Measuring snow water equivalent for hydrological applications: part 1, accuracy of observations

Sveta Berezovskaya*, Douglas L. Kane

Water and Environmental Research Center, University of Alaska Fairbanks, PO Box 5860, Fairbanks, Alaska 99775, USA
**Corresponding author, e-mail:* ffslb2@uaf.edu

ABSTRACT

An experiment in northern Alaska has been carried out to evaluate the accuracy of snow water equivalent (SWE) estimations in tundra snowpack. In northern basins, water constrained in the snowpack contributes significantly to both the seasonal and annual water balance. It is critical to realize and address the problems of measuring and processing observational snow data so that this data can be used properly to advance understanding of changes in hydrological systems. A combination of well-developed depth hoar at the base of tundra snowpack and extensive surficial organic soils in permafrost regions can significantly affect snow water equivalent and snow depth sampling accuracy. Experiment in Alaska's Arctic suggest that end-of-winter SWE can be overestimated from 4 to 20% depending on the sampling techniques applied. This error results from the fact that the depth of tundra snowpack is often overestimated. As observers probe the snow depth, it is difficult to recognize the snow-ground interface, and organic material is often incorporated into the snowpack depth estimate. This causes the average snow depth to be overestimated by 11 to 31%.

KEYWORDS

Arctic, Alaska, snow water equivalent, snow depth, tundra snowpack

1. INTRODUCTION

One of the themes highlighted for the 16th International Northern Research Basins Symposium is better understanding of time-space changes in hydrological systems. Our study approaches this task in terms of data quality and accuracy issues. In high latitude watersheds, end-of-winter snow water equivalent (SWE) is a key input for snowmelt runoff analysis and prediction. Even though researchers have made great advances in developing modeling tools to describe snow evolution processes (Liston and Elder, 2006; Liston *et al*., 2007), we still face the challenge of reproducing spatial and temporal snow cover variability accurately, due to the complex interactions involved and limited observational data available for the remote arctic regions. The few snow data available are often marred by problems of measuring and processing. If we can successfully address these limitations, snow data can be used properly to advance our understanding of changes in hydrological systems.

This study is aimed at evaluating estimates of basin average end-of-winter SWE measured in tundra snowpack. Our data comes from Alaska's Arctic, north of the Brooks Range. This area is characterized by *tundra snow*, which differs from lower latitude snowpack in that it is colder, on average shallower, and host to steeper temperature gradients (Benson and Sturm, 1993). Certain properties of tundra snowpack affect SWE sampling accuracy. First, it consists of hard, high-density, wind-packed layers that can be difficult to penetrate with snow sampling instruments. Second, a coarse, lower density depth hoar layer prevails at the base of the snowpack (Sturm and Benson, 2004). Depth hoar crystals can easily fall out of the SWE sampler, so observers have to take care to ensure that the whole snow column is captured.

The snow-ground interface is usually a subtle boundary of large depth hoar crystals and soft organic material. The presence of the organic layer over impermeably frozen mineral soil is typical for Alaska's Arctic. On permafrost sites, lower annual soil temperatures cause reduced rates of plant debris decomposition. As a result a thick, dense ground cover (moss, lichens, vascular plant roots and litter) effectively insulates the mineral soil, lowering soil temperatures and furthering development of organic material referred to as the "*organic layer*". The depth of this organic layer is about 10 - 20 cm, but in some places depth can reach 50 cm (Slaughter and Kane, 1979). By winter's end, the organic layer is very desiccated. The steep temperature gradient within the snowpack, accompanied by a steep vapor pressure gradient, leads to a vertical flux of water vapor, up to 0.025 g cm^{-2} day^{-1} (Slaughter and Benson, 1986). The vertical gradient can cause up to 50% of the water initially available in the organic layer to migrate into the snowpack over the course of the winter.

As far as snowpack measurements go, a snow depth probe can easily penetrate this fluffy, relatively dry organic mat, so it is often inadvertently incorporated into the measured snow depth. This brief paper addresses how the organic layer affects snow depth measurements and snow water equivalent estimates of tundra snowpack. The discussion below covers SWE sampling techniques, results of a snow depth accuracy experiment, and the effect of snow depth overestimation on SWE.

