow profile by levelling.

After the snow has melted, the profile of the ground surface is surveyed between the two end points and the snow depths obtained as the difference between the two profiles (Fig. 5). This method is especially useful where repeated snow surveys are needed. Then, permanent markers allow the re-occupation of the same snow survey transect without have to re-survey the ground surface profile.



**Fig. 5. Snow and ground profiles across (top) an incised tributary valley (bottom) a broad valley with a deep drift on its south slope, McMaster River, Cornwallis Island. The snow in parts of the valleys is too deep to probe so that the accumulation is obtained as the difference between the surfaces of the snow and the ground, surveyed by levelling. The ground profiles were re-used in different years when the cross sections were re-occupied, using markers (cairns or stakes hammered into the ground) to identify the positions of the transects.**

## (2) Density measurements

Snow samplers are commonly used to obtain snow cores which allow the determination of snow density ( $\rho$ ) by:

$$\rho = w/(d\alpha)$$

where  $w$  is the weight of the snow core,  $d$  is snow depth and  $\alpha$  is the cross sectional area of the core obtained by  $\pi r^2$ , with  $r$  being the inside radius of the cutter. The sampler is a metal or plastic tube, the bottom end being fitted with a cutter comprising a number of sharp blades made of high quality steel. The upper end usually has (1) a slightly larger diameter which allows the snow sample to slide out easily when tipped over, (2) two holes that permit a rod to be inserted to serve as a temporary tee handle on which the surveyor can exert body weight to push the sampler through icy layers, and (3) threads to accept extension tubes.

To obtain a snow core, the sampler is inserted vertically into the snow until it reaches the ground surface. The snow depth is read off from the graduations marked on the side of the sampler. The sampler together with the sample may be put on a cradle and weighed by a special scale that directly gives the snow weight. This is usually not a reliable method in the open areas where the scale reading is affected by wind shear. An alternative is to retrieve the core by turning the sampler upside down to tip the snow into a bag and then weigh the bag and its content using a more sensitive balance at some site protected from the wind (or bring back to the camp for weighing).

Several points should be noted. (1) Gloves should be worn at all times to avoid warming the snow sampler by the hands, otherwise some of the snow may melt, refreeze and adhere to the tube; (2) the cutter should be sharpened by a file whenever the blades become dull, or it will not cut through ice easily; (3) avoid grinding the sampler against pebbles, gravels or rock which may underlie the snow; (4) to push through hard layers, insert the cross-bar through the holes in the upper end of the sampler (for those samplers with such an option) and then throw the body weight on the sampler, using a torque motion to push the sampler through hard layers, but never apply a hammer or the top end of the sampler will be ruined; (5) make sure that the sampler fully penetrates the snow by observing the presence of some soil particles or organic materials attached to the bottom of the core, by feeling the jarring sensation as the cutter hits the gravels, or by matching the sampler reading of snow depth against the snow rod measurements of depth; (6) make sure that the entire snow core is retrieved.

The last point is particularly important in the Arctic where the snow often has a depth hoar layer that tends to disintegrate upon impact by the sampler. Pushing the sampler deeper to obtain a plug of fine-grained soil or organics may help to retain the hoar but for loose soil or rock substrate, it may be necessary to dig around the sampler before lifting the tube that contains the snow core. This will slow down the operation considerably but the practice is similar to those used in some other countries (e.g. the Nordic countries) which require the core to be dug out every time a measurement is made.

Several types of snow samplers are used in Canada (Goodison 1978b), though some of them (e.g. Meteorological Service of Canada or MSC sampler) are no longer manufactured. Field tests of three samplers (MSC, Eastern Snow Conference or ESC-30, and Standard Federal or Mount Rose) were

made in early May 1982 (air temperature -25 to -20°C) at Eureka and Resolute where the snow depths were chosen to be 0.6 m and the densities were 340-345 kg m<sup>-3</sup> as determined by the stratigraphic method. The results showed that (1) larger diameter of the tube increases the accuracy of density determination - the Mount Rose overestimated by >10%, the MSC overestimated by >5% and the ESC was ±5% of the snow pit value, errors which are comparable to those found by Farnes *et al.* (1982); (2) the ESC with a plastic body of greater length than the lower segments of the other samplers (but no extension is possible) allows the length of the snow core to be seen through the body of the tube and helps to survey some moderately deep snow cover without having to add another segment; (3) the bulging cutter of the ESC sampler and the lack of a cross bar attachment to take on the body weight made it difficult to penetrate snow of only moderate hardness, consequently it took 3 to 5 times longer than the MSC and almost 10 times longer than the Mount Rose to obtain a comparable core. Generally speaking, the larger the diameter of the cutter, the greater the snow core volume and hence the more precise the density measurements. This is important for shallow snow cover found in many parts of the polar desert. For deep snow, a narrow sampler allows easy penetration, especially where there are many hard or icy layers.

For very shallow snow (<0.25 m), the snow sampler gives very imprecise results because of the limited volume of the sample. One easy solution is to mark off a known area, say 0.2 m by 0.2 m, measure the depth at its four corners and bag all the snow from this area for weighing. The product of the area and the average depth gives the snow volume sampled.

**Table 1: Characteristics of several snow samplers (after Goodison 1978b and Farnes *et al.* 1982)**

	Canadian MSC	ESC-30	Standard Federal	Adirondack
Material	Aluminium	Clear plastic	Aluminium	Fibreglass
Length (cm)	109	126	76	154
No. of teeth	16	16	16	None
Max. depth of sample (cm)	100	120	>500	150
Cutter: I.D. (cm) Area (cm <sup>2</sup> )	7.05 39.1	6.18 30.0	3.77 11.2	6.74 35.7
% error <sup>(1)</sup>	7.0	-0.3	10.0	-0.2

<sup>(1)</sup> after Farnes *et al.* (1982)

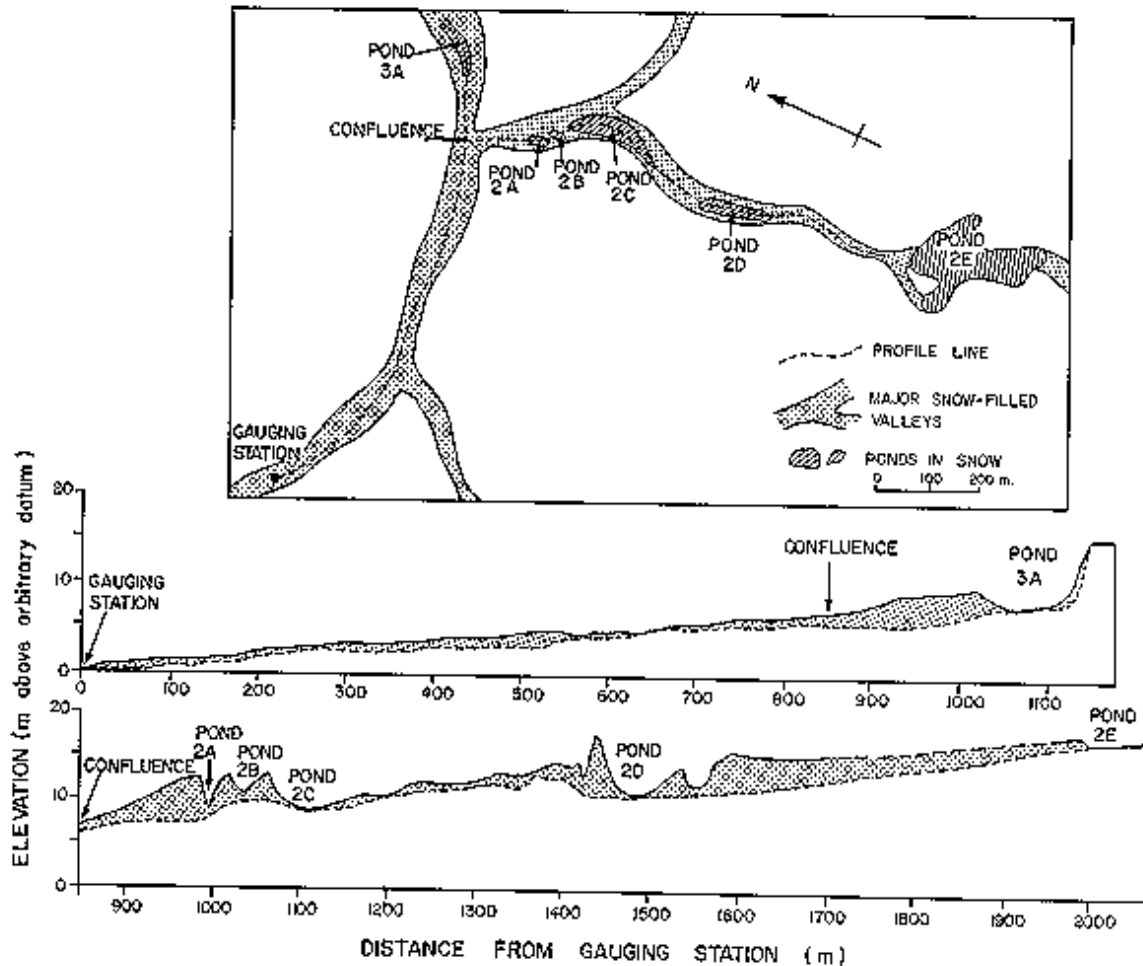
## SNOW COVER IN SMALL AREAS

For hydrometeorological investigations requiring information for small areas that measure <0.5 km<sup>2</sup>, detailed mapping of the snow cover is often needed.

