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CLIMATIC ASPECTS OF SUB-POLAR REGIONS

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ABSTRACT

In global terms, sub-polar land masses are situated such that unique life zones evolve from weak annual regimes of insolation, low temperature, and meagre precipitation. Though broad climatic similarities may seem to occur over vast areas, even where terrain contrasts are notable, there are important differences between the tundra and boreal forest as well as continental and maritime zones. These are denoted by marked biological productivity gradients. Agriculture is commercially viable for local markets in some high latitude regions outside the continuous permafrost zone, but slow biochemical action reduces the efficiency of dry matter production despite a long photosynthetic period.

Low amounts of precipitable water are available in Arctic air-masses; however, the paucity of growing season precipitation may be offset by the judicious use of water provided by the thawing of the permafrost active layer and the ablation of high altitude snow fields.

Local windiness is as much related to terrain features as to pressure gradients at the top of the Ekman layer. Winds are strongest in the treeless region and may freeze exposed flesh, extract heat from or even damage exposed buildings, but this resource can also be used to generate electric power.

In searching for a sustained yield operation, natural resource developers need to prudently examine local and micro-climates. The regular meteorological network is sparse and may not be particularly representative. Only areas with proven climatic advantage are worthy of investment, even in the temperate fringes of the Boreal Zone.

SOMMAIRE

En général, dans la région subpolaire, les terres sont situées telles que des zones biologiques uniques s'épanouissent en dépit des régimes de faible insolation, des températures peu élevées et des précipitations légères. Il existe de grandes similitudes climatologiques dans ces régions subarctiques, même si les diversités topographiques sont remarquables. On note cependant des distinctions climatologiques importantes d'une part entre la toundra et la forêt boréale et d'autre part entre la zone continentale et la zone maritime. Ces régions sont marquées par de forts gradients de productivité biologique. Dans certaines hautes latitudes, l'agriculture est commercialement viable en ce qui concerne les marchés locaux, surtout à l'extérieur de la zone de pergélisol. Vers les pôles cependant, l'efficacité de la production de la bio-masse est réduite à cause de faibles réactions biochimiques dans le sol et en dépit d'une prolongation de la période photosynthétique.

Les masses d'air arctiques produisent peu d'eau précipitable, mais la rareté des pluies peut être compensée par une utilisation judicieuse des eaux de fonte dans la zone active du pergélisol ainsi que l'ablation des couches neigeuses à haute altitude.

Le vent local est aussi bien relié au relief du terrain qu'aux gradients de pression au sommet de la couche d'Ekman. Les vents sont les plus forts dans les régions sans arbres, et la force de ces vents peut faire geler la chaire exposée, refroidir ou même endommager les immeubles; mais cette ressource peut également produire l'énergie électrique.

Les promotteurs des richesses naturelles doivent examiner prudemment les méso et micro climats afin de maintenir une production viable. Le réseau météorologique ordinaire est inégalement réparti pour pouvoir représenter fidèlement une région limitée. Les investisseurs ne devraient considérer que les régions climatiquement favorables et ce même dans les frontières tempérées de la zone boréale.

PREFACE

This study represents a broad literature review of climatic and biological linkages in the Tundra, Taiga, and Boreal Forest regions of the Northern Hemisphere. The text borrows considerably from an earlier paper on the Tundra region prepared by G.A. McKay, B.F. Findlay and H.A. Thompson, in 1969*.

B.F. Findlay prepared the basic manuscript. R.A. Treidl contributed sections on evaporation, the frost-free season and the growing season. The work was originally prepared in 1975 for a study group of the International Society of Biometeorology dealing with crop production in higher latitudes and maritime areas.

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Introduction

The sub-polar realm is transitional between the heavily-populated temperate regions and the true arctic. The term is broadly interchangeable with sub-arctic. In this paper, the focus of attention is directed to the territory occupied by the boreal forest in North America and Eurasia. Equivalent areas are very small in the Southern Hemisphere.

Several references are made to tundra or arctic conditions as well, for this too is a pioneer zone where many important related studies have been done recently. Crop production on the tundra is only possible under artificial conditions, though animal husbandry has been practised for centuries in Eurasia.

In terms of net or primary productivity of vegetation, there is a significant latitudinal gradient from the tundra to the temperate deciduous forest zones, as Walter (1973) has demonstrated. The region is characterized by a very short growing season, but a long photosynthetic period with low respiration losses.

Table 1

Primary Production in Eastern European Forests
(Walter 1973 from Laurenko, Andrejev and Leontjev)

Vegetation	Tonnes/ha
Southern tundra (dwarf shrubs)	1.2
Forest-tundra (birch-spruce)	1.4
Northern spruce forest, mosses, lichens	1.5
Central spruce forest, bil berries	3.0
Southern spruce forest, wood sorrel	5.0
Deciduous forest (oak)	5.6

Salient aspects of the sub-polar climates are illustrated in this paper by circumpolar charts which extend equatorward to about 55° N. Lat. It may be generally said that the continent centres of this region have particularly long and harsh winters, though in maritime zones the severity is ameliorated. Summers are short and briefly very warm inland from the sea. Coastal areas are characterized by much cloudiness producing cool conditions where arctic vegetation is more common.

In documenting the climate of this vast area there are important data limitations to be considered. Firstly, in view of sparse human settlement the distribution of meteorological stations is widespread. Secondly, none of these stations measures all atmospheric parameters which are known to affect the biome, and with many parameters, what is measured is representative only of local conditions. Finally, some elements are not measured particularly well for reasons of instrument technology. Nevertheless, recent progress toward network enhancement has been notable in all countries belonging to the sub-polar realm.

Climatic Controls

Over the broad region there are four major climatic controls: the character of the solar energy input, the nature of immediate and adjacent surfaces, atmospheric circulation (weather systems), and topography. The physical factors which produce biologically important local climates have comparatively different levels of importance. Local climatic knowledge is critical in understanding vegetation communities, the distribution of small animals, and the limits for types of agricultural activity. However, meso- and micro-climates are very terrain-dependent and can only be mentioned here in refining the qualities of the principal climatic elements.

Solar Energy

The annual and daily cycling of solar energy received on a unit surface is quite different from that experienced at lower latitudes (Fig. 1). Since the angle of incidence at high latitudes is relatively small, the energy received on a horizontal unit area in a unit time is also small; however, in summer this is compensated by the increased length of day. Consequently the total energy available in June and July is approximately the same as at temperate latitudes. This factor and local cloudiness account for the solar radiation distribution shown in Figure 2.

Much of the incident solar radiation is reflected back into space because of the extent and duration of snow and cloud cover. Typical reflection coefficients are given in Table 2.

