

THE MAPPING OF SNOWFALL AND SNOW COVER

by

G. A. McKay *

INTRODUCTION

The presence of a snow cover has major implications to all outdoor activities and is of particular importance in the planning, design and management aspects of renewable resources, transportation, construction and recreation. Because the snow resources are complex and dynamic, their description requires vast amounts of information. Maps provide an excellent means of presenting and storing this information.

Most maps suffer from the deficiencies which have long been recognized to exist in snow data, i.e. the lack of precision and the unrepresentativeness of measurements. Whereas these hazards may not be serious in many forecasting routines, they seriously limit the value of maps for other purposes such as evaluating a total water resource, or making inter-regional comparisons. A more positive approach is needed to data acquisition and interpretation if maps are to properly serve the rapidly increasing demand for snow resource information.

Within recent years networks for the measurement of snow have been substantially enhanced. The accumulated data and new sources of information now make possible the preparation of maps of increased variety and detail. However, the supply of data is still not adequate to meet many of the important demands of our times.

Conservation measures in the Arctic pose an immediate need for precise detail on snow cover. Information on the impact of pipelines on permafrost is urgently required; this is an energy balance problem in which snow cover is a key factor. Details are required on trafficability, and on the variability. The depth of snow is critical to the survival of living things, their food and water supplies, as well as protection from the cold. Knowledge of the snow cover is essential for the rational development of water and other resources within this area.

Farther south the needs are equally pressing and new demands are continually arising. In addition to their traditional roles maps are needed to aid planners, developers and operators in making decisions such as selecting the best areas for placing highways, developing ski and snowmobile recreational facilities, assessing the accessibility and operating problems of proposed airports, etc.

Until recently snowfall and snow-cover maps have had a more academic than practical value. Generally they were mean-value maps prepared on the basis of a skeletal network so as to obtain rough comparisons of snowiness and the duration of winter. Over the past 25 years more precise and detailed information

* Canada Department of the Environment, Atmospheric Environment Service

has made possible a greater variety of maps. New demands, technology and the electronic computer will stimulate the production of an even greater variety. Snow maps are now being used or can be extensively used in water resource planning, development and operations; in the determination of snow loads; in the planning and development stages of tourism and recreation; in the planning of fertilizer sales; in land-use evaluation; in the allocation of funds for highway maintenance; in evaluating the probabilities of survival and shaping conservation procedures for plants and wildlife, etc. These many new applications require and can benefit substantially from more precise and complete detail than is generally now possible in conventional mapping.

THE STATUS OF MAPPING

The mapping of snowfall in North America dates back to 1894 when Harrington produced maps of monthly snowfall for the period 1884-91 for the United States. Brooks published the first thorough study of snowfall and climatology of eastern United States in 1915; however, it was not until 1921 that the first series of monthly snowfall maps of Canada appeared in the Canada Year Book. Subsequently, regional and national maps of snowfall have been published on a fairly routine basis by national agencies or organizations. The reader is referred to "A Survey of Great Lakes Snowfall" by M. K. Thomas (1964) for a more complete review of early mapping activities.

Regional and local maps provide much more detail. Some recent reports which contain maps for eastern North America are:

- Snowfall, Snowfall Frequencies and Snow Cover Data for New England, by Lautzenheiser, 1969
- The Climate of Southern Ontario, by Brown, McKay and Chapman, 1968
- The Climate of Northern Ontario, by Chapman and Thomas, 1968
- The Climate of Quebec, Climatic Atlas, by Wilson, 1971
- Climat du Québec Méridional, by Ferland and Gagnon, 1967
- Climat du Québec Septentrional, by Gagnon and Ferland, 1967
- The Climate of Northern New York, by Dethier and Pack, 1967
- The Climate of Western New York, by Pack and Dethier, 1969
- Survey of Frozen Precipitation in Urban Areas as Related to Climatic Conditions, by Bilello, 1967
- Lake Effect Snowfall to the Lee of the Great Lakes; Its Role in Michigan, by Eichenlaub, 1970
- Snow in Ohio, by Miller and Weaver, 1971
- Snowbelts of the Great Lakes, by R. A. Muller, 1962

Two publications of particular interest in the mapping of snow cover are:

- 1) "Problems in Mapping Snow Cover" by Espenshade and Schytt, 1956. This document provides an excellent discussion of errors, variability, the use of indices, regionalization, and cartographic methods for the preparation of "current" snow data maps, and it also includes 23 maps.
- 2) "Snow Cover" by J. G. Potter, 1965, provides a remarkably complete description of Canadian snow cover. In addition to numerous tables and probability graphs, the report contains 22 maps which present information on snow depth, duration and dates of appearance and disappearance.