2. SWE SAMPLING TECHNIQUE

The standard method of obtaining SWE is by gravimetric measurement using a sample core. This method serves as the basis for snow surveys in many countries and allows researchers to determine the depth, average density and water equivalent of snowpack. A snow survey usually includes both gravimetric SWE sampling and snow depth measurements collected over a large area; this technique is often referred to as "double sampling". Snowpack is extremely heterogeneous in Alaska (Sturm and Benson, 2003). Double sampling yields an areal SWE estimate with a lower variance than is possible by collecting snow cores only. Rovansek *et al*. (1993) showed that double sampling provides improved SWE estimates and recommended sampling 12 to 15 snow depths for each snow core. However, this optimal ratio of snow depths to water equivalent appeared to vary greatly (from 1 to 23), depending on weather and snow conditions. Currently, we use an optimal ratio of 10; that is, five snow cores are accompanied by 50 depths, taken every 1 meter along a randomly chosen L-shaped transect.

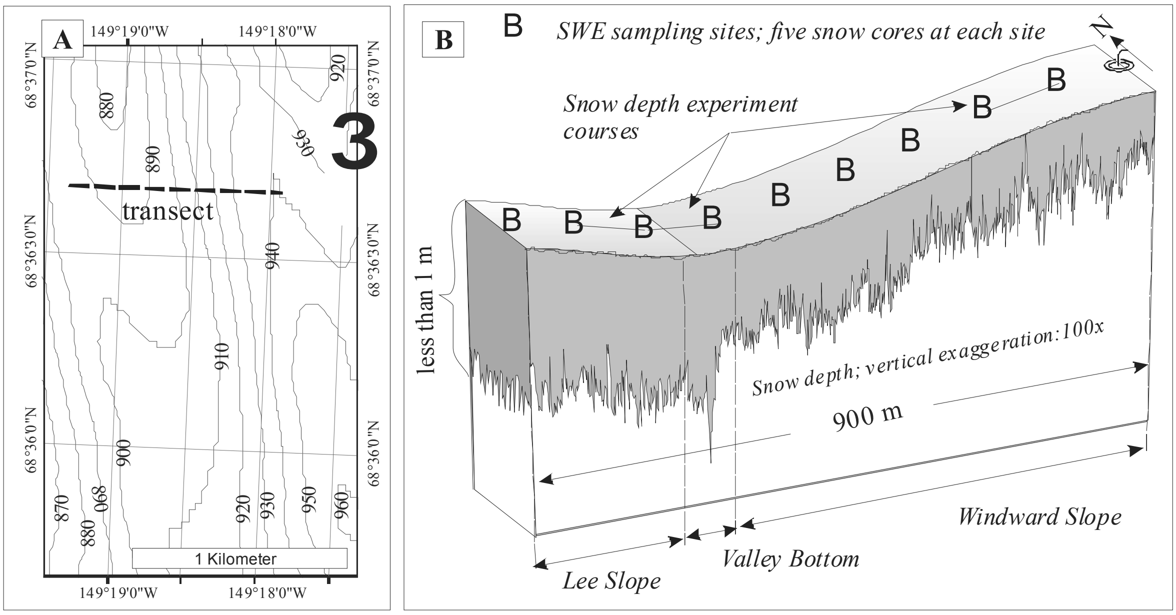

Fig. 1. The Imnavait Creek basin at the Kuparuk River headwaters (A). The Imnavait Creek basin "east to west" transect (B).

Snow cores are sampled using fiberglass tube ("Adirondak") with an inside area of 35.7 cm^2, equipped with metal teeth on the lower end to cut through dense layers. The advantage of the Adirondak for shallow snowpack is that it has a larger diameter than many other types of snow tubes and thus provides a larger sample. To obtain a snow core, the Adirondak tube is pushed vertically through the snow; at this point the snow depth is recorded. The tube is then driven further into the organic layer and tipped sideways, retaining the vegetation plug that ensures the complete snow column was sampled. The vegetation plug is then removed and the snow is collected to be weighing later, in the laboratory. This procedure allows estimating both snow density and snow water equivalent.