Table 2

Reflection coefficients for typical surfaces
(Kondrat'ev, 1954; Fritz, 1951)

Surface	Reflectivity in %
Exposed with continuous snow cover	80
Exposed with changing (melting) snow cover	55
Wet, after snow melt	15
Tundra in the warm season	25
Coniferous forest with snow cover	12
Deciduous forest	18
Sand surface with grassy patches	25
Complete stratocumulus cloud cover	56 to 81

The reflection of solar radiation from the tundra therefore varies from about 25 per cent in early summer to about 80 per cent when snow cover arrives. Cloud cover reaches a maximum in autumn and is at its minimum in the winter months. The reflectivity is dependent also on solar elevation and wave length, e.g. from a water surface it amounts to about 65% at 5 degrees at 16% at 25 degrees solar elevation.

Nature of Surfaces

Broad-scale differences in the radiative and thermal properties of the land, sea, snow and forests result in the major climatic shears which are apparent on most maps. Relative to the continents, the oceans act as heat sinks in summer, and heat sources in winter. The temperature characteristics of the Arctic seas are transmitted to the overlying air by the wind to coastal regions. As a result of these processes and ocean currents, the tundra extends southward to James Bay and Newfoundland. Where warm ocean currents penetrate northward into Arctic latitudes, such as into the Barents Sea, the tundra is displaced far to the north.

The melting of snow and ice requires considerable thermal energy. This process, combined with the high reflective and radiative properties of the snow, delays spring on the tundra. The extensive snow and ice fields profoundly affect not only the local and general climates, but also the character and movement of low and high pressure areas and frontal systems.

Weather Systems

The favoured positions of low pressure systems and the principal storm tracks for typical winter and summer months are shown in Figures 3 and 4. By inference, high pressure areas tend to be more persistent in those areas least frequented by cyclones.

A major airmass and wind trajectory analysis by Bryson (1966) demonstrated a close relationship between the tree line in Canada and the median position of the Arctic Front in summer. This correspondence has also been shown to occur in Eurasia by Krebs and Barry (1970). Strong net radiation gradients through the forest tundra transition zone as noted by Hare and Ritchie (1972) supports this contention of marked interaction processes between the surface and the atmosphere. However, there may be a tendency among operational meteorologists working with the sparse reporting networks to place frontal positions along the physical boundary of the tree line, for reasons of convenience.

Winter storms are most frequent over the ocean areas south of Alaska, southwest of Iceland and south of Spitzbergen. High pressure areas then dominate continental areas and the polar basin. The July pattern is significantly different. While the frequency south of Alaska and Iceland is diminished, there is an increased incidence of low pressure areas to the northeast of the continents and over the pole.

The prevailing storm tracks in winter extend from Newfoundland, by Greenland into the Barents and Kara Seas, and also into Baffin Bay. Secondary tracks lie from west to east along latitudes 60 and 75 degrees north over the continents. In July, the predominant track is from Newfoundland toward Spitzbergen, while there is a second preferred track northeastward into Davis Strait.

Topography

Mountain ranges profoundly influence continental-scale circulations causing large masses of air to rise and descend. The northward displacement of the tree line near the Mackenzie River valley is a manifestation of dynamic warming of air as it descends from the Western Cordillera. There are many other areas where downslope winds from the mountains have a pronounced ameliorating effect on temperature. In classical range and basin topography, humid climates occur on windward slopes, and relatively arid climates occur downwind of the ranges. Mountain climates are cold because of the decrease of air temperature with height; however, nocturnal or winter temperatures in the valleys and on the plains are frequently lower than on the adjacent slopes because of the drainage and ponding of cold air.

Smaller land features may also exert a major control on local climates. Lakes profoundly moderate local temperature regimes and increase early winter precipitation. Hills as well as mountains induce katabatic and anabatic winds while air is funneled, sometimes rapidly, through passes and along valleys. Rugged terrain offers a greater resistance to air flow than smooth terrain, and as a result winds are often much stronger over the open sea than on the coast, and stronger over the open tundra than in treed or sheltered sites selected for habitation. Adjacent areas with contrasting surface cover and roughness may have sharply contrasting energy and moisture balances. These induce local air circulations which act to destroy air-density imbalances across their boundaries. Lake breezes which tend to nullify sharp thermal gradients along shore lines illustrate this effect.

Pattern of Climatic Elements

Radiation

Attenuation of the solar beam by a comparatively thick atmospheric column and high surface reflectivities greatly reduce the amount of short wave radiation available for heating the air, the soil and evapotranspiration.

Much long-wave energy is lost at night from the air and surface, particularly snow. The long photoperiod in summer fortunately helps to compensate, making extensive plant growth possible. The annual absorbed solar radiation in Canada decreases from 80 Kly at the boundary of the closed boreal forest to 50-55 Kly at the forest-tundra edge (Hare and Ritchie, 1972). For albedo reasons, a very strong spring net radiation gradient is also characteristic of the taiga zone having the effect of delaying the onset of spring over the tundra and reducing the duration of the thaw season by 48 days in western Canada and 30 days in eastern Canada. Very large clear-cut areas within the boreal zone having a continuous snow cover might also be expected to have a rather late spring. Much potentially effective radiation is thus lost early in the season before photosynthesis is possible; thus mid-summer absorbed radiation is much less than the annual values would suggest. Hare and Ritchie quote 15 per cent for the growing season at the Canadian arctic tree-line. Dolgin (1970) indicates about 11 Kly in July at the equivalent Eurasian tree-line.

The radiation balance determines to a considerable extent the heat budget of a given area. Net radiation is roughly correlated with major vegetation boundaries. Drozdov (cited by Hare and Ritchie) has related net production with annual net radiation and notes the energy conversion amounts to 1-1½ per cent of the net value in the boreal zone. Net radiation in a given season also correlates with degree-days above 10°C for the same season (Budyko 1963).

Alteration of the surface can drastically change the energy balance. Clearing of areas underlain by permafrost with a high ice content will often lead to extensive geomorphological alteration with attendant hydrological changes, not usually desirable from a land conservation standpoint.

In view of difficulties in interpreting net radiation measured at a site over a variable terrain, the use of temperature sums in projecting productivity seems more practical.

Temperature

Low summer temperatures strongly limit biological productivity. Biochemical action requiring heat for the breakdown of nutrients needed in plant assimilation is sluggish in cold soils. There seems to be a lack of primary nutrients (NPK) in many sub-arctic soils which may be related to an absence of birds and small animals (Billings 1975). Also nitrogen-fixing bacteria and leguminous plants are not plentiful. Walter (1973) notes that nutrient quantities available to plants rather than light may determine the composition of the herbaceous stratum. Photoperiod response may initiate plant growth before positive temperatures are established, but the occurrence of rather warm conditions (~20°C) is necessary for seed germination and this may not occur in some years (Billings 1975). In spring and fall when the temperature regime fluctuates near the freezing point root tissue injury may occur in high-ice soils.

