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NATIONAL RESEARCH COUNCIL OF CANADA
ASSOCIATE COMMITTEE ON SOIL AND SNOW MECHANICS

TECHNICAL MEMORANDUM NO. 14

CANADIAN PAPERS PRESENTED AT THE
OSLO MEETINGS OF THE
INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS
AUGUST, 1948

ANALYZED

Ottawa
December 1948

PREFACE

The International Union of Geodesy and Geophysics held its first postwar meeting in Oslo in August, 1948. This important meeting was attended by ten delegates from Canada, the chief delegate being Dr. J. T. Wilson of the University of Toronto, who is Chairman of the Council's Associate Committee on Geodesy and Geophysics and also a member of the Associate Committee on Soil and Snow Mechanics.

One of the constituent bodies of the Union is the International Association of Hydrology. This operates through a number of Commissions, one of which is the Commission on Snow and Ice (previously known as the Commission on Snow and Glaciers). The meetings of this Commission were of special interest to Canada in view of the importance of snow and ice in the Dominion.

Accordingly, the undersigned was privileged to attend these meetings as Chairman of the Associate Committee on Soil and Snow Mechanics, accompanied by Mr. G. J. Klein, and Mr. P. D. Baird, both being members of the Associate Committee. Four Canadian papers were presented to the Oslo meeting and the Associate Committee has pleasure in reproducing these papers in this Technical Memorandum for general convenience. In addition, the Committee has been privileged to include also a paper by Mr. O. H. Hoover of the Dominion Water and Power Bureau, which was prepared for the Washington meeting of the International Association of Hydrology, held in 1939, but was not published at that time.

These papers point the way to Canadian studies in the field of snow and ice which are now being planned by the National Research Council through its Divisions of Mechanical Engineering and Building Research.

Ottawa, December, 1949



R. F. Legget
Director

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REPORT ON EXPEDITION SNOW CORNICE

by

P. D. Baird
Director, Montreal Office,
Arctic Institute of North America

and

D. J. Salt, University of Toronto

Note: An illustrated account of the early stages of this Expedition was presented to the Oslo meeting of the International Association of Hydrology by Mr. Baird. This report deals with the scientific work assisted financially by the Associate Committee on Soil and Snow Mechanics of the National Research Council. More general accounts of the Expedition are to be found as follows:

Journal of Arctic Institute of North America.
Volume 1, No. 2, 1948 (autumn). pp.107-112

Science Illustrated. Volume 4, No. 3, March,
1949. pp. 21-26.

REPORT ON EXPEDITION SNOW CORNICE

Expedition 'Snow Cornice' to the Seward Glacier, Yukon Territory, conceived and directed by Walter A. Wood of New York, was a co-operative, scientific venture sponsored by the Arctic Institute of North America during the summer of 1948.

It was decided that in view of the international character of the Institute and of the territory to be investigated (the Yukon-Alaska border) it was most desirable to have Canadian as well as American personnel included in the party.

An application for a grant was made to the National Research Council to ensure such participation of Canadians through the Associate Committees of Geodesy and Geophysics and Soil and Snow Mechanics. Grants were made equally through these Committees, totalling initially \$3000 and later increased to \$4000.

The personnel who were able to take part as a result of this were P.D. Baird of the Montreal Office of the Arctic Institute, D.J. Salt from the Geophysics Department of Toronto University, and A. Bruce Robertson from the Dept. of Medicine of that University as assistant to the geophysicist and medical officer of the party.

The program of the Expedition was mainly glaciological (under the direction of Dr. Robert P. Sharp of the California Institute of Technology) but also included studies of the geology and botany of the area and meteorological observations. Daily reports were radioed to first order U.S. Weather Stations of measurements taken on instruments provided by the U.S. Weather Bureau and the Dominion Meteorological Services. In addition, local ground control and ground stereogrammetrical surveys were established.

In addition to the team supported by the above-mentioned grant, 17 persons took part in the expedition including another team of three scientists of the National Research Council. (1)

The first Canadian party left Eastern Canada in early June, Baird travelling with the leader to assist in the logistics and initial stages of the establishment on the glacier, Salt and Robertson travelling via Whitehorse, Y.T., where plans had been made to transport them and Canadian equipment directly to the Glacier by the expedition aircraft.

The late arrival of this plane, which was specially equipped for the operation, delayed the start of the field work considerably. The first landing on the Seward Glacier was made on June 30 and Baird and M.M. Miller of Columbia were left to set up camps and start observations. The remainder of the Canadian group, after technical and customs difficulties had caused a change in plans, reached the Glacier July 17 after Baird had left for other engagements.

The logistical arrangements continued to be difficult and much equipment had to be dropped by parachute instead of being landed on the Glacier.

General studies were intended on the immense accumulation area of the Glacier. Thermal borings were made down to 204 feet but when achieved (mid-July) the temperatures found were uniformly zero centigrade, a surprisingly early dissipation of the winter's cold wave. Pits were made down to 50 feet and crevasses deeper than this descended to obtain density, melt water, and other physical characteristics of the firn. Stakes were also set to observe horizontal and vertical movements of the firn mass. The observations with which the Canadian party were most concerned were of the thickness of the glacier. Three methods were tried - seismic, acoustical (see Northwood above) and radar by B. Steenson of the California Institute of Technology. The latter two were frankly experimental and the seismic method was expected to provide a check on their accuracy.

The seismic equipment provided, however, was old and did not function satisfactorily; considerable difficulty was experienced in getting sufficient energy into the firn for satisfactory reflections. The radar method, using a somewhat modified apparatus with the antennae buried in the firn, produced a very reasonable transverse profile across a small tributary glacier. This method seems the most promising for future studies.

The seismic results as reported by D.J. Salt are given below:

Operations:

The equipment was assembled on a sled for ease of movement and test shots were carried on near our camp.

Mounted on the sled was a panel of six amplifiers, an expander control and a circuit control panel. Each amplifier had a separate 90 volt "B" supply. The equipment had been made by The Engineering Laboratories of Tulsa, Oklahoma.

On top of the amplifier case was mounted a six channel camera recorder with oil damped galvanometers. The motor-driven film spool, damaged on delivery at the Glacier, was replaced by a crude hand-cranked device. Timing lines were put on the record every one hundredth of a second by a vibrating reed which interrupted a light beam. The timing lines were not well focussed because of a casting which had broken in the parachute drop. Over the recorder was a light-proof sateen bag with elastic fitted hand and head holes to permit operation while preventing fogging of the record paper.

To the left of the amplifiers was the tuning fork and its amplifying circuit to control the timing device, mounted on a box containing storage batteries for the filament supply.

There were six large geophones, all variable reluctance type, damped with British American No. 250 transmission oil.

The charges of 60 percent high-velocity gelatin were fired by electric blasting caps for seismograph use; the caps were detonated by a plunger type of blaster.

After working in the glacier outlet area for about two weeks, hope of obtaining results with the equipment was abandoned and the equipment moved back to the airstrip camp where conditions were more suitable for operation and there was hope of at least slight success.

Results

The seismic work on the South Crillon and Klooch Glaciers, both Alaskan glaciers (2), was carried out when the firn line was at its highest point and the dynamite charges were set off in natural occurring vertical water pipes in the ice, which provide a good path for the passage of seismic energy.

In the deep firn of the Seward Glacier it was impossible to get enough energy to penetrate the snow cover to reach a reflecting horizon. Investigation in crevasses revealed that snow conditions were unfavourable throughout the upper layers to a depth of approximately 70 feet so that without any sort of drill rig our work was hampered quite considerably.

The available apparatus used for melting holes in the firn would have been satisfactory but the diameter of the dynamite sticks was too large to be forced down the hole. We therefore moved the equipment to the landing strip and fired the charges of dynamite in crevasses adjacent to the camp. This gave some improvement in the results.

Depth Determinations:

We were finally able to obtain echoes from what was assumed to be the ice rock interface at the camp south of the landing strip.

The following curves were obtained by plotting the first arrival time (time of refracted wave) against the horizontal distance of the detector from the shot point:

The curves in Figure 1 were obtained at the Seward gap camp;

The curves in Figure 2 were obtained by setting off charges in a crevasse near the airstrip;

The curves in Figure 3 were obtained by setting off 5-pound charges in another nearby crevasse which had 20 feet of water in the bottom. It was on these records (D-1, D-3, D-4,) and only on these records that echoes appeared. Even putting the dynamite in a crevasse and tamping it with snow was not effective.

More than one echo appeared on each of these records but only one appeared consistently.

Echoes from crevasses were eliminated by shooting in three directions as shown in Figure 4, and noting which of the echoes disappeared.

Record No.	Geophone No.	Detector to S.P. Distance in feet	Arrival Time or Echo in Milliseconds.
D-1	1	100	384
	6	500	384
D-3	1	100	361
	6	500	363
D-4	1	100	394
	6	500	393

There is some discrepancy in these arrival times but the reason for this is the difficulty in finding the time break on the record. When only the firing circuit is in operation and only a cap is fired, the time break appears quite clearly, but when the geophones are in operation marks appear on the traces very similar to the time break, both before and after the cap is fired; this makes choice of the correct zero time position very difficult and sometimes impossible. This does not affect

the velocity determined from the curve but does affect its intercept time at zero distance.

A possible explanation of these small peaks over the record is that movement of the geophone pots in the holes due to melting of the snow causes their appearance on the records.

Depth Calculation:

Assuming a simple straight line reflection path through a single velocity layer we get for the depth Z:

$$Z = \frac{1}{2} \sqrt{v^2 t^2 - x^2}$$

where x is the horizontal distance from the shot point to the detector or geophone.

t is the arrival time after having applied the necessary corrections to it.

v is the velocity in the layer

For x = 100 ft. the average t = 380 millisecs. and

v = 8500 ft./sec.

Corrections to be applied to t.

Weathering Correction:

Usually t_i is known: (t_i = the intercept time and is determined from the graph in fig. 3). There is no reliable value of t_i but w_i the thickness of the weathered layer is known to be about 60 feet. This was measured in a crevasse as the distance from the surface to the water table.

v_0 from determinations in the gap camp is approximately 5000 ft./sec. (see fig. 1)

v_1 is approximately 8500 ft./sec. (see fig. 2)

Therefore we can calculate

$$t_i = 9.7 \text{ millisecs.}$$

Now t_w is the correction to be subtracted from the arrival time and

$$t_w = t_i \sqrt{\frac{v_1 - v_0}{v_1 + v_0}} = 4.94 \text{ millisecs.}$$

Correction to be added to arrival time to correct for shot point being 10' below the base of the weathered layer.

$$t' = \frac{\Delta E}{v_1}$$

where t' is the time correction.

ΔE is the elevation difference between the shot point and the base of the weathered layer.

$$t' = 1.2 \text{ milliseecs.}$$

$$c_1 = -t_w + t' = -4 \text{ milliseecs.}$$

$$t = 376 \text{ milliseecs and } Z = 1600 \text{ ft.}$$

CONCLUSIONS:

The depth of ice and snow at airstrip camp was 1600 ± 100 feet.

From a study of Figure 3 and Figure 4, it can be seen that the seismic velocity parallel to the crevasse direction, is higher than that at 45 degrees to the crevasse. Record D-1, shot perpendicular to the crevasse, did not provide enough information to give conclusive results but it does seem to indicate a velocity lower than that of the other two.

This effect is probably due to the discontinuities in the ice due to crevasses and small fractures.

While not able to present any long list of depth determination, I feel that we have overcome most of the difficulties peculiar to this area in carrying out seismic work and anyone who intends doing similar work on ice fields and glaciers might study these recommendations.

1. If there is any doubt as to the depth of snow cover over the ice than have a drill rig in your complement of equipment. A simple heat boring device operated by electric current from a gasoline driven generator is satisfactory. If it is possible to dig through the snow cover then a simple ice chopper made from a wood chisel attached to a long wooden shaft would be useful.

2. The dynamite has to be tamped with water; if a heat boring device is used to drill the hole after ice is reached the water formed will not run away.

3. The geophones should be watertight and cable from them should be long enough so that the geophone may be buried. This prevents shocks due to their dropping down in the hole as melting proceeds. It also keeps the damping oil at a fairly constant temperature, preventing it from heating up by the sun.

4. Unless it is necessary to use crevasses in which to fire the charges; avoid working in a crevassed zone. Echoes from crevasse walls tend to mask the first echoes and the seismic velocity varies with the direction of the profile with respect to the crevasse direction. (see Figure 4)

5. Use amplifiers which do not tend to oscillate as the "B" battery resistance increases. We found it impossible with the equipment on hand to prevent oscillations. Cold batteries produce an effect similar to that caused by old batteries, consequently our equipment was always oscillating and in the mornings when the equipment was very cold, having been standing all night, it was severe.

6. Electromagnetic damping in the geophones and galvanometers is preferred because of the wide range of temperatures to which the instruments are subjected.

7. Develop the records in a roll film tank (we did not have one with us at the time but used large developer pots); it requires much less developer than any other method and solutions can be kept at the required temperature much more easily. A box of rockwool is a useful gadget to put the developer tank in while development is in progress.

8. Use light portable equipment where possible. Seismic equipment for use in rough terrain has been designed and is available.

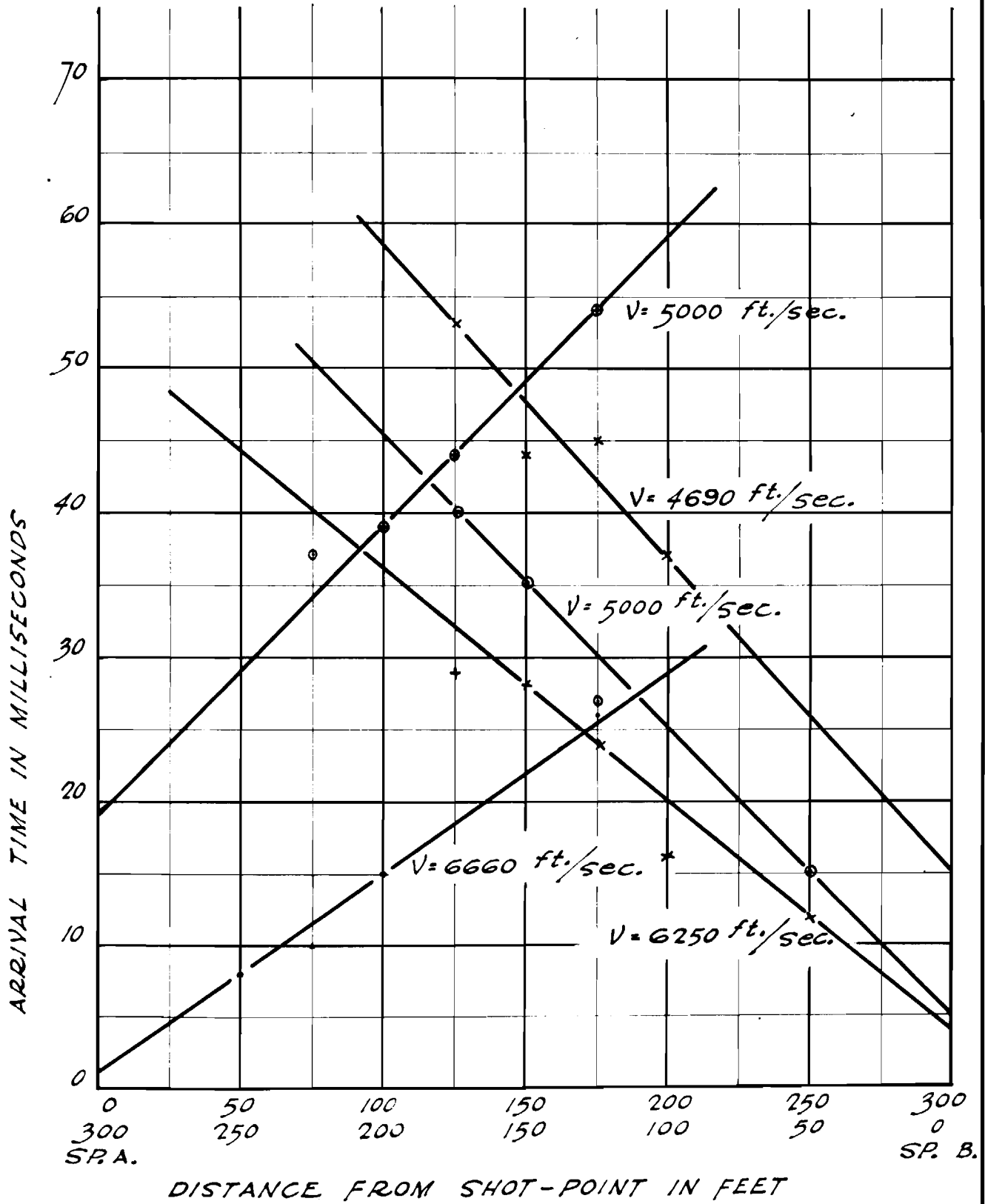
9. I do not think that shielded geophone cable is essential although some of the hash on the records may be due to pick up from atmospherics; however, it did not seem too serious during our operations.

The glaciological team led by Dr. Sharp intends to return to the Seward Glacier in May 1949. The establishment of a research station hut on a nunatak at 6100 feet to enable such future studies to take place year by year was one of the most important features of the 1948 expedition which in many respects other than that of the seismic apparatus was a trial run of methods. The foundation has been laid for a continuing co-operative scientific venture in a unique and interesting corner of Canada.

1. Depth measurements in the Seward ice fields by sonic echo ranging. N.R.C. Div. of Physics Rept. No. PS-300 by T.D. Northwood and F.W. Simpson, Dec. 1948.
2. Seismic soundings on the S. Crillon and Kloooh glaciers, Geophysical Journal, Vol. 87, No. 496, 1936.

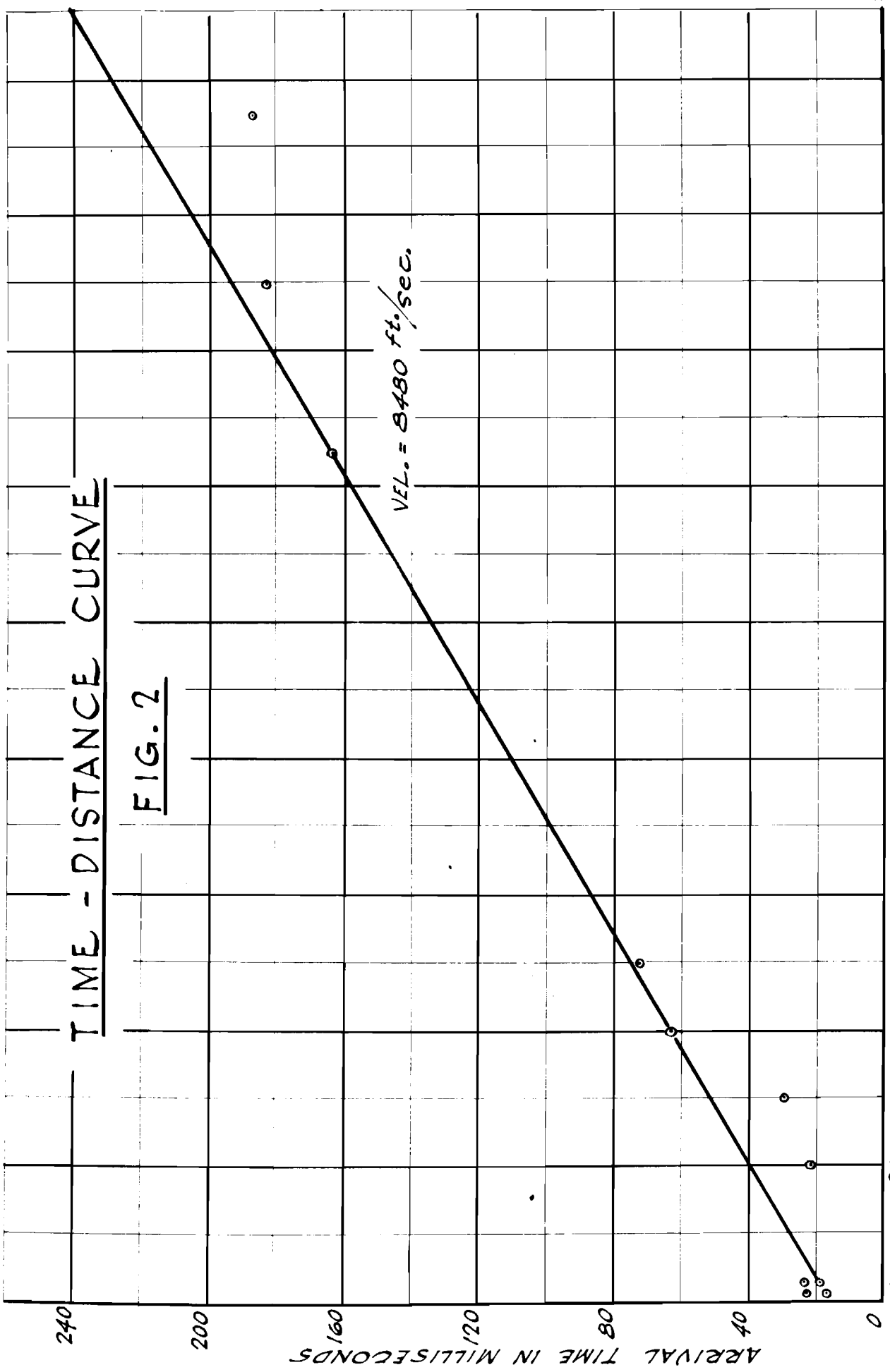
TIME-DISTANCE CURVE

FIG. 1



TIME - DISTANCE CURVE

FIG. 2



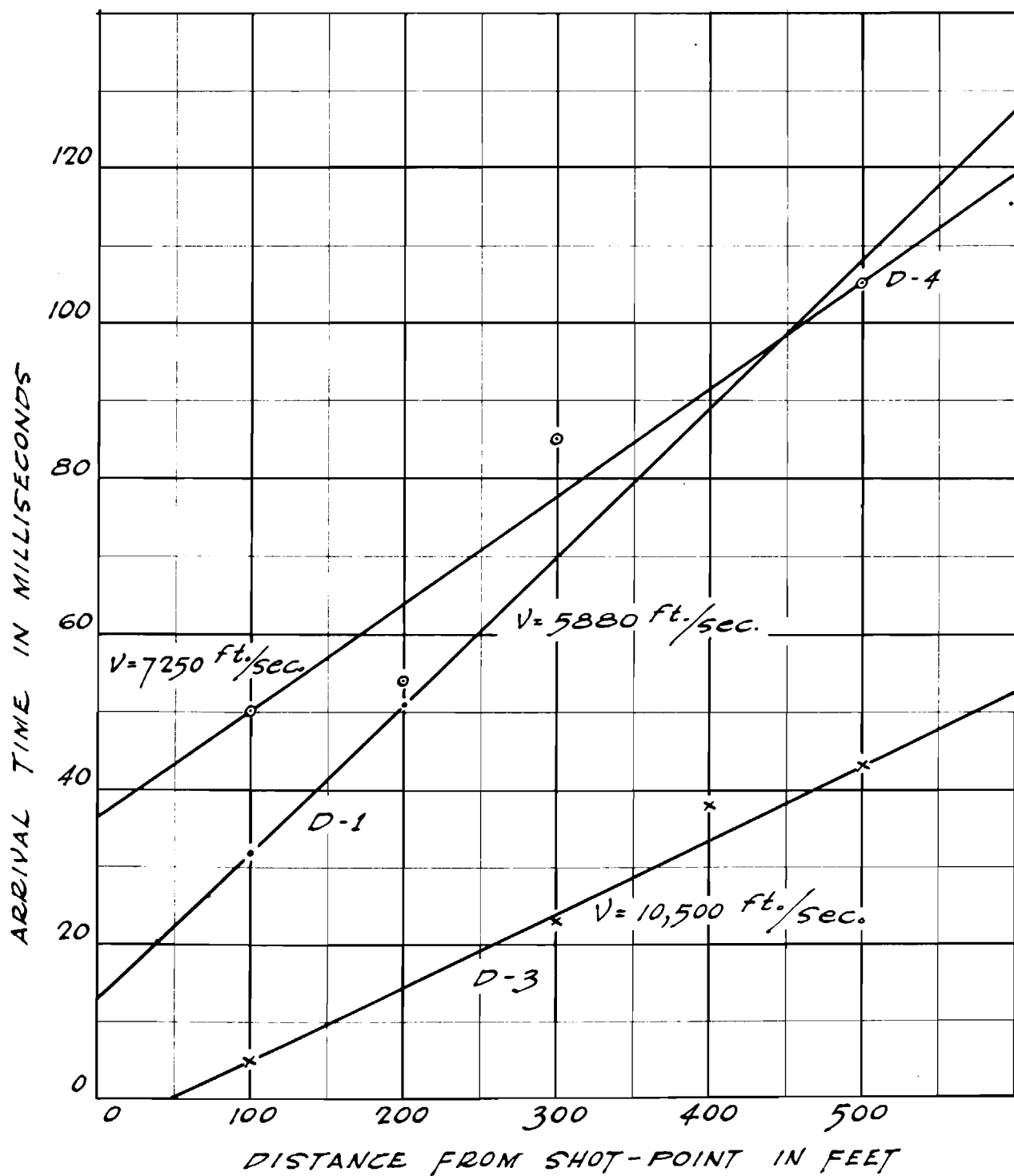
VEL. = 8480 ft./sec.