To obtain areal average snow depth, an additional fifty depth measurements are collected using a T-shaped graduated rod (T-probe). The probe is simply pushed through the snow to the snow-ground interface, often including some organic material into the estimated snow depth. To quantify this effect on a basin's average snow depth, we conducted a snow depth experiment (see section 6) in the Imnavait Creek basin.

3. IMNAVAIT CREEK BASIN DESCRIPTION

The study domain covered 2.2 km^2 of Imnavait Creek, a sub-domain of Alaska's Arctic, located in the northern foothills of the Brooks Range at 68.613°N, 149.32°W (Figure 1A). The topography of Imnavait Creek is characterized by gently rolling hills best described by wavelengths of 1 km and amplitudes of 25-75 m. The hills are elongated on south- and north-trending ridges. The west-facing slope is much gentler and longer than the east-facing slope; it constitutes 78% of the basin area.

The Imnavait Creek watershed falls within a large region of sedge tussocks and mosses that cover much of northern Alaska. Occasional groupings of willows, approximately 40 cm high, occur in hillside water tracts and in the valley bottom. The surface organic soils vary from live organic material at the surface to partially decomposed organic matter between 10 and 20 cm in depth. Silt, overlying a glacial till, makes up the mineral soil (Kane *et al*, 1989). Overall, the topography and vegetation of Imnavait Creek are representative of the foothills area north of the Brooks Range.

4. DATA

Snow depths were collected every meter across the Imnavait basin transect (Figure 1A). In 2006, 900 snow depths were taken using the standard snow sampling technique, and 300 snow depths were measured within the snow depth experiment (see section 6). In addition, 50 snow water equivalent samples were taken along the same transect. It should be noted that research teams in this area measure 900 snow depths and 50 SWE every year at the peak of snow accumulation, usually at the end of April. Most of the data in this study are from 2006, unless another year is specified.

5. SNOW DEPTH EXPERIMENT

This simple snow depth experiment included sampling by two methods. First, snow depths were taken every meter along a 900 m transect of the Imnavait Creek basin by experienced observer. Further, we refer to these snow depth as *"standard"*.

Second, measurements were taken at the top and bottom of the snowpack, through the three 100 m courses in the valley bottom, and on the windward and lee slopes (Figure 1B). The probe was pushed though the snow until it hit impermeable ground. The first record was taken at the top of the snowpack. Afterwards, the snow was shoveled to create access to the snow-ground interface, and the second record was taken at the bottom of the snowpack (Figure 2). As snowpack forms, snow grains fill in the upper vegetation; the boundary is fuzzy and determining the bottom of the snowpack is quite a subjective process. For this study, the "bottom" was assumed to be when, to visual observation, the interface appeared to be more than 80% vegetation by volume. This sampling method, even though fairly labor intensive, yields measurements that more closely reflect real snowpack depth. Further, the difference between the top and bottom records is referred to as *"true"* snow depth, as this number represent our most accurate efforts.

Results showed that the average depth of organics is 10 cm on leeward and windward slopes, ranging from 0 to 24 cm. Average organic layer depth for the valley bottom course is slightly less (8 cm) due to the presence of ice in the channel (Table 1). True snow depths were compared against the standard snow depths. Figure 3 suggests that standard snow depth is generally overestimated in the Imnavait Creek area. For 2006, the average difference between standard and true depths is 9 cm for the slopes and 5 cm for the valley bottom. Given the relatively shallow snowpack, overestimation is about 11-31% of snow depth (Table 1).