Daily air temperatures are generally 10-15°C in the cloudy summer (Figure 7), but may rise to 20-25°C during brief sunny spells. The mean daily range of temperature in summer is about eight degrees. The coldest months are December through April; Figure 8 shows the mean daily temperature in the Canadian sub-arctic in February is about -20°C and the mean daily range varies from about ten degrees in continental areas to about six degrees elsewhere. In Europe, the average temperature is about 10° warmer, but in Asia it is 10° cooler. In open forests, temperature extremes of -63°C at Snag, Yukon, and -68°C at Verkhoyansk and Oymyakon, U.S.S.R. have been measured. Topography and vegetative cover are probably important factors in the temperature regimes at such sites. Temperatures lower than -35°C have persisted for periods of up to 20 days at several locations.

Standard meteorological measurements of air temperature are taken at 1.2 metres above the ground, within a louvred screen which is generally well-exposed. This height was selected not only for convenience, but also to avoid strong vertical temperature gradients which often occur near the ground (see Figure 9). Strong temperature inversions are persistent features of the winter regime. Screen level measurements are better estimates of the free air temperature than of temperatures of the ground surface or objects such as leaves, rocks, or branches, all of which may have significantly different temperatures depending on their radiative and thermal properties. The need for standard exposure for climatological reference purposes is further illustrated by the findings of de Percin and Falkowski (1956). They observed that lowest winter temperatures occurred in snow-covered, non-vegetated hollows; and highest winter temperatures occurred in open, windy areas, or in areas where the heat loss was reduced by trees.

As shown in Figure 9 the diurnal cycle of temperature is strongly controlled by the input of solar radiation. The diurnal cycle is an important phytogenetic factor and it may be interesting to compare the month to month variation at two widely separated Canadian sub-arctic locations, Ennadai Lake (Keewatin) and Fort Chimo, (Quebec), as is illustrated by Figure 10. Both show similar features in the variation, i.e. two minima and two maxima. The absolute minimum is seen to occur in October around 6°C. From then a steady increase is noted toward a late winter maximum while a secondary minimum is observed at snow melt time in May.

In summer, near the sea coast cold air advection quickly offsets the influence of solar radiation on the land, and there is little diurnal variation in temperature. There, and in general during the arctic winter, variations in air temperature are highly related to cloud cover and advection processes.

Frost-Free Season and Growing Season

Based on ten year's data the average length of the frost-free season was charted for the sub-polar regions of Canada (Figure 11). Generally increasing from east to west, lengths vary from 22 days at Cape Hopes Advance to 56 at Coppermine and 77 at Aklavik. Inland they range to over 100 days within the warming influence of the Great Slave Lake while only a short distance away Fort Smith Airport has a frost-free season of only 59 days. Sheltered locations within the Arctic Archipelago islands enjoy 54 days at Cambridge Bay, 68 days frost-free on the average at Frobisher Bay Airport.

Again it must be emphasized that these findings are based on screened thermometer readings, while microclimatic variations may bring about significant departures only short distances away.

Figure 12 shows the distribution of the average growing season based on the concept of effective growing season, the onset of which is defined at the end of a period of 5 consecutive days in spring with a mean temperature equal to or higher than 5.6°C. The end is similarly defined as the first day following 5 consecutive days with mean temperatures lower than 5.6°C. Less uniformity is observed here and the effect of large topographic features such as Great Slave Lake is less noticeable. The longest growing season is found in the Yukon where 140 days are available for vegetative growth. Similar values are achieved near the south shore of Great Slave Lake, dropping slowly from there toward the mouth of the Mackenzie River where it is 92 days. Smaller values are found going last from there, viz. 75 at Baker Lake and only 40 at Cape Hopes Advance. The climatic enclave at Frobisher Bay enjoys 96 days, the Arctic Archipelago islands barely one month south of 75°N and 50 days south of 70°N. Similarly, mountainous areas experience brief seasons.

Growing Degree-Days (5.6°C)

Reference is made to Figure 13 based on 15 years of data (1953-1967). This map shows a distribution of an even more pronounced gradient stretching from Aklavik in the Northwest to Churchill in the Southeast. Some homogeneity at values exceeding 800-900 units prevails to the south and west, while values less than 200 units characterize the arctic coast and the offshore islands. It is interesting to compare Frobisher Bay (159) with Holman, Victoria Island (193) i.e. higher thermal resources in the west despite vastly different growing seasons, 96 east versus 51 west, or frost-free season, 68 east versus 23 days west.

Precipitation

Precipitation regimes are quite variable, being controlled at a given place by the distance and trajectory of air movement from the moisture source, as well as the intervening terrain responsible for directing air currents. Thereby, precipitation processes are stimulated or dampened. Greater than 1,000 mm of rain and snow water-equivalent are recorded in the Stanovoy and Kamchatka ranges of eastern Siberia while over 4,000 mm fall on the first range of the Coast Mountains of British Columbia and Alaska (Figure 14). Over most of the sub-arctic annual precipitation equals ~500 mm and the amount of snow water accumulating in eight months of winter is about the same as the rainfall during the shorter summer. In maritime regions there is customarily more rain than snow.

Normally there is adequate precipitation for vegetative growth, in view of the prevalent summer maximum, supplemented by snow melt, though locally there can be seasonal deficiencies during mid-summer when serious forest fires have resulted. Extensive surface water areas during spring and summer provide excellent breeding grounds for waterfowl but also for biting flies which severely harass the well-being of residents and their domestic animals.

The available moisture within the soil for plants has wide local variation being a geomorphological as well as climatic factor. Run-off rates, slopes, exposure to drying winds, the distribution of "wet" permafrost, ground level plant structure and soil texture are some further complications in local water balance regimes.

Snow Cover

For at least six months of the year the ground is snow-covered (Figure 15). The blanket provides insulation for dormant plants and hibernating animals and is a good transportation surface for man, though when the crust is soft, mobility is limited, sometimes precariously, as is the case for long-legged animals. Above the snow cover extremely low night-time temperatures may occur since snow radiates as a black body. The reflection of sunlight from the snow surface and the abrasiveness of snow driven by the wind may cause physical damage to plants. Optimal snow depths for plant growth are estimated by Rikhter (1963) to be about 50 to 60 cm. Grazing animals would, of course, prefer to have no snow cover, and several authors (Kelsall, 1968 and Henshaw, 1968) have stated that caribou and reindeer will not feed in snow depths greater than 50 to 80 cm or when the density exceeds 0.50. Light penetration is negligible below 50 cm in dry snow, and below 20 cm in wet snow (Rikhter, 1963).