*Snow and topographic surveys*

Quite often, the topography underlying the snow has to be known because (1) the relationship between topography and snow distribution is a useful source of information, (2) snow depth at some locations cannot be obtained by probing and the depth has to be assessed using the difference between the snow surface and ground surface topographies (Fig. 5).

An example is the survey of snow profiles which influence the storage and discharge of streamflow during the breakup period. Snow jams are common along most High Arctic valleys (Woo and Sauriol 1980), with the height of the snow marking the maximum possible limit of the temporary meltwater ponds. A longitudinal profile of the snow and the valley-floor indicates the position and the potential depths of the ponds (Fig. 6). Where major snow dams are encountered, the three-dimensional configuration of the dams and their underlying topography need to be mapped to determine the size of the meltwater impoundment (Fig. 7). The geometry of the snow dam has to be known in order to study the process of dam decay (Xia and Woo 1992).



**Fig. 6.** Snow surface profile along two valleys of McMaster River, Cornwallis Island, showing sites where potential ponding of snow meltwater can occur.

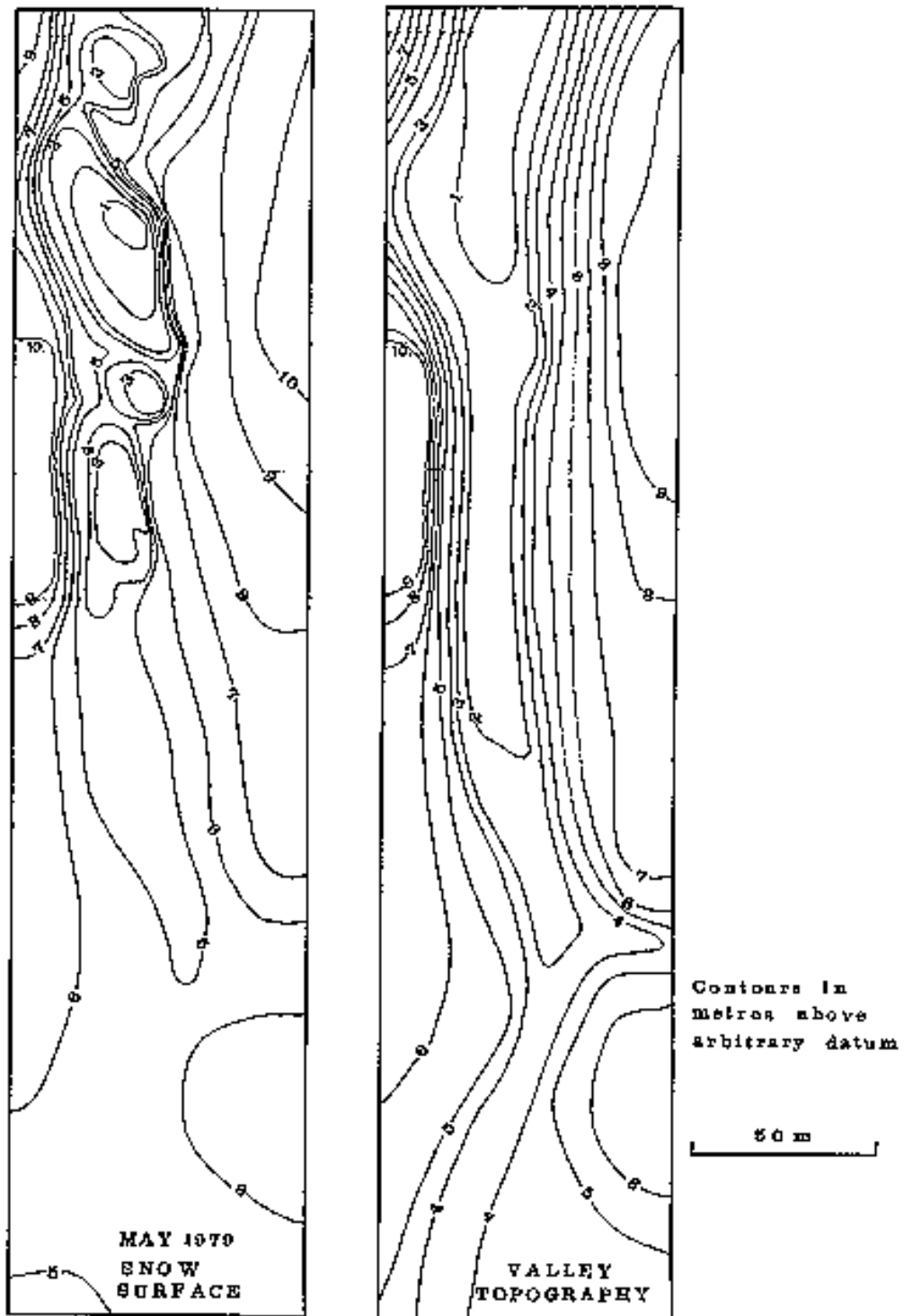
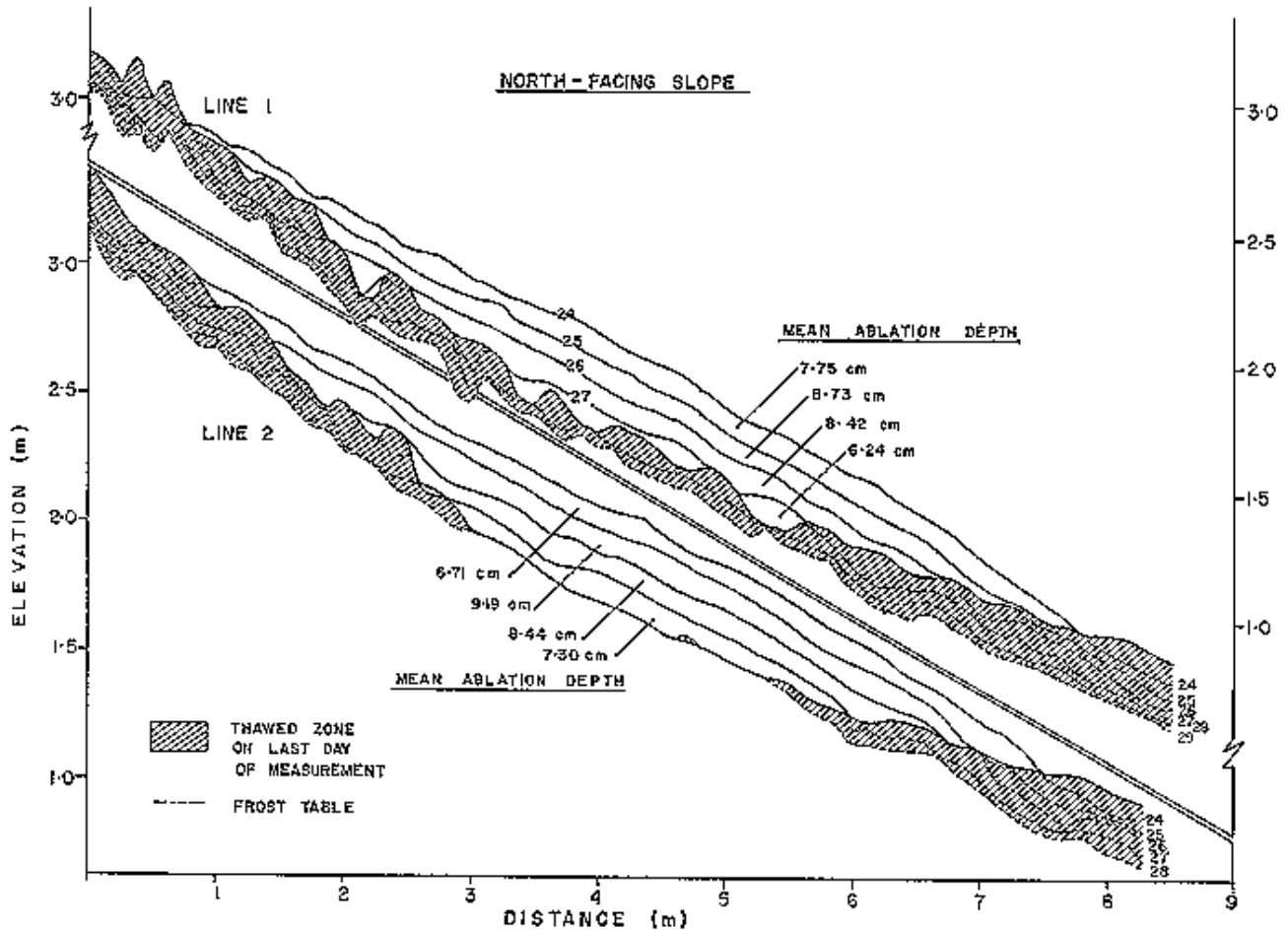