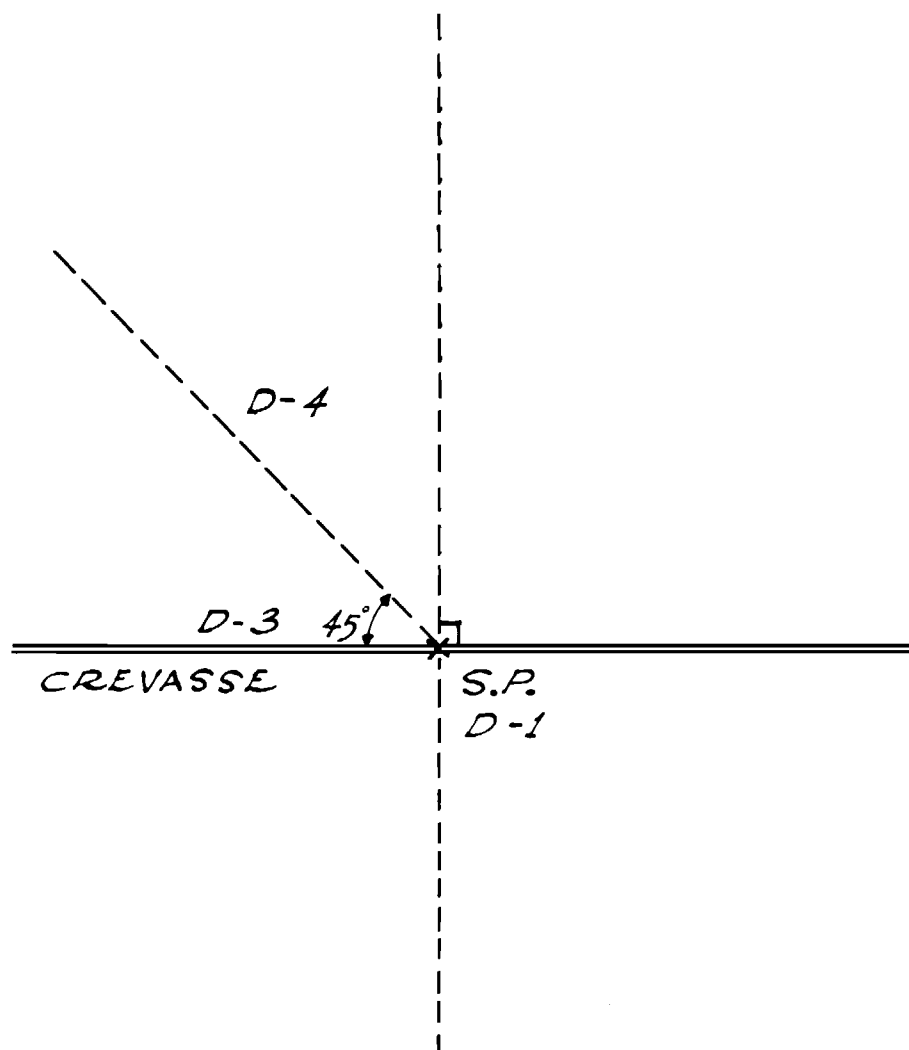
DISTANCE FROM THE SHOT-POINT IN FEET

T.M. 14

TIME DISTANCE CURVE

FIG. 3





RELATIVE CREVASSE AND
PROFILE DIRECTIONS

FIG. 4

CANADIAN SURVEY OF PHYSICAL CHARACTERISTICS
OF SNOW-COVERS

George J. Klein

SUMMARY

During the past two winters, the specific gravity, hardness and other physical characteristics of each layer in the snow-cover were measured once each week at a number of observation stations. The aim of the measurements was to obtain specific data on snow conditions in different areas which would be useful in many problems and which would form the basis for future snow studies. The method and instruments are described, and the results of the first winter's observations are presented.

INTRODUCTION

Large scale systematic snow observations have formerly been of three kinds: (a) meteorological measurements of snowfall, (b) hydrological snow surveys to determine the quantity of water stored as snow in river basins in order to predict the spring run-off, and (c) snow surveys for avalanche control as developed in Switzerland. Of these, only the latter have been concerned with the physical condition of the snow.

The properties of different forms of fallen snow vary so greatly that data on snow depth alone are quite inadequate for such problems as snow removal from highways, railways and airports; the development of over-snow motor vehicles, and the resistance of sleigh runners and aircraft skis. The scarcity of snow-cover data appropriate to these and similar problems, some of which are of considerable economic importance, led the Associate Committee on Soil and Snow Mechanics of the National Research Council of Canada to conceive the idea of the survey herein described and to develop the technique and instruments which have now become the standard in Canada for obtaining specific data on fallen snow.

The survey has been in operation during the past two winters and was conducted by the Meteorological Service of the Department of Transport and the Associate Committee on Soil and Snow Mechanics of the National Research Council of Canada.

In the following description "snow" refers to a mass of snow rather than an individual grain or crystal.

OBJECT OF THE SURVEY

The object of the survey was to carry out periodic measurements of the physical characteristics of the snow-cover at a number of observation stations in order to obtain useful data applicable to a wide variety of winter problems, especially to those in which the condition of the snow is an important factor. The survey was also intended to provide a basis for future studies of the fundamental properties of the various forms of fallen snow.

OBSERVATION STATIONS

Figure 1 shows the distribution of the observation stations in the 1947 survey.

A fair comparison of the results of several stations is difficult except when there is uniformity in the amount of shelter from sun and wind. Because intermediate degrees of shelter are not easily defined the survey was limited to two types of stations: exposed stations with a flat unprotected test area free from disturbances due to trees, buildings, etc., and sheltered stations with a test area exposed only to precipitation, e.g., a narrow strip along the south edge of a small clearing in moderately to heavily wooded country. Only exposed stations were used in the 1947 survey.

The test area at Old Glory Mountain was adjacent to the Meteorological Station at the top of the mountain; all others were on or adjacent to airports.

At Churchill, completely exposed areas are unsuitable for snow measurements because of the prevalence of shifting bare patches which are produced by strong, steady winds. A test area slightly sheltered from the wind but exposed to the sun was therefore chosen at Churchill.

The principal topographical features of each station are given below.

- | | |
|-----------|---|
| Arnprior | - Very flat, open farm land with scattered wooded areas. |
| Churchill | - Very flat barren country with practically no trees. |
| Edmonton | - Elevation 2200 ft. - very flat, open farm land with scattered wooded areas. |
| Gander | - Flat, heavily wooded country. |
| Goose Bay | - Flat, heavily wooded country with low brush in the immediate vicinity of the airport. |
| Malton | - Very flat, open farm land with scattered wooded areas. |

- Moosonee - On the bank of a river in very flat barren country with some thinly wooded areas.
- Old Glory Mt. - Elevation 7790 Ft. - surrounded by mountains of approximately the same elevation.
- Whitehorse - Elevation 2400 - on the bank of a river in a heavily wooded valley with mountains of 6,000 to 7,000 ft. elevation within 10 miles in most directions.
- Winnipeg - Very flat, open farm land with very few trees.

The elevations which have been omitted in the above table were all less than 800 ft. above sea level.

FUNDAMENTAL CONSIDERATIONS

The physical properties of a material generally depend upon certain of its basic features such as composition and structure. Experience has shown that this is true for snow.

Snow is a very porous material. Taking wet snow as the general case, it may be considered to be a mixture of ice, air and water. The relative proportions and the physical properties of each constituent will therefore influence the physical properties of the snow. Since the properties of ice vary with temperature, temperature will be a contributing factor.

The size and shape of the grains which make up a mass of snow have a considerable influence upon its properties. New snow, because of its fragile crystals, is structurally weaker than old snow which has grains of compact form, and the cohesion of wet snow depends upon grain size just as the cohesion of damp sand depends upon its grain size.

The snow grains often become bonded together during settling. This bonding can add considerably to the structural strength of the snow.

We may therefore consider the basic features upon which the physical properties of snow depend and which

distinguish one form of snow from another to be: (a) temperature, (b) relative proportions of ice, air and water, (c) average size and average shape of its grains, and (d) degree of bonding between the grains.

Temperature and average grain size can be measured without difficulty; the relative proportions of ice, air and water can be expressed in terms of specific gravity and percentage free water content, and average grain shape may be described with reference to a suitable chart such as the "Grain-Form Density Scale" adopted in the survey.

The most direct measure of the degree of bonding is the tensile strength of the snow. Tensile strength measurements, however, are rather inconvenient for routine use in the field. A more common measurement is that of snow hardness although it is perhaps a little less direct.

Any layer in a snow-cover can therefore be described by measurements of:

- (1) snow temperature,
- (2) specific gravity,
- (3) percentage free water content,
- (4) average grain size,
- (5) average grain shape, and
- (6) snow hardness.

INSTRUMENTS

The instruments, which were designed especially for the survey, had a number of convenient features. The complete set, shown in Figure 2, weighed 16 lbs. including the carrying case.

Snow Sample Cutters

The cutters and knife shown in Figure 3 were used to obtain samples of 250 cc. volume. In determining the specific gravity of a snow layer, either two or four samples

from the layer, i.e., 500 or 1,000 cc., were weighed at a time. The soft snow cutter, shown at the left, had a handle shaped to facilitate rotation about its axis in order to avoid compressing the snow. The removable cover plate was used only when samples tended to slide out of the cutter or when the specific gravity of a cohesionless layer was being determined. The hard snow cutter is shown at the right. The knife was used to trim the ends of the samples.

Balance

The beam type balance, shown in Figure 4, was ideal for specific gravity and percentage free water content measurements. It was more accurate than a spring balance and its auxiliary rider simplified free water content measurements. The auxiliary rider contained a spring clamp which could be released by pressing the button on the rider. The counterweight at the left could be raised or lowered to alter the sensitivity without disturbing the zero adjustment of the balance.

Hardness Gauge

Various instruments have been employed to measure snow hardness such as the Swiss "Kegelsonde" (1) and Nakaya's impact cone mounted on a pendulum (2). The gauge used in the survey was a spring balance type similar to one developed by Eugster and referred to by Seligman (3), and was chosen because it was very compact and covered an extremely wide range.

Two gauges are shown in Figure 5; the one at the left is the low hardness gauge and the one at the right is the high hardness gauge. The latter had a spring ten times as stiff as that of the former. The corresponding spring and graduated push rod are shown beside each gauge. The discs at the bottom of Figure 5 had areas of 100 and 10 cm² and were held in place on the end of the push rod by the friction of a rubber washer cemented to the back of each disc. Two smaller discs having areas of 1.0 and 0.1 cm² were permanently attached to the end of the rod.

The gauges were generally used horizontally against the wall of a test trench. When used vertically, a small correction was made for the weight of the moving parts. The reading was obtained by slowly pressing the gauge against the snow and noting the value on the graduated scale at which the disc began to enter the snow. The hardness, in gms/cm², was obtained by multiplying the reading by the

corresponding factor given below.

<u>Disc Diameter</u> cm.	<u>Disc Area</u> cm ²	<u>Multiplying Factor</u>
11.28	100	1
3.57	10	10
1.13	1	100
0.36	0.1	1,000

The low hardness gauge was normally used with only the 100, 10 and 1 cm² discs (0 to 1,000 gms/cm²) and the high hardness gauge with only the 1 and 0.1 cm² discs (1,000 to 100,000 gms/cm²). Readings to the nearest half division were considered sufficiently accurate.

Cup, Magnifying Glass and Spatula

These are shown in Figure 6 and were used for observing the size and shape of snow grains. The circles engraved on the bottom of the cup had radii which varied by one millimeter steps and formed a scale for observing grain size. The spatula was used to place and arrange the granules in the cup and to break up aggregates. A folding scale which was used for depth measurements is also shown in Figure 6.

Thermometers.

Each set of instruments contained two 100 to -10°C mercury filled thermometers and two 50 to -100°C liquid filled thermometers. Four thermometers with a 100 to -50°C range would have been more convenient but were not commercially available. The thermometers were laboratory grade, 12 inches long.

GRAIN-FORM DENSITY SCALE

While there is an infinite variety of snow grain forms, the important feature is the degree of compactness of the shape of the grains. This feature has been given the name "grain-form density".

The scale of grain-form density used in the survey is shown in Figure 7, and although the classification is more or less arbitrary this does not in any way detract from its usefulness. It was intended to be merely a scale of the degree of compactness of grain shape and not a classification of the various forms of snowflakes and snow grains. The purpose was to provide a simple scale of grain shape which would indicate the texture of a snow layer when both average shape, as described by the appropriate class in the scale, and average size of its grains were given. The criterion of grain-form density was taken as the relative structural strength of the grains or crystals due to shape alone. Each class refers to many different shapes of grains but all shapes in any one class have approximately the same influence on the properties of a mass of snow. While the classes may not be uniformly spaced an attempt was made to arrange them in proper order. A description of each class is given below.

<u>Class</u>	<u>Description</u>
A.	Very slender needles, and plane crystals with very slender rays and not more than three pairs of delicate branches per ray. This class is limited to new snow crystals of very slender proportions and open pattern.
B.	Plane crystals of new snow with many delicate branches, and very feathery hoar crystals.
C.	Plane crystals and needles of new snow having somewhat more substantial form than classes A and B, and partly settled snow grains of similar structural strength.
D.	Plane crystals and needles of new snow having still more substantial form than class C, and partly settled snow grains of similar structural strength.
E.	Hexagonal plate crystals of new snow or hoar and cup crystals of hoar. The plate crystals may or may not have various forms of small notches in their sides or small extensions at their corners.
F.	New snow crystals in the form of columns having a length to diameter ratio of four or less, and partly settled snow grains of similar structural strength.

- G. Graupel or soft hail, i.e., snowflakes which have received a thick coating of rime during their fall to earth. Flakes with thin to moderately thick coatings belong to the class preceding G in which their shape including the rime deposit would place them.
- H. Grains of settled snow and old snow with crystal facets. The facets are produced by sublimation and their presence indicates that no recent melting has occurred.
- J. Grains of settled snow and old snow with no crystal facets. Grains which have lost their facets by abrasion during drifting or by melting which may or may not be followed by freezing, and hail belong to this class.

The above classes can usually be identified very easily although the facets of class H are sometimes difficult to recognize. A method which will serve to demonstrate the difference between classes H and J is to observe the amount of sparkle when direct sunlight falls on a sample of old snow. If facets are present, they will give a distinct sparkle effect; the fractures of broken grains are seldom flat and will not produce such clear cut reflections.

PROCEDURE

The procedure followed at each station has been described in detail in Report MM-192 of the National Research Council of Canada (4). An outline is given below.

At each station a suitable area of about 500 sq. ft. was selected for the weekly and daily observations. A depth gauge in the form of a post marked off in inches was set up at one edge of the test area.

Weekly Observations

Once each week a new test trench, about 3 ft. x 3 ft. was dug down to the ground and the boundaries of the snow layers were located by examination of the section or by preliminary hardness tests. Air temperature, total depth of the snow-cover and the depths to the layer

boundaries were measured, and snow temperature, hardness, average grain size, average grain shape and specific gravity were determined for each layer. Percentage free water content was only determined when the snow temperature was very near 0°C. and then for only three or four representative layers. Each trench was filled in on completion of the measurements.

Daily Observations.

Observations of air temperature, total depth of the snow-cover, average size and average shape of the grains in the uppermost layer, wind speed, amount of sunshine, and the amount and kind of new precipitation were made each day. These were intended to establish continuity from one set of weekly measurements to the next.

Most of the daily and weekly observations were made at about 10:30 and almost all of the remainder at about 15:30 local time. The aim was to obtain approximately the daily mean value of air temperature.

Some observers reported wind at the time of the observation in miles per hour, while others used the Beaufort Scale or descriptive words. Further, the amount of sunshine was reported either in hours of sunshine for the previous day or as "overcast", "partly cloudy", "clear", etc. for the period since the last observation. This variation was no fault of the observers. Report MM-202 (5) was subsequently issued to ensure a greater degree of uniformity in the following winters' surveys. These amendments, however, were not in effect during the 1947 survey.

Description of the Measurements

Most of the measurements were quite simple and were made in the usual way. A few, however, require further explanation.

The temperature of a snow layer was always taken at the center of the layer thickness. Hardness, grain size and grain shape measurements were generally taken as average values for the layer.

Grain size was taken as the maximum dimension (X, Figure 7) of a single grain.

Whenever new snow contained graupel, the average size of the graupel, as well as the average size and shape

of all the other crystals were recorded, e.g., G 1.2, B 3.0; otherwise only the average size and average shape were recorded.

Percentage free water content was determined by a simple calorimetric method. From 300 to 400 gms. of hot water, between 50 and 80°C, were placed in the balance bucket and its weight and temperature were measured. The balance was then set at zero and again balanced using only the auxiliary rider. A sufficient quantity of the wet snow was added to bring the temperature to between 5 and 15°C. The mixture was stirred to make sure that all ice particles were completely melted. The final temperature and the weight of snow which had been added were then determined. The percentage free water content was found by the use of nomograms for the following equation:

$$\text{F.W.C.}\% = 100 - \frac{5}{4}(T_1 - T_2)\frac{W}{S} + \frac{5}{4}T_2$$

where W =weight of water, gms.

S =weight of snow, gms.

T₁=initial temperature of water, °C.

T₂=final temperature of water and melted snow, °C.

No corrections were made for the loss of heat to the air or for the thermal capacity of the bucket which was made of aluminum and weighed slightly less than 50 gms.

Wind speed, amount and kind of precipitation and the amount of sunshine were obtained from the records of the Meteorological Station adjacent to the test area.

The total depth of the snow-cover, the depths to the layer boundaries and the amount of precipitation were measured in inches and wind speed in miles per hour - the standard units in Canada. The characteristics of the snow, however, were either expressed nondimensionally or were measured in metric units to facilitate comparison with the comprehensive Swiss researches in snow mechanics.

RESULTS OF THE 1947 SURVEY

The results discussed here were obtained at exposed stations during the period from the middle of January to the middle of May 1947. They clearly demonstrate the value of surveys of this kind.

In order to facilitate analysis, the observations were plotted as graphs, examples of which are given in Figures 8 to 13. These graphs retain practically all details making it possible to examine the conditions under which certain changes occurred. They also reveal general trends and disclose features which might otherwise escape notice.

General Results

The results of all the stations taken together show several notable features of a general nature.

Air temperature and wind had a decided influence on the condition of the snow-cover, while the effects of sunshine were relatively small. The flow of heat from the earth appeared to cause some changes in the snow structure particularly in the lower half of the snow-cover. Isolation of the effects of any one factor, however, is not feasible because it is the combination of factors which is most important.

Wet snow conditions were surprisingly rare and were almost entirely confined to the short period of the spring thaw represented by the final steep slope of the snow-cover depth curves shown in Figure 14. At Gander the main thawing period occurred late in February.

The maximum rate of ablation occurred at Goose Bay early in May when the snow-cover depth decreased 20" in two days.

One inch below the surface the snow was harder than 100 gms./cm² in 70% of all cases. Only rarely did the depth of moderately soft snow at the surface exceed 10 inches. Generally most of the snow-cover and frequently all of it had reached or passed the settled stage.

The most significant characteristic of a snow layer was hardness. Hardness, together with shape and size of grains would, in nearly all cases, give a fairly complete description of the layer.

Table I gives the range of specific gravity and hardness for the different kinds of snow layers.

There were relatively few cases of wet settling snow - often called "wet new snow" - and therefore the figures for this type should be regarded as only approximate.

The dividing line between settled and old snow was arbitrarily taken as 1 mm. grain size.

Types 5 and 6 often contained depth hoar - in fact some layers were almost entirely composed of hoar crystals.

Snow Conditions at the Different Stations

The total depth of the snow-cover at the different stations has been plotted in Figure 14. It should be noted that at Goose Bay the snow-cover depth was much greater than at Gander which is only 400 miles south-east of Goose Bay. Gander and Goose Bay are about 30 and 130 miles inland respectively. The small amount of snow at Gander was due to fairly mild weather with the occasional rain.

Malton and Arnprior - about 200 miles apart - had quite different snow-cover depths. Temperatures and the frequency of precipitation were generally similar, but the amount of snow which fell at Arnprior was usually twice the amount which fell on the same day at Malton. The depth curves for the two stations have approximately the same general shape.

Air temperature and wind speed data for each station are presented in Table II. The values in the table refer to that part of the month for which the corresponding snow-cover depth curve in Figure 14 is shown as a solid line.

The snow conditions at the different stations are summarized below. The figures for snow hardness are all in gms/cm² and "settled snow" refers to snow which has reached or passed the settled stage, i.e., settled snow, old snow and loose granular snow.

Arnprior

Conditions near the surface varied from fairly soft snow to very hard crust. Classes H and J were about equally common and the snow layers were usually separated

by thin ice sheets. The hardness of settled snow layers generally varied from 30 to 1,000. During the latter half of March there was a thick spring crust - hardness 8,000 - at the surface.

Churchill

Strong winds caused drifting and blowing snow on completely exposed areas. Most of the snow at the test area was deposited by the wind; only about one quarter was due to direct precipitation. The wind rapidly transformed new snow into settled snow which, since temperatures were very low, was always class H and had considerable sparkle in bright sunlight. There were never any ice sheets between snow layers which made it difficult to pick out the layers by eye.

The snow at Churchill and on the Barrens has a reputation of always being extremely hard but this was not entirely supported by the measurements - possibly because the test area was sheltered a bit from the wind. The hardness of settled layers generally varied from 100 to 1,000 with a few subsurface layers up to 4,000 hardness. On exposed areas the snow may have been as hard as that at Winnipeg where wind and temperature conditions were more or less similar. No extremely hard crusts which are formed by melting and freezing were found during the test period.

The size of settled snow grains increased with depth in much the same manner as shown for the lower half of the snow-cover in Figures 11, 12 and 13. This was more pronounced at Churchill than at any other station - possibly because of the absence of ice sheets between snow layers. The coarse layers near the ground, however, were generally fairly hard and dense and could not be described as "loose granular snow".

Edmonton

The entire snow-cover was relatively soft due, apparently, to the exceptionally low winds. Only one hardness reading of 600 was obtained - all others were 400 or less. Temperatures were fairly low and while crusts were reported these were seldom ice sheets. All settled snow layers prior to March 14th were class H.

Gander

Since there was very little snow at Gander, relatively few measurements were obtained. Wet spring snow with

coarse grains, spring crust and ice were most common.

Goose Bay

Goose Bay had the deepest snow-cover of all the stations with the exception of the one on Old Glory Mountain. Temperatures were moderate and strong winds were common. From the start of the measurements until the end of April there was a layer, 12 to 15" thick, of loose granular snow - hardness 40 to 100 - near the ground, and throughout April there was a fairly thick crust - hardness 2,000 to 4,000 - at the surface or immediately below freshly fallen snow. The hardness of all other settled snow layers was between 100 to 1,000. The high winds caused new snow to settle rapidly. With only a few exceptions the settled snow was of class J and thin ice sheets between layers were very common.

Malton

During the last two days of January a 4" layer of hail fell accompanied by rain. This layer became a crust - hardness above 10,000 - which was present in the snow-cover until the spring thaw began. There was also a solid ice layer on the ground which gradually increased to 3½" thickness at the beginning of the spring thaw. The hardness of all other settled snow layers was between 100 and 1,000. Settled snow was generally of class J and the layers were usually separated by thin ice sheets.

Moosonee

Up to the end of March there were no ice sheets between layers in the upper half of the snow-cover, but there were some in the lower half which may have been formed during the early part of the winter when the temperatures were not quite so low. Prior to the middle of April there was a layer of loose granular snow near the ground and all settled snow was class H. Thawing conditions began about the middle of April and resulted in very hard snow of class J throughout the snow-cover depth.