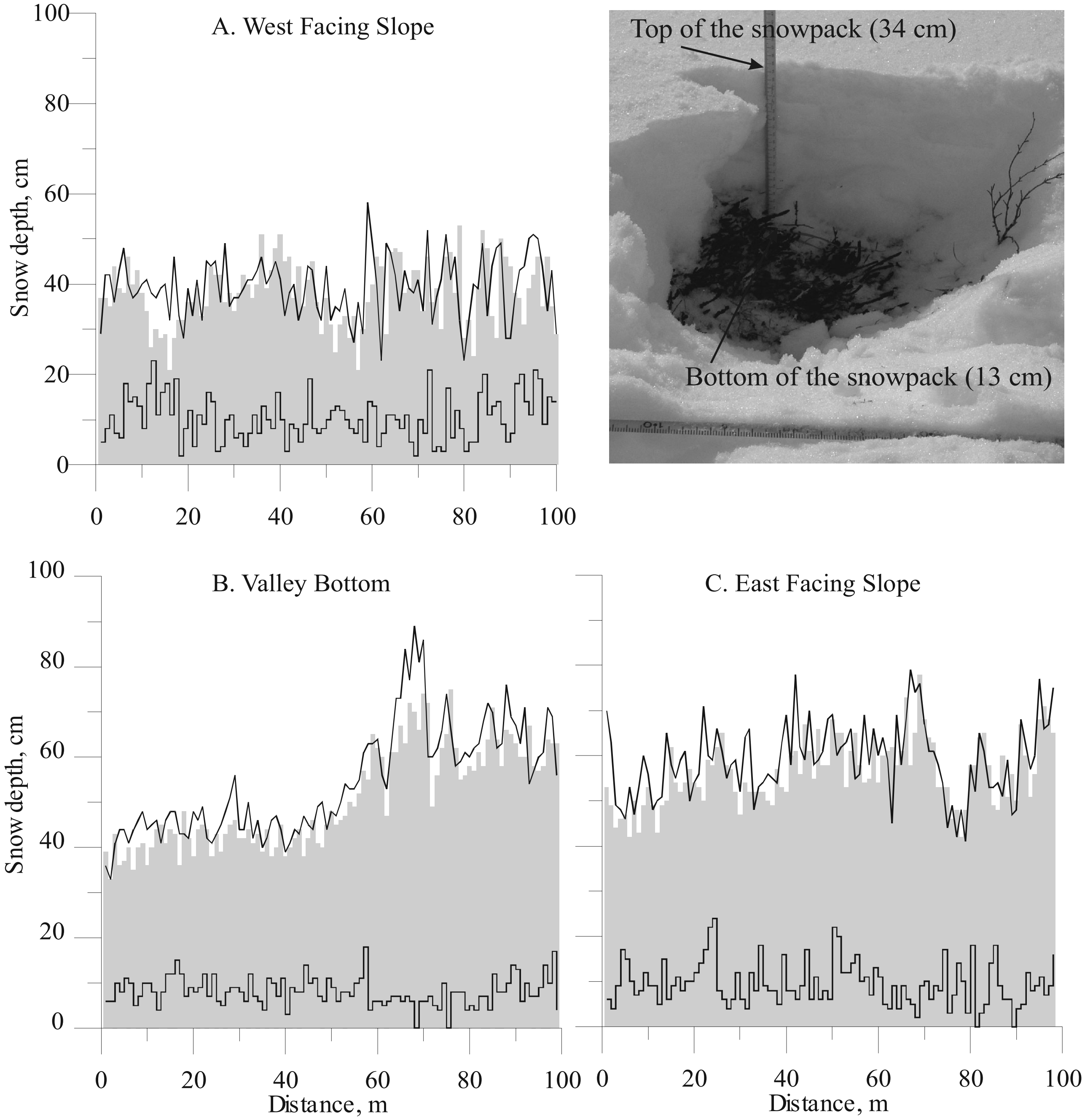

Fig. 2. Snow depth experiment. Top black line shows observations taken at the top of snowpack from impermeable frozen ground; black step line shows observations taken at the bottom of the snowpack (i.e. 0 is ice on the river channel). Grey filled area represents standard snow depth measurements.

Table 1 - Impact of organic layer on snow depth measurements, based on 100 points sampled at each location.