Both authors made extensive use of climatological data in preparing these reports, since these provided the best coverage and continuity of records.

A map of the average density of the seasonal snow cover for North America was prepared by Bilello, 1969a, and in 1971 McKay and Findlay prepared maps of the snow cover water equivalent for Canada using regionalized snow density relationships and both snow survey values and climatological measurements of snow depth.

Other documents which merit consideration because of the relevance of their content are:

- "Snow Cover, Its Formation and Properties", by Richter, 1945
- "Guide on the Measurement and Mapping of Seasonal Snow Cover" -
in preparation - by M. R. de Quervain for the International
Commission of Snow and Ice
- "Water Content of Freshly Fallen Snow", by Potter, 1965.

Maps of an applied nature which have been prepared in recent years include:

- Frequency of Maximum Water Equivalent of March Snow Cover in
North Central United States by U.S. Weather Bureau, 1964
- Mean Snow Depth - Month of Greatest Depth, Arctic Environment,
by Hastings, 1961
- Maximum Annual Snow Cover, by Bates and Bilello, 1966
- Distribution of Maximum Annual Water Equivalent of Snow on the
Ground, by H. C. S. Thom, 1966
- Maps of Snow-Cover Probability for the Northern Hemisphere, by
Dickson and Posey, 1967
- Maximum Snow Load on the Ground (Canada), by D. Boyd, 1970.

Maps based on the water and energy balance should be added to this list because it is the water balance probably more than any other factor that has brought the apparent deficiencies of measuring the water equivalent of snowfall and snow cover more sharply into focus. Water balance type mapping has been discussed by Nordenson (1968). Balance type maps of snowfall or snow cover have not been published for eastern North America to our knowledge. Total precipitation maps which incorporate snowfall have appeared in:

- "The Use of a Square Grid System for Computer Estimation of
Precipitation, Temperature and Runoff in a Sparsely
Gauged Area", by Solomon et al, 1968.

Others are in preparation for national atlases.

Mapping programs currently underway include the preparation of maps of:

- Annual Snowfall
- Median Dates of Snow-Cover Formation and Loss
- Median Maximum Depth of Snow Cover

by the Canadian Atmospheric Environment Service, to be included in the Hydrological Atlas of Canada. These maps are to be based on data for the period 1941-1970 and will be prepared on a 1:10,000,000 scale. The coefficient of variation will be used to show variability and bar charts to illustrate the seasonal snow regime.

The target for completion of the Atlas is 1974. Heindl (1970) has outlined a proposed United States National Water Atlas which would contain mean annual water content of snowfall with bar charts showing monthly means and extremes, the mean snow pack water content on April 1, and snowfall as a component of a mean annual precipitation map. These maps would appear on scales of 1:5,000,000 for national use and 1:2,500,000 for major basins.

MAPPING

Purpose is undoubtedly the dominant factor in mapping; however, data availability also poses serious restraints and often makes desired maps quite unfeasible. Purpose is usually reflected in the scale of the map. Maps of a scale of 1:5,000,000 or more are used mainly to provide background for general planning and also for educational purposes. These maps show only the general patterns resulting from the influence of topography and the general circulation but omit meso- and micro-scale effects. Accordingly, they should not be used as a basis for information for local studies. Larger scale maps, i.e. greater than 1:1,000,000 attempt to show fields in detail. Since there is seldom sufficient data for their construction, supplementary information and physical as well as statistical relationship must generally be used to obtain a rational analysis. A common weakness of these maps is that they usually impute far more precision than is warranted from the basic data (McKay and Thomas, 1971).

DATA

Data of sufficient length, quality and homogeneity for statistical treatment, and of sufficient areal coverage to show the features of interest are essential for mapping. Until recently only climatological data have approached these specifications, at least on a national scale. Measurements of snow depth have been made on at least a monthly basis over the past 50 years at most Canadian climatological stations. Starting in 1941 all principal weather stations started reporting snow depth on a daily basis, and after 1952 the water equivalent of the snow on the ground was measured at many first-order climatological stations in the United States (U.S. Weather Bureau, 1964).