Fig. 7. Snow surface and valley topography along a section of McMaster River showing the configuration of several snow dams that span across the steep-sided valley.

Another example is the profile of late-lying snowbanks which are important local sources of slope runoff (Young and Lewkowicz 1988). The size of the snow patches changes continually and the water source area, hence the meltwater supply, vary accordingly. Mapping the cross profile of the snowbank will show its changing extent (Fig. 8).

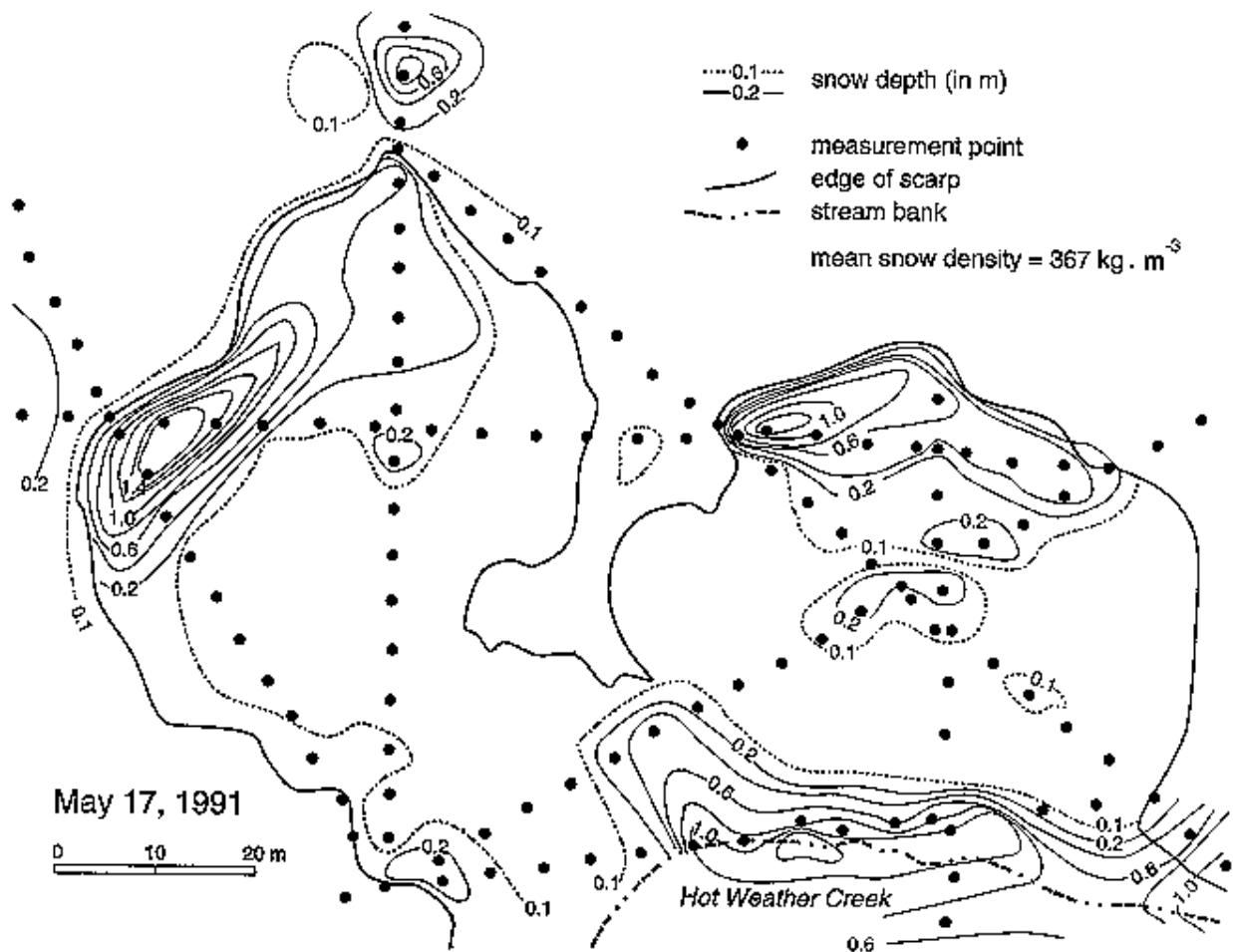


**Fig. 8.** Changing cross profiles of two late-lying snowbanks on a north-facing slope during the melt season of June 1975, Vendom Fiord, Ellesmere Island. Also shown are the depths of ground thaw along the profiles on various days.

### *Snow cover mapping*

To map the snow cover of an area, a number of transects covering most parts of the area is required. The number and the spacing of the transects depend on the complexity of the terrain. Usually, the more rugged the area, the more uneven the snow cover and the more transects are required. Along each transect, snow depths are probed and snow densities are observed. Past studies suggest that snow density is considerably less variable than snow depth over a small area and therefore much fewer density measurements are needed.

In planning the transects, large scale (1:1,000 to 1:50,000) maps or low altitude aerial photographs of the snow-free period are useful as base maps to lay out the snow survey lines. Field assessment of the snow distribution is necessary to confirm the feasibility and the adequacy of the survey lines before the actual surveys are carried out, making sure that the major snow patches are not overlooked and that the lines can be traversed safely (e.g. no dangerous cornices). Figure 9 shows the survey lines used to map the snow in a small area in Hot Weather Creek basin, Ellesmere Island, where active layer detachment slides have highly scarred the landscape. The transects are irregularly placed to capture the variations of the snow cover.



**Fig. 9. Snow depth in a small area with active layer detachment slides, Hot Weather Creek, Ellesmere Island. The survey lines were designed to capture the variable pattern of snow distribution.**

In carrying out the snow survey, the necessary items include: snow rods and a snow sampler, together with their accessories (hammer and wrench in case of probing deep snowdrifts, a portable scale or plastic bags with waterproof marker labels to carry the snow samples back to the base for weighing),

a pocket measuring tape, field book and pencil(s), a penknife to sharpen the pencil if required, aerial photograph (preferably laminated) and an outline map containing the proposed transects, prepared in advance. The map may be taped to the field book to avoid being inadvertently blown away by wind (a map or an air photo flying in the wind can travel much faster than a surveyor can run in the snow). It is always helpful having some rubber bands to tie around the field book to hold down the pages or to attach the air photo to a clipboard so that the sheets do not flap in the wind. It is also useful to have a snow shovel close by, and to carry some tall stakes as temporary markers. Sun glasses are essential and for many people, sun tan lotion should be applied to the exposed parts of the face. Dress warmly but make sure that some of the heavy clothing can be taken off since it can get sweaty during the snow survey (unlike ski pants and thick vests, skidoo suits are sometimes too awkward to take off and put on in the field). Always wear gloves when handling the snow sampler but one may wish to add a pair of thick mitts while travelling on snowmobile. A hat and a heavy parka with a hood are useful as are snow boots with felt liners and a pair of thick woolen socks. The felt liners should be aired each day.