Snow depth, cm	Valley Bottom	Lee Slope	Windward Slope
Standard snow depth	51	57	38
Top*	54	58	39
Bottom*	8	10	10
True snow depth	46	48	29
Difference	5	9	9
Difference, %	11	16	31

* Rod is pushed all the way to the impermeable ground. First record is taken at the top of the snowpack. Afterwards, hole is shoveled to take a record at the bottom of the snowpack. The difference between two is assumed to be a "true" snow depth.

6. EFFECT SNOW DEPTH OVERESTIMATION ON SWE ESTIMATES

Snow water equivalent is defined as

$$SWE = (SD * \rho_s) / \rho_w \tag{1}$$

where ρ_s is snow density, ρ_w is water density and SD is snow depth. Alternatively, snow water equivalent can also be formulated without snow depth. Density is defined as the ratio of mass per unit volume. Since the mass of the sample is the same whether it is snow or water, the relationship can be expressed using respective densities and volumes.

$$\rho_s * A * SD = M = \rho_w * A * SWE \tag{2}$$

where A is the inside area of the probe and M is the sample mass (water or snow). Snow water equivalent can also be defined as

$$SWE = M / (\rho_w * A) \tag{3}$$

In the following discussion, SWE estimated from Eq. 1 is referred as "*standard" SWE* and SWE estimated from Eq. 3 is called "*core" SWE*. Core SWE is estimated without using any snow depth information.

To mitigate any individual snow depth measurement errors, the basin water equivalent was estimated from fifty core SWE samples. Ten SWE sites (5 samples at each site) are equally distributed along the Imnavait transect at 100 meter interval (Figure 2). Since these sites are regularly distributed across the basin, capturing all terrain and vegetation classes, we assume that 50 SWE samples provide a reasonable basin average.

Table 2 - Basin average SWE, estimated from the standard sampling technique (standard), average transect snow depth and basin average density (transect) and fifty snow cores without snow depth measurements (snow cores).

Year	Snow cores	Standard	%	Transect	%
2001*	119	126	6	129	9
2005	119	124	5	123	4
2006	80	95	19	90	12
2007	100	120	20	112	12

* Forty snow cores were sampled in 2001, four at each site.

Core SWE often underestimates the water amount contained in the snowpack (M.Sturm, personal communication). In attempting to quantify underestimation in shallow tundra snowpack conditions, Woo *et al.* (1997) showed that a larger tube diameter increases the accuracy of density determination; he also showed that the Canadian sampler (similar to the Adirondak in diameter) captures snow density within 5% of snow pit estimates. In May 2007, we compared Adirondak densities versus stratigraphic method densities and observed similar results, i.e. sometimes Adirondak underestimated snow densities. For further analysis, we assume that in average Adirondak accuracy varies from 0 to 5 %.

Results show that the standard procedure (five snow densities together with fifty snow depth measurements) yields an estimated 95 mm of SWE in the Imnavait basin. Often many (on the order of 1000) snow depths are sampled along the traverse at 1 m intervals, and then snow density is used to estimate areal SWE (Eq. 1). The transect average snow depth, together with the average density based on the snow cores, yields 90 mm SWE. An average of 50 snow cores suggests that there is 80 mm SWE in the basin. Table 2 shows that in 2001, 2005 and 2006, standard and transect double sampling techniques provide larger amounts of water in the snowpack compared to the core SWEs. Given that snow depth is overestimated, the standard double sampling technique can overestimate SWE up to 20%. SWE estimated by the transect technique is 4 - 12% higher than snow coring.

7. DISCUSSION

As shown above, using average snow depth, acquired with standard snow depth probes, to calculate SWE can cause overestimation of tundra snowpack water content. The difficulty in these interpretations is that actual, accurate SWE is unknown.

Any type of correction to existing snow depth records is difficult to effect, because the error varies strongly from observer to observer, as well as depending on the snow and soil conditions at each site. Avoiding snow depth overestimation will require either adjusting instrumentation or modifying sampling technique. For reliable snow depth observations, instrumentation should reach the ground, but does not penetrate further into the organic material.