A map of the late winter snow cover (Figure 16) shows that on the average the depth is about 60-80 cm in the continental interiors. As with precipitation, mountainous areas have considerably higher values with depths of over 120 cm being found in Norway, and more than 180 cm of snow in the mountains of southern Alaska.

Although snowfall may be fairly uniform over a region, it is quickly redistributed by the wind, and in mountainous areas by slides. Scour and sedimentation result in varied cover and density, with numerous exposed areas and drifts. The eroded snow accumulates along the upwind side of valleys and along the edges of obstacles, such as shrubs or rocks, which diminish the wind speed.

Interception of snow by the tree canopy limits the amount of snow reaching the ground in an evergreen forest. Greater accumulation therefore occurs in an open deciduous bush which reduces the wind speed and does not inhibit snow from reaching the ground. The variability of accumulation with vegetative type and land form is well illustrated in Figure 17.

Snow falling within a forest remains light and fluffy, provides good insulation and is easily penetrated by air, water vapour, animals and birds. In the open, under the influence of the wind, freshly fallen snow rapidly increases in density, and the snow cover is generally compacted and capable for supporting the weight of a man. A comparison of densities is given in Figure 18.

Evaporation

A limited amount has been published on evaporation in the sub-polar belt. Owing to the cool summer temperatures and a precipitation maximum during that time of the year, evaporation is often assumed to be below and to lag behind the addition of soil moisture by rain. The existence of permafrost furthermore inhibits the drainage of melt water below a shallow depth with the result that excess surface water in the form of bogs is usually present in the low lying parts. On higher land, especially where soil moisture is lower greater surface heating and high wind speeds may promote more efficient evaporation. Additional evaporation is also promoted by long diurnal periods of insolation in the warm season.

Though technically water stress is largely non-existent and plant cell sap concentrations are comparatively low, the widespread moss and lichen surfaces have the capacity to detain surface water in copious quantities and thus render it unavailable for assimilation by the root systems of vascular plants.

To provide some insight into the general field of high latitude evaporation, data from several stations which have short records of pan evaporation are presented. The figures given are mean monthly net evaporation values, computed from the water added, the water taken out and the daily precipitation. The lengths of records are stated in parenthesis.

Table 3

Class A Pan Evaporation

Station	Location	Elev.(m)	May	June	July	Aug.	Sept.
Churchill	58°45'N 94°04'W	35		115(2)	152(11)	116(11)	72(5)
Fort Selkirk	62°49'N 137°22'W	454	130(7)	151(11)	139(11)	93(11)	47(9)
Fort Smith	60°01'N 111°58'W	203	168(3)	180(7)	169(8)	141(9)	58(5)
Haines Junction	60°06'N 137°35'W	599	147(7)	186(10)	165(11)	122(11)	55(9)
Normal Wells	65°17'N 126°48'W	64		176(10)	154(11)	93(11)	45(4)
Resolute	74°43'N 94°59'W	64			97(8)	56(7)	
Yellowknife	62°28'N 114°27'W	682		210(7)	214(9)	150(9)	65(7)

It should be noted that unadjusted pan values are higher than true evaporation from a water surface or evapotranspiration from the land. This is because the pan is not insulated from advected energy largely taking the form of sensible heat transfer through the pan. Also the rim of the pan creates mechanical turbulence which increases the evaporation rate. Pan values are often adjusted to "lake evaporation" using a coefficient which averages 0.7. However, there is always argument against adjusted values so the raw data are presented here allowing the reader to make his own interpretation.

Wind

In exposed areas, a strong wind may force animals and insects to take cover; it rearranges snow, exposing food for grazing, presenting a varied pattern of soil protection, creating barriers to travel, or causing a hard snow crust over which movement is easier. The severe restriction on winter activities imposed by the combination of strong winds, blowing snow and low temperatures is of major importance. In the growing season wind stress may reduce the photosynthetic period by causing the closing of stomata.

It is difficult to present a meaningful hemispheric map of wind because airflow is so highly variable and easily influenced. Many settlements are in sheltered locations and wind measurements taken there are seldom representative of the general flow of air. Topography in conjunction with persistent weather systems produce the prevailing winds. The direction of these winds may be deduced from Figures 3 and 4 by considering topography and position relative to the favoured locations of low pressure areas. The higher frequency of low pressure systems in winter in many coastal areas results in greater wind speeds occurring in that season.

Strong winds are a very critical bioclimatic factor. The per cent of the time winds are in excess of 11 mps is shown in Figure 19. Coastal strips have the highest frequency, and sheltered areas, such as treed valleys, the least. It should be remembered that coastal winds used in this analysis were measured in locations with some shelter. In more exposed locations winds of over 45 mps are not uncommon, e.g. Cape Hopes Advance on the tundra recorded wind speeds of 56, 55, 51, 47, 45, 43, 41 and 41 mps, over eight consecutive hours in November 1931.

Officially-recorded winds are measured at 10 metres above the ground on relatively unobstructed terrain. Friction between the air and the ground results generally in an increase of wind speed with height, the greatest rate occurring near the ground itself. Consequently, an animal will find relief from strong winds by lying down as well as by seeking shelter. The shelter produced by an obstacle such as a grove of trees can be felt downwind of the object at distances of up to 20 times the height of the object, and reductions of wind speed of 60 per cent can generally be realized within a distance of four times the tree height (Read, 1964). The impact of trees on wind speed is clearly shown by winds measured near Churchill, Manitoba (Figure 20).

Temperature and Wind

The combination of strong winds and low temperatures may result in high energy advection, the loss being greatest when the surface of the animal or ground is wet. The cooling effect may be estimated on the basis of a formula which incorporates these two factors. Hart (Kelsall, 1968) has shown a windchill of 1100 kg cal m^{-2} hr^{-1} to be critical at Caribou calving time. This corresponds to an air temperature of $-7^{o}C$ and wind speed at 5 mps, or $0^{o}C$ and 12 mps. Table 3 shows the risk of such contingent strong winds and low temperatures at two tundra locations.