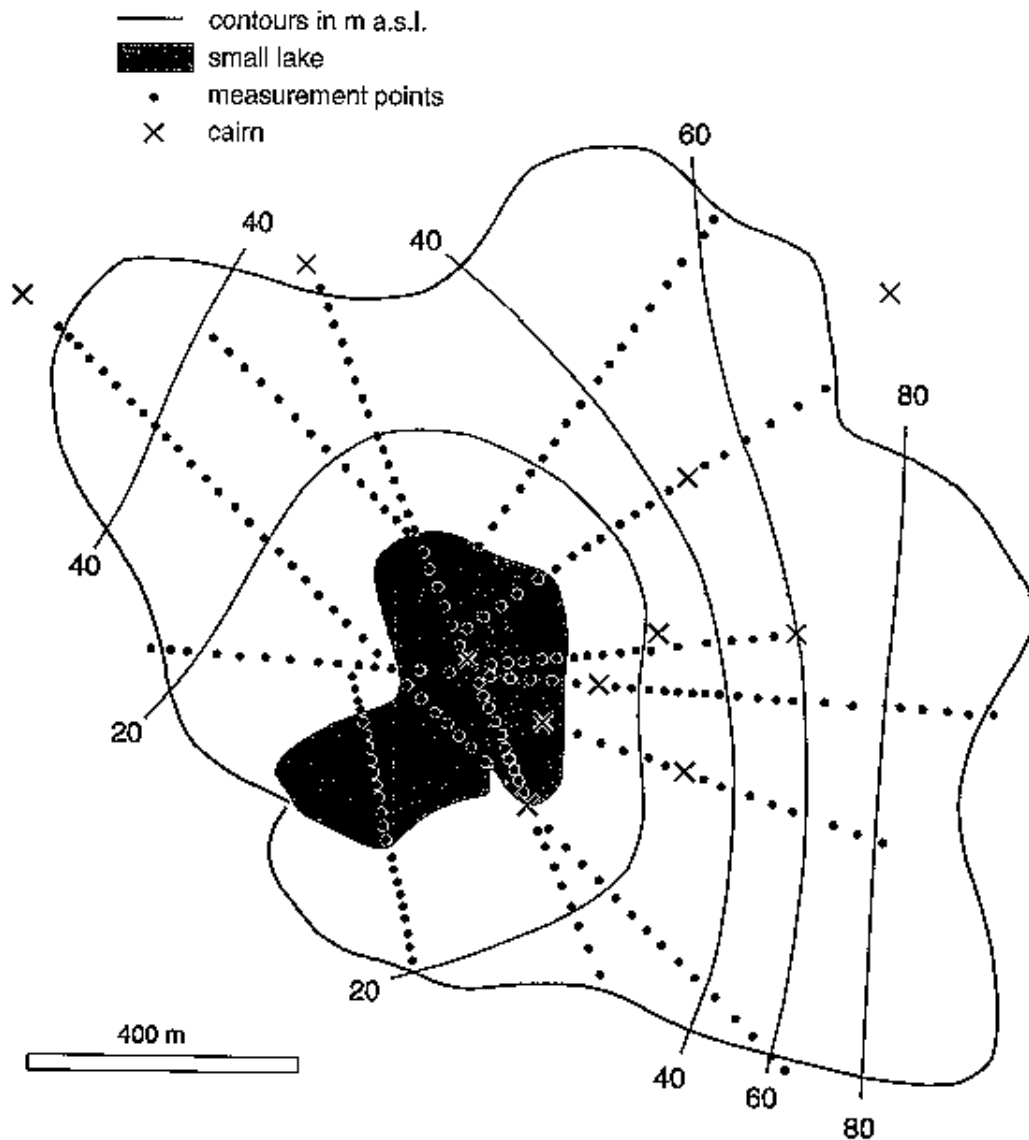
In the field, the end points of each transect should be correctly identified and the survey line is anchored by erecting a stake or by piling a cairn at each end point. As far as possible, these points should be visible along the length of the transect. It is also helpful to identify features along the transect which can be located on the maps or aerial photographs. Where a transect crosses another transect, the location should be recorded. To maintain a straight line during the survey, check the track against the alignment of the end points. At regular intervals (measured by horizontally laying the snow rod of known length, or approximated by pacing the distance), take snow depth measurements with the rod. It is important not to miss major snow features such as local drifts or snow-free knolls. For a transect of 100 m length, there should be 20 to 40 depth measurements and 1 or 2 density samples.

The survey points are transferred onto the a large scale topographic map (or aerial photograph) of the study area by locating the end points of the transect and then dividing the distance uniformly by the number of points surveyed along the line. The exact positions of depth measurement cannot be easily determined unless there are features nearby that are recognizable on the aerial photograph. Notes indicating where the transect lines cross are helpful in adjusting the position of the survey points. Figure 10 shows the positions of temporary cairns set up during the survey of the snow cover on Small Lake basin near Resolute, Cornwallis Island. It also shows the transects with their snow depth measurement points. The resulting snow distribution map is a reasonable representation of the snow cover because the positions of the deeper snow drifts were verified by an oblique aerial photograph taken in the melt season (Woo *et al.* 1981). Several snow patches lying between the transects were missed by the survey because their presence could not have been detected during the survey but was revealed after some snowmelt events had occurred.

#### *Delineation of snow-free zones*

Aerial photography is a useful and economical (for most oblique photographs) tool to delineate snow-free zones, particularly where the snow is patchy and the terrain is rugged. The snow cover map obtained by ground survey can be superimposed onto the vertical aerial photographs; or the

snow-free areas indicated by oblique aerial photographs can be transposed onto the snow cover maps. This can (1) improve the precision of locating the snow-covered and snow-free sites, (2) provide supplemental areal snow cover information missed by the transects. It is interesting to note that by superimposing a sequence of aerial photographs taken at different times and assuming uniform spatial melt rates between time intervals, Granberg (1973) was able to compile a snow cover map for subarctic Schefferville area with a much higher resolution than a similar map produced by the interpolation of snow stake data.



snow survey of Small Lake basin, 6-9 June 1978

**Fig. 10.** A radiating pattern of transects used to survey the snow distribution in Small Lake basin near Resolute, Cornwallis Island. This survey captured most of the deep snowbanks though oblique aerial photograph taken during the snowmelt season showed that the survey missed several small snow patches located between the transect lines.

## SNOW IN SMALL CATCHMENTS

Many water balance and hydrological process studies are carried out in small catchments with areas of 1 to 500 km<sup>2</sup>. Mean snow cover condition or snow distribution pattern on a meso-scale is often needed for such arctic catchments. Hydrological investigations on such a scale do not require local snow information such as deep snowbanks on individual slopes or detailed changes in snow distribution along a river valley.

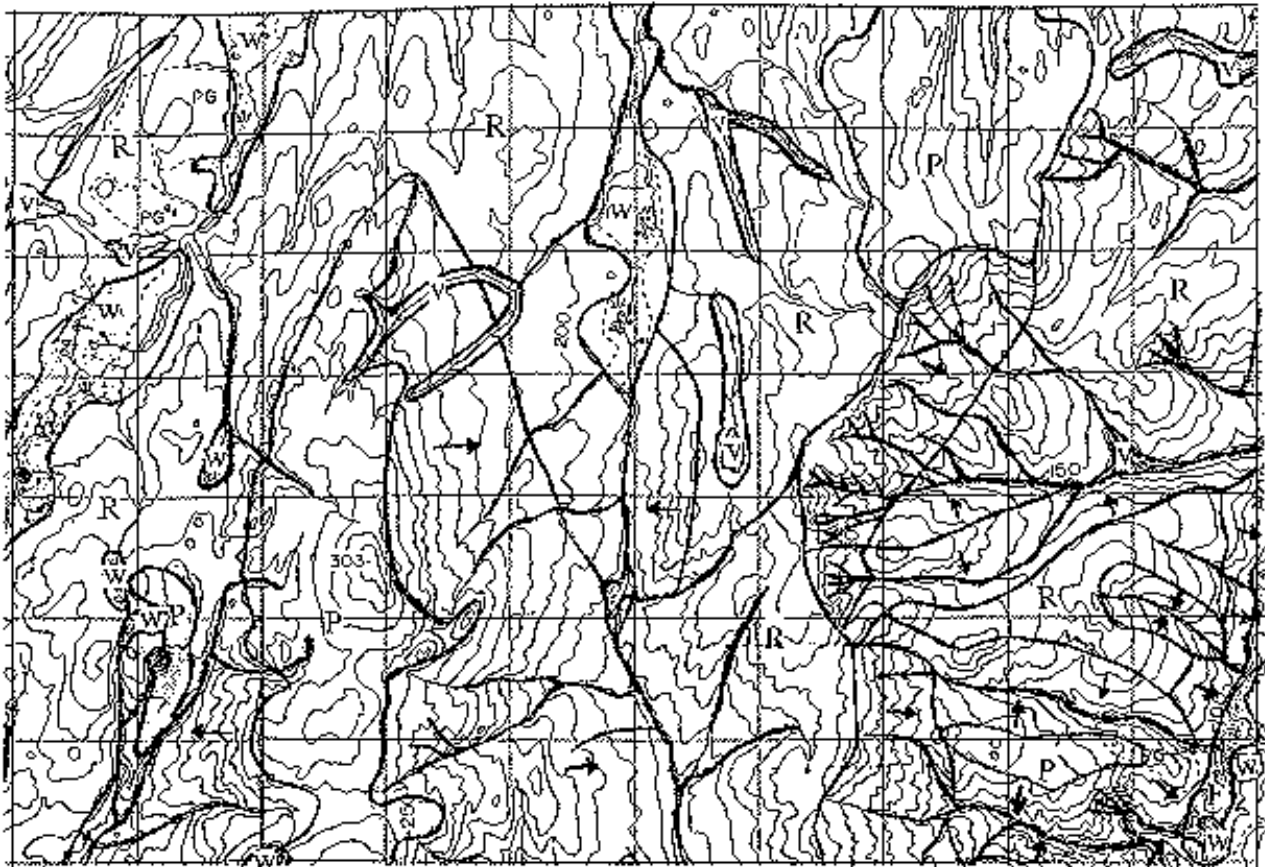
It is not practical to run many long transects across the catchment but failure to provide adequate snow survey coverage may yield biased estimates of the mean. Past experience demonstrates that in the Arctic where vegetation is not a factor affecting snow distribution, terrain has a major effect. (Woo and Marsh 1978). Terrain-based snow surveys allow the determination of mean catchment snow values and produce sufficient spatial snow information for most hydrological studies.