Old Glory Mountain

Relatively high temperatures caused new snow to settle very rapidly. Practically all layers had very coarse grains of class J and there were many ice sheets, some fairly thick, between the snow layers. The hardness of most layers was between 100 and 1,000. Toward the end

of April the entire snow-cover became wet with a hardness range from 20 to 300. The maximum free water content during this period was about 15%.

Whitehorse

Settled snow layers were class J with hardness ranging from 20 to 1,000. Ground temperatures were lower than air temperatures indicating that the weather preceding the tests was appreciably colder than during the test period. The results obtained at Whitehorse, therefore, may not entirely represent snow conditions in that area.

Winnipeg

Steady winds and low temperatures were very common with the result that the entire snow-cover, except for an occasional thin layer of new snow at the surface, was hard wind packed snow of class H. Both hardness and specific gravity were definitely high for class H, the hardness varying from 200 to 8,000. The snow grains at all depths and particularly near the surface were appreciably smaller than found elsewhere. A number of thin crusts, some of them ice, occurred between snow layers but they were not as common as at most other stations.

CONCLUSIONS

The results provide a great deal of general information about snow and the variety of forms in which it occurs on the ground, and clearly demonstrate that surveys of this kind yield data which can be of considerable assistance to both users and designers of winter equipment.

The 1947 survey gives a fairly clear picture of snow conditions on exposed areas across Canada. Subsequent measurements may alter this picture to some extent, but the consistency of the results indicates that the general outline will not change appreciably. If the survey is extended over about four winters it should provide a reasonably complete picture.

The results show that snow conditions on unsheltered areas, such as airports, are generally fairly hard and that the hardness of the snow on the Barrens, in spite

of its reputation, is not greatly different from that on wind swept areas in most other parts of the country. In fact, the hardest form of snow, i.e., frozen spring crust, did not occur at Churchill during the test period nor for some time prior to the tests.

Although little would be gained by increasing the number of exposed stations, the value of the survey will be increased by the addition of an equal number of carefully selected stations sheltered from both wind and sun. It is hoped that the survey will be extended in this direction.

The instruments, grain-form density scale and the general method proved to be entirely satisfactory. The system of weekly measurements supplemented by daily observations produced excellent results and made the best use of the observer's time and effort.

The method used in the survey provides a simple means for defining the physical characteristics of a snow-cover. It appears to fill a general need which has existed in many problems associated with snow.

ACKNOWLEDGEMENTS

The author wishes to express his sincere thanks to all who have contributed to the success of the survey. Thanks are due to the observers who faithfully carried out the observations, and to Dr. Andrew Thomson, Controller of the Meteorological Service of the Department of Transport; Dr. O. M. Solandt, Chairman of the Defence Research Board; Robert Legget, Chairman of the Associate Committee on Soil and Snow Mechanics, and J. H. Parkin, Director of the Division of Mechanical Engineering of the National Research Council of Canada for their valuable cooperation which is deeply appreciated.

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TABLE I

Type of Snow Layer	Grain Size mm.		Specific Gravity			Hardness gms./cm ²		
	Min.	Max.	Min.	Max.	Jsual Range	Min.	Max.	Usual Range
1. Dry New Snow	0.2	7	.048	.11	.07 - .10	0.5	20	1 - 10
2. Dry Settling Snow	0.2	5	.09	.22	.10 - .20	5	200	10 - 100
3. Wet Settling Snow	0.2	5	.10	.24	.15 - .20	20	100	20 - 100
<u>Class H</u>								
4. Dry Settled Snow	0.2	1	.20	.33	.23 - .30	25	8,000	80 - 800
5. Dry Old Snow (excluding 6)	1	7	.20	.34	.23 - .30	50	9,000	80 - 1,000
6. Loose Granular Snow	1	9	.11	.30	.18 - .28	15	200	20 - 100
<u>Class J</u>								
7. Dry Settled Snow	0.2	1	.20	.43	.25 - .35	25	6,000	100 - 6,000
8. Dry Old Snow	1	8	.20	.53	.25 - .45	50	20,000	100 - 20,000
9. Wet Old Snow	1	4	.28	.52	.35 - .50	20	500	50 - 500