Table 4

Percent frequency of simultaneous occurrences of specified temperatures and wind speeds in June (1956-1956)

Wind Speed Ranges	Temperature Ranges ^{o}C		
	-7 or lower	0 or lower	6 or lower
Cambridge Bay, NWT			
4 - 8	1.2	17.0	43.0
9 - 13	1.0	7.1	14.4
14 and over	0.3	0.9	1.3
Baker Lake, NWT			
4 - 8	0.9	10.1	36.0
9 - 13	0.4	5.6	14.2
14 and over	0.0	0.3	1.2

Extreme conditions which have been experienced in the Canadian Arctic include instances of winds of 45 mps with a temperature of $-30.0^{o}C$ at Winter Harbour, and 27 mps with $-37.0^{o}C$ at York Factory. It is often assumed that lowest temperatures occur with light winds; this not always the case, particularly in coastal areas. De Percin and Falkowski (1956) report that at Churchill "strong winds occur as frequently with low temperatures as with high temperatures."

Discussion

Thus the sub-polar region has at best a marginal climate for agriculture. Reindeer herding may be sometimes profitable in the tundra, though many animals are endangered by inclement weather during the calving and rutting seasons, by blizzards or winters of deep soft snow. Annually, their hides are damaged by hordes of biting and burrowing flies.

Crop production and animal husbandry are conditionally feasible in the forest zone where slopes and soils are carefully selected according to better meso- and micro-climates, and where the animals are not harassed by hungry insects and mammalian predators.

The most successful high latitude farming ventures are situated in areas which would naturally support a closed boreal forest or mixed forest as these regions have the greatest heat energy in the form of higher summer temperatures, adequate precipitation and moderate wind speeds if part of the forest is left in place. On the other hand the frost-free season tends to be significantly shorter in forest clearings. Hare and Ritche note that standing phytomass values are 300-400 tons ha^{-1} here compared with 25 tons just north of the arctic tree-line. Coastal regions are generally impoverished due to heavy summer cloudiness and cold ocean currents.

Frost dangers are lessened and longer growing seasons promoted when south-facing slopes of modest altitude offering some shelter from cold winds are selected for cultivation. The summer approaches rapidly once snowmelt has taken place, thus the danger period for radiation frost on sloping ground is quickly passed. Low-lying portions of valleys and extensive permafrost regions are always to be avoided.

Crop selection favours hardy species which enter dormancy early (if perennials), and germinate shortly after snowmelt. Suitable crops become progressively limited taxonomically at higher latitudes, and it becomes increasingly expensive and difficult to obtain the necessary fertilizers for the crop and enough native fodder to keep livestock into the fall.

The establishment of extensive high latitude agricultural districts would be a precarious measure and such decisions are unlikely. Smaller zones of activity profiting from anomalous soil, meso-climates and markets can be viable when there is a favourable combination of scientific agricultural advice, sensible decision-making, hard work, and a prevailing philosophy of optimism.

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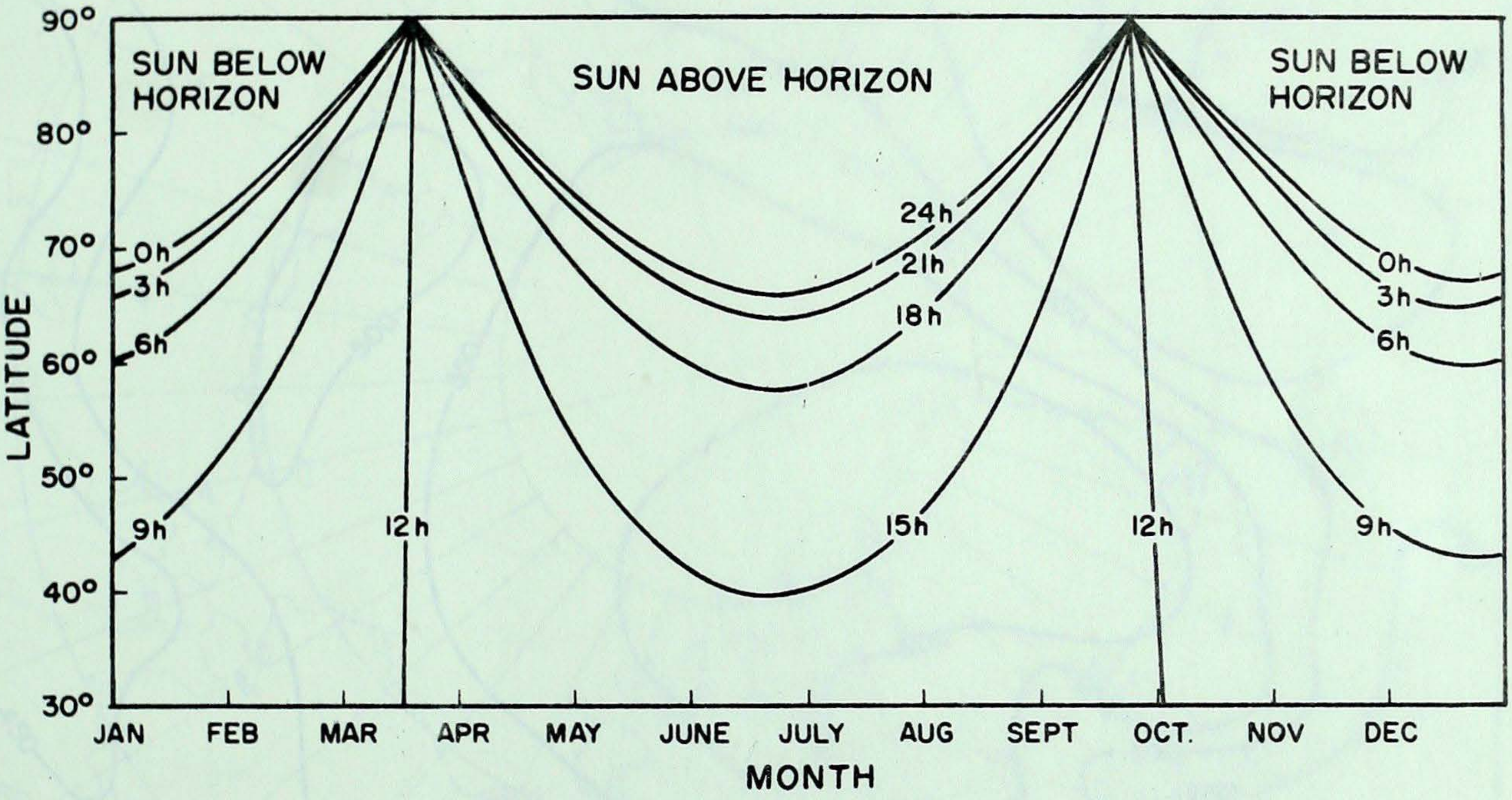


FIGURE 1 Duration of daylight (hours)