### *Operations*

Before embarking upon the survey, aerial photographs and topographic maps of the catchment are examined to identify the types of terrain commonly found in the catchment. Stereoscopic photographs are most useful in allowing the delineation of individual terrain units. Note that the delimitation of terrain boundaries varies between operators and different terrain borders may be delineated by the same operator during different trials of the terrain mapping exercise. Figure 11 provides an example of mapping an area on the Fosheim Peninsula, Ellesmere Island, between Blacktop Peak and Hot Weather Creek. After a terrain map of the catchment is obtained, suitable snow survey transects are selected.

In deciding on the transects, ensure that each terrain type has replicated survey lines. Each line should yield a mean snow value that is supposed to be representative of a terrain unit. This often requires that the lines cross the lineament of the snow features. For example, a transect should run across instead of along a valley; it should run up or down a slope to cross the slope convexities and concavities. If possible, the line may extend the full length of the terrain unit (e.g. from the top to the bottom of a slope), though it is not always feasible or necessary in the case of a flat area. Figure 12 shows the terrain units within McMaster basin and the transects used for its snow survey.

Detailed maps of the catchment with the terrain units and with the proposed transect lines should be prepared in advance of the survey. Two copies of these maps (one set as a spare) should be brought to the field, together with aerial photographs of the survey area. The photographs should best be laminated and put between hard covers or on a clipboard to avoid being bent or creased. Waterproof paper is preferred for the field book and always carry a spare pencil, a penknife and a pocket measuring tape. Where the catchments are moderately large (>10 km<sup>2</sup>) or far from the base camp, a global positioning system (GPS) is useful to locate the survey line or to return to camp in case of dense fog or a white-out. It is also a good practice NOT to make too many tracks across the catchment so that in the event of being lost without a GPS, it is still possible to follow one's own track to get back to some recognisable point.



- |   |                   |   |
|---|-------------------|---|
| F | flat valley floor | gullies shown as black lines            |
| P | plateau           | slopes of various orientations          |
| R | rolling area      | shown by arrows                         |
| V | valley            |   |
| W | wetlands/lakes    | one square represents 1 km <sup>2</sup> |

**Fig. 11. Terrain units in an area east of Blacktop Peak and west of Hot Weather Creek (lower right corner), Fosheim Peninsula, Ellesmere Island, mapped on a 1:50,000 topographic sheet. Boundaries delineated based on aerial photo interpretation, and checked in the field.**

Experience suggests that it is most efficient to survey with a pair of surveyors travelling on snowmobiles. One snowmobile tows a sled with a box *securely* fastened onto it. The box should carry the snow rods and its accessories (see snow depth measurement), a steel metre-tape for the ease of measuring shallow snow, one (or two) snow sampler, a scale robust to use in the field (though it is more accurate to weigh the snow indoors because of frequent windy conditions in the Arctic), plastic bags for snow samples and waterproof marker to mark the bags (or pre-mark the bags), a tool box with screw drivers, pliers, screws and spare parts, etc. in case there is a need to fix the sled or the snowmobile, a spare rope strong enough for towing a broken down snowmobile, snow shovels, a hand trowel to scoop up snow samples, a hand saw in case a clean snowpit face is needed, sleeping

bags, a first aid box and a rifle. There should be sufficient room in the box to carry the sampled snow back to camp but everything should be tightly packed so that items will not bounce out of the box while travelling. At least one of the snowmobiles should carry a spare can of fuel and motor oil and both snowmobiles should be filled up before leaving for the field site. Delicate or breakable objects, such as cameras or thermos bottles, should be carried by the surveyor in a pack sack. The surveyor should dress warmly, with a face mask or scarf (long snowmobile rides are always colder than one thinks) but with clothing that can be taken off easily when hot. Always carry spare food for long trips that may take the surveyors a long time to walk back to camp should the machines break down in the field.

In the field, the transect lines need not be located with great precision since micro-scale mapping is not required. Uniform spacing of depth measurements will provide systematic sampling of snow depths and there should be 10 to >50 depths per transect, depending on the length of the line and the variability of the snow within the terrain unit. At this scale of survey, each depth measurement point may be 2-5 m apart across a gully and 10-20 m apart on a long slope. Note that a zero value should be recorded for a sample point that is bare of snow. At least two density measurements should be taken along each transect. During the survey, it is better for one surveyor to park the vehicle at one end of the transect, walk along the line and probe the snow depth at regular intervals while the other surveyor takes note and travels on a snowmobile. The latter surveyor takes longer pauses to obtain snow density samples and then catches up with the other surveyor on foot. At the end of each line, both surveyors return on one machine to pick up the parked snowmobile and then move on to the next transect.

Where the snow is too deep to probe (e.g. across an incised valley), the snow surface may be surveyed by levelling. The end points of the survey line are marked and when the snow is melted, the ground surface is surveyed. The depth of snow is then obtained by plotting the two profiles (Fig. 5). If the snow survey is to be repeated in different years, prominent cairns should be piled up at the end points so that only the new snow profiles and not the topographic profile, need to be surveyed.

#### *Basin snow computation*

The mean snow depth of each transect is computed and then the values are grouped under various terrain types. Owing to the limited number of snow density measurements but low variability of density compared with snow depth, the density values for each terrain type, regardless of from which transect they belong, are pooled to obtain the overall mean for that type of terrain. The area of each terrain type within the catchment is measured from the map prepared for the survey. With these information, the mean snow water equivalent for the catchment (S) can be calculated by:

$$S = \frac{\sum_{i=1}^n \rho_i d_i a_i}{\sum_{i=1}^n a_i}$$

where  $\rho_i$ ,  $d_i$  and  $a_i$  are the density, depth and area of terrain type  $i$ , for a total of  $n$  terrain types in the catchment. Table 2 shows the end-of-winter mean snow conditions on different terrain types in

McMaster River basin near Resolute, Cornwallis Island, and the basin snow water equivalent calculated using equation 3. For comparison, the cumulative winter snowfall and the snow on the ground measured at the Resolute weather station nearby are also presented. The areally weighted snow survey results clearly demonstrate the underestimations by the weather station data and they also show the non-representativeness of extrapolating point data to a drainage basin for water balance calculations.