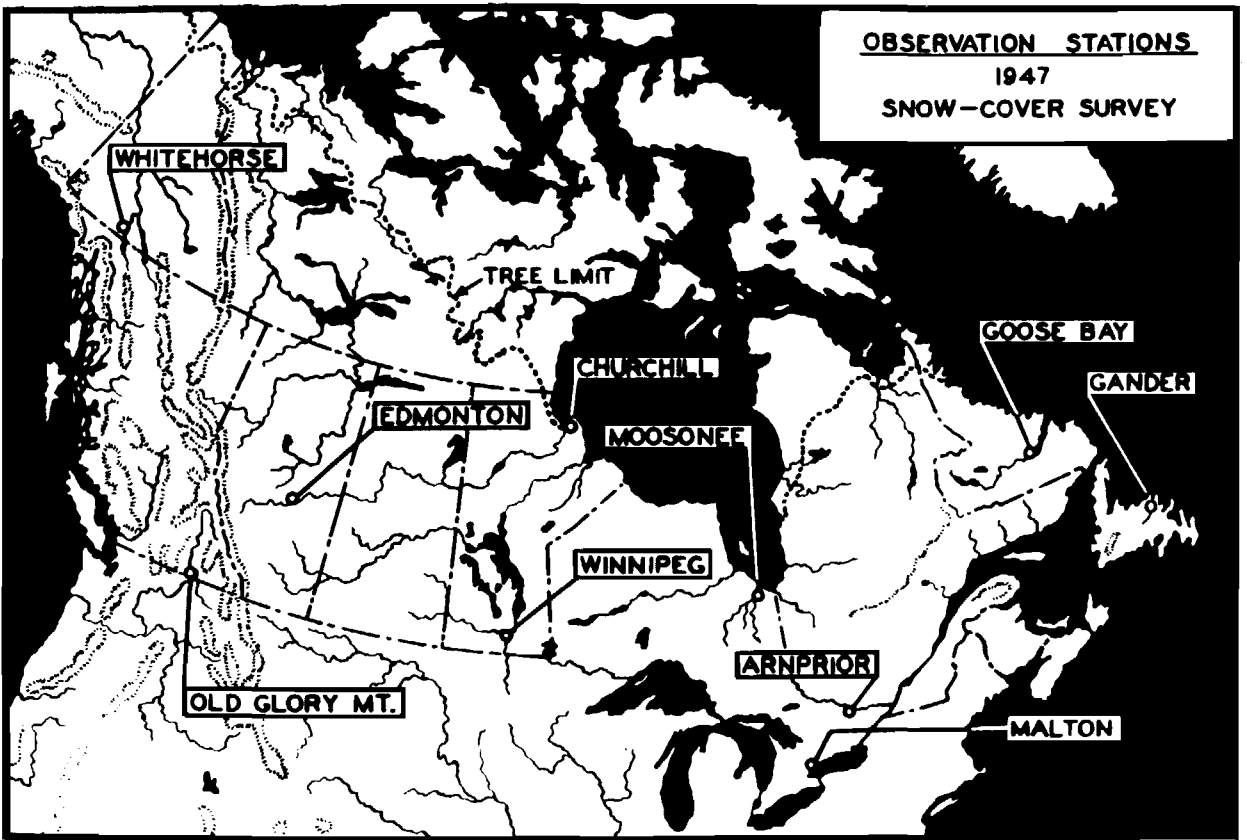


FIG. 1



FIG. 2

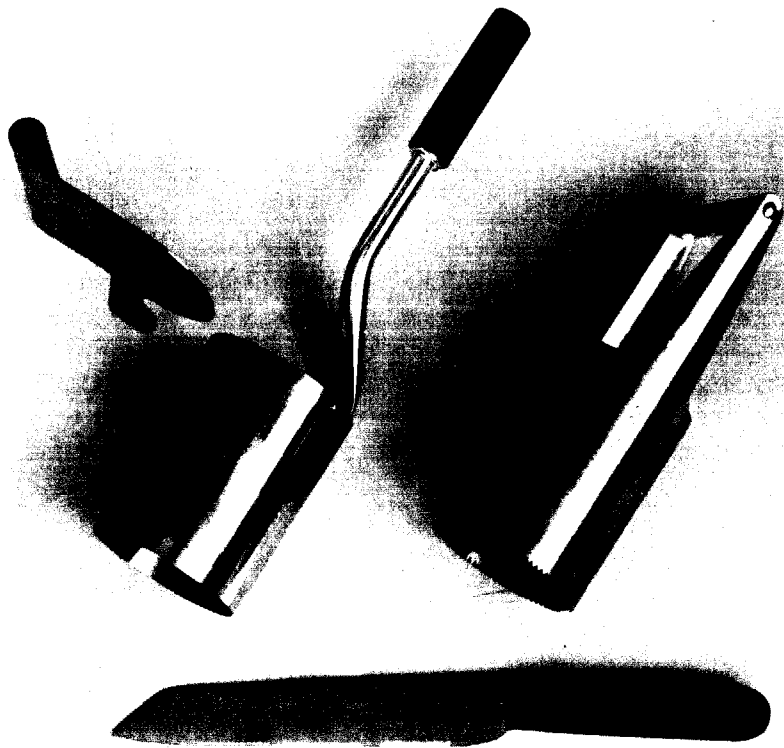


FIG. 3

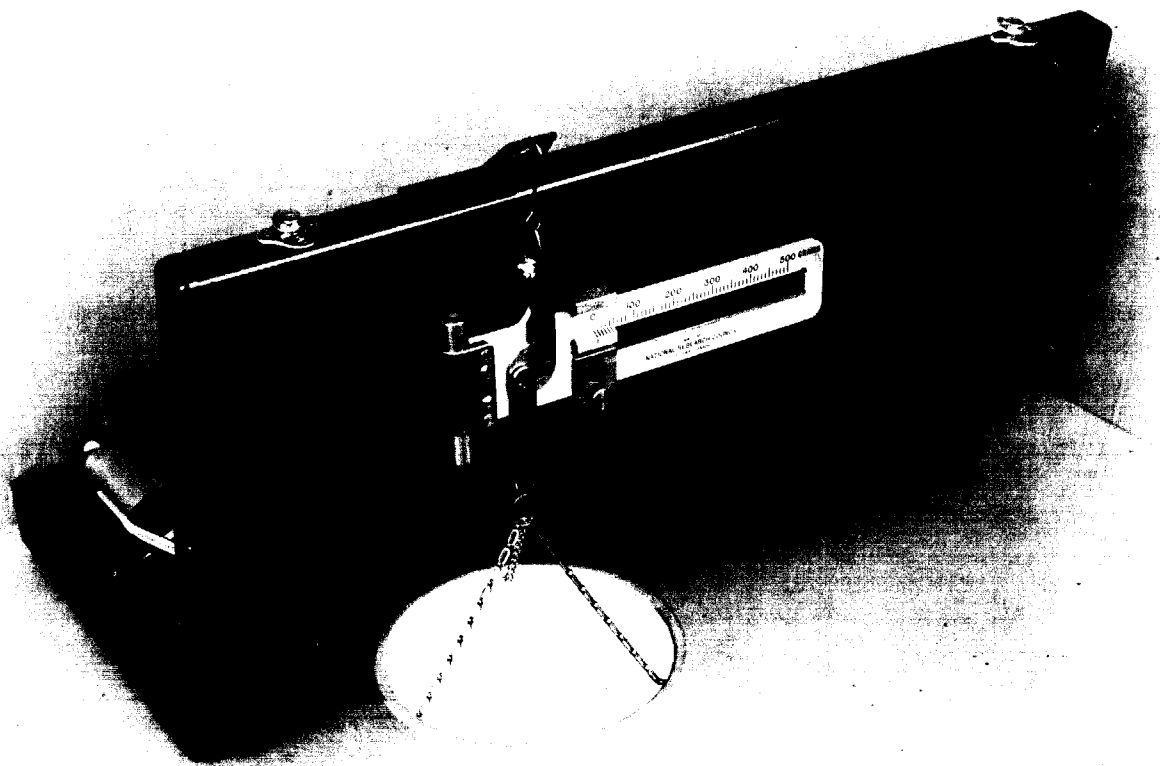


FIG. 4

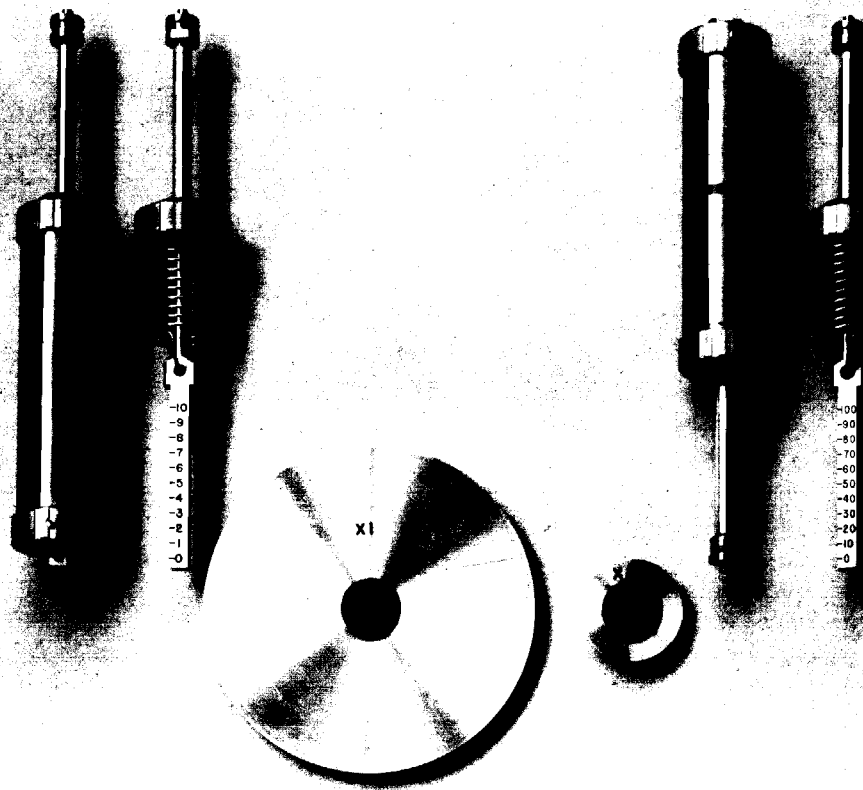


FIG. 5

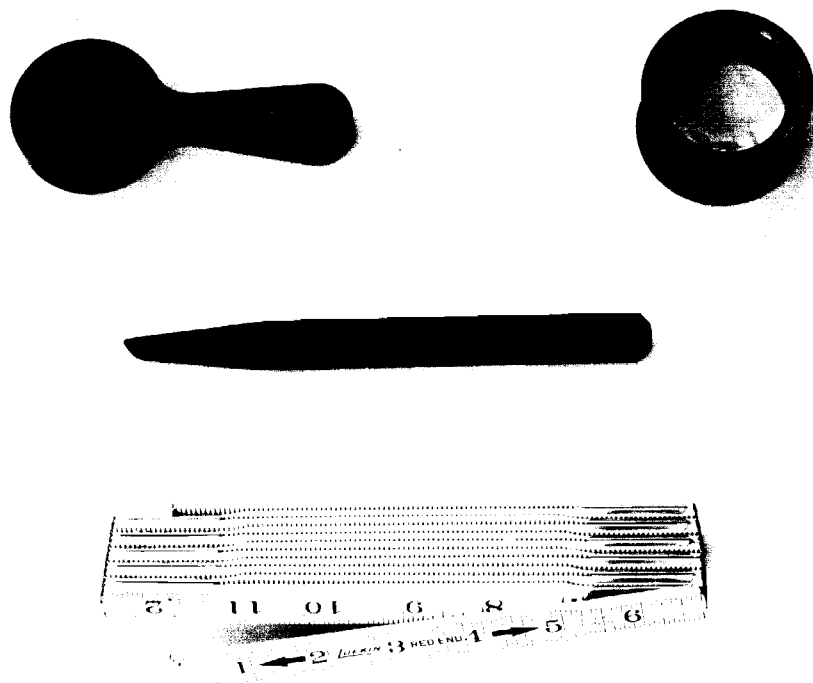


FIG. 6

GRAIN-FORM DENSITY SCALE

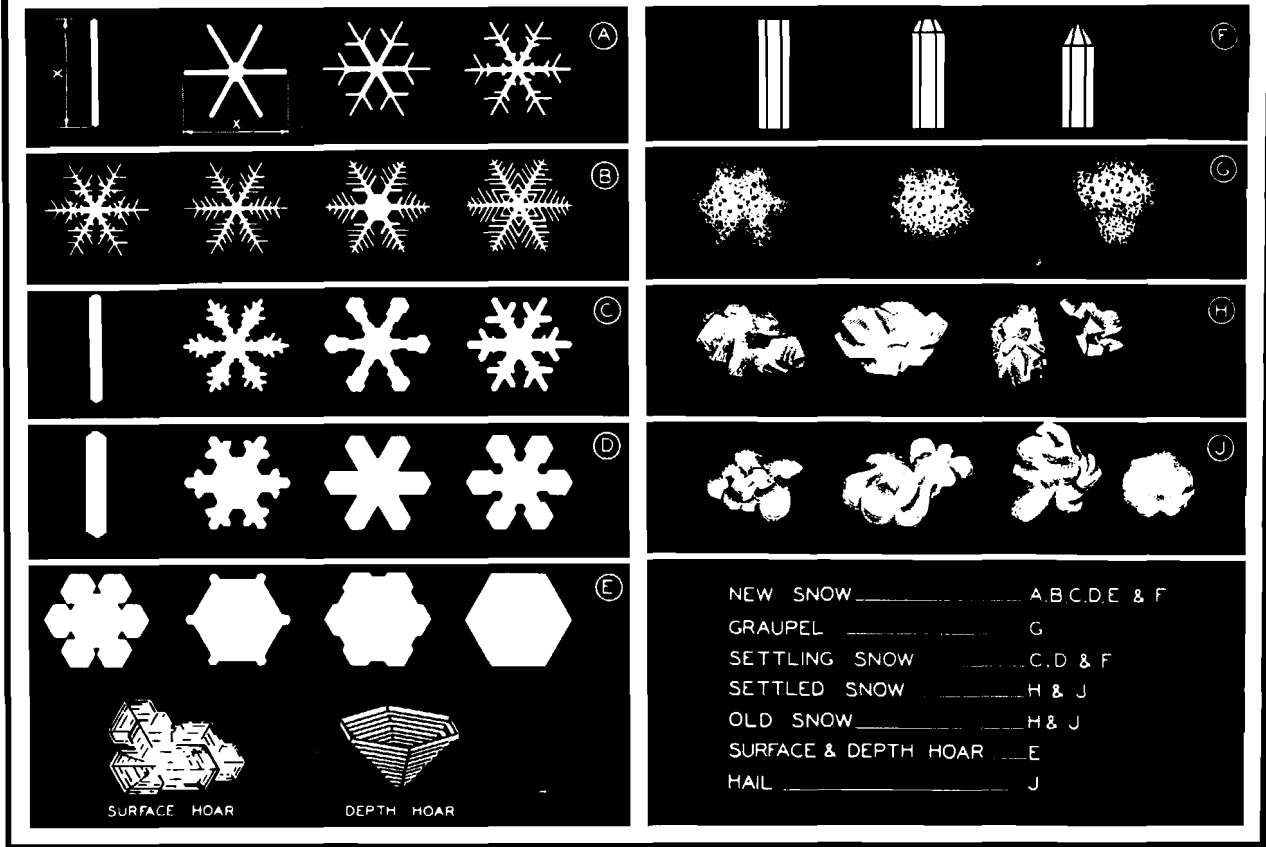


FIG. 7

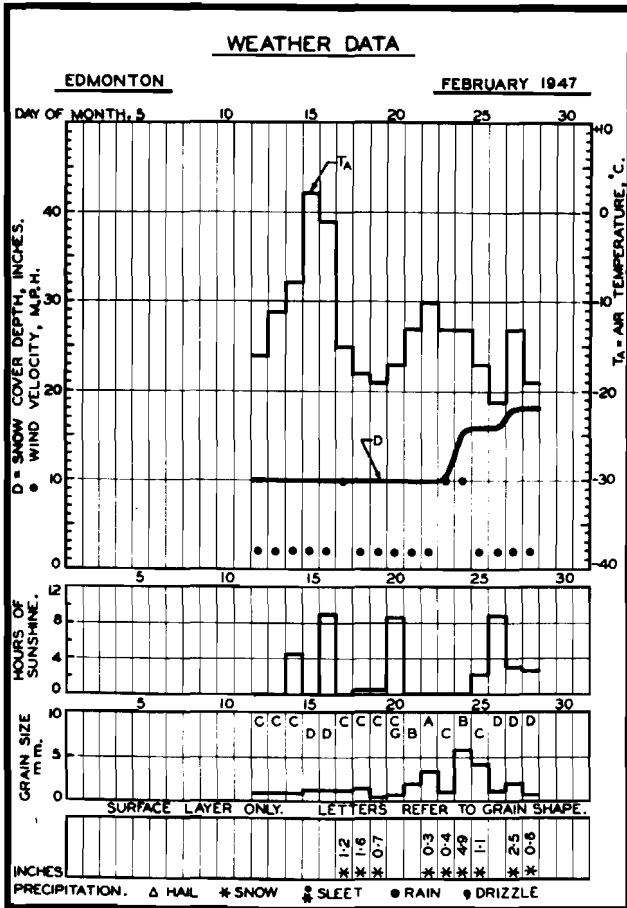


FIG. 8

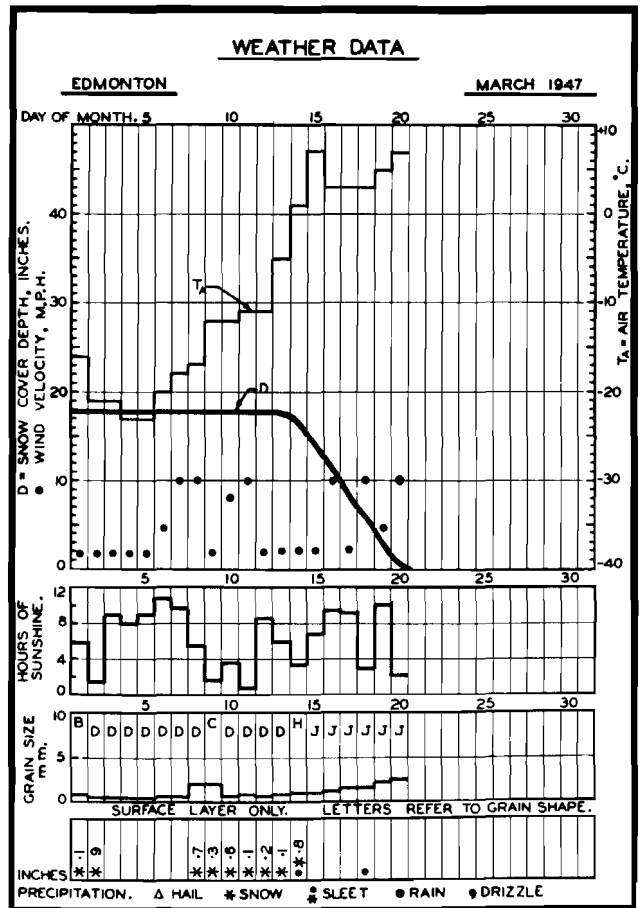


FIG. 9

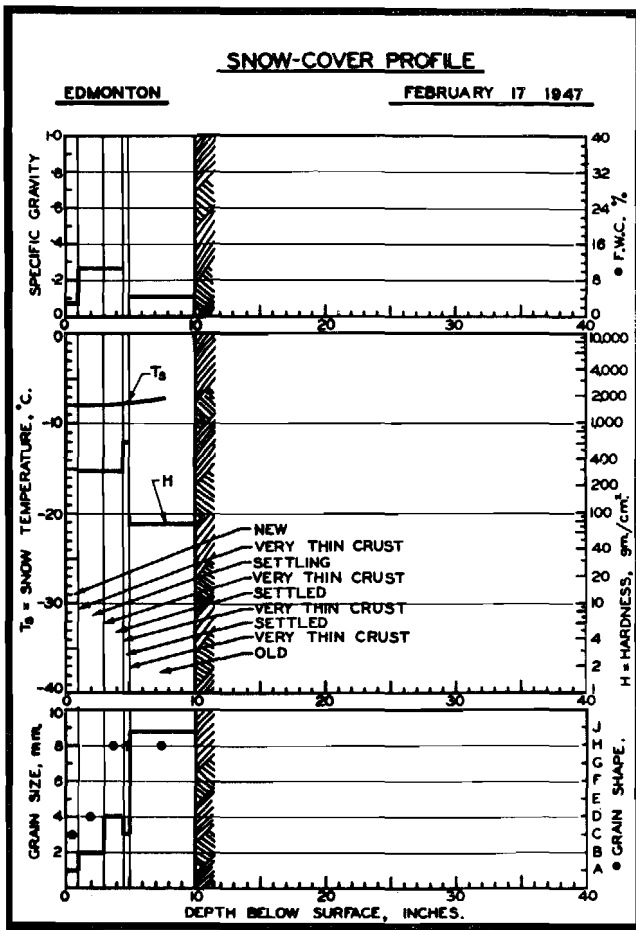


FIG.10

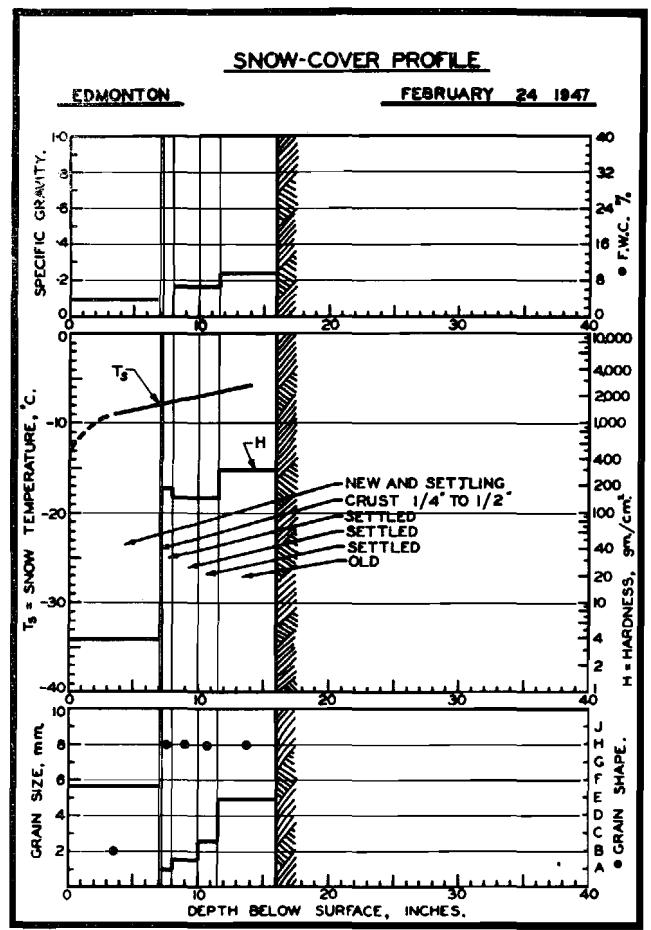


FIG.11

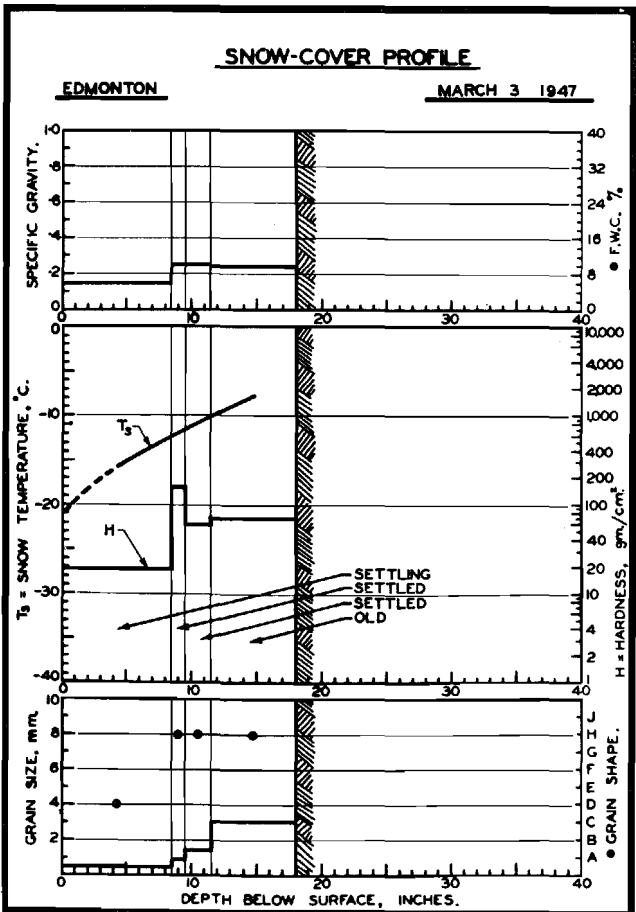


FIG.12

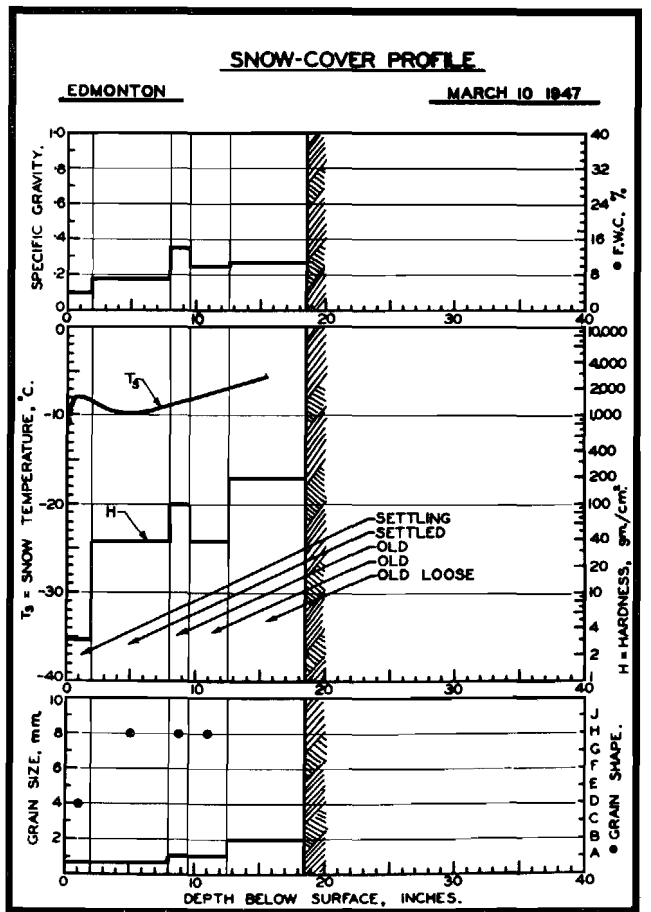


FIG.13

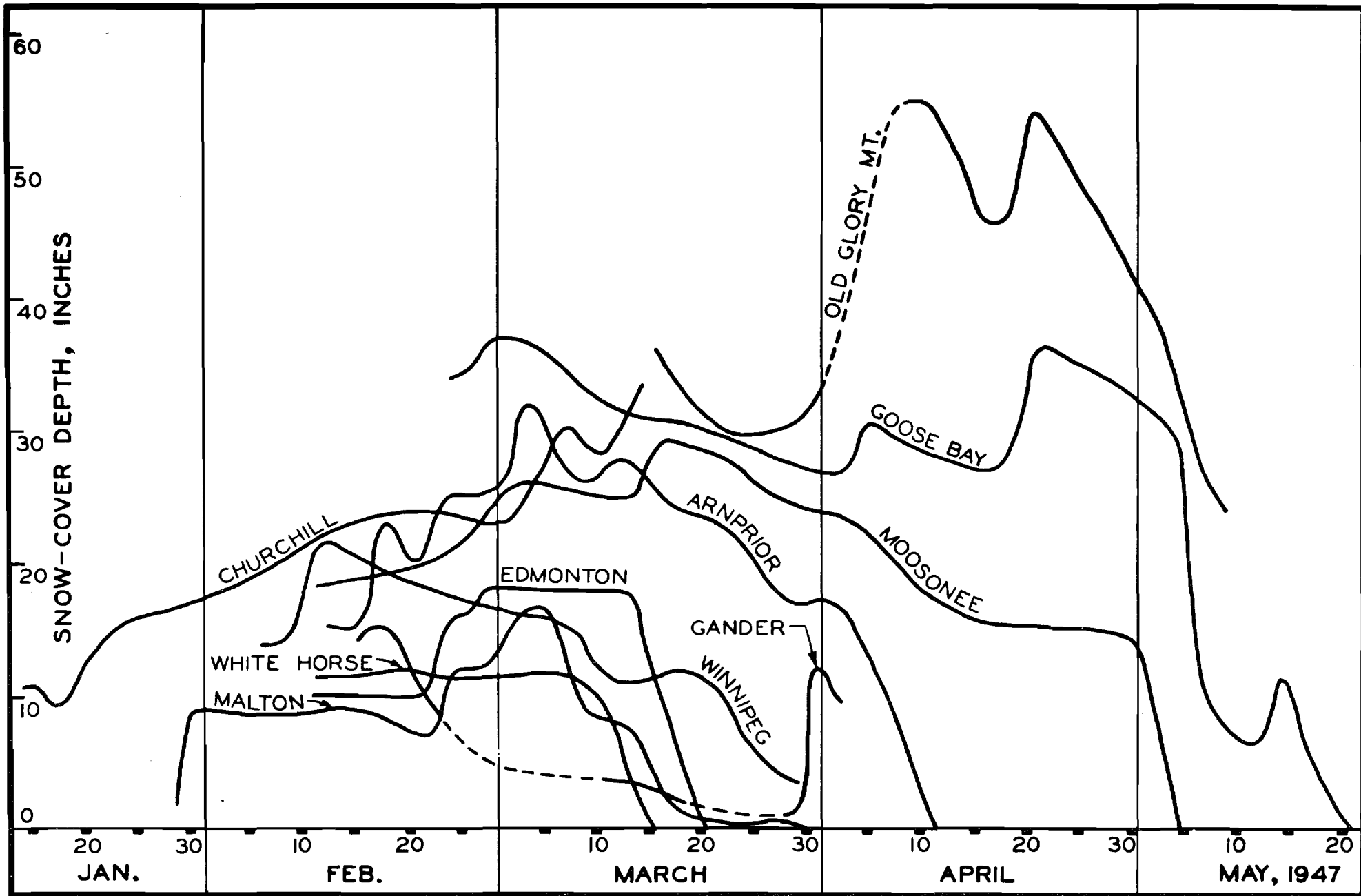


FIG. 14

CANADIAN INTEREST IN SNOW AND ICE RESEARCH

by

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CANADIAN INTEREST IN SNOW AND ICE RESEARCH

The Dominion of Canada stretches between two oceans, the Atlantic and the Pacific, from the borders of the United States of America as far south as latitude 41° to the North Pole. It extends over 48° of latitude and 84° of longitude. Within these bounds, it has an area of about 3,700,000 square miles, thus being the largest country in the western hemisphere and the third largest country in the world. The whole of this vast region is covered with snow for at least a short time during every winter; well over ninety per cent of the area is blanketed with snow for a winter period of several months. Despite the fact that over a third of Canada is still covered with forests, and that more than one half of its area is accounted for by the barren land of the Canadian North, the importance of snow and ice to Canadian living can readily be appreciated. That importance is at last being given recognition; this paper is an attempt to summarise this awakened interest of Canadians in the materials which are the concern of the International Commission on Snow and Glaciers.

The development of Canada as a modern agricultural and industrial nation has naturally been conditioned by its rigorous winters. In most parts of the country, agricultural work is possible for little more than half the year. This gives rise to an unusual intensity of activity during the short growing season and is one of the major causes of that "seasonal employment" which is so marked a feature of the Canadian economy. Until relatively recently, long distance travel during the winter by any means other than by railway was almost unknown, save only in the far reaches of the North. Here winter travel is essential, being often easier than at any other time of the year. Records of the endeavours of the early explorers of the North and the unimaginable hardships to which they were exposed have paved the way for widespread appreciation of the exploits of such men as those on the staffs of the Hudson's Bay Company and the Royal Canadian Mounted Police in their annual winter travels.

It is only about ninety years ago since these words were penned by a serious student of Canadian affairs: "We can scarcely credit the story that a railway between Quebec and Halifax is seriously contemplated. We are satisfied that no sane man either at home or abroad would invest one brass farthing in such a concern.....Were a snowstorm to set in and it be as it is on our well-conducted roads, impossible to go forward or return, the passengers in the cars would most certainly be devoured by wolves or frozen to death..... Great undertakings may be very captivating to men of enlightened minds and visionary ideas, but it is only fools who would embark upon them."(1). "Fools" did embark upon them, to their credit and to the benefit of Canadians of today. They tackled

the problems of the snow, the difficulties of ice, and the varied complexities of winter conditions with the result that road rail and air services today operate throughout the Dominion the year round. The water power plants which serve all parts of the country never stop; water supplies are perennial.

In meeting the problems of snow and ice, Canadians have made an approach which has been almost exclusively empirical. A great volume of sound knowledge has been accumulated by men who did not fear to experiment. Tribute to this practical approach must be a leading statement of this paper for it is upon the foundation thus provided that scientific enquiry can alone advance. A start has been made at this application of science. Snow and ice are at last coming to be recognised as materials as complicated as they are widespread, well worthy of detailed and meticulous study.

Hydrological Aspects of Snow and Ice;

Since all but a negligible proportion of the centrally generated electricity used in Canada is derived from water power plants, it is not surprising that early attention was paid to the possibility of forecasting stream flow from winter studies of snow and ice. The natural resources of the Dominion are administered by the several provinces, control having passed to them at different times from the central government. Both federal and provincial organisations are therefore concerned with these snow and ice studies. The Dominion Water and Power Bureau works in close association with the provinces, its activities being nation-wide; its estimates of run-off are made in conjunction with the U.S. Geological Survey. It operates snow survey courses on the eastern slopes of the Rockies, obtaining accuracies of about 90% to 110% in this western area. In eastern Canada, similar work is done but in the Lake of the Woods area, for example, errors sometimes of the magnitude of 40% are found in run-off predictions for reasons not yet explained.

As an example of a provincial service there may be mentioned the snow survey work of the Division of Water Rights of the Department of Lands and Forests of British Columbia. This system has been developed since 1935 and now consists of 48 courses extending across the southern part of the province, from the coast to the summit of the Continental Range and as far north as latitude 53°. The courses are tied in with the extensive network of similar snow surveys in the western United States, the work of which is so well and widely known. In some areas, forecasts of spring run-off are consistently good with annual errors varying from 1% to 10%. In others,

similar satisfaction has not yet been obtained. Study proceeds as to the causes or error, possibilities under consideration including:

- (a) The "soil priming" factor in watersheds the surface of which consists largely of soil;
- (b) Snow evaporation during the melting period, particularly in areas subject to the famous "Chinook" winds;
- (c) The effect of forest cover.

Similar snow survey work is carried out in Ontario by the Hydro Electric Power Commission of Ontario, in conjunction with the Dominion Water and Power Bureau. In Quebec the Shawinigan Water and Power Company has conducted similar investigations since 1928 and the Quebec Streams Commission is now extending this work. It is certain that the importance of this type of snow investigation, now so well recognised generally, will inevitably lead to its extension and further correlation across the Dominion.

It is somewhat surprising that the same attention does not yet appear to have been devoted to the hydrological aspects of snow in relation to agriculture. The Dominion Meteorological Service and other agencies regularly measure and report snow depths at many points across the country, but the detailed study of snow depth in relation to ground infiltration has yet to be fully developed. Possibilities of snow as a fertiliser have been suggested in a paper by Shutt to the Royal Society of Canada (2) but no extensive investigation has yet been initiated. Experiments have been carried out, however, on the control of snow drifts in order to increase the depths of snow on fields in order to augment ground water. This investigation and similar work has been undertaken by the federal Department of Agriculture.

More recently, renewed attention has been given to ice, in the form of glaciers, as a source of stream flow. The popular belief that the glaciers on the eastern slopes of the Rockies are "retreating" is now under scientific observation. The paper presented to this Conference by Mr. V. Meek, Controller of the Dominion Water and Power Bureau, summarises the present status of this important work (3).

These several aspects of the hydrological value of snow and ice studies are well recognised; the surveys and practices described are not peculiar to Canada. They have served usefully to direct the attention of scientists towards

winter conditions and, at least to some degree, are linked to broader and more general interests in snow and ice now to be described.

Ice Problems:

The rivers and lakes of Canada provided almost the only transportation routes for the first two hundred years of the country's development. They are still important arteries of transport, the Great Lakes and associated waters constituting the greatest system of inland waterways in the world. It has been asked "If the invention of the thermometer had preceded the discovery of the St. Lawrence, would the white man have gone back to Europe?" - a hypothetical and scarcely accurate bit of rhetoric which epitomises the rigorous effect of winter on this transportation system. From the very earliest days of settlement, the coming of the ice and its "break-up" have provided annually two serious interruptions to the use of rivers and lakes. To meet these difficulties the famous amphibious "ice-boats" of the St. Lawrence were developed and are still in use (4).

Once the ice has formed, rivers and lakes again become traffic arteries, although now for surface vehicles rather than boats. Four inches of ice have come to be regarded as the minimum thickness necessary for the safe passage of a horse with its loaded sleigh; thereafter, until the coming of spring, the loads transported over ice are usually limited by the size of vehicle rather than by the strength of the ice. In the spring of 1948, for example, valuable mechanical and electrical equipment, weighing in all 220 tons, was safely transported by tractor trains for a distance of 325 miles over the ice of Great Slave Lake on its way to a far northern water power site.

With increasing use of ice for such transportation purposes, including the now widespread use of ice for the landing of aircraft, empirical methods for the determination of ice thickness and strength are ceasing to be adequate. Study is therefore being given to this complex problem, or group of problems. Many devices have been developed for rapid determination of ice thickness notably by the National Research Council, using such modern methods as supersonic and electronic techniques, but so far without real success. The problem is one of unusual difficulty but of comparable importance.

A theoretical analysis of the strength of a floating ice sheet has been completed but not yet published. Much experimental work can even now be envisaged but little

has been done except in connection with the "Habbakuk" project of the recent war. Although no Canadian reports on this have yet been released, so that no reference to them may be made in this paper, a general account of the scheme has recently been published by Perutz (5). A floating aerodrome was visualized, for Atlantic use, constructed of ice. An extensive programme was carried out, much of it at Jasper Lake in the Canadian Rockies. Laboratory work had been started by the British Department of Scientific Research (Admiralty) and was later continued in Canada under the auspices of the National Research Council to the direction of Professor G.M. Williams. The development of "pycrete" (a combination of ice and wood pulp) is described by Perutz in his paper: this interesting material is suggestive of other possible avenues of research.

It was not inappropriate that the "Habbakuk" work should have been done in Canada in view of the pioneer work on the properties of ice carried on for many years by Dr. H. T. Barnes of McGill University. In his presidential address to Section III of the Royal Society of Canada in 1909 (6), and later, in his well known textbook "Ice Engineering" (7), Dr. Barnes brought together a remarkable collection of information, supplemented by the results of his own extensive experiments, some of which are still remembered around McGill in almost traditional manner in view of their unusual character.

A prime interest of Dr. Barnes was the prevention or the alleviation of the "ice-jams" which occur in most of the rivers of Canada when the ice begins to move in the spring. Dr. Barnes did much work, and achieved some success, with the use of thermite for breaking up the ice packs, particularly in the St. Lawrence at Montreal. Flood conditions due to ice packing are sometimes so serious in that vicinity that the harbour is still surrounded by a massive protection wall, the gaps in which are annually closed at times of flood danger. Much more serious are the annual flood conditions at the scattered settlements along the Mackenzie River system (Canada's largest river), due to its flow from south to north. The thawing of tributary streams before the main stream has broken up gives rise annually to floods of such proportions that in some areas, no buildings or equipment can safely be left within sixty feet above the normal water level; they have to be moved up the steep banks in the fall and replaced after the flood has subsided.

Despite the work of Dr. Barnes, the problems of dealing satisfactorily with ice jams on Canadian rivers remains. Possibly the most dramatic evidence of the force of

ice, when thus constrained, was the destruction of the famous "Honeymoon" bridge at Niagara Falls in January 1938 (8). This steel arch bridge, with a span of 1244 feet, was built in 1898 with its supports presumably fixed well above any possible flood water or ice level. Despite its successful performance for forty years, the combination of wind, temperature and ice conditions in the spring of 1938 on the Niagara River caused such a blockage of ice in the constricted gorge below the Falls that the level of the ice at the bridge site gradually rose until it was above the level of the arch supports. As the ice moved slowly downstream, the great bridge was pushed off its bearings as if it were matchwood, collapsing on to the ice and eventually disappearing into the depths of the river. The corresponding rise in water level did much damage to adjacent power houses, one being completely flooded and filled with large ice blocks, necessitating months of inactivity while repairs were effected.

This was an unusual mishap for a water power plant but until comparatively recent years other power plants (and water system intakes) have been much troubled with "frazil ice" - the thin needle-like form of ice which will form in large quantities under certain conditions of super-cooling. Much investigation of this problem has been carried out in Canada, notably by Mr. John Murphy. The result of this work has been the development of design features for water intakes of both power and water supply plants which satisfactorily obviate the blockages so often caused in the past by "frazil" (9).

Another problem which arises in connection with Canada's water power plants is the determination of the amount of ice pressure to be allowed for in the design of dams and other water retaining structures. When it is noted that the figure generally used is 10,000 pounds per foot of dam, exerted at maximum water level, the economic significance of this problem will be at once apparent. Again, the problem is complex with the result that little study has been made of it. One of the very few fundamental approaches to the problem is provided by the work of Brown and Clark who carried out some singularly interesting experiments in a Montreal cold-storage warehouse, in connection with the dam design for one of the Dominion's most northerly power plants, that at Island Falls on the Churchill River in northern Saskatchewan (10). It would appear that no accurate field measurements of the pressures actually exerted by ice have yet been made. A special committee of the American Society of Civil Engineers has recently been reconstituted to deal with this problem. It is hoped to conduct experimental work in Canada, in the field and in the laboratory, in the near future in conjunction with

the current construction programme of the Hydro Electric Power Commission of Ontario.

Ice pressure is of similar importance in connection with the construction of marine structures on the east coasts of Canada, many of which are ice-bound for a portion of each winter. This freezing of the sea approaches to the Dominion has led to the development of a powerful Canadian fleet of ice-breaking vessels, now under the federal Department of Transport. First in the St. Lawrence and later in the Hudson Bay area, these sturdy vessels assist the spring "break-up" with a view to speeding up the opening of the navigation season. Design of the most recent vessel for Canadian winter service - the "Abigweit", the largest ice-breaking train-ferry vessel ever to be built - brought to light the dearth of information regarding the design of vessels intended for ice breaking (11). No record appears to exist of any approach to the problem other than that of experience; in view of the forces involved, and of the economics of the problem (the "Abigweit" for example has a displacement of 7600 tons), it would appear that here, also, is a field for research yet unexplored (12).

No review of Canadian ice problems would be complete without brief reference to a singularly informative report by Kerry (13). A case is made out in this paper for further study of the temperature variation in the waters of the Great Lakes and the St. Lawrence in view of possible improvements to the navigation season suggested by the fact that water has its maximum density at 38°F. The paper, and the relevant discussion, provide a most useful fund of information and are fruitfully suggestive of yet another direction in which Canadian ice investigations may be expected to advance.

Snow Problems:

The problems to which snow gives rise are mainly related to the fact that some of it falls where it is not wanted and has to be removed. Its deposition can not yet be controlled. The invaluable records now provided by the Dominion Meteorological Service make it possible to predict local snowfalls within a fair range of accuracy. There is always the possibility, however, of a fall such as that which occurred in the Toronto district on the night of December 11th 1944 when 33 inches fell during less than twenty-four hours. The entire metropolitan area of Toronto, with its million people, was immobilised for a full day and all normal city services were disrupted for more than a week. Fortunately

such occurrences are rare but when they do happen, they demonstrate in no uncertain manner the dependence of modern means of transportation upon snow clearing equipment.

Even the smallest Canadian municipalities now maintain some snow clearing equipment, often operated in connection with other automotive equipment of more general use; the larger cities have large investments in their special snow clearing machinery. In all but exceptional cases, such as that just described, snow falls are cleared almost as rapidly as they occur. Indeed, in the city of Ottawa it was charged last winter that snow was cleared too quickly and too efficiently with the consequence (it was alleged) that frost was allowed to penetrate beneath city streets to a depth which endangered water supply pipes. This matter is to be studied in detail. Disposal of the snow is often a problem. In some cities it is dumped on vacant land; in others, onto local lakes or frozen river surfaces. In Montreal, manholes are specially located so that snow may be dumped directly into them, the heat of the sewage and other waters carried by the sewers being sufficient to melt the snow and carry it away as water to the out falls in the St. Lawrence.