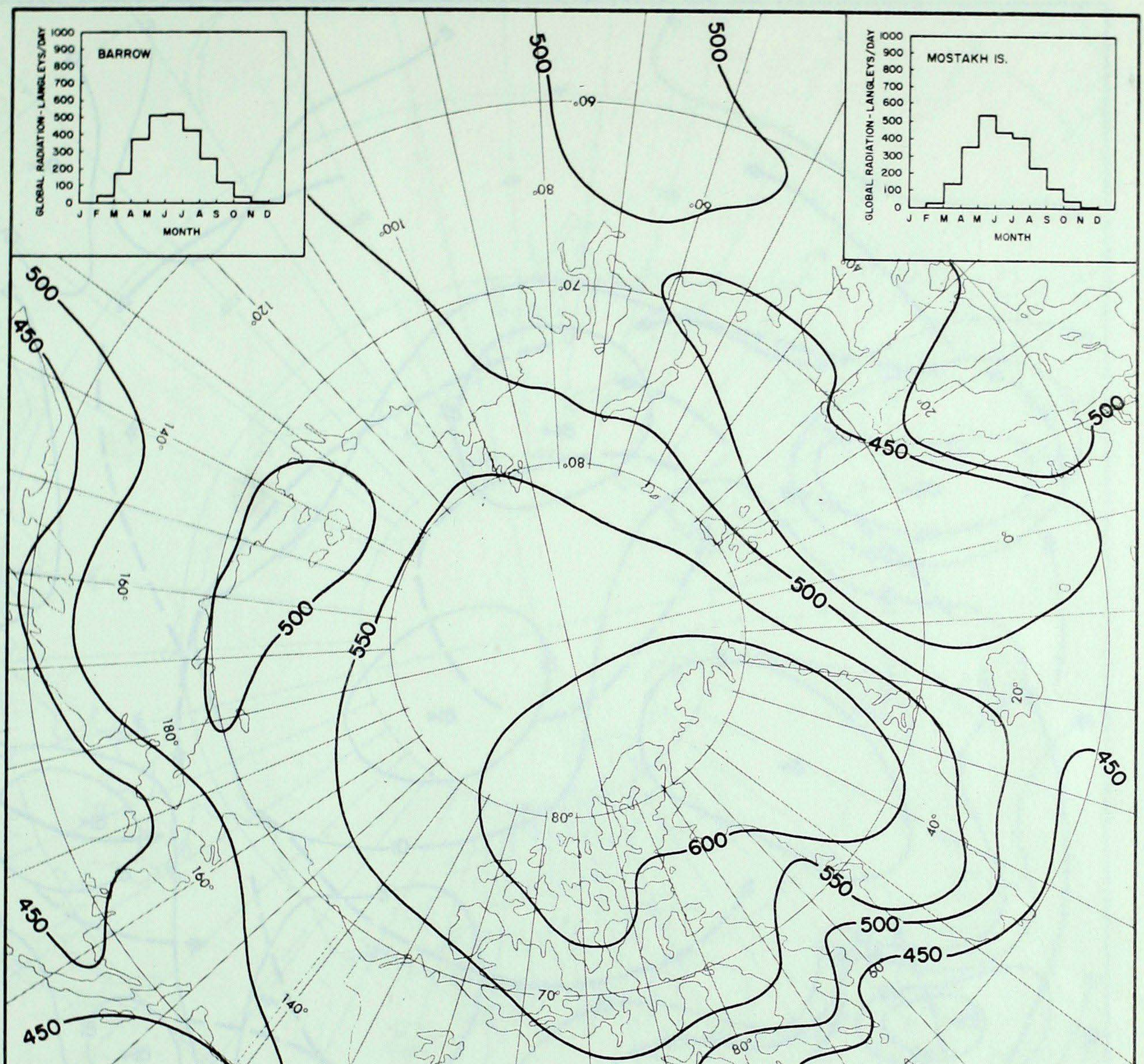


FIGURE 2 Mean daily total solar radiation (Langleys) for June and the annual regime (after Budyko, Vowinckel and Orvig, Titus, Löf et al)