**Table 2**

**Snow accumulation at the end of winter on various terrain types; and comparison of McMaster basin snow storage with Resolute weather station total snowfall and snow-on-the-ground data (all values in mm water equivalent unit)**

	1976	1077	1978	1979	1980	1981	1982
Hilltop	45	25	86	37	28	22	40
Plateau	119	70	152	84	104	75	165
Flatland	108	85	222	107	119	117	129
Gully	264	302	450	572	365	305	501
Valley	496	437	440	477	523	457	430
N-slope	160	102	208	108	98	92	118
E-slope	133	98	236	124	120	108	179
S-slope	102	76	185	88	68	139	106
W-slope	165	145	201	92	130	106	186
Basin Mean	121	95	175	111	107	149	120
Total Snowfall	64	31	112	77	72	51	52
Snow on the Ground	66	46	89	119	61	61	42

The terrain-based snow survey results can also provide a meso-scale approximation of snow distribution in the catchment. This is useful to estimate the proportion of basin area that gradually become snow-free, and hence subject to evaporation losses, during the snowmelt season. Figure 12 shows the snow distribution in McMaster basin for several periods during the melt season of 1978.

The maps are derived from an end-of-winter snow survey followed by depleting the snow for various terrain units according to energy balance computations of snowmelt (Heron and Woo 1978) until the various units become snow-free (Woo *et al.* 1983).

## **REGIONAL SNOW COVER**

### *Considerations*

The regional snow cover can best be mapped using satellite imagery. At a coarse level, imagery from the NOAA AVHRR allows the mapping of snow covered areas, if the snow is distinguishable

from the clouds. At a finer resolution, LANDSAT imagery can be used though it is much more costly and the satellite passage is infrequent and does not cover all the Arctic Islands. One of the early applications was made by Grey (1976) to map the snow cover of Somerset Island and Boothia Peninsula (Fig. 13). However, only the snow cover extent and not the snow water equivalent, can be observed.

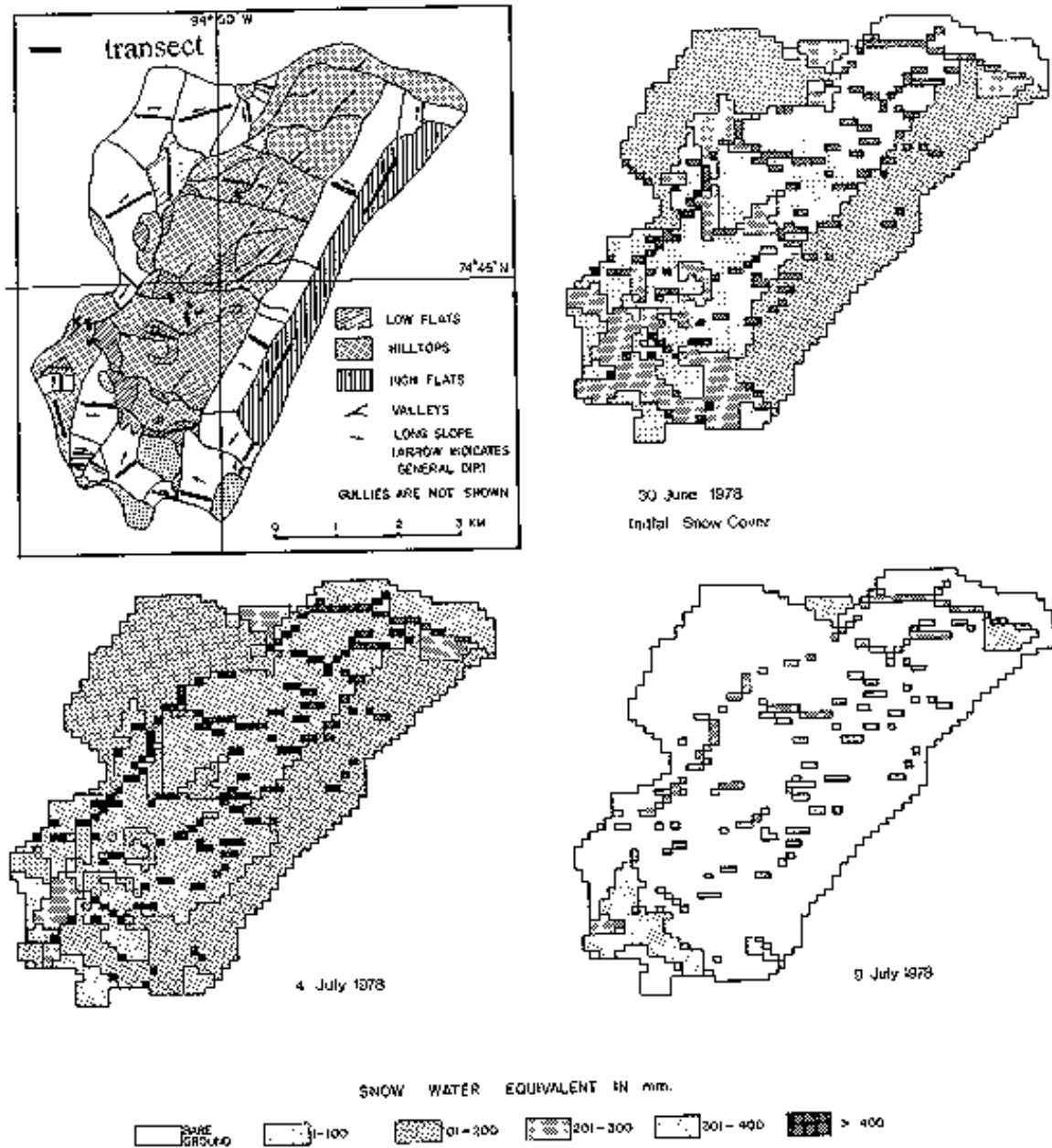
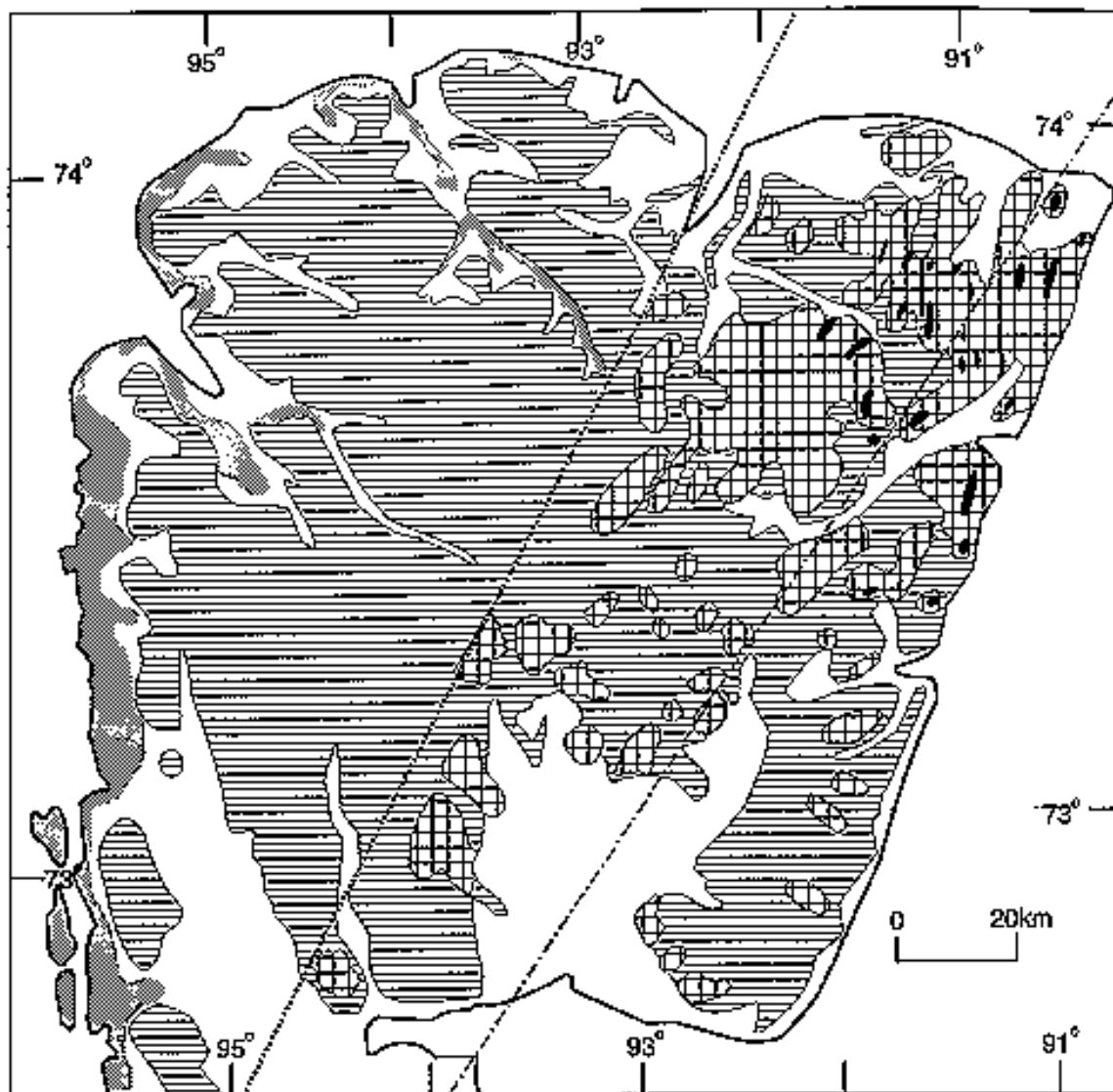


Fig. 12. Snow distribution in McMaster basin, Cornwallis Island, at the end of winter 1978 and subsequent computed snow cover conditions during the melt season. Inset shows the terrain units demarcated in the basin and the snow survey transects.