Correspondingly, all major highways, and many strategic minor highways, are kept open the year round by the various provincial highway departments responsible (the federal government being charged only with highway work in the Northwest Territories and the Yukon). The efficiency of this highway clearing is remarkable. In recent years, the province of Ontario has been materially assisted in its snow clearing work by a special weather predicting service provided by the Dominion Meteorological Service, which is passed on to highway users. The costs of winter road maintenance, however, are very high. Taking the province of Ontario as an example, three million dollars is the average current expenditure for one winter. This covers only the cost of snow removal and the "skid-proofing" of roads by the use of sand (200,000 cubic yards a year) and special chemicals (40,000 tons). Already the supply of suitable sand is critical and the damage done to vegetation, to concrete pavements and to the undercarriages of automobiles by chemicals is serious. Here are two "minor" problems demanding attention.

It is difficult to prepare any accurate estimates of the cost of snow removal in Canada especially in view of the variation of climatic conditions with locality and time. Ontario's expenditure is typical. Montreal and Toronto each spend about one million dollars every year. The total cost,

to provinces and municipalities, certainly exceeds ten million dollars each year and may well be considerably higher. A comparable figure is the total of twenty-one million dollars for the thirty-six States (of the U.S.A.) in what is called the snow-belt; it is to be noted that their climatic conditions are not nearly so rigorous as those of the Canadian provinces.

These vast sums are well and carefully spent. It can not be suggested, however, that the efficiency of snow moving equipment is as high as it might be. The possibility of some improvement in the handling of this one snow problem alone would seem to justify an extensive research programme. There are, however, comparable problems of almost equal magnitude. For example, the figures quoted do not include the cost of providing and installing the many thousands of miles of "snow-fencing" which are so familiar a feature of the Canadian winter landscape, by the sides of roads and of railways. The location of these fences is again a matter which appears to be decided entirely empirically. Many fences are probably well placed but the researches of Finnie, in Michigan, have indicated the great possibilities for improvement (14). The problem is one involving aerodynamics; the first steps in treating it accordingly have been taken in Canada and, in conjunction with field tests, they indicate already some interesting possibilities.

The railways have been mentioned; they have their own snow clearing difficulties. Although their costs for winter operations are not published, they are known to run also into millions of dollars. In level areas, the problems are similar to those on highways; so also is the equipment, although somewhat heavier. In mountainous regions, special problems are encountered; rotary plows have to be used, and in some locations special snow sheds erected to obviate dangers from avalanches. In yard areas, and at busy terminals, critical problems may often arise in the maintenance of switches during bad storms. In the Montreal terminal area, for example, over one thousand men may be employed during a storm merely for maintaining switches. And the special problems caused by snow drifting in cuttings and depressed areas are well known if only because of the publicity which they attract, as when a train in Saskatchewan was "snowed in" completely for over a week during the bad winter of 1946-47.

Air transportation too, has its special winter problems. There is the very technical matter of the icing of propellers and of wing tips upon which much research has been carried out in Canada, with attendant success. Airports have also to be maintained, bringing their own special snow-clearing problems. Large snow-blowers are now regularly used for this

purpose, the practice being merely an extension of highway clearing. Alternatively, the practice of rolling and compacting the snow has often been adopted, especially for smaller and more isolated airports. The idea is a simple one; its effective prosecution carries many difficulties with it, some of which are still unresolved. When it is noted that Canada maintains over one hundred civil airports, the magnitude of this problem and its economic significance will be apparent.

Another associated problem is the use of skis in place of the usual wheels for the landing of aeroplanes on snow and ice. For light planes, skis are practically standard winter equipment. Their proper design became a matter of concern to the National Research Council in 1934 and Mr. G. J. Klein was assigned the task of investigating the problem. Many discouragements were met with in this work in view of its complexity but Mr. Klein was able to present a review of his findings at the 1939 meeting of this Commission. His work has now been described in a published report summarising an acceptable theory which meets the many facts which have been recorded (15). The work still goes on, its continuation over more than a decade indicating the complex nature of the problems involved.

The problems presented by aircraft skis are not dissimilar from those involved in the design and operation of sleighs for over-snow transport, possibly the most widespread and amongst the most important of all Canadian winter problems. While it is true that major highways and all railways are now kept open throughout the winter, probably ninety per cent or more of the total mileage of Canadian highways are not so maintained for winter travel, thus necessitating the use of over-snow vehicles. Sleighs still predominate in this field. In logging operations, they are of cardinal importance so that it is not surprising that one of the first Canadian studies of the over-snow transport problem was in connection with the design of logging sleighs. Mr. W.E. Wakefield of the Forest Products Laboratories of the federal Department of Mines and Resources conducted this research work and has published a valuable report (16). Both this work, and that of Mr. Klein are linked to similar studies carried out in Sweden, notably by Soderberg.

Although slow-moving sleighs are still invaluable for much winter transport, faster moving vehicles are an inevitable result of the application of automotive practice to this unusual field of transport. Many ingenious over-snow automobiles have been developed. One of the most successful is a Canadian machine, the "Auto-neige" designed

and manufactured by Mons. Bombardier of Quebec. Over six hundred of these vehicles are successfully in regular use in Canada. This was the machine which provided the basic ideas for the Canadian Army's "Snowmobile" developed during the war years and given its first large scale public trial on "Exercise Musk-Ox". This remarkable journey was made by a special Moving Force of the Canadian Army using twelve snowmobiles, supplied and assisted by R.C.A.F. planes. The Force left Churchill, Man., on February 14th, 1946 and reached Edmonton, Alta., on May 6th, after a journey of 3130 miles, penetrating far north of the Arctic Circle, most of which was made under most severe winter conditions (17). The entire Exercise provided much invaluable information about northern conditions, not the least important being that over-snow travel with automotive equipment was possible over a route which included conditions almost as bad as could be met with anywhere. The economics of this method of travel, however, have yet to be investigated. Enough is known of the operation of existing vehicles to make further improvements imperative before they can be widely adopted. The whole problem of "over-snow" travel is a challenging one; it seems reasonably certain that considerable advance is to be expected over present-day methods.

Importance of Fundamental Studies:

It is well realised that the foregoing brief review is essentially a listing of what might be called applied scientific or engineering problems. Were it not for one common feature the review might be inappropriate for such a meeting as this. All the problems involve water in one of its solid forms - snow and ice being the common terms used to describe the more common varieties of the frozen form of water. Empirical approaches can usefully be made to individual problems without any consideration being given to such a common link. When, however, a scientific approach is made to such problems, the common factor becomes of prime importance. Snow and ice as materials call for fundamental study, basic to any real understanding of the more applied problems which have been considered.

This view of the matter was adopted by the Associate Committee on Soil and Snow Mechanics of the National Research Council of Canada very early in its work relating to over-snow travel. Constituted to deal with a special war problem, and including within its membership (as is the practice with N.R.C. Associate Committees) both civilian and military personnel, the Committee is now concerned with all the terrain of Canada with special reference to the

operation thereon of tracked vehicles. Soil, muskeg, "permafrost" and snow and ice are the materials under study through the Committee. From the outset of its work, their interrelation has been kept in view, as has the need for basic study of the materials in question as an essential foundation for more applied researches.

The Committee has been fortunate enough to have Mr. G. J. Klein as a member since its inception. In his work on aeroplane skis, Mr. Klein had found the need for a basic study of snow as a material. He therefore brought to the Committee a background of useful preliminary investigation. Against this background and with his invaluable advice and the help of the Dominion Meteorological Service and other agencies, the Committee was able to arrange for the Snow Survey across Canada which is described by Mr. Klein in his companion paper (18). As is therein explained, the main object of the Survey was to provide actual knowledge as to the properties, and not merely the water equivalent, of the snow encountered at selected locations across the Dominion. Without this knowledge, no detailed snow researches could be carried out effectively.

A review of the literature which was naturally studied as a start to these Committee projects, showed that relatively little had been done on snow and ice as materials. As the most suggestive publications were those from Switzerland, personal contact was established with Swiss workers with the most helpful results. Dr. Haefeli of the Zurich Polytechnique and Dr. Bucher of the Snow Research Institute at Davos, and members of their staffs, have not only been most courteous in the provision of information but their own work and their achievements have been a source of inspiration to the start of Canadian research into snow and ice.

As a further preliminary, the Committee arranged for the holding of a Conference of those Canadians experienced in snow work. This was held at Ottawa in September 1947; a record of the proceedings is available (19). The Conference was organised jointly by the Committee already named and the corresponding Associate Committee on Geodesy and Geophysics (the National Committee for Canada of the International Union of Geodesy and Geophysics). The hydrological aspects of snow and ice were recognised as an important part of the general picture, and that part which had received a good deal of public attention. It was hoped that the Conference would show the complete interrelation of the hydrological and the many other aspects of snow and ice study then appreciated. These hopes were more than fulfilled. Seventy experts attended the Conference and in the course of two days discussed

well over one hundred different problems associated with snow and ice. A partial list of these accompanies this paper as an Appendix. Most striking was the repeated emphasis upon the necessity for a knowledge of the basic properties of snow and ice as materials. Sir Charles Wright, who was glaciologist to the Scott Terra Nova Expedition and who attended the Conference, was particularly emphatic on this point. This paper is, in effect, a digest of the proceedings of this important meeting.

The Conference decided that there should be a continuing Research Sub-committee, to be operated (in the first instance at least) jointly by the two Committees. The main purposes of this Sub-committee would be to correlate work being done on snow and ice in Canada and to promote the initiation and development of further work to the maximum extent possible. The Chairman of this Joint Sub-committee (Mr. P.D. Baird) is present at this meeting of the International Commission, as are also Mr. Klein and the Chairmen of the two main committees mentioned (Dr. J.T. Wilson and the writer). This may be some evidence of the keen desire of Canadian workers to associate themselves with fellow workers in other lands and of their hope that the remarkably broad aspects of snow and ice research, which have been so briefly sketched in this paper, going far beyond the confines of hydrological interest, may commend themselves to those from other countries in which snow and ice are important features.

The Future:

There has been in recent years in Canada a remarkable awakening of interest in the northern part of the country. As an indication of this there may be mentioned the inauguration of the Arctic Institute of North America, with headquarters in Montreal, which is mobilising public interest and support for Arctic investigations (20). This public attention to northern problems carries with it an appreciation, at least of a general character, of the importance to the Dominion of snow and ice. It is, therefore, singularly appropriate that circumstances have led to the renewed scientific activity in the same direction which is indicated in this paper. It can consequently be predicted with a reasonable degree of certainty that real advance in the fundamental study of snow and ice may be expected in Canada in the years immediately ahead.

This advance will be a cooperative effort on the part of all the agencies mentioned, directly and indirectly, in the foregoing notes. There will be the most complete pooling possible of information assembled by interested private companies, and by municipal, provincial and federal

governmental agencies. The special interests of the Dominion Water and Power Bureau are being described to this Conference by its Controller, Mr. V. Meek. The companion paper by the Controller of the Dominion Meteorological Service, Mr. A. Thomson (21), shows clearly the vital concern of this Service with problems of snow and ice, especially in view of the extension of its services in the far north.

It is in concert with such sister organisations that the National Research Council is working and will continue to work in this field. Through its committee service, the Council provides means for active cooperation between all interested agencies. Through its operating Divisions - of Physics, Mechanical Engineering and Building Research - it prosecutes active research into appropriate winter problems. The Division of Mechanical Engineering is investigating aeronautical icing and aircraft ski design; it will be investigating over-snow transport and snow clearing problems. The Division of Building Research, in turn, will be concerned with static problems of ice and snow and consequently of the fundamental properties of these materials. In conformity with Swiss practice, this work on "Snow Mechanics" will be carried on in close association with similar work in Soil Mechanics. Within the next few years it is hoped to establish snow research stations in the Canadian north and in the mountains of the continental divide. The National Research Council anticipates with pleasure the active assistance of Swiss workers in this work, this being further evidence of the desire on the part of Canadian authorities for international cooperation in this field of scientific interest such as is so fortunately the case in so many other branches of science. It is hoped that this Conference will result in real advance towards this most desirable goal.

APPENDIX

List of Canadian Research Projects on Snow and Ice Suggested at the Ottawa Conference, 1947.

I. Fundamental Research:

1. Establishment of observation and research stations.
2. Correlation and expansion of existing snow surveys, and standardization and distribution of data so obtained.
3. Maps of snow cover and its seasonal variation.
4. The physics of snow-melting, particularly as related to absorption of solar heat.
5. Knowledge of the properties of various types of ice, and conditions under which they are formed.
6. The importance of cyclic trends of solar radiation as affecting severity of weather.
7. Seasonal forecasting of snowfall.

II. Hydrology and Meteorology:

1. Correlation of snow accumulation and run-off, finding variables involved and their individual importance and effect.
2. Accurate prediction of run-off as affecting power development and flood conditions.
3. Influence of snow meltwater on ground water storage.

III. Snow Control and Clearance:

1. Location of existing types of snow fences and wind-breaks for highest efficiency.
2. Development of more efficient means of control of snow drifting.
3. Improvement of snowplow design.
4. Development of more efficient means of snow and ice removal.
5. Development of non-injurious chemicals for road treatment.
6. Development of anti-slip treatment for roads and sidewalks.
7. Design of self-cleansing highways.

IV. Oversnow Travel:

1. Properties of snow as affecting skis, sleds, or toboggans, and effect of heating sliding surfaces.
2. Design of over-snow tracked vehicles.
3. Starting of tracked vehicles in cold weather.
4. Take-off and landing with aircraft skis.

V. Agricultural Effects:

1. Evaporation from snow surfaces as affecting snow storage.
2. Amount of run-off available for irrigation purposes.
3. Preservation of moisture in dry farming areas by drift prevention.
4. Run-off as affecting erosion and soil conservation.
5. Value of snow cover (a) as a fertilizer, (b) as protection against frost penetration, and (c) as promoting the slow absorption of water by soil.
6. The effect of infiltration of snow meltwater into frozen or semi-frozen soil.
7. The effect of permafrost on crops and plant growth.
8. Frost action in problems of land clearing.
9. Snow mechanics as affecting the trafficability of farm vehicles.

VI. General Ice Problems:

1. Physical properties of ice, such as strength and friction.
2. Means of reducing or increasing such properties.
3. Conditions governing the formation of various types of ice, particularly frazil ice, and their critical nature.
4. Means of preventing the formation of ice, such as frazil ice or that against dams and other structures.
5. Pressure of large ice sheets on engineering structures.
6. Prevention of ice jams with consequent floods and structural damage.
7. Study of living glaciers.
8. Effect of rain on ice.
9. Rapid means of detecting thickness of sea ice.
10. Rapid means of estimating strength of sea ice.
11. Storage of ice for refrigeration purposes.

VII. Ice Problems Affecting Navigation:

1. Eliminating and controlling formation of ice on various parts of a ship.
2. Means of facilitating the removal of such ice after formation.
3. Means of predicting the close of the navigation season.
4. Means of lengthening the navigation season on the Great Lakes.
5. Means of clearing ship channels more effectively.
6. Movements of ice under wind, and controls for such movements.
7. Navigation in Arctic drift ice.
8. Forecasting of iceberg seasons.
9. Tracing the path of icebergs.
10. Design of ice-breaking vessels.

VIII. De-Icing Problems:

1. Data on super-cooled liquid particles in air, and their characteristics when encountered by moving objects.
2. Means of de-icing electrical conductors.
3. Elimination of "galloping" conductors.
4. Icing of aircraft propellers.
5. Icing of aircraft wings and fuselage on the ground.
6. Icing of aircraft wings in the air.

IX. Permafrost:

1. Identification and mapping of permafrost areas.
2. Determination of the nature of soils in which permafrost occurs.
3. Determination of the thermal conductivity of frozen ground.
4. Means of lowering the level of permafrost.
5. Foundation on permafrost.

X. Engineering

1. Frost boils and frost heaving of roadbeds.
2. Depth of frost penetration as affecting the depth of laying pipe services.
3. The validity of the use of the number of degree-days of freezing as a factor in runway design.

4. Airborne machinery necessary for the construction of airports on rolled snow or ice-covered lakes.
5. Construction of ice roads for tractor trains.
6. Means of transporting and storing fuel in the far north.
7. Damage to wharves caused by ice movements.

XI. Electromagnetic Effects:

1. Electrostatic charges on snowflakes.
2. Determination of snow and ice depth by electromagnetic waves.
3. Effect of blowing snow and ice crystal haze on ultra-high frequency radio waves, and on navigation and communication.
4. Detection of snow storms by electromagnetic waves.

XII. Comfort Problems:

1. Clothing in the far north.
2. Physiological and psychological effect of proper clothing and food.
3. Housing in the far north.

XIII. Miscellaneous:

1. Prediction of snow slides in mountainous areas.

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GLACIER OBSERVATIONS
IN THE CANADIAN CORDILLERA

by

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Note: Mr. Meek's paper was published in Vol. 37 of the Canadian Geographical Journal, pp. 190-209, for November, 1948, illustrated by many excellent photographs. In view of this, the photographs have not been reproduced in this Report.

Glacier Observations in the Canadian Cordillera

In connection with studies of the water resources of the mountainous rivers of British Columbia and Alberta, the Dominion Water and Power Bureau, Department of Mines and Resources, in 1945, initiated an annual survey of certain typical glaciers in the Canadian Cordillera. In addition to obtaining glacier information of general scientific value, the ultimate purpose in view is the determination of the effect of glacier variation on run-off, particularly the amount of run-off which may be expected in future from our glacier resources. A limited number of glaciers were selected for observation purposes, each reasonably accessible and considered to be typical of the general area of location. The studies in the Coast and Selkirk Ranges have been conducted under the direction of Mr. C.E. Webb, District Chief Engineer, Vancouver; those in the Rocky Mountain Range, under Mr. O.H. Hoover, District Chief Engineer, Calgary.

Glacier Phenomena

Glaciers are formed by great depths of snow accumulating in mountain basins at high altitude; the weight of the snow, assisted by surface melting, causes the lower layers to compact and to turn into ice. Under the pressure exerted, together with gravitational effect, the ice slowly extrudes through the valley outlets of the basin, the flow resembling that of a river. When the slowly moving mass of ice in the valley reaches lower altitudes, melting takes place during the summer months, forming glacial streams. When the annual amount of melting equals the rate of ice flow, the glacier becomes more or less stabilized, advancing in winter and retreating in summer; if the annual melting exceeds the forward movement, the toe of the glacier retreats from year to year. Our present glaciers are the remnants of the continental ice cap which once covered a large part of the northern half of the continent. "Alpine" glaciers are those flowing directly from the upper icefield; "Piedmont" glaciers are formed by a union of one or more Alpine glaciers into a single stream.

The year to year changes in individual glaciers depend upon the amount of ice supplied from the upper icefield, the rate of ice flow and the quantity melted away on the tongue; if more ice is supplied than is melted, the glacier advances, while if melting exceeds supply, recession takes place. Annual temperature, precipitation, sunshine, amount of moraine covering and the topography of the valley modify the result so that many factors are

involved. There may be also a considerable time lag before gradual changes in the icefield are reflected by the valley glacier. Long-term general variations of regional glaciers are caused by changes in climate, particularly the factors of temperature and precipitation. At the present time sufficient data have not been accumulated to determine the physical laws governing glacier phenomena.

Observations by Alpine Club of Canada

Although glacier observations in Canada under governmental direction began only in 1945, sporadic observations and studies of the variations of a number of glaciers in the mountainous regions of British Columbia and Alberta have been made by members of the Alpine Club of Canada over a long period of years, the first on record being for the year 1887. In addition to photographs, the recorded observations usually have included the distance from a reference point to the nearest ice of the glacier toe; a limited number of observations were made of the rate of glacier flow. Reports on these observations, together with excellent articles on the formation, characteristics and phenomena of glaciers, have been published in the Canadian Alpine Journal from time to time; three of the more noted investigators and writers were, - W.H. Sherzer, W.S. Vaux and A.O. Wheeler.

The observations of Canadian glaciers recorded in the Canadian Alpine Journal reveal a general and practically continuous recession since 1887. This recession coincides with a similar glacier retreat in the Swiss Alps so that the earlier pattern of Canadian glacier variation probably was somewhat similar to that in Europe. In brief, beginning in 1812, there was a general advance of all glaciers which reached a maximum in 1825; a period of decrease then set in, followed by a less positive increase which reached a maximum about 1850; then ensued a period of marked decrease and in 1870, all the glaciers were definitely retreating. The period 1875 to 1894 was indecisive, certain glaciers advancing and others retreating; since then the decrease has become almost universal and has continued more or less positive in character until the present time.

Records of Glacier Variation

In 1894 an International Commission on Glaciers with headquarters at Lausanne, Switzerland, was appointed by the International Congress of Geologists meeting at Zurich and a general record of glacier variation throughout the world was kept for many years, reports being received from the Canadian Alpine Club covering observations in Canada. The Commission ceased to function during World War I but was

reconstructed under the auspices of the Section of Scientific Hydrology of the International Union of Geodesy and Geophysics at its full meeting at Stockholm in 1930. Glacier data also have been compiled by the Smithsonian Institute at Washington. The studies underway by the Dominion Water and Power Bureau will provide current data on glacier conditions in Canada.

Methods of Observation

The methods of observation used to date by the Bureau include the following procedures:

1. The setting up of fixed reference marks near the toe of each glacier under observation. These markers are tied in to permanent topographical features.
2. The annual measurement of the distance from a reference point or base line to the nearest ice of the toe; or alternatively, the annual mapping of the forefoot. In the latter case, successive yearly plottings show clearly the average advance or recession across the whole forefoot.
3. The setting up of camera stations from which photographs can be taken annually to show overall changes in the glacier.
4. The study of the rate of glacier flow by means of placques or markers set out on the ice along a base line crossing the glacier some distance above the toe. The base line is set perpendicular to the direction of flow and the deviation of the markers from the base line is measured trigonometrically each year. Field trials of different markers are under way.
5. Determination of annual ablation by means of a surface cross-section line run across the glacier tongue perpendicular to the line of flow and some distance up from the toe.
6. It has been recommended that aerial photographs be taken of each glacier at about five-year intervals to cover the general outline of the glacier and adjoining icefield. These would indicate the general shrinkage or extension of the supply reservoir which is actually more important from the long-term run-off viewpoint than the yearly local change of the glacier tongue.

Glaciers Under Observation

For the purposes of the Dominion Water and Power Bureau studies, typical glaciers in each mountain range were selected. In the Coast Range, two areas, Garibaldi Park and Mount Waddington, are comparatively accessible and considered to be representative of the range; the Helmet, Sentinel and Sphinx Glaciers were chosen in Garibaldi Park and the Franklin Glacier in the Mount Waddington area. In the Selkirks, Kookanee Glacier in the southern portion and the Illecillewaet in the more northerly region were adopted. In the Main Range of the Rockies, glaciers in the Banff and Jasper National Parks have been used including Victoria, Peyto, Saskatchewan, Athabaska, Freshfield and Lyell Glaciers; the Yoho and Angel Glaciers were also inspected. The distribution of these glaciers and their specific locations are shown on the accompanying map which covers adjoining parts of British Columbia and Alberta; the general location is indicated on the inset map of Canada. A typical view of each glacier, selected from those taken in 1945, 1946 and 1947, is shown in the appended photographs.

Records of the observations by the engineers of the Dominion Water and Power Bureau covering two full years are now available for most of the above glaciers. A short description of each glacier, together with a brief review of previous and current observations is given below. The observations are also summarized in tabular form.

COAST RANGE

1. Sentinel Glacier

The Sentinel, Sphinx and Helmet Glaciers are located in Garibaldi Park about 60 miles north of Vancouver. The Sentinel is typical of all the glaciers in the Park. It is of the Piedmont type being composed of several smaller glaciers which unite into a short trunk. Observations for the year 1935-36 showed a mean recession of 240 feet on two shallow projections of the toe. In 1945 the base line previously used could not be located but photographic evidence indicated a recession of about 900 feet from 1935 to 1945, being 90 feet per year. For the two-year period of 1945-1947, the recession was 141 feet or 70 feet per year. The forward movement during 1946-47 was 10 feet.

Observer - P.W. Strilaeff, Field Engineer, Vancouver.

2. Sphinx Glacier

The Sphinx Glacier lies two miles north of the Sentinel. Its forefoot is very indefinite and irregular; it is difficult to approach at present owing to huge blocks of ice near the toe. The moraines deposited by its recession are undisturbed and provide an excellent geological record of its retreat. No measurements were made but photographs were taken in 1945, 1946 and 1947.