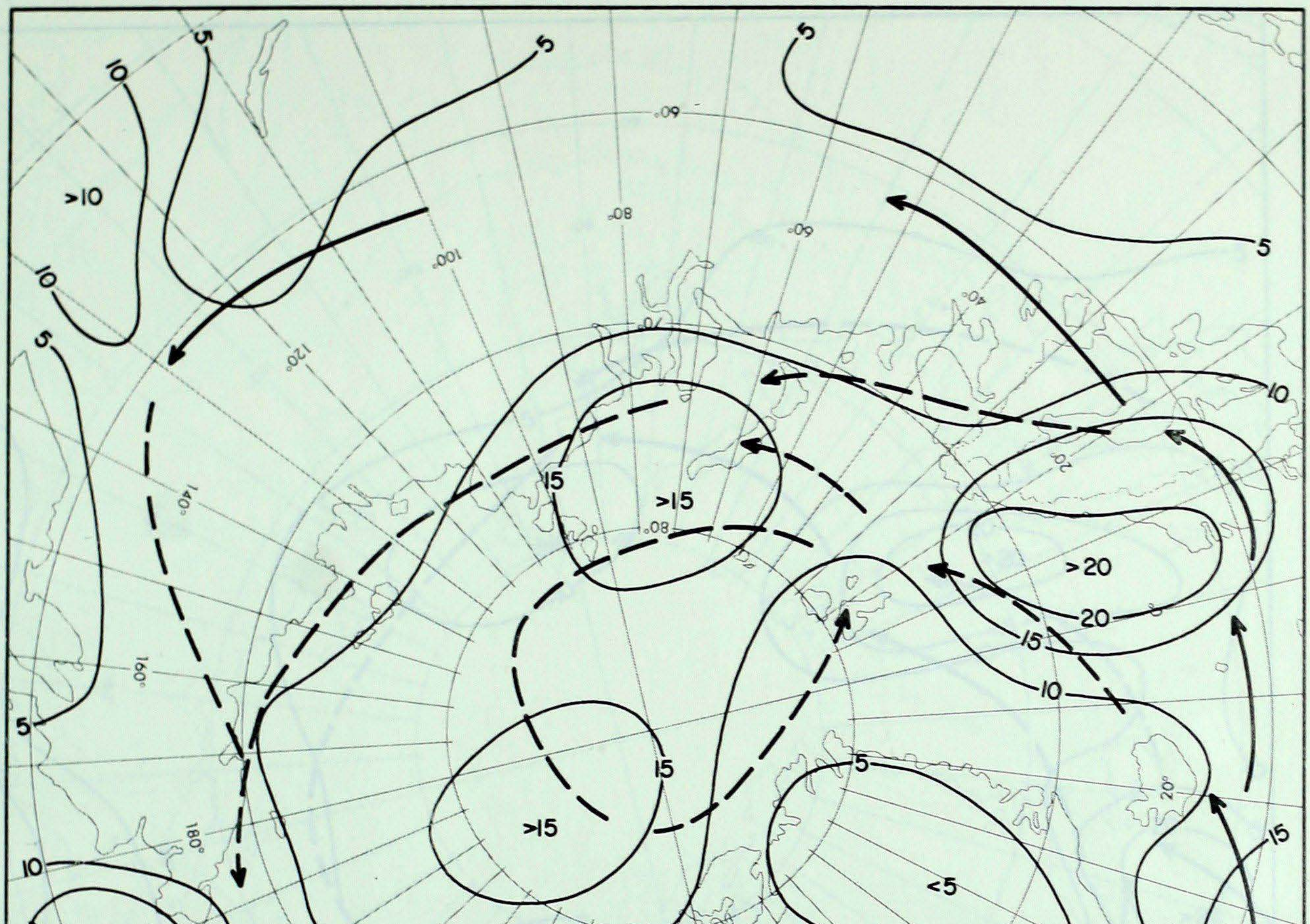


FIGURE 3 Percentage frequency of cyclonic centres in a 650,000 sq. km. area and principal storm tracks in August (after Klein, 1957)

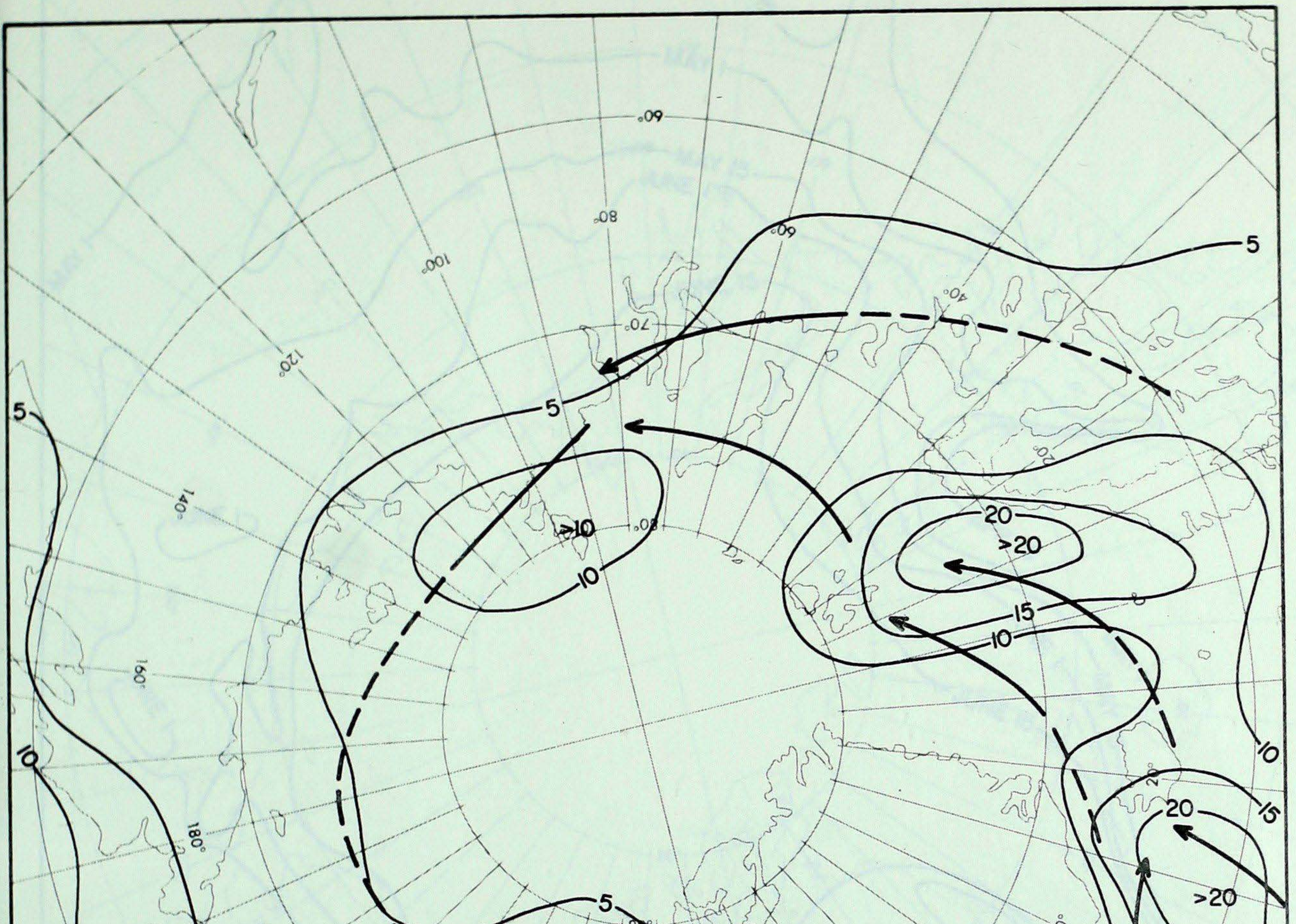


FIGURE 4 Percentage frequency of cyclonic centres in a 650,000 sq. km. area and principal storm tracks in February (after Klein, 1957).