Snow cover mapping from LANDSAT imagery, 1973, northern Somerset Island (modified after B.J. Grey)

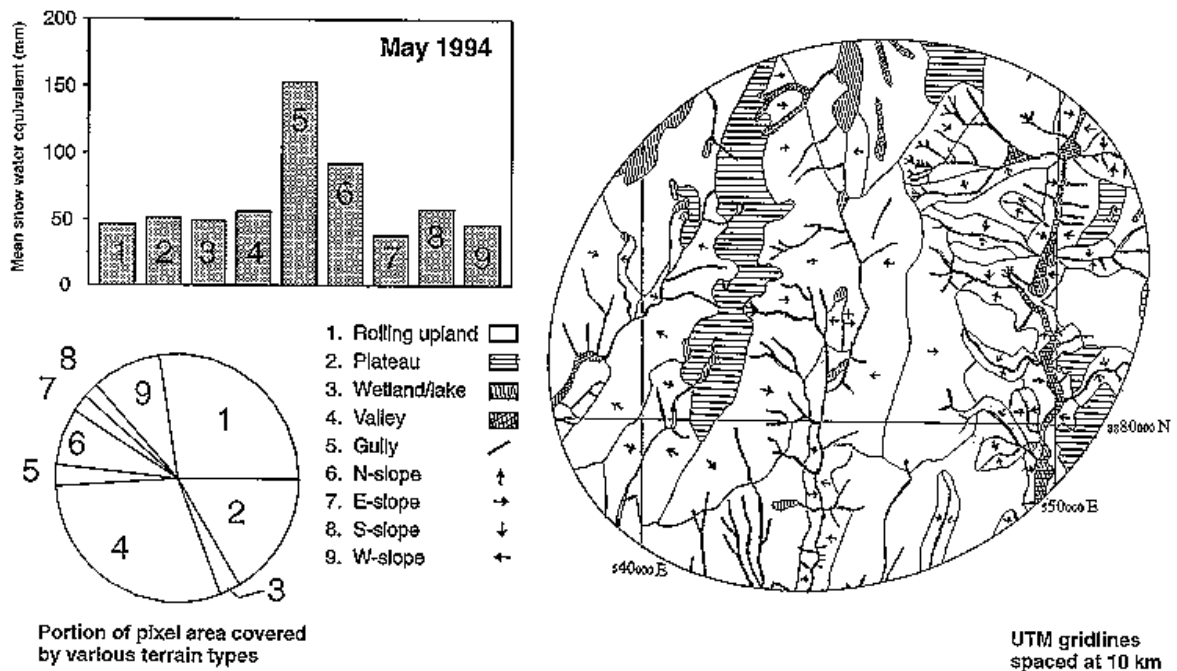
- |   |                        |   |  |
|---|------------------------|---|--|
|  | snow covered, 29 May   |  | no data east of this line before 16 June |
|  | snow covered, 16 June  |  | no data west of this line after 16 June  |
|  | snow covered, 30 June  |  | stippled areas were snow free on 29 May  |
|  | snow covered, 5 August |   |  |

Fig. 13. Snow cover of northern Somerset Island, 1973, mapped from LANDSAT imagery. Note that several passes of the satellite spread over a period of two months were needed to produce this map.

The Special Sensor Microwave Imager (SSM/I) passive microwave satellite data (brightness temperature) is a promising tool to map the snow water equivalent over large areas, as has been tested for the Canadian prairies (Goodison 1989). There is no adequate algorithm developed for many Arctic or subarctic areas to convert the brightness temperatures into snow water equivalent values, though an attempt was made by Gan (1997). To develop such an algorithm or to verify the results, ground snow survey data are required.

### Operations

For mapping the snow water equivalent of the Arctic Islands, the 85 GHz channels (horizontal and vertical polarization) are suitable since they offer the finest spatial resolution among all the SSM/I frequencies (Woo *et al.* 1995). Even so, the field of view of a pixel on the Earth's surface is an ellipse with axes measuring 13 and 15 km. To obtain the mean snow water equivalent for a pixel, extensive ground surveys are needed. Following the principle of the small basin snow survey, terrain is considered to be the prime factor that influences snow distribution. The target area for the survey is therefore mapped according to several major terrain types distinguishable on the 1:50,000 topographic maps (Fig. 11). Micro- and intermediate-scale features such as short slope facets or tundra ponds are not considered separately. For example, eight major terrain types are recognized for the Fosheim Peninsula, Ellesmere Island, including plateau, rolling upland, wetlands, lakes, flat valley floors, valleys, gullies and long slopes of various aspects (Fig. 14).



**Fig. 14.** Ellipse represents the area for one pixel of the SSM/I passive microwave satellite imagery with Hot Weather Creek on the right side. This pixel was divided into various terrain units and snow surveys were carried out in early May 1994 to obtain the water equivalence for the various terrain types. The mean snow water equivalent for this pixel, estimated by summing the products of the fractional areas and the water equivalence of various terrain types, was found to be 50 mm.

Before the field work, a terrain map should be prepared and the proposed transects marked on topographic sheets that have UTM grids. The various terrain types should not only be replicated, but should be repeated at different parts of the target area to make sure that the survey result captures the variability of snow cover conditions from one part of the region to the other. Note that because of the large area to be covered, there will be far fewer transects per unit area than for the small catchment snow survey, and the intervals between sample points along a transect will also be larger. As far as possible each transect should cross an entire terrain unit. Thus, a transect across a valley may be tens of metres long but a transect across a rolling upland may be several kilometres in length.

In view of the large areal coverage of the survey, field work requires one or more teams, each with two persons on two snowmobiles. One snowmobile tows a sturdy but manoeuvrable sled with a box containing the necessary snow survey and survival equipment (see section on small basin snow survey). Begin and finish the field day with a full meal and carry extra food and drinks (in good thermos) for emergency needs. A Global Positioning System (GPS) is vital, but also carry aerial photographs for landform identification in case the GPS fails. Carry the GPS close to the body (e.g. the inside pocket of the parka) and minimize its exposure to the air in order to protect the battery against the coldness. A combination of the GPS and the topographic map with the UTM grids allows easy identification of the transects in the field and can guide the surveyors back to camp in a heavy fog, blowing snow or white-out.

In the field operation, the logistics of going from one transect to another should be worked out in advance to avoid wasting travel time. Once a transect location is reached, the starting point is confirmed by the GPS. Except for short transects which are surveyed on foot, typical transect lines are traversed by snowmobiles. To maintain the proper orientation of the transect line during the traverse, one can drive towards a pre-oriented prominent object, such as a cleft on a distant slope or a tor on some far away hill; or move along a direction that subtends a fixed angle with the shadow of the driver; or follow the direction pointer on the GPS. To avoid bias, the snowmobiles stop at approximately equal distances, depending on the scale of the terrain feature. For example, the interval between consecutive stops on a valley transect may be 10 m, but across the rolling upland, the distance between each stop may be 30 m. It is not necessary to measure the distance exactly, and driving the snowmobiles at constant speed while keeping a mental count of a fixed number (say, 20 counts) between individual stops, the distance between stops will be roughly equal. At each stop, four snow depth measurements may be taken as one surveyor walks to the corners of a 10-metre (or 10-pace) square while the other surveyor takes note. This avoids taking single extremely deep or extremely shallow values to represent one particular site. As for density measurements, there should be at least one taken at each end of the transect and a third one taken somewhere in between.