Observer - P.W. Strilaeff.

3. Helmet Glacier

Helmet Glacier is typical of the "Alpine" basin type of glacier with a northern exposure. It has two tongues about half a mile apart, on each of which observations were made in 1935 and 1936 by the British Columbia Mountaineering Club which showed a recession of 112 feet for the East Tongue and 85 feet for the West Tongue in one year. The observations of 1945-1947 show average annual recessions of 55 feet and 50 feet respectively. For the period 1935-1947 the West Tongue receded 546 feet or an average of 45.5 feet per year. The amount of forward movement on the East Tongue was 14 feet in the year 1946-1947.

Observer - P.W. Strilaeff.

4. Franklin Glacier

This glacier is formed on the slopes of Mount Waddington which is situated about 165 miles northwest of Vancouver; it discharges into the Franklin River which flows into Knight Inlet near its head. Observations regarding its recession were instituted by Mr. D. Munday of the Canadian Alpine Club in 1927. During the period 1927-1945 the total recession was 4520 feet, being a yearly average of 251 feet. During the two-year period 1945-1947 the average was 292 feet.

Observer - A.V. Gallon, Field Engineer, Vancouver.

SELKIRK RANGE

5. Kokanee Glacier

The Kokanee Glacier is located about 20 miles north-west of Nelson, on the north side of the highest ridge in the southern limits of the Selkirk Mountains.

The glacier has two tongues about one mile apart, one at the head of Joker Creek and the other at the head of Coffee Creek, the tongues of both being in basins well below the main ice field.

Although no previous records have been compiled, it can be deduced from Geological Survey Map No. 203B, based on 1923 topographic surveys, that Coffee Creek tongue has receded about one-half mile and the Joker Creek Tongue about one-quarter mile since 1923. Observations covering 1945-1947 show the average annual recession of the Joker Creek tongue was 56 feet and that of Coffee Creek tongue 93 feet.

Observer - W.P. Harland, Field Engineer, Vancouver.

6. Illecillewaet Glacier

This glacier which is located on the west side of the main divide of the Selkirks is three miles south of Glacier, on the Canadian Pacific Railway. It is the source of one of the main tributaries of the Columbia River. The glacier proper has an area of about nine square miles.

Records on the Illecillewaet date back to 1887 having been kept more or less continuously since that date by members of the Alpine Club of Canada. Large alders growing near the toe in 1887 indicated that the glacier had been in this maximum position for many years. Since then the recession has been rapid but appears to be retarding since 1931. The average annual rate of retreat was 28 feet from 1898 to 1905, 83 feet from 1905 to 1911, 134 feet from 1911 to 1931 and 43 feet from 1931 to 1945. The average annual recession for the years 1945-1947 was 55 feet.

Observer - W.P. Harland.

ROCKY MOUNTAIN RANGE

7. Victoria Glacier

The Victoria Glacier originates in Abbot Pass and is fed by snow and ice avalanching from the cliffs and hanging glaciers of Mounts Victoria and Lefroy. Its tongue lies in the valley of Lake Louise at an altitude of about 6,000 feet, being buried under a mass of morainal material which makes observations of its true position very difficult. It has been under intermittent observation since 1898, the average rate of retreat for the period 1898-1912 being 18 feet per year; for 1945-1947 the rate was 33 feet.

Observer - W.T. McFarlane, Senior Engineer, Calgary.

8. Peyto Glacier

The Peyto Glacier flows from the Wapta Icefield, the extent of which is about 40 square miles and general elevation 9,000 feet. It is the source of the Mistaya River. It was first photographed in 1897 and measurements were made in 1933 and at intervals thereafter. The average yearly recession since 1897 has been estimated at 42 feet, varying from 21 feet per year for the period 1897-1933 to 133 feet per year for the period 1939-1942. For the period 1945-1947 the recession averaged 45 feet per year and the rate of flow was 70 feet per year.

Observer - W.T. McFarlane.

9. Freshfield Glacier

This glacier belongs to the Freshfield Icefield which is situated on the Continental Divide between tributaries of the North Saskatchewan and Columbia Rivers, its drainage being principally to the Saskatchewan. The icefield has an area of about 22 square miles and the trunk glacier has a length of about nine miles discharging through a deep, narrow valley. It forms the headwater of the Howse River.

The glacier is easy of access, fairly smooth and ideal for purposes of record. Records, consisting either of photographs or measurements, are available dating back to 1902. The total recession since 1902 is 3,525 feet, an average of 80 feet per year for 45 years; during the last 25 years the recession averaged 104 feet per year. Observations by the Bureau were undertaken in 1947.

Observer - W.T. McFarlane.

10. Saskatchewan Glacier

This glacier has its source in the Columbia Icefield and forms one of the headwaters of the North Saskatchewan River. The surface of the glacier is very rough and its toe is irregular. Surveys to record its recession began in 1945, no previous observations being known. During the two-year period 1945-1947 the total recession was about 250 feet.

Observer - W.T. McFarlane.

11. Athabaska Glacier

The Athabaska Glacier, also having its source in the Columbia Icefield, is considered to be excellent for observation purposes being fairly smooth and having a well defined toe. It is readily accessible from the Banff-Jasper Highway about 80 miles north of Lake Louise. Prior to the surveys covering both recession and flow which began in 1945, no records are known. The amount of recession for the two years was very irregular at different points of measurement varying from 50 to 220 feet. The rate of ice flow averaged 63.5 feet per year for the two years.

Observer - W.T. McFarlane.

12. Angel Glacier

The Angel Glacier, which is at the base of Mount Edith Cavell in Jasper National Park, is more or less isolated and does not belong to any particular icefield. It was placed under observation in 1945 but is now not considered to be of value for record purposes as the tongue is not now connected to the upper glacier and the toe is completely covered with rock and difficult to locate. The amount of recession 1945 to 1947 varied from 40 to 200 feet.

Observer - W.T. McFarlane.

13. Yoho Glacier

This glacier is the largest southern outflow from the Wapta Icefield and is located about 20 miles from Yoho Station on the Canadian Pacific Railway. It is the source of the Yoho River. When first discovered it presented a magnificent ice-fall which for many years attracted visitors. It was placed under observation by members of the Canadian Alpine Club in 1901 and intermittent records were kept until 1931. It was inspected in 1945 but was found to have retreated up the valley until it is now a hanging glacier unsuitable for recording purposes; previous reference points could not be located. From the Alpine Club records the annual rates of recession were 1901-1904, 37 feet; 1906-1918, 33 feet; 1918-1931, 46 feet. The average rate of forward movement of the ice was 103 feet per year as observed for ten individual years between 1906 and 1918.

Observer - W.T. McFarlane.

14. Lyell Glacier

This glacier forms part of the Lyell Icefield on the Continental Divide and is approached from the Banff- Jasper Highway about 60 miles north of Lake Louise. It was inspected in September 1947, photographs taken and a reference base line established; however it is not regarded as well suited for observation purposes owing to its steep forefoot. It has apparently receded rapidly in recent years.

Observer - W.T. McFarlane.

Summary of Observations

<u>Glacier</u>	<u>Period of Record</u>	<u>Annual Rate of Recession Feet</u>	<u>Annual Rate of Forward Movement, Feet</u>
COAST RANGE			
1. <u>Sentinel</u>	1935-1936	240	
	1936-1945	90	
	1945-1947	70	10 (1946-1947)
3. <u>Helmet</u> - West Tongue	1935-1936	85	
	1936-1945	36	
	1945-1947	50	
- East Tongue	1935-1936	112	
	1945-1947	55	14 (1946-1947)
4. <u>Franklin</u>	1927-1934	221	
	1934-1945	270	
	1945-1947	292	
SELKIRK RANGE			
5. <u>Kokanee</u> - Coffee Creek	1923-1945	120	
	1945-1947	93	
- Joker Creek	1923-1945	60	
	1945-1947	56	
6. <u>Illecillewaet</u>	1898-1905	28	
	1905-1911	83	
	1911-1931	134	
	1931-1945	43	
	1945-1947	55	

Summary of Observations (Cont'd)

	<u>Period of Record</u>	<u>Annual Rate of Recession Feet</u>	<u>Annual Rate of Forward Movement, Feet</u>
ROCKY MOUNTAIN RANGE			
7. <u>Victoria</u>	1898-1903	17	147 (1900)
	1907-1912	19	
	1945-1947	33	
8. <u>Peyto</u>	1897-1933	21	
	1933-1936	79	
	1936-1939	117	
	1939-1942	133	
	1942-1945	77	
	1945-1947	45	
9. <u>Freshfield</u>	1902-1922	95	
	1922-1937	87	71
	1937-1947	137	71
10. <u>Saskatchewan</u>	1945-1947	125	
11. <u>Athabaska</u>	1945-1947	135	63
12. <u>Angel</u>	1945-1947	120	
13. <u>Yoho</u>	1901-1904	37	
	1906-1918	33	103
	1918-1931	46	

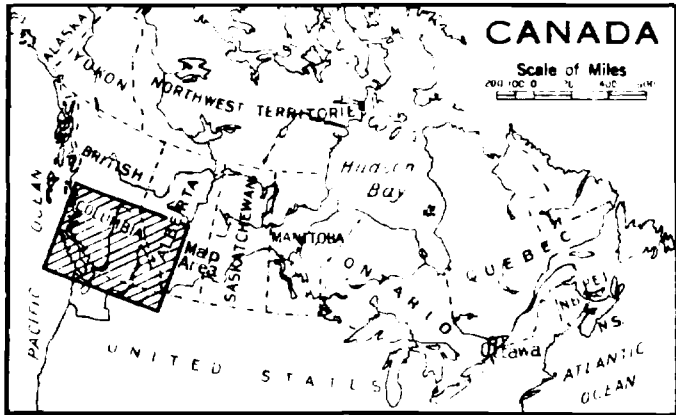
A weighted average for all the years of record prior to 1945, on ten of the above listed glaciers for which records are available for 1945-1947, shows a recession of 83.2 feet, as compared with 88.6 feet for the period 1945-1947. This would indicate that the general rate of recession has accelerated during recent years. There are not sufficient data to draw conclusions in regard to variations in rate of flow.

Conclusion

It is generally agreed that the recession of our glaciers has been caused by a gradual long-term change in climatic conditions, primarily a slight increase in annual mean temperature; probably there has also been a lower rate of precipitation in the mountains and longer

periods of sunshine. It is everywhere evident that, in former times, glaciers were of much greater extent than at present and that there has been a decrease and shrinkage for many years. Annual district variations in temperature, precipitation and sunshine determine if an individual glacier will advance or retreat over a short period of years and these same forces acting over longer periods of time determine the long-term trend. On individual glaciers the rate of change may be affected by conditions of the valley such as steepness of the slope, width of tongue and amount of moraine covering. It is expected that the systematic observations now being made annually by the Bureau will yield data which will be invaluable for studies correlating weather and climatic conditions with glacier phenomena.

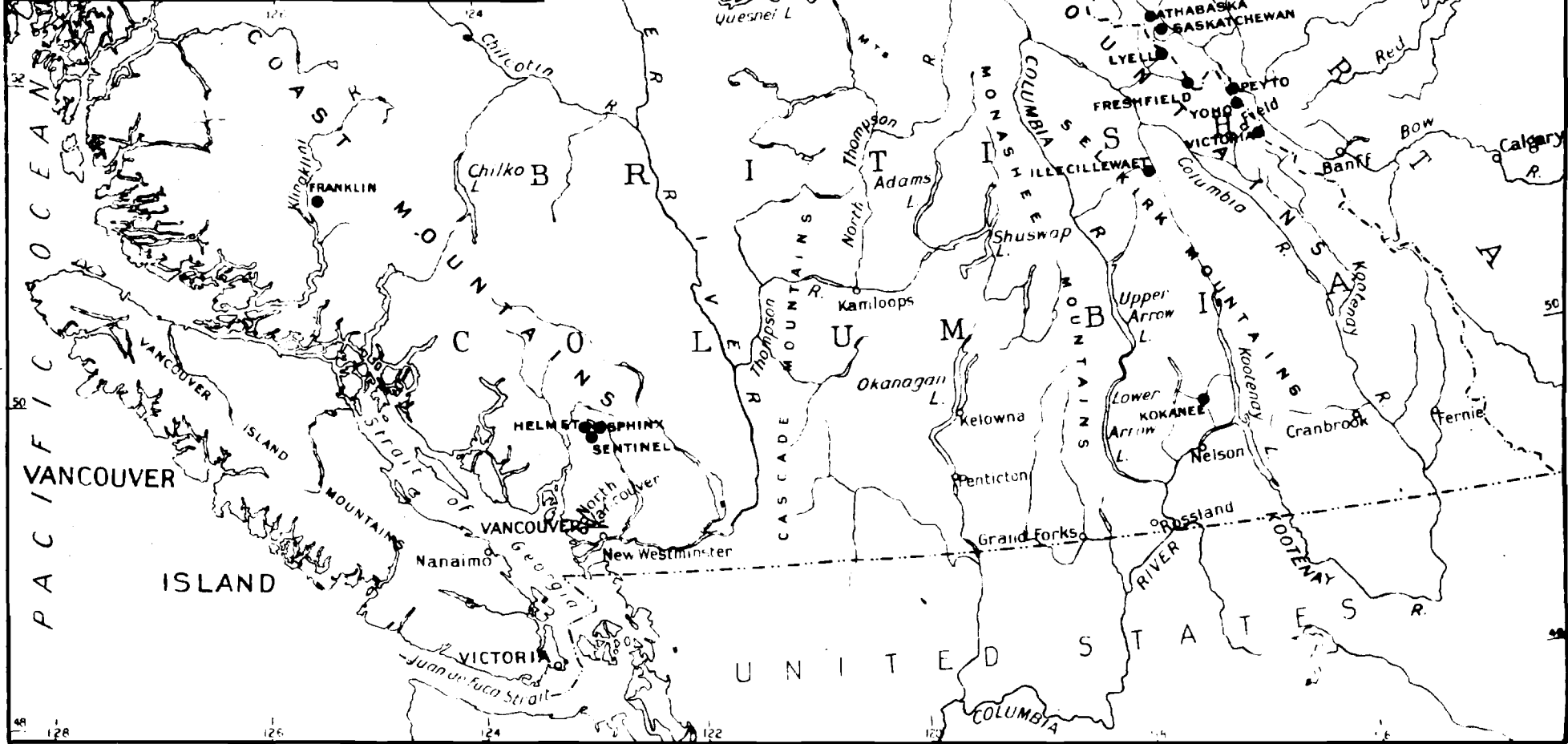
As glacial run-off constitutes an important part of the flow of many of our rivers, the effect of glacier variation on stream flow is of primary importance to the Bureau. The measurement of the discharge of glacial streams in close proximity to the glaciers of origin is usually not practicable owing to poor channel conditions in moraine material and would be of little value owing to the extremely capricious flow. On the lower reaches of streams largely of glacier origin, more satisfactory records can be secured and these may be compared with those obtained on non-glacial streams. When sufficient data have been accumulated, studies will be undertaken in respect to the effect of glacier variation on stream flow, although these will be complicated by the many factors involved.



GLACIERS IN SOUTHERN ALBERTA AND BRITISH COLUMBIA

Scale of Miles
25 0 25 50 75 100

Location of Glaciers ●



EFFECTS OF CHINOOK (FOEHN) WINDS
ON SNOW COVER AND RUNOFF

by

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Note: This paper was originally written for presentation to the Washington meeting of the International Association of Hydrology, held in 1939. As Mr. Hoover's paper was not presented at that time, the Associate Committee on Soil and Snow Mechanics is pleased to do so now, together with the other Canadian contributions to the Oslo meeting of the International Union of Geodesy and Geophysics, August, 1948..

EFFECTS OF CHINOOK (FOEHN) WINDS
ON SNOW COVER AND RUN-OFF

by O.H. Hoover.

Summary:

With particular reference to Alberta and Western Canada, the characteristics and effects of Chinook winds are discussed. A concise statement is given on the Phenomenon and Maintenance of these winds. An exposition is cited showing how moisture laden air at the Pacific Coast in winter may move easterly over the Continental Divide into a cold area and arrive as a dry air fully as warm as when leaving the coast.

An example of a Chinook which occurred in this area between March 17 and 24, 1939, is given and diagrams by meteorological and hydrological graphs illustrate the effect of this Chinook on snow cover and run-off. In the Appendix, meteorological data and daily weather maps upon which the fronts have been plotted, show the initiation of this Chinook as the wind crossed the Rocky Mountains eastward. The text of this paper contains about 3000 words.

EFFECTS OF CHINOOK (FOEHN) WINDS ON SNOW COVER AND RUN-OFF

The type of wind known as the Chinook in North America, which blows as a southwest or westerly wind on the eastern slope of the Rocky Mountains and eastward into the Province of Alberta, Canada, and into the States of Montana and Wyoming in the United States, is not only common to this area in North America, but occurs very probably from like causes at other points in various countries.

In Switzerland on the northern side of the Alps, a similar wind is known as the foehn, and blows from the south up, over and down from the Alpine range. In the south of Greenland on the west coast, during the southeast winds, which have been elevated over the higher portions of the island, the temperatures on occasion in winter, are reported to be distinctly higher than that of the atmosphere where the winds have originated.

Origin of Name

Chinook Indians from the early days have inhabited the region of the Columbia river on the westerly side of the Rocky Mountains in America, and owing to the supposition that these winds originated in this area, the name Chinook (probably first applied by Indians living on the east side of the divide) has from these early days characterized this unusual wind.

Characteristics and Effects of Chinook Winds

Chinook winds in Alberta, and in particular at Calgary, always blow from the southwest or west. Usually at the beginning the sky is overcast, excepting for the characteristic demarkation in the southwestern sky called Chinook Arch. This panorama comprises an arch-shaped strip of clear blue sky bounded underneath by mountain contours, and on top by a clearly marked edge of the clouded sky. As viewed from Calgary, the blue strip extends some 10 to 20 or more degrees above the mountain horizon, and if one travels toward the mountains it is found that the blue portion forming the arch frequently extends some 20 to 30 miles east of the most easterly mountain range, but this distance may vary greatly with various stages and intensities of Chinook winds. Through this arch-shaped strip the warm winds pour down the eastern mountain slopes and spread out over Alberta.

It is a commonplace experience that this Chinook-affected area in the dead of winter may be snapped out of a sub-zero condition into a balmy soothing state, at temperatures ranging from 25 to 50 degrees F or more above zero. On occasion in the city of Calgary it is possible, and has been experienced by the writer that, in walking westerly in the city, the temperature has changed from a sub-zero condition to that of at least 40°F above zero, in moving a distance of not more than a city block. This marked the beginning of a Chinook. Not all Chinooks, however, originate in such sudden fashion, but in most cases the change is much more gradual.

No precipitation appears to ever accompany these winds. The air is very dry and has a great affinity for moisture. To use a local expression it is said to lick up the snow, and in consequence, it uncovers the prairie range lands, making it possible in Southern Alberta for pasture grazing, during nearly every winter season. Irrigationists in this section often remark that the snow-fall during winter does not contribute very materially to the top soil moisture in the following spring. The main reason for this is due to the fact that much of the snow was lost to evaporation by Chinook winds.

Signs Preceding a Chinook

Not in all instances does there appear to be a visible sign which will definitely forecast the approach of an on-coming Chinook. In very cold weather, however, winds are often slightly preceded by a falling barometer, and the pressure remains relatively low while the winds last. Another indication which is believed to be a good sign at Calgary, (especially for the layman) is as follows: If the cold north wind veers gradually through the north, northeast, east, southeast and south, taking possibly $1\frac{1}{2}$ or 2 days for the operation, generally the veering will continue to the southwest quarter, when a Chinook will develop. If this veering is rapid, a partial Chinook arch will form, but will not remain, and the wind will switch back to the north, with the consequent return of cold weather. Very seldom if ever, does the north wind back through the northwest to the west and southwest to produce these warm winds.

The Phenomenon and Maintenance of Chinook Winds.

The fundamental cause and related facts concerning the origin etc. of Chinook winds are not as yet believed to be fully understood. The inflowing Chinook air is

generally Polar Pacific (symbol P_P). On occasion, however, it may be called Maritime Pacific (M_P) if warmer than usual, and originating farther south in the Pacific.

The advancing front of Chinook winds, as revealed in aerological soundings, have a distinct warm front up to great elevations. This front in moving eastward leans forward over the cold mass at an angle with a slope varying from 1:100 to 1:300, and the former figure seems to be nearer correct when first crossing the Rockies. The cold air displaced by the Chinook and underlying the warm front is Polar Continental, or known in America as Polar Canadian, (symbol P_C). The sudden change in temperature is owing to the rapid displacement of the P_C air.

In the atmosphere, winds are set in motion by the relative three-dimensional distribution of the temperature and pressure fields. The atmosphere really acts as a heat engine with the sun as its fire, and in order to detect the action of this great prime mover in the local region of the Rocky Mountains, three major forces which act upon air masses may be considered.

1. The force due to the earth's rotation, called the Coriolis. With this may be considered the centrifugal force if the path of the air current is curved. As these forces are each necessarily at right angles to the motion, they do not involve the performance of work on the air particles, so are not the cause of the motion and will not be considered further.
2. The force of friction. This always acts parallel and opposite to the surface current. Its operation, however, deflects the wind obliquely across the isobars from HIGH to LOW, and its equal and opposite reaction is found partly at right angles to the isobars in the form of a reduction of the effectiveness of the Coriolis force, and partly along the isobars in opposition to the gradient wind. Friction is work consuming, and hence is obviously not a cause of the motion.
3. The force due to the interaction of the temperature distribution and the pressure field, such as for example generates land and sea breezes. Since this force depends on action in three dimensions, its intensity can only be gauged indirectly from surface weather maps, by noting some phenomenon that involves work being done on particles of air. Such an indication is a zone with different barometric tendencies on the two sides. There is a component of wind known as the isallobaric which blows from regions of rising pressure to regions of falling pressure,

at right angles to the isallobars (lines of equal time rate of pressure change). It is independent of the instantaneous distribution of the isobars, and so may possibly blow from regions of HIGH pressure to regions of LOW. In this way the pressure field would aid the wind motion, doing work upon the air particles and accelerating them.

In the case of Chinook winds, we know that they will occur when a LOW is deepening or moving in eastward, and forming up in northern Alberta. While barometric pressure falls in southern Alberta, it is building up on the coast; in other words, an isallobaric gradient is noticeable between the Pacific coast and southern Alberta. Therefore the Pacific air is being accelerated into the deepening LOW. In these circumstances it is usual to forecast a Chinook.

Here then is evidence of the atmospheric heat engine at work. The condition favourable for the local production of acceleration, a large gradient both of pressure and of temperature, is especially well fulfilled in winter in the Rocky Mountain region, owing to the juxtaposition of the cold, high-pressure Polar Continental air, and the warm, low-pressure Pacific air. The mountains may contribute to the suddenness with which the Chinook is accelerated by holding back the Pacific air until it spills through. This indication is manifest by a fairly steady and very large pressure gradient, with isobars parallel to the Rockies, which however is greater than the observed winds would indicate. The additional heat in the Pacific air in the form of the latent heat of the moisture contained also plays its part, as will be seen.

It is known that the Chinook current of air, as it leaves the Pacific Coast on its eastward journey, is usually heavily laden with moisture, and the same air as it reaches Alberta is extremely dry. It is further known that this air, upon arrival in Alberta some 3000 feet or more above the Pacific Coast altitude, is as warm as, or warmer than when leaving the coast. The warm condition of this air occurs just after having traversed several high mountain ranges covered with snow, and without further consideration it would be reasonable to believe that a loss rather than a gain in heat would result.

This phenomenon, it is believed, has been correctly explained at various times heretofore, and without much doubt is the result of the following circumstances: When a mass of air having a relative humidity below the saturation point is lifted in the atmosphere, it expands and becomes colder at approximately the rate of 1°F per 180 feet, or 1°C per 100 meters raised. This is sometimes

called the temperature lapse rate for dry air, the ordinary adiabatic lapse rate.

In the formation of a pound of water from water vapor by precipitation, some 970 B.t.u.'s or 244,000 calories of heat units are released to the air. Similarly, in the freezing of a pound of water an additional 144 B.t.u.'s., or 36,000 calories of heat are liberated. Hence in the creation of a pound of snow some 1110 B.t.u.'s or 280,000 calories of heat are released. This is commonly called the heat of condensation. Some idea of the energy value for this heat transfer will be realized when it is remembered that 1 B.t.u. is the equivalent of 778 foot pounds of energy.