Snow survey records for some areas have equally long records, but survey networks often have been developed to serve specific watersheds, rather than for regional or national purposes. Beginning in 1953, Canada, the U.S. Weather Bureau, CRREL and the U.S. Soil Conservation Service co-operated in the measurement of the snow cover and ice, thereby developing a network which covered most of North America (Bilello, 1969b). Canada started publishing snow survey data for eastern Canada in 1954-55 as a result of a recommendation made at the 1955 meeting of the Eastern Snow Conference. In 1962-63 a national snow survey program was started by the Meteorological Service at its own stations and "Snow Cover in Canada" was converted to a national publication in which observational data submitted by all organizations are published.

Because of the deficiencies of climatological and snow survey networks, supplementary information such as measurements obtained by lysimeters, snow stakes, natural gamma radiation from the soil, etc. can be used to great advantage. Among the interesting supplementary sources are satellite pictures whose use has been described by Barnes and Bowley (1969). As with aerial photography, space pictures can be used to map the areal extent of snow cover; the authors suggest that a resolution of ten miles is possible on flat terrain on a 10 x 10-mile watershed when accurately located. They also indicate a 200-ft. resolution for the Earth Resources Technical Satellite. It is reasonable to conclude, in view of our rapid rate of technological advance, that refinements and new techniques will be developed which will provide very useful mapping information. The

following text concerns mainly the mapping of data obtained from conventional sources.

DATA INTERPRETATION

The key issue in mapping of snow data is in its interpretation from the point of view of instrumental accuracy and comparability, representativeness and sampling error. Because of network deficiencies, most mappers must rely on more than one set of data. This may pose major problems such as in the case of deriving snow cover from snowfall information when there has been extensive horizontal transport of snow or melting of the snow cover.

The problem is almost equally complex when several different instruments have been used to measure the same element. Mapping generally involves extrapolation and interpolation, and this can be extremely complicated with snow cover because of the intricate effects of topography. One set of data can usually be expressed in terms of the other, when the physical relationships are well understood. Fairly approximate relationships often suffice for mapping purposes, for the cartographer "flags" supplementary data and gives them due weight in the actual analysis. Unreasonable values generally stand out and are investigated. Unless the departures can be rationalized, the values are rejected.

Finally, isolines are often too dogmatically fixed in relation to data, without regard to the probable errors. The variability of the data must be well understood before isolines can be placed with confidence and intervals determined which do not provide the consumer with a false impression of confidence in the results. Since isolines are the main method of mapping snowfall and snow cover, it is necessary to know the errors inherent in the data, the variability of the mapped element in space and time, and its relationship to other variables such as climatic and topographic values. Each of these requirements pose major problems.

BIAS

Climatologists have reduced difficulties posed by instruments through the use of standard instruments, instrument exposures and operational procedures. While this provides comparable data, it is well recognized that measured values of snowfall and snow cover are merely indices and, therefore, unsatisfactory for many purposes. Accordingly attempts have been made to adjust them to obtain more precise estimates. Soviet Union hydrometeorologists have recommended corrections of 40 to 60 per cent for snowfall measurements to overcome the deficiency caused by wind, in catches by gauges with a 500 cm² orifice exposed 2 m above the snow surface (Nordenson, 1968). Tollan (1970) corrects snow-gauge catches for the Filefjell Basin in Norway by 50 per cent for the same reason. Hare and Hay (1971) consider it possible that precipitation estimates for the Canadian Arctic are deficient by 40 per cent - based on water and energy balance considerations. There is clearly ample evidence of the inadequacy of present snow gauges to cope with the air turbulence induced by the gauge and its surroundings.

Snow tubes also have their limitations as noted by Freeman (1965), who found biases of about + 9 per cent for the Federal sampler, and + 7 per cent for the Canadian MSC sampler. Considering the variety of samplers in use and that the bias is a function of the condition of the cutter, a cartographer may be hard pressed to evaluate the magnitude of the correction to be applied to get more meaningful estimates.

AREAL VARIABILITY

Some of the claimed deficiencies in gauge-catch of snowfall may be due to orographic effects. Snowfall amounts have been demonstrated to be highly associated with land forms, vegetative cover, and the occurrence of long fetch of wind over water areas. Most climatological stations are located in sheltered locations to avoid inclement weather, and the extrapolation of information from these sites is a problem of major proportions. Those who have evaluated snowfall measurements have generally used either the measurements of snow on the ground near the gauge area, or runoff as standards. Because of the influence of wind and the biased location of climatological stations, their correction factors probably adjust for topographic influences as well as instrumental deficiencies.