Given the extreme snow cover heterogeneity, particularly in the Arctic tundra, we still believe that the double sampling technique gives a reasonable estimate of *spatial snow variability* at each site (Kane and Berezovskaya, 2007). This information can be used to locate a representative place to sample snow cores and to estimate snow water equivalent from snow cores only. For example, at each site an observer would still take 50 depth measurements, then use these to locate an average spot for snow core sampling.

8. CONCLUSIONS

This study suggests that snow water equivalent from any type of double sampling technique tends to overestimate SWE. The experiment in the Imnavait Creek area shows that the depth of tundra snowpack is typically overestimated, because low density organic material (overlaying impermeably frozen ground) may not always be distinguished by the probing observer. Error is larger for the sedge tussocks areas on the windward slopes with shallow snow cover and decreases toward the valley bottom due to the snow-river ice interface at the bottom of the snowpack. In April 2006, the average snow depth based on 100 points courses was overestimated from 11 to 31%. Whereas snow depths show a systematic overestimation error, estimations by snow core tend to be close to, or to underestimate, SWE. The difference between snow core and double sampling SWEs varies from 4 to 20%. The reality is that the true SWE values lie somewhere in between.

ACKNOWLEDGMENTS

UAF/WERC faculty, staff and students collect snow data each year; we greatly appreciate their contribution. Field work by Molly Chambers and Ken Irving contributed a great deal. The authors also greatly appreciate valuable suggestions made by Matthew Sturm. This work is supported through the National Science Foundation, Office of Polar Programs, grant no. OPP-0335941.

REFERENCES

Benson, C.S., W. Harrison, J. Gosink, L. Mayo and D. Trabant (1986) The role of glacierized basins in Alaskan Hydrology, in Kane, D.L., ed., *Symposium: Cold Regions Hydrology: American Water Resources Assoc.*, 471-483

Benson, C. S. (1982) Reassessment of winter precipitation on Alaska's Arctic Slope and measurements on the flux of wind blown snow. *Geophysical Institute, University of Alaska Report UAG R-288*, September 1982, pp.26

Benson, C. S. and M. Sturm (1993) Structure and wind transport of seasonal snow on the Arctic Slope of Alaska. *Annals of Glaciol.,* **18**, 261-267

Kane, D.L. and S. Berezovskaya (2007) Strategies for measuring snow water equivalent for hydrological applications: part 2, spatial distribution. *16th Northern Research Basin Symp* this volume, Petrazovodsk, Russia, Aug 27 – Sep 2.

Kane, D.L., Hinzman, C. S. Benson and K. R. Everett (1989) Hydrology of Imnavait Creek, an arctic watershed. *Holarctic Ecology* **12**, 262-269

Kane, D.L., L.D. Hinzman, C.S. Benson and G.E. Liston (1991) Snow hydrology of a headwater arctic basin 1. Physical measurements and process studies. *Water Resources Research*, **27**(6), 1099-1109

Kane, D.L., J.N. Luthin and G.S. Taylor (1978) Heat and mass transfer in cold regions soils. *IWR-65, Institute of Water Resources*, UAF

Liston, G. E. and K. Elder (2006) A distributed snow-evolution modeling system (SnowModel). *J. Hydrometeorology*, **7**, 1259-1276

Liston G.E., R. B. Haehnel, M. Sturm, C. A. Hiemstra, S. Berezovskaya and R. D. Tabler (2007) Simulating Complex Snow Distributions in Windy Environments using SnowTran-3D, *J. Glaciology*, **53**(181), 241-256

Rovansek, R.J., D.L. Kane and L.D. Hinzman (1993) Improving estimates of snowpack water equivalent using double sampling. *Proceedings of the 61st Western Snow Conference*, 157-163

Sturm, M. and C. S. Benson (2004) Scales of Spatial Heterogeneity for Perennial and Seasonal Snow Layers. *Annals of Glaciol.* **38**, 253–260

Woo, M-K (1997) A guide for ground based measurement of the arctic snow cover. *Canadian Snow Data CD*, Meteorological Service of Canada, Downsview, Ontario, p.30