Pp air moving inland and eastward from the Pacific Coast toward British Columbia, is generally quite moist, and often approaching the dew point. This air, therefore, if caused to rise, will very soon be cooled below the saturation point, resulting in precipitation and consequent liberation of the heat of condensation, which in turn will retard the ordinary adiabatic lapse rate of the air temperature by about 50 percent.

This reasoning being correct, the following explanation for the appearance of warm and dry air in the Calgary winter Chinook winds, would appear to be in order. Moisture laden air at the Pacific Coast, in its movement eastward over several irregular mountain ranges, is mechanically forced upward to an altitude of possibly 10,000 feet. During the ascent the air cools at about 50 percent of the ordinary adiabatic rate, or at 1°F per 360 feet. With an initial temperature at sea level of 50°F ., the temperature at 10,000 feet as the air passes over the Continental Divide, would be reduced to 22°F . and a very large percentage of the moisture would have been withdrawn in the form of rain, hail or snow.

Descending the Rocky Mountains to Calgary's altitude of 3400 feet, the air would be re-heated at the normal adiabatic rate of 1°F . for 180 feet through a descent of 6600 feet, or to a resultant temperature of 59°F . Some temperature reduction should be made owing to the fact that not all of the air is caused to rise to the 10,000 feet level, but comes through where passes exist at lower elevations. If 9° were allowed for this reduction, the air would then arrive at Calgary or points of like altitude at a temperature of 50°F .

Example:

On March 17, 1939, one of these Chinooks began to develop in Calgary, and in two days' time about 10 inches of snow cover had almost disappeared. This warm wind continued until March 24, which is longer than the usual Chinook period, and maximum temperatures of over 70°F. were recorded at Lethbridge and many other points.

Plate 1 shows graphs of Relative Humidity, Temperatures and Sea Level Barometric Pressures at Calgary for a few days previous to and during the period of the Chinook of March 17 to 24, 1939.

Plate 2 shows by graphs the maximum and minimum temperatures for a few days before and during the period of the Chinook for representative stations from Victoria B.C., at the west coast to Island Falls in Saskatchewan, about a thousand miles to the east. This temperature chart shows clearly the progress of the Chinook eastward by the pronounced temperature effect.

In this instance the winds penetrated deep into Saskatchewan, some 500 miles east of the Rocky Mountains, and small prairie streams which had been dry all winter, were suddenly transformed into the maximum high run-off stages for the year. These streams normally develop spring freshet stages between April 10 and 25. On occasion, however, Chinook winds advance this spring flow period, and when such happens, as in 1939, the run-off is extremely rapid with maximum stages much higher than usual, but covering a shorter period of time.

Plates 3 and 4 show hydrographs of stream flow in cubic feet per second for 4 typical stream stations during March 1939. On plate 3 the flow for Ross creek at Irvine, 200 miles east of the mountains, is shown and also the run-off for Swiftcurrent creek, some 120 miles further east. Plate 4 shows similar flow data for Lodge creek and the Frenchman river located on the 49th parallel of north latitude at 160 and 270 mile intervals respectively east of the Rocky Mountains. These demonstrate very clearly the effect of the warm Chinook winds on a snow-covered prairie section of country and they also show that in a matter of 3 or 4 days the streams of such an area may assume peak run-off stages for the season.

In the Appendix, Table 1 shows meteorological data for the 7 day period March 18 to 24, 1939, as obtained by the United States and Canadian Meteorological Services.

From this date it will be observed that the air having a mean temperature on the outer coast and lower mainland varying from 47.5° to 49°F., on arrival at prairie points within 200 miles east of the mountains, has a mean temperature of about 49°F., and some of these prairie towns had temperatures of 20° to 30°F. below zero only 2 or 3 days prior to the beginning of the Chinook.

It will be noted that during the Chinook winds' period very heavy rains occurred at certain outer points along the British Columbia coast. At Rivers Inlet for instance 8.83 inches of rain were recorded in 7 days. At inland and mountain points in British Columbia some rain was recorded but in a more spasmodic manner. On the eastern side of the divide, however, where the Chinook had become effective, no precipitation was recorded.

Plates 5 to 9 show daily weather conditions for Canada from March 17 to 22, as prepared from the daily Weather maps as issued by the Meteorological Division, Canadian Department of Transport, Air Services. Air fronts have been drawn on these maps showing the advance of the March, 1939, Chinook.

Acknowledgment:

Able assistance was given the writer by the Controller and Officials, particularly Mr. F. Graham Miller, of the Meteorological Service of Canada, in the collection of information and data contained in this report.

Table 1

Meteorological Data March 18-24, 1939

Outer British Columbia Coast.









<u>Station.</u>	Mean Temp. °F.	Highest Temp. °F.	Lowest Temp. °F.	Precipi- tation Ins.	Wind.
Rivers Inlet	-	-	-	8.83	-
Quatsino	47.0	54.0	37.0	1.78	-
Clayoquot	48.0	58.0	41.0	2.40	SE & W
Bamfield	-	-	-	1.65	SW: NW: W & S
Mean	<hr/> 47.5°F.				
	<u>Vancouver Island</u>				
Victoria	47.4	56.4	38.4	0.42	N:W, Calm SW.
	<u>Lower Mainland</u>				
New Westminster	50.6	73.0	37.0	1.20	-
Agassiz	52.4	72.0	34.0	1.28	-
Kamloops	47.7	66.5	37.0	-	Variable
Okanagan Centre	45.6	67.0	32.0	-	-
Penticton	49.1	70.0	38.0	-	Variable
Mean	<hr/> 49.1°F.				
	<u>Mountains</u>				
Revelstoke	37.7	61.0	26.0	1.60	-
Glacier	34.9	48.0	21.0	0.63	-
Golden	41.6	59.0	24.0	.0	Variable
Barkerville	39.6	52.0	8.0	0.21	S. SW
Banff	49.3	62.0	35.1	-	SW
Helena	49.4	67.0	30.0	-	
Mean	<hr/> 42.1°F				
	<u>Prairies (within 200 miles of Mountains)</u>				
Cardston	50.4	68.0	22.0	0	-
Lethbridge	53.3	73.9	30.0	0	SW
Calgary	43.8	67.3	22.0	0	W:SSW
Medicine Hat	47.4	71.0	24.5	0	SW
Havre	51.6	76.0	17.0	0	-
Mean	<hr/> 49.3°F				

Table I (continued)

Meteorological Data March 18-24, 1939.

Station	Mean Temp. °F.	Highest Temp. °F.	Lowest Temp. °F.	Precipi- tation Ins.	Wind.
	<u>Prairies</u> (more than 200 miles east of mountains)				
Malta, Montana	42.9	71.0	3.0	0	-
Glasgow "	46.0	74.0	6.0	0	-
Opheim "	40.0	61.0	10.0	0	-
Edmonton, Alta.	38.2	59.0	21.0	0.21	SW
Moose Jaw, Sask.	38.6	65.0	0	0	-
Saskatoon "	32.8	44.0	21.0	0	-
	<hr/>				
Mean	39.8°F.				

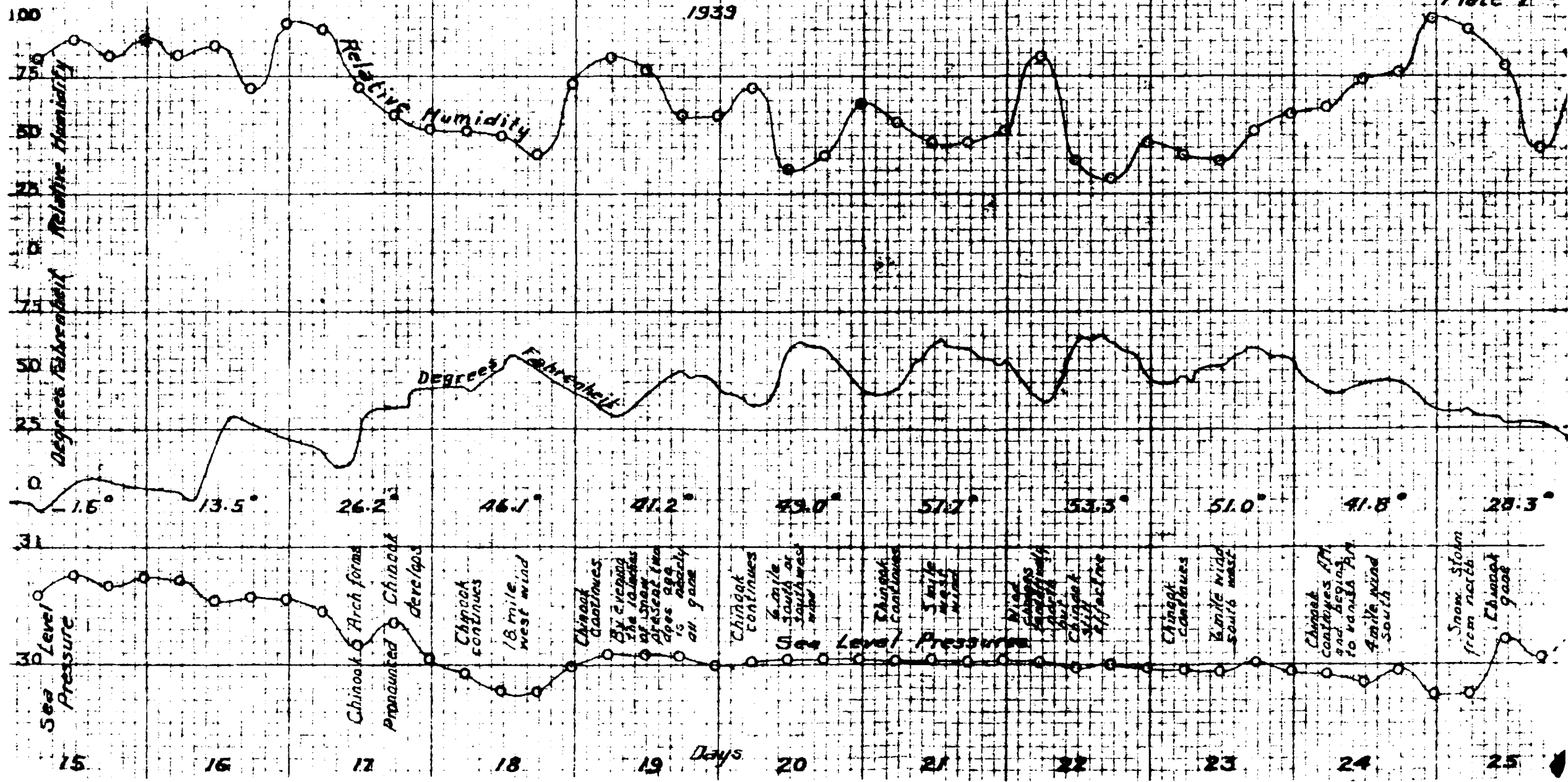
METEOROLOGICAL SYMBOLS USED

Isobars	
Surface cold front	
Fading cold front	
Surface warm front	
Surface occluded front	
Cold frontogenesis	
Stationary front	
Polar Continental Air	P C
Polar Pacific Air	P P
Modified Polar Pacific Air	N PP
Tropical Gulf Air	T G
Rain, or precipitation area	

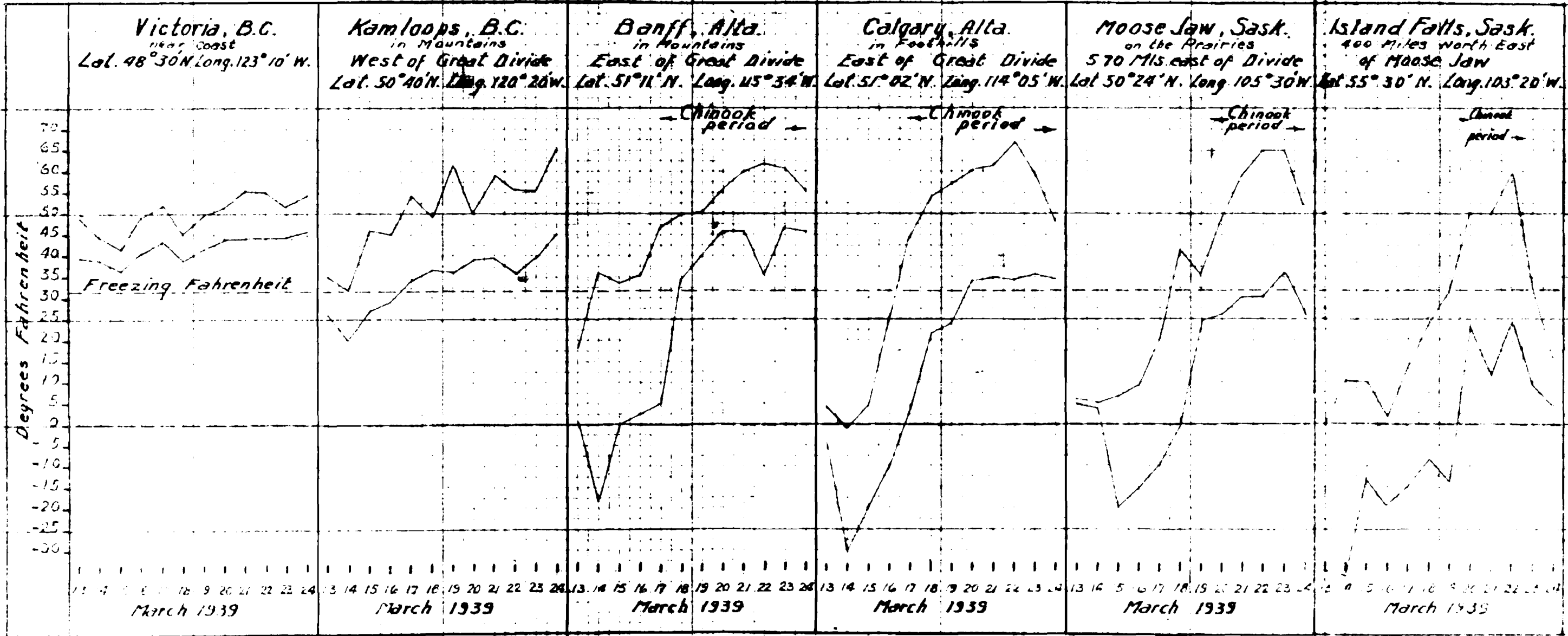
Graphs Showing Relative Humidity, Temperatures Fahrenheit, and Sea Level Pressures at Calgary

March 15 to 25
1939

Plate 1



Graphs Showing Maximum and Minimum Temperatures in Degrees Fahrenheit for several Stations in the Path of the Chinook of March 17 to 24 1939

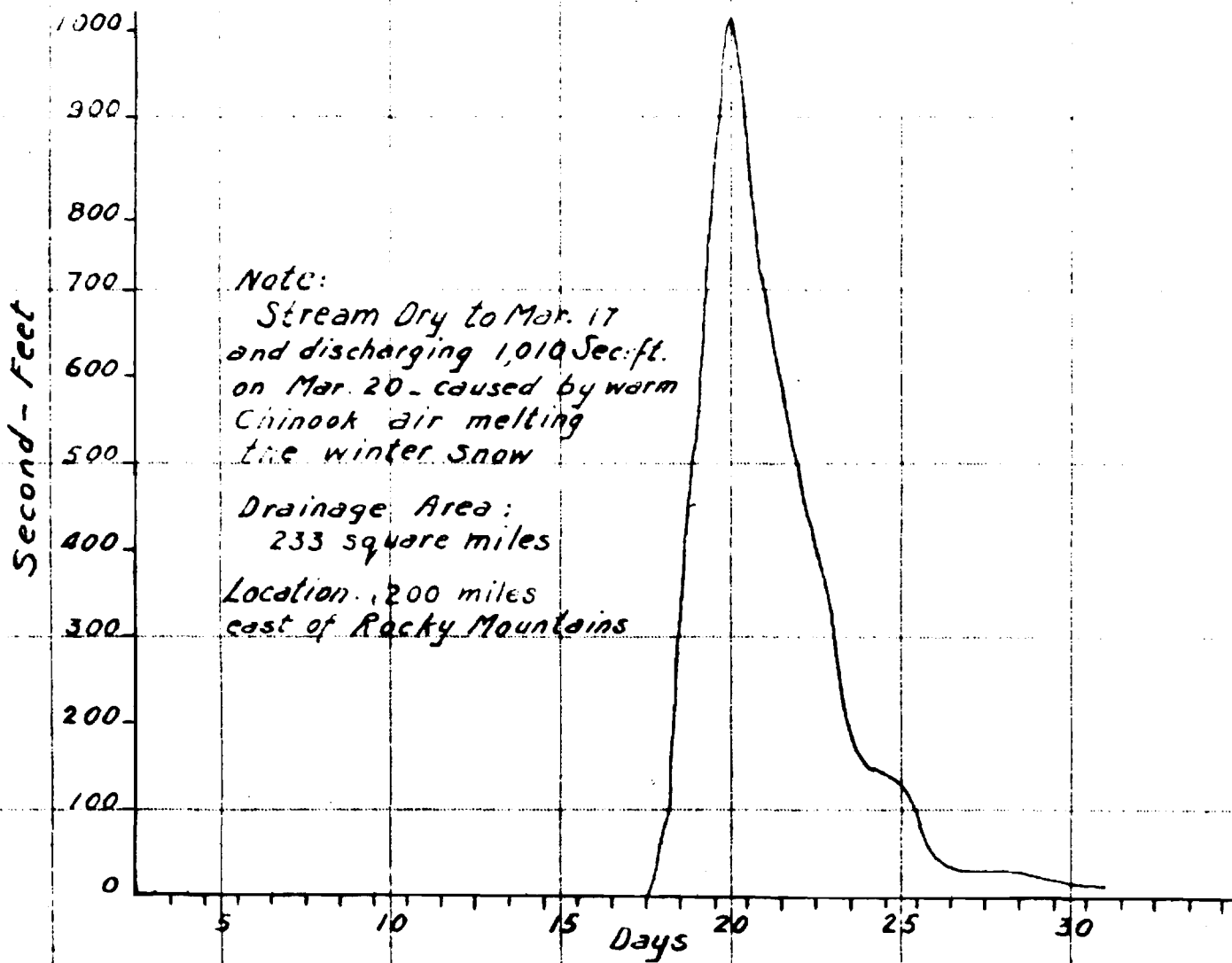


Ross Creek at Irvine

Lat. $49^{\circ} 57' N.$; Long. $110^{\circ} 16' W.$

Plate 3

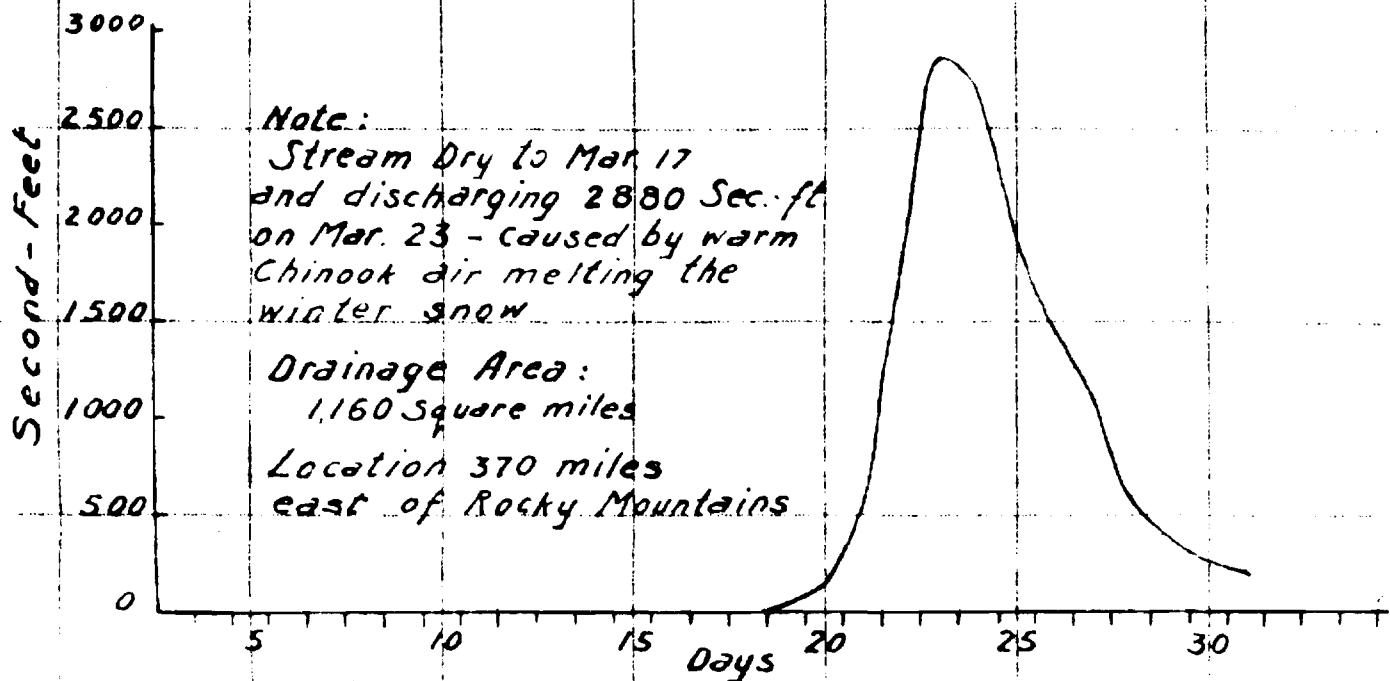
HYDROGRAPH showing RUN-OFF
In Cubic Feet per Second for March 1939



Swiftcurrent Creek at Swiftcurrent

Lat. $50^{\circ} 17' N.$; Long. $107^{\circ} 48' W.$

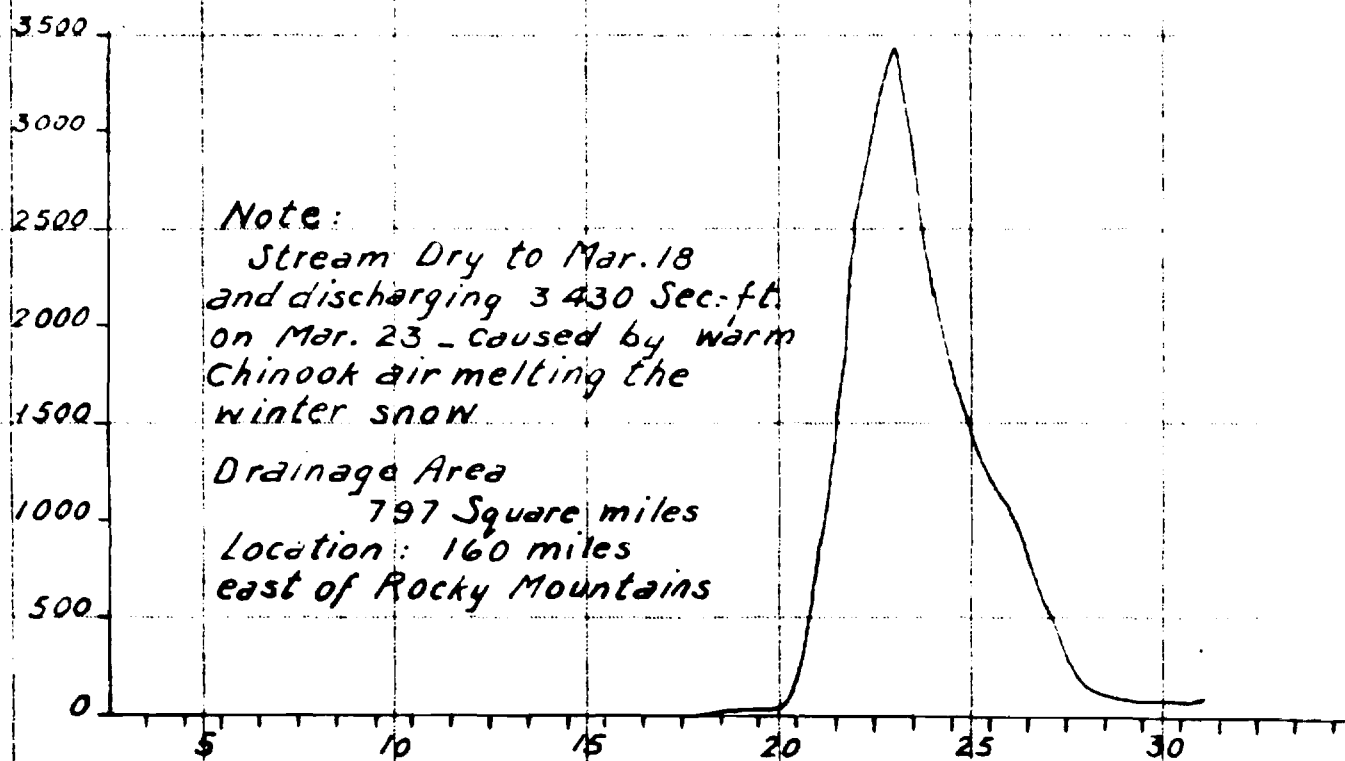
HYDROGRAPH showing RUN-OFF
In Cubic Feet per Second for March 1939



Lodge Creek at International Boundary

Lat. 49°00' N., Long. 109°45' W.