The capability of expressing point climatological measurements in terms of areal snowfall is one of the key challenges confronting today's mappers. Relationships have been developed which aid in this regard such as by Richter (1945) and Kuz'min (1960), who provide remarkably comprehensive reviews of the differences in snow accumulations over different types of terrain. The transposability of such results is valid only in a qualitative sense, however, and it is apparent that much work remains to be done to establish similar relationships for other areas before snowfall maps of desired detail can be made available for North American snow regions.

Snow survey values are equally difficult to interpolate, being highly biased. Survey courses are usually intentionally placed in locations which have above-normal accumulation so as to ensure continuity of measurement including dry or warm years, and also to ensure a high correlation with water yield. This bias may not exist when the networks have been established for other purposes, such as the study of the physical characteristics of snow cover.

SAMPLING ERROR

Cartographers, as previously noted, must minimize the risk of misinterpretation of maps by using a map scale commensurate with the reliability of the data, and by using a meaningful isoline interval (Espenshade et al, 1956). Generally the sampling errors are poorly understood. Areas of high variability are ignored and snow measurements made in areas of uniform cover. The use of small-scale maps reduces the risk of misinterpretation by effectively broadening the zone covered by an isoline. Many users insist on larger maps in which case the analyst must determine the sampling error in the most convenient manner possible and select an interval which adequately conveys the degree of reliability of the data. The resulting map will probably not have the desired "eye appeal". Physical relationships are frequently used to obtain further interpretative skill; however, the reliability of the product is usually highly questionable.

AREAS FOR IMPROVEMENT

The deficiencies in present snowfall mapping relate basically to data inadequacies. Maps are needed which show absolute values in sufficient detail to be of value in the computation of heat fluxes between the atmosphere and the soil, or to enable planners to select highway routes and ski slopes. Part of the present deficiency can be overcome by sound practices, but the major requirement is for superior networks and methods of observing snow, as well as more intensive knowledge on the relationships between land forms and snowfall and snow cover. On the other hand, current information could be exploited to much greater advantage, such as through the use of computerized mapping of probability values.

PRACTICES

Among the practices which can greatly improve snow mapping, yet is often neglected, is zonation of those areas which have similar physical and climatic characteristics. Data for such zones can be treated as relatively homogeneous, i.e. the zones are conservative with respect to snow deposition and retention. The feasibility of zonation can be readily appreciated from an inspection of Figures 1 and 2 which show vegetative and snow-cover information for two locations. Zonation is virtually essential for the development of height dependency and similar relationships.

Height dependency curves, coaxial correlations and multiple regression techniques which obtain relationships between physiographic factors and both snowfall and snow cover should be exploited in interpolation. Electronic computers can greatly facilitate their determination and application. Caution should be used in their application because of the usual hazards of transposition and also because their predictive skill may be deceiving in remote areas. Also such empirical approaches may fail when conditions depart significantly from average because they inadequately express the physical relationship. For example, it is common practice to assume that precipitation increases with height are due to elevation; they are more likely caused by slope and aspect - high level plateaux can be quite arid.

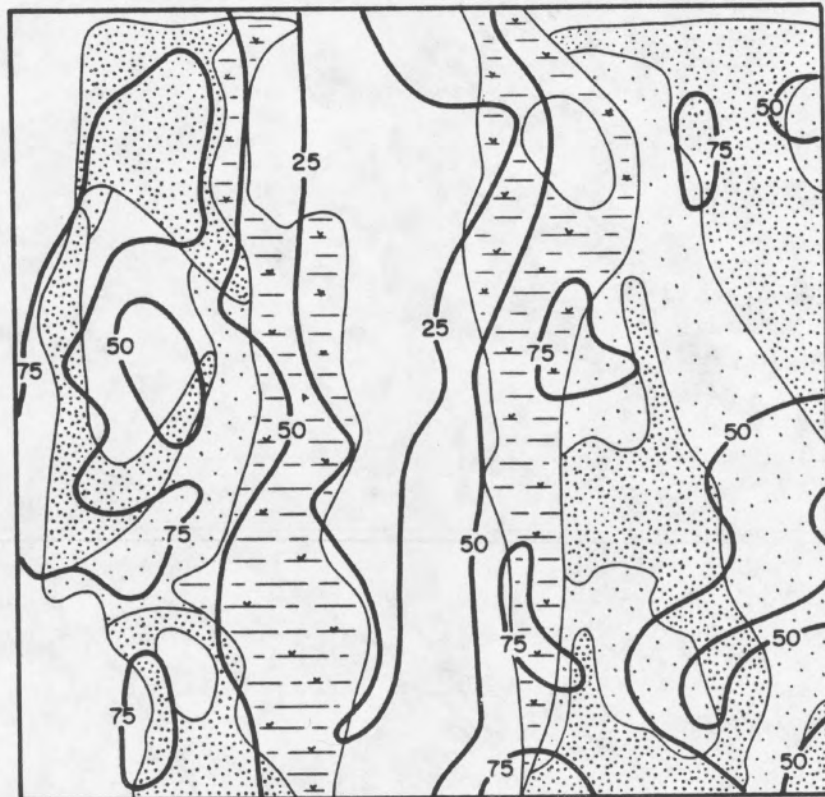
Another good practice is to review all pertinent historical maps and studies. For example, studies of snow storms near the Great Lakes such as those by Richards and Derco (1963), and Muller (1962), provide excellent information on height-dependency relationships as well as definition of zones prone to heavy "circulation-snowfall". These can be very useful in mapping regional snowfall and snow cover. Formerly determined patterns should not be casually rejected.