#### *Pixel snow computation*

The snow water equivalent ( $s$  in mm) for each terrain type  $j$  is calculated as

$$s = \rho d$$

where  $\rho$  and  $d$  are snow density and snow depth. To obtain an areally weighted snow water equivalent for an area covered by a pixel, the mean snow water equivalent for each terrain type is weighted by the area covered by that terrain. For a pixel that includes  $n$  types of terrains, the weighted mean snow value  $S_p$  is

$$S_p = \frac{\sum_{j=1}^n (s_j a_j)}{\sum_{j=1}^n a_j} = \sum_{j=1}^n s_j f_j$$

with  $a_j$  being the area,  $w_j$  being the water equivalent, of terrain  $j$ , and

$$f_j = a_j / \sum_{k=1}^n a_k$$

being the fractional area within the pixel occupied by terrain  $j$ . To quantify subpixel variability, the snow condition is treated as a variate grouped into various classes, each represented by the water equivalent of a terrain type. Variability may be expressed as the standard deviation ( $v$ ) of the grouped variate

$$v = \left[ \sum_{j=1}^n f_j (s_j - S_p)^2 \right]^{0.5}$$

where  $S_p$  is the mean snow water equivalent for the pixel,  $s_j$  and  $f_j$  are the water equivalent and fractional snow coverage of terrain  $j$ .

An example is given in Figure 14 which shows the snow water equivalent for different types of terrain determined by a snow survey carried out in early May 1994 in central Fosheim Peninsula, Ellesmere Island. Using equation 5, the snow water equivalent for a pixel centred near Hot Weather Creek was found to be 50 mm.

## GENERAL REMARKS

- (1) In conducting field surveys, particularly in the remote Arctic, the most important consideration is safety. The weather can be quite unpredictable, the transportation equipment can break down and help is always farther away than one thinks. Carry spare parts, spare fuel and spare food.
- (2) Make preparations ahead of time. This includes preparing the survey equipment, obtaining whatever topographic maps and aerial photographs that are necessary, defining the survey sites or lines and making a sound plan of the logistics. Once in the field, however, be prepared to modify the plan if necessary.
- (3) Consider the accuracy of the results. This implies choosing instruments that yield low errors, ensuring sufficient precision in making the observations, obtaining representative (unbiased and adequate) measurements, and not mixing up the data from different subpopulations (e.g. pooling data from too large an area or using results obtained between snowstorms to calculate some mean values).

- (4) Efficiency of data acquisition is important (e.g. reduce the frequency of visits to a gauge for maintenance, or minimize the number of days needed for a basin survey). This may sometimes compromise the accuracy consideration but a decision has to be made regarding the error that is acceptable to the study.
- (5) The snow survey design should match the scale of investigation. Implicit in this are the considerations of spatial coverage of the survey, the snow cover pattern as affected by micro- and meso-scale features, the level of detail required and the travel time involved. The issue pertaining to snow information and scale is addressed further in another paper (Woo, 1998).

## References

- Benson, C.S. (1982) *Reassessment of winter precipitation on Alaska's Arctic slope and measurement on the flux of wind blown snow*. Geophysical Institute, University of Alaska, Fairbanks, Alaska, 26 pp.
- Benson, C.S., Holgren, B., Timmer, R. and Weller, G. (1975) Observation on the seasonal snow cover and radiation climate at Prudhoe Bay, Alaska during 1972. In: Brown, J. (ed.) *Ecological Investigations of the Tundra Biome in the Prudhoe Bay Region, Alaska*. Biological Papers of the University of Alaska, Special Report No. 2, 12-50.
- Farnes, P.E., Peterson, N.R., Goodison, B.E. and Richards, R.P. (1982) Metrication of manual snow sampling equipment by Western Snow Conference Metrication Committee. *Proceedings, 39th Eastern Snow Conference (same as Proceedings, 50th Western Snow Conference)*, Reno, Nevada, 120-132.
- Gan, T.Y. (1997) Passive microwave radiometry of snow in Mackenzie River basin and Northwest Territories. *Mackenzie Basin Impact Study Final Report*. Atmospheric Environment Services, Downsview, 100-103.
- Goodison, B.E. (1978a) Accuracy of Canadian snow gage measurements. *Journal of Applied Meteorology* 17, 1542-1548.
- Goodison, B.E. (1978b) Accuracy of snow samplers for measurement of shallow snowpacks: an update. *Proceedings 34th Eastern Snow Conference*, Hanover, New Hampshire, 36-49.
- Goodison, B.E. (1989) Determination of areal snow water equivalent on the Canadian prairies using passive microwave satellite data. *Proceedings IGARSS'89*, Vancouver, July 1989, vol.3, 1243-1246.
- Goodison, B.E. and Metcalfe, J.R. (1989) Canadian participation in the WMO solid precipitation measurement intercomparison: preliminary results. *WMO/IAHS/ETH Workshop on Precipitation Measurement, St. Moritz, Switzerland*, 3-7 December 1989, 121-125.
- Goodison, B.E. and Metcalfe, J.R. (1992) The WMO solid precipitation intercomparison: Canadian assessment. *WMO Technical Conference on Instruments and Methods of Observation (TECO-92)*, Vienna, Austria, 11-15 May 1992, 221-225.
- Goodison, B.E., Metcalfe, J.R. and Wilson, R.A. (1988) An inexpensive remote snow depth gauge. *Proceedings Third WMO Technical Conference on Instruments and Methods of Observation (TECIMO-III), WMO Instruments and Observing Methods Report No. 22*, Geneva, 111-116.
- Granberg, H.B. (1973) Indirect mapping of the snowcover for permafrost prediction at Schefferville, Quebec. *Proceedings of the Second International Conference on Permafrost, North American Contribution*, National Academy of Sciences, Washington, D.C., 113-120.
- Grey, B.J. (1976) Seasonal snowline from Landsat imagery: Somerset Island and Boothia Peninsula, 1973, 1974 and 1975. Glaciology Division, Water Resource Branch, Inland Waters Directorate, Environment Canada, Ottawa, 20 pp. plus 7 figures and 2 appendices.
- Heron, R. and Woo, M.K. (1978) Snowmelt computation for a High Arctic site. *Proceedings 35th Eastern Snow Conference*, Hanover, New Hampshire, 162-172.
- Metcalfe, J.R., Ishida, S. and Goodison, B.E. (1994) A corrected precipitation archive for the Northwest Territories. *Proceedings 6th Biannual AES/DIAND Meeting on Northern Climate* (ed. by S.J. Cohen), Mackenzie Basin Impact Study Interim Report No. 2, 110-117.

- Potter, J.G. (1965) Water content of freshly fallen snow. *Canadian Department of Transport, Meteorological Branch CIR-4232, TEC-69*, 12 pp.
- Williams, G.P. (1957) An analysis of snow cover characteristics at Aklavik and Resolute, Northwest Territories. *National Research Council of Canada, Division of Building Research Paper No. 40*, Ottawa, 12 pp.
- Woo, M.K. (1998) Arctic snow cover information for hydrological investigations at various scales. *Nordic Hydrology* 29, 245-266.
- Woo, M.K., Heron, R. and Steer, P. (1981) Catchment hydrology of a High Arctic lake. *Cold Regions Science and Technology* 5, 29-41.
- Woo, M.K. and Marsh, P. (1978) Analysis of error in the determination of snow storage for small High Arctic basins. *Journal of Applied Meteorology* 17, 1537-1541.
- Woo, M.K., Marsh, P. and Steer, P. (1983) Basin water balance in a continuous permafrost environment. *Proceedings, Fourth International Conference on Permafrost*, Fairbanks, Alaska, National Academy Press, Washington, DC, 1407-1411.
- Woo, M.K. and Sauriol, J. (1980) Channel development in snow-filled valley, Resolute, N.W.T., Canada. *Geografiska Annaler* 62A, 37-56.
- Woo, M.K., Walker, A., Yang, D.Q. and Goodison, B.E. (1995) Pixel-scale ground snow survey for passive microwave study of the arctic snow cover. *Proceedings 52nd Eastern Snow Conference*, Toronto, Ontario, 51-57.
- Xia, Z.J. and Woo, M.K. (1992) Theoretical analysis of snow-dam decay. *Journal of Glaciology* 38, 191-199.
- Yang, D.Q., Goodison, B.E., Metcalfe, J.r., Golubev, V.S., Elomaa, E., Gunther, T., Bates, R., Pangburn, T., Hanson, C.L., Emerson, D., Copaciu, V. and Milkovic, J. (1995) Accuracy of Tretyakov precipitation gauge: result of WMO intercomparison. *Hydrological Processes* 9, 877-895.
- Young, K.L. and Lewkowicz, A.G. (1988) Measurement of outflow from a snowbank with basal ice. *Journal of Glaciology* 24, 358-362.