HYDROGRAPH showing RUN-OFF Plate 4
In Cubic Feet per Second for March 1939



Note:

Stream Dry to Mar. 18
and discharging 3430 Sec.-ft.
on Mar. 23 - caused by warm
Chinook air melting the
winter snow.

Drainage Area

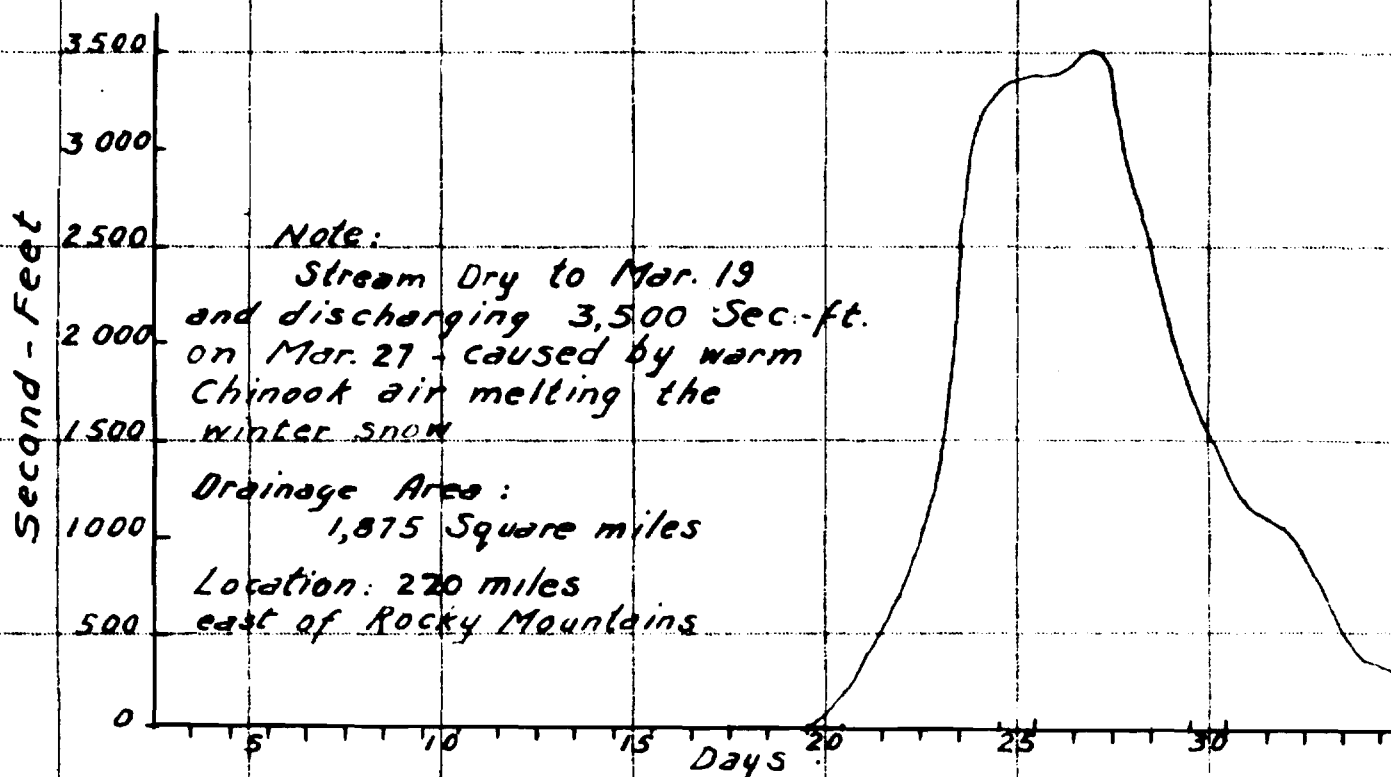
797 Square miles

Location: 160 miles
east of Rocky Mountains

Frenchman River at International Boundary

Lat. 49°00' N., Long. 107°17' W.

HYDROGRAPH showing RUN-OFF
In Cubic Feet per Second for March 1939



Note:

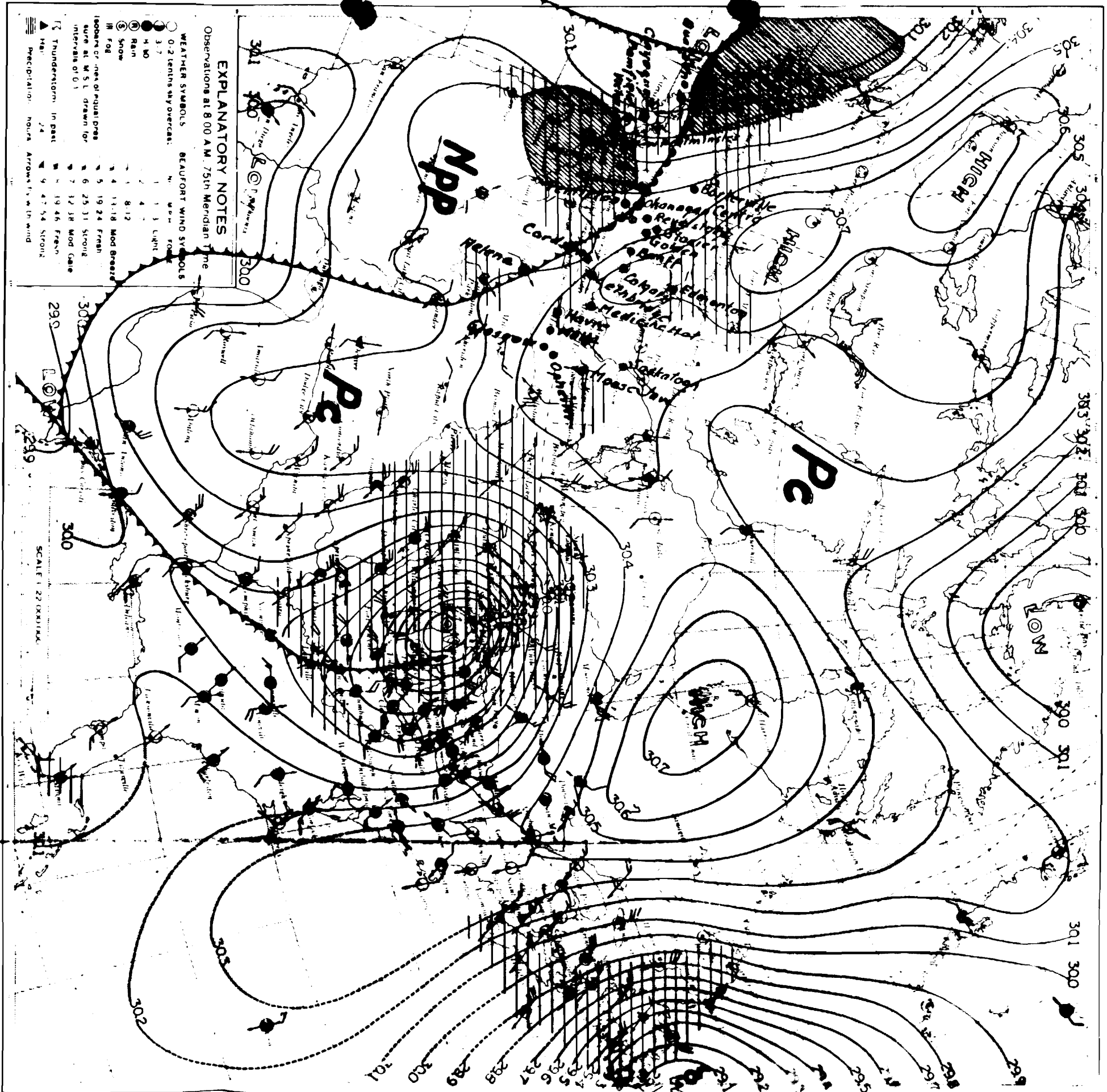
Stream Dry to Mar. 19
and discharging 3,500 Sec.-ft.
on Mar. 27 - caused by warm
Chinook air melting the
winter snow.

Drainage Area:

1,875 Square miles

Location: 270 miles
east of Rocky Mountains

CANADA—DEPARTMENT OF TRANSPORT
 AIR SERVICES—METEOROLOGICAL DIVISION *Plate 5*
DAILY WEATHER MAP
 Mar. 15, 1939



EXPLANATORY NOTES

Observations at 8 00 A.M. 75th Meridian Time

WEATHER SYMBOLS BEAUFORT WIND SYMBOLS

0-2 tenths sky overcast: N. S.P.P. FOG

3-7 1 1 1 1 LIGHT

4-10 2 2 2 2

RAIN

SNOW

IN FOG

Isobars of equal pressure at M.S.L. drawn for intervals of 0.1

Thunderstorm in dark

HAZ. 24

Precipitation: Hours. Arrows with wind

1-4 8-12 Mod Breeze

5-13-16 Mod Fresh

17-19-24 Fresh

25-31 Strong

32-38 Mod Gale

39-46 Fresh

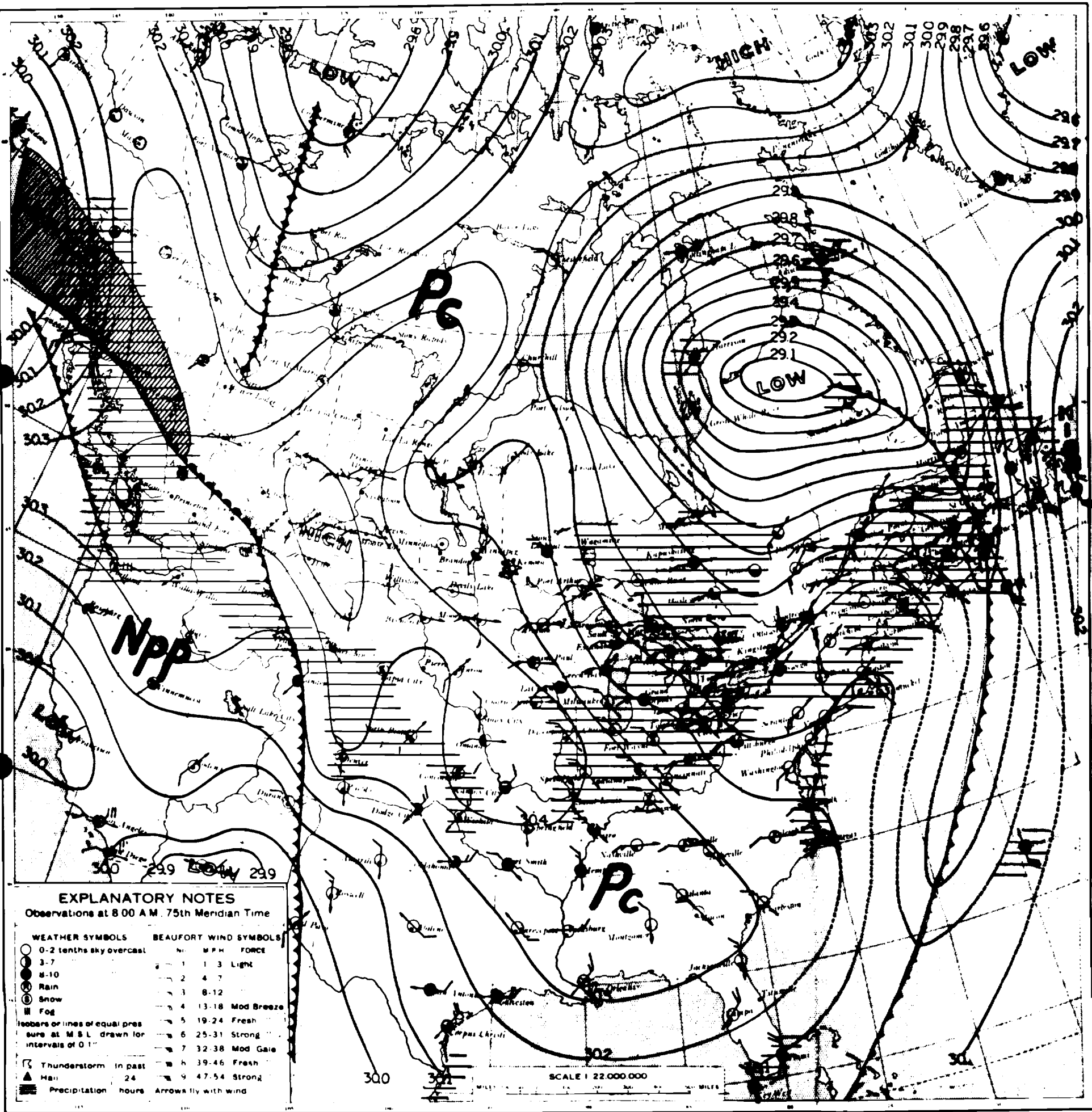
47-54 Strong

SCALE 1:22 000 000

TORONTO (5) WEDNESDAY, MARCH 15, 1939

Mar. 17, 1939

CANADA—DEPARTMENT OF TRANSPORT
 AIR SERVICES—METEOROLOGICAL DIVISION *Plate 7*
DAILY WEATHER MAP



EXPLANATORY NOTES
 Observations at 8 00 A.M. 75th Meridian Time

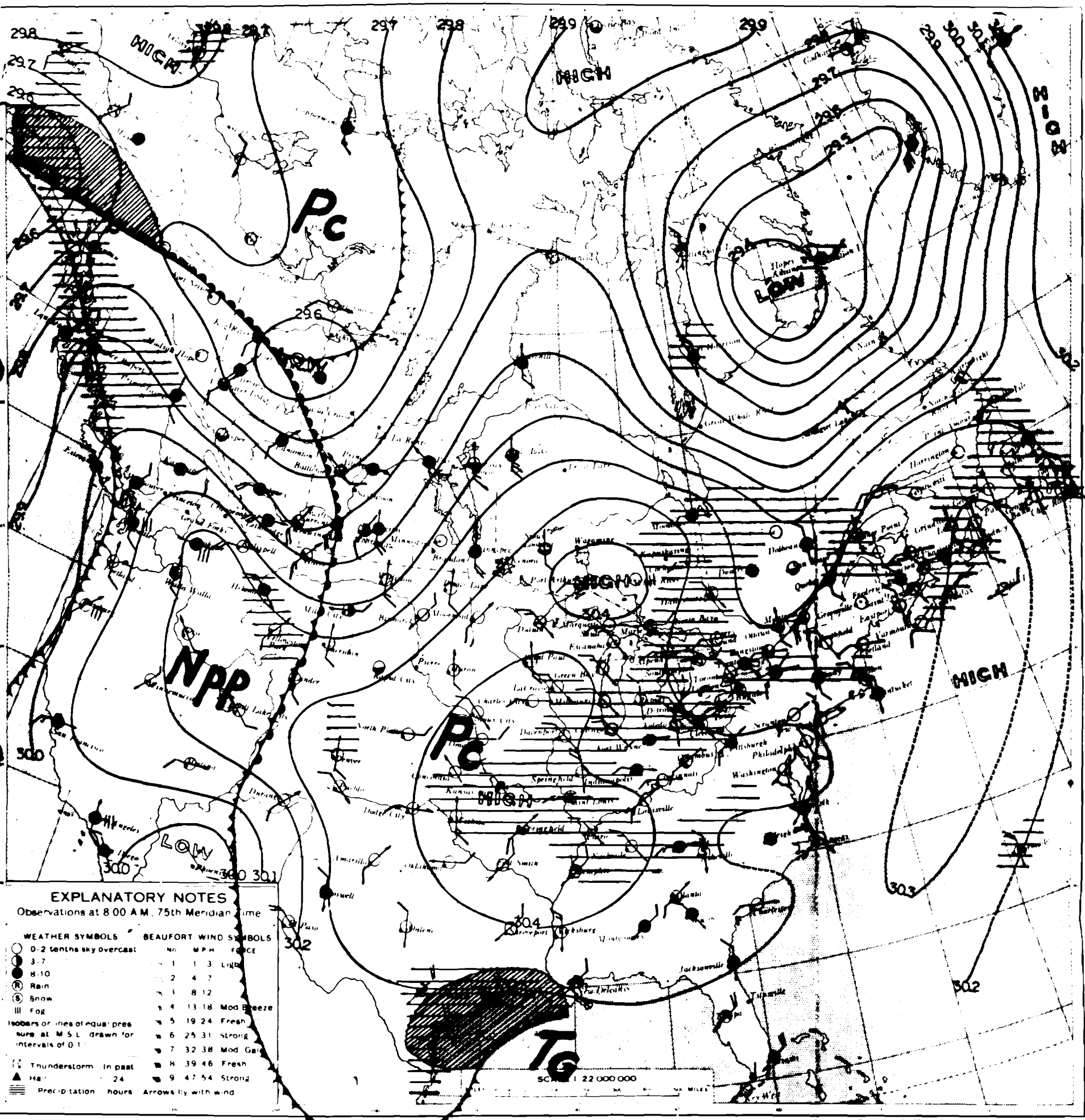
WEATHER SYMBOLS	BEAUFORT WIND SYMBOLS	NO. M.P.H.	FORCE
○ 0-2 tenths sky overcast	1	1-3	Light
● 3-7	2	4-7	
⊙ 8-10	3	8-12	
☔ Rain	4	13-16	Mod Breeze
❄ Snow	5	19-24	Fresh
☁ Fog	6	25-31	Strong
☁ Isobars or lines of equal pressure at M.S.L. drawn for intervals of 0.1"	7	32-38	Mod Gale
☁ Thunderstorm in past	8	39-46	Fresh
☁ Hail	9	47-54	Strong
☁ Precipitation hours	Arrows fly with wind		

TORONTO (5) FRIDAY, MARCH 17, 1939

Mar. 18, 1939

CANADA—DEPARTMENT OF TRANSPORT
AIR SERVICES—METEOROLOGICAL DIVISION Plate 8

DAILY WEATHER MAP



EXPLANATORY NOTES

Observations at 8 00 A.M. 75th Meridian Time

WEATHER SYMBOLS

- 0-2 tenths sky overcast
- 3-7
- 8-10
- ⊖ Rain
- ⊖ Snow
- ⊖ Fog
- ⊖ Thunderstorm in past
- ⊖ Hail
- ⊖ Precipitation hours

BEAUFORT WIND SYMBOLS

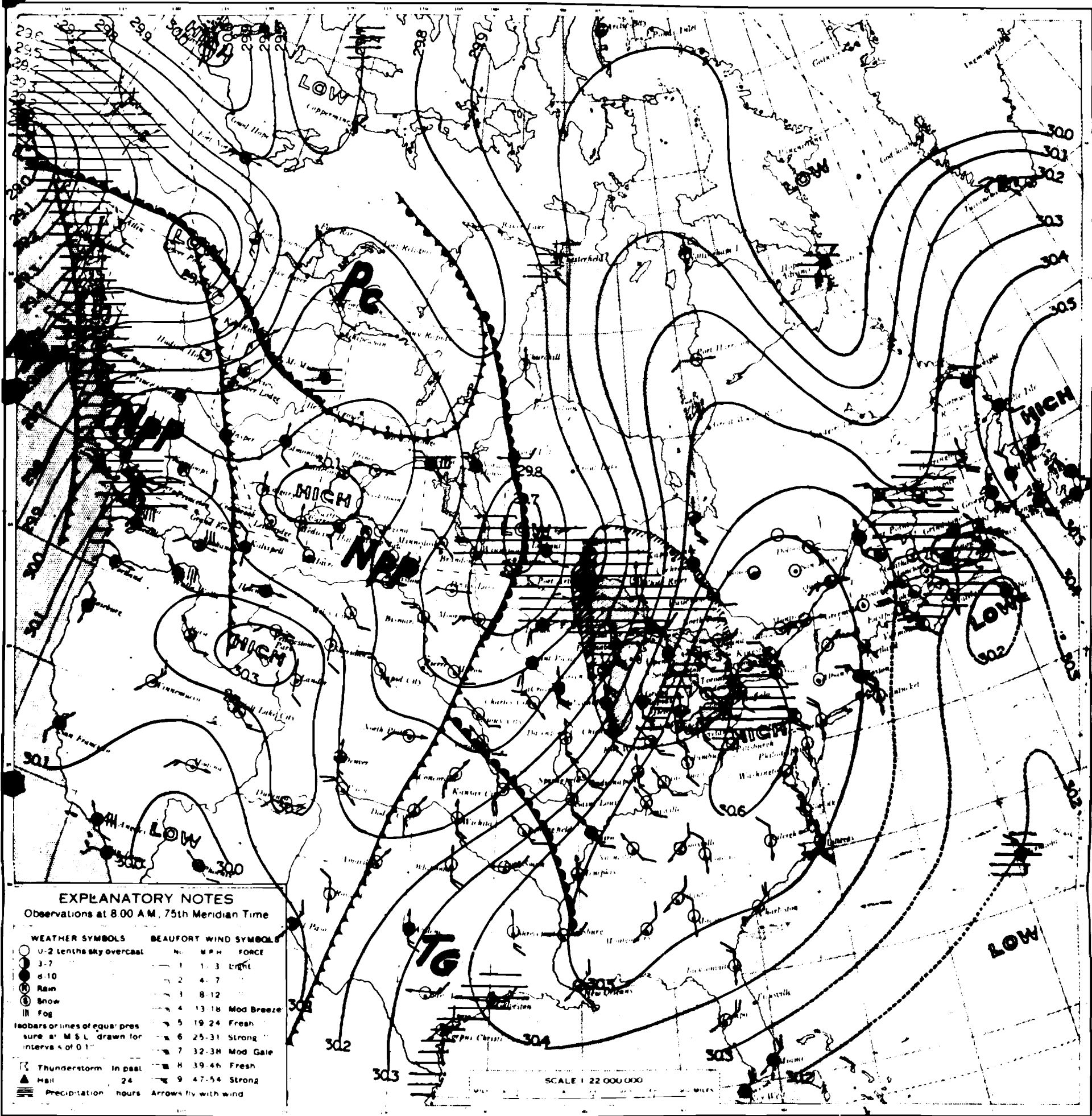
- | No. | MPH | FORCE |
|-----|-------|------------|
| 1 | 1-3 | Light |
| 2 | 4-7 | |
| 3 | 8-12 | |
| 4 | 13-18 | Mod Breeze |
| 5 | 19-24 | Fresh |
| 6 | 25-31 | Strong |
| 7 | 32-38 | Mod Gale |
| 8 | 39-46 | Fresh |
| 9 | 47-54 | Strong |

SCALE 1:22 000 000

TORONTO (5) SATURDAY, MARCH 18, 1939

Mar. 19, 1939

CANADA—DEPARTMENT OF TRANSPORT
 AIR SERVICES—METEOROLOGICAL DIVISION *Plate 9*
DAILY WEATHER MAP



EXPLANATORY NOTES
 Observations at 8 00 A.M. 75th Meridian Time

WEATHER SYMBOLS	BEAUFORT WIND SYMBOLS	NO.	M.P.H.	FORCE
○ (with horizontal lines)	— (with 1 bar)	1	1-3	Light
○ (with vertical lines)	— (with 2 bars)	2	4-7	
○ (with diagonal lines)	— (with 3 bars)	3	8-12	
○ (with wavy lines)	— (with 4 bars)	4	13-18	Mod Breeze
○ (with horizontal lines and dots)	— (with 5 bars)	5	19-24	Fresh
○ (with vertical lines and dots)	— (with 6 bars)	6	25-31	Strong
○ (with diagonal lines and dots)	— (with 7 bars)	7	32-38	Mod Gale
○ (with wavy lines and dots)	— (with 8 bars)	8	39-46	Fresh
○ (with horizontal lines and dots)	— (with 9 bars)	9	47-54	Strong

☁ U-2 tenths sky overcast
 ☁ 3-7
 ☁ 6-10
 ☁ Rain
 ☁ Snow
 ☁ Fog
 ⚡ Thunderstorm in past
 ⚡ 24
 ☁ Precipitation hours
 → Arrows fly with wind

TORONTO (5) SUNDAY, MARCH 19, 1939