The question of period-of-record requires considerable attention. The period is not unrelated to purpose. Climatologists have agreed on 30-year normal periods, and where comparability is desired there is a decided advantage in adhering to the adopted standard. Stability of frequency distribution is reached over different periods for different elements and sampling periods, and when this is of importance the analyst should ensure that he is treating with an adequate depth of records. On the other hand, greater operational predictive values may be obtainable from records of shorter duration than those used for normal periods. The analyst must become fully cognizant of the nature of the data which he is using as well as the use of the maps which he is preparing in order to make a sound choice of his analytical period. Where the data are insufficient, reconstructed values which are used to augment the data must be adequately adjusted to obtain estimates which conform to the analytical period.

The water and energy balance techniques provide a form of quality control for the mapping of snowfall and should be fully exploited. At present these appear to be the superior way of overcoming the problem of instrumental and topographically induced biases. Instructions on these approaches have been prepared by Nordenson (1968), and Lettau (1969). Balance techniques which incorporate topography have been adapted to computer mapping by Solomon et al (1968). Such procedures have remarkable versatility and overcome massive computational problems, and the use of such methods will become mandatory as the mapping of snow cover in greater detail becomes both necessary and feasible. The output must, of course, be treated with due caution, being only as good as the models and data on which it was produced.

An essential practice in mapping is the interpretation of terrain and other climatic factors. Data acquisition methods which ensure the archiving of this information in data processing files so that they will be readily available for mapping purposes are a high priority requirement.

SNOW COVER AND VEGETATION



LEGEND

CLOSED COVER FOREST

OPEN WOODLAND

TAMARACK-BOG AND SPRUCE-MUSKEG

MUSKEG OR CLEAR

25 = DEPTH OF SNOW IN INCHES

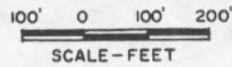
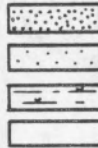
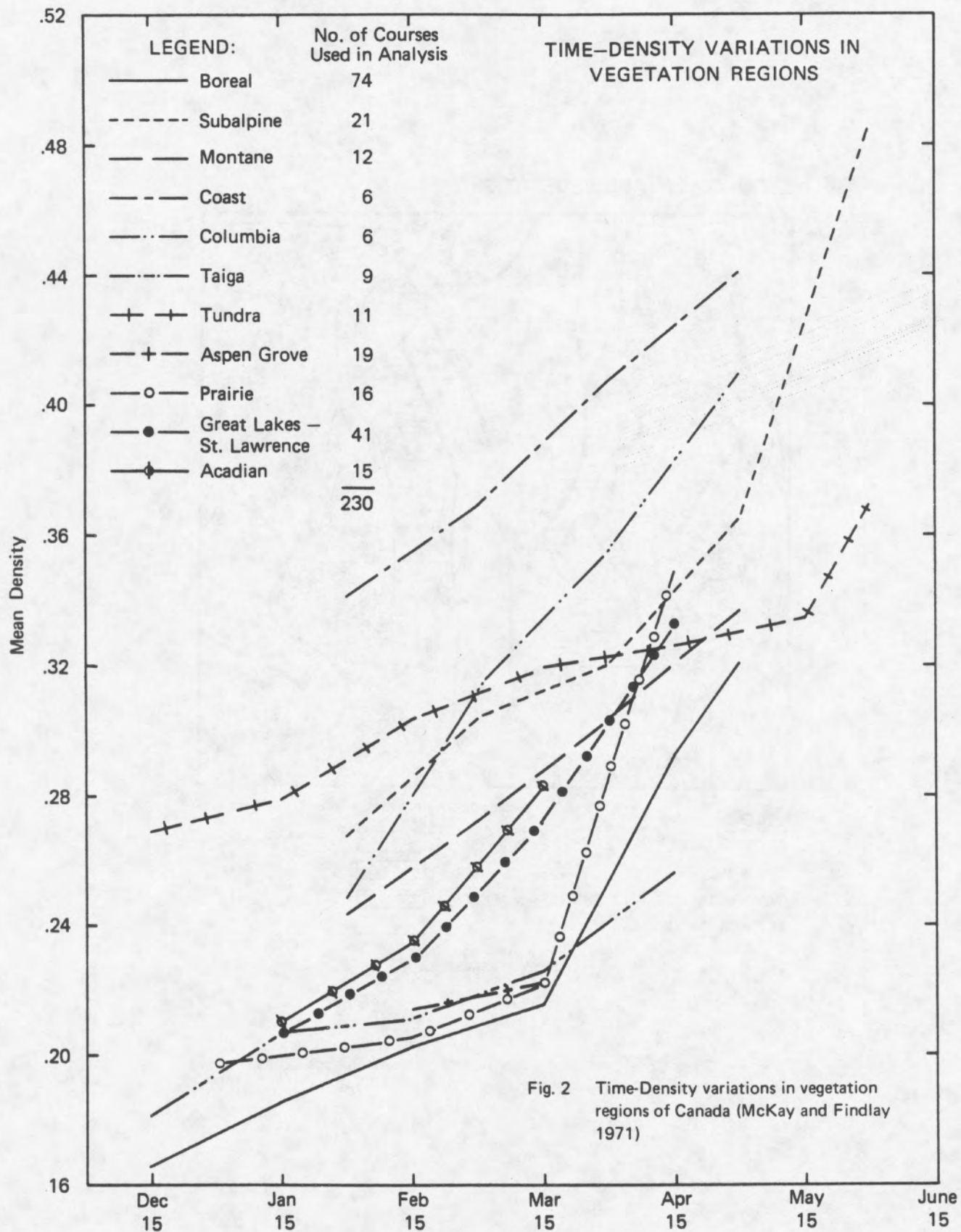


Fig. 1 Snow Cover and Vegetation near Knob Lake, Quebec-Labrador (McKay, Findlay and Thompson 1970)



NETWORKS

The development of superior networks and observational methods is a generally recognized need. Mapping from moving platforms appears to be the most promising and economical way of getting the desired detail. Ordinary photography permits delineation of areas of snow cover. Colour infra-red photography provides better contrast for identification and better detail when haze is present. Photogrammetry allows the mapping of volumes. Fundamental to these techniques is adequate ground control, which provides also information on depth and water equivalence not obtainable by some of these methods.

DATA

Superior instruments are required as part of a network enhancement program. Those techniques which do not interfere with the natural state are the most appealing. The use of natural gamma radiation has been shown to be a very efficient, accurate and rapid method of surveying which can replace more cumbersome techniques in areas where snow depths are less than 300 m (Komarov and Popov, 1970), (Peck et al, 1970). The possibilities of obtaining more precise measurements of snowfall is less encouraging.

Finally, much more can be done with presently available data. Probability maps produced using programs such as the "Synagraphic Mapping Program" (SYMAP) of the Laboratory for Computer Graphics and Spatial Analysis, Harvard University (Tomlinson, 1970) have great operational potential. Better presentation techniques are possible for conventional maps. Perhaps the greatest need here is for better communication between the mapper and users or potential users to determine the most effective method of data presentation.

PHYSICAL RELATIONSHIPS

Mesoclimatic studies which improve our knowledge of snowfall and snow-cover relationships to topography remain a major requirement for the development of models which can be used in mapping. Excellent studies have been undertaken such as those at Knob Lake (Findlay, 1966), but many more are required because of the complexity of controls which influence snow.

CONCLUSION

In summary, maps of snow cover and snowfall will play a much more important role in the immediate future. This role relates to planning, development and operations, i.e. practical problems of our times. To adequately serve these requirements, more precise and detailed maps are needed. Current maps are affected by serious instrumental and network biases which must be overcome. Better instruments, interpretation techniques, and networks are required to overcome these deficiencies. The expanded use of techniques presently available, e.g. water and energy balance methods and models which make use of the electronic computer, is required to meet current demands.

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