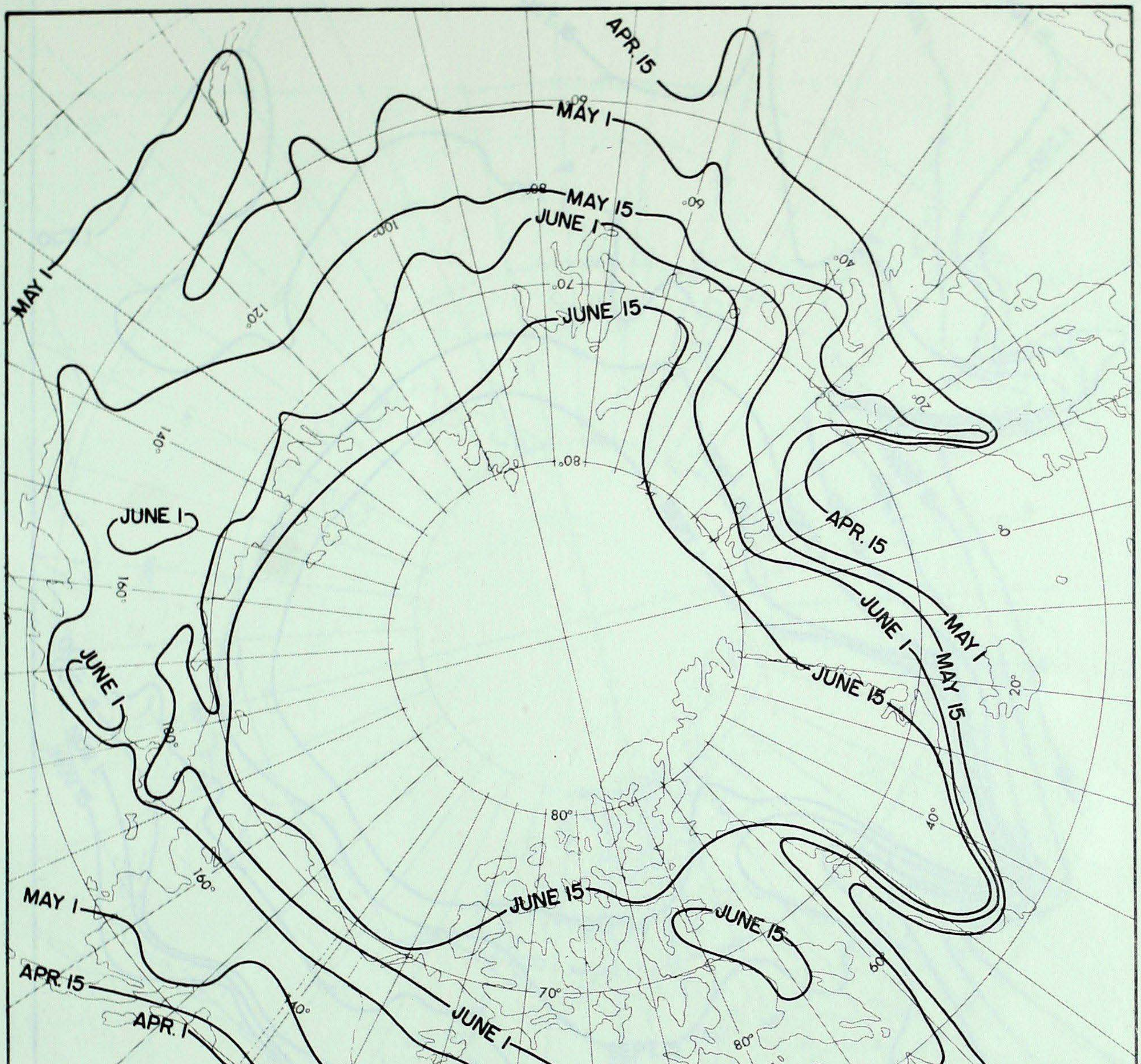


FIGURE 5 Date on which the mean daily temperature rises above $0^{\circ}C$ (1951-1960)

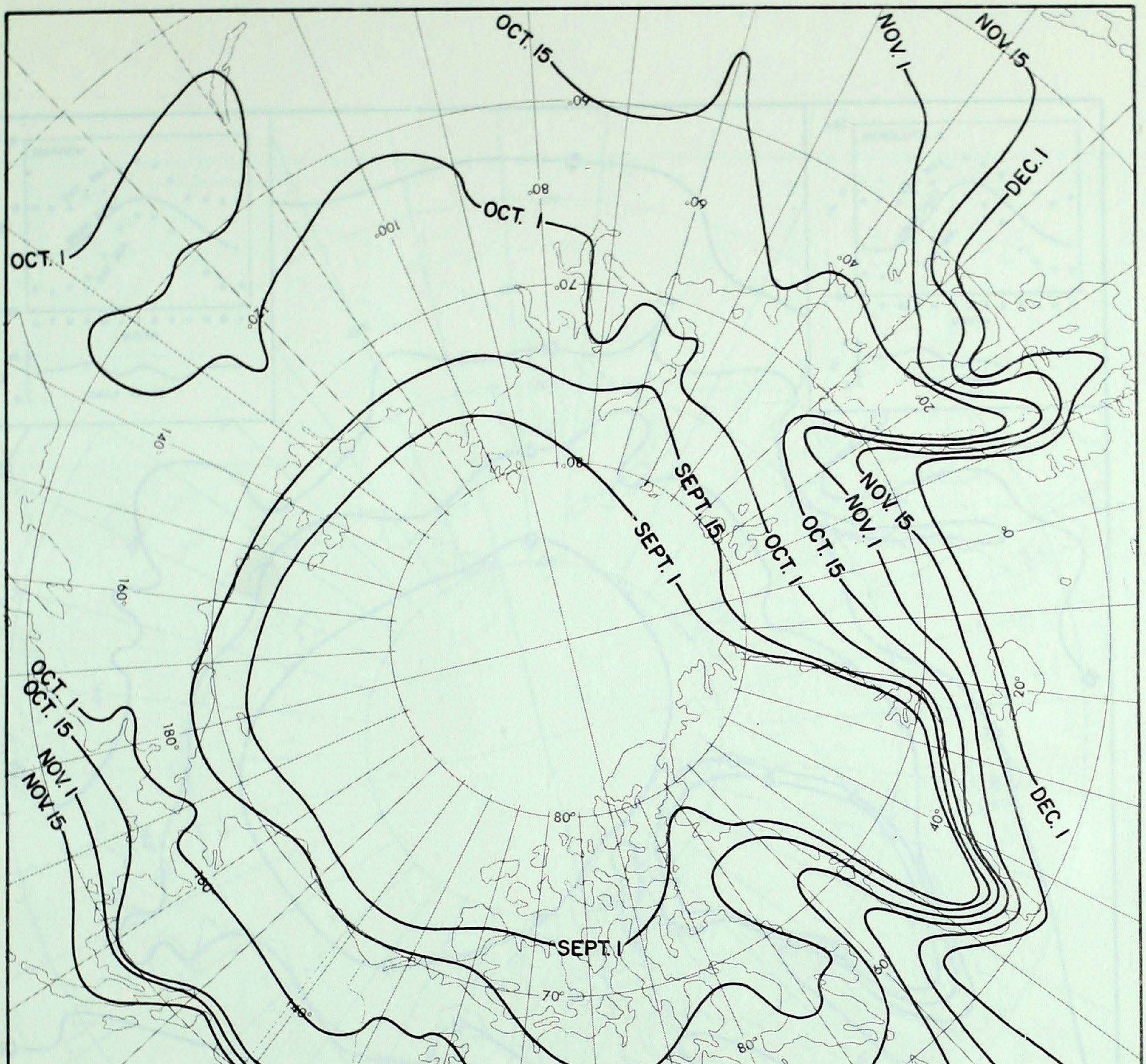


FIGURE 6 Date on which the mean daily temperature falls below 0°C (1951-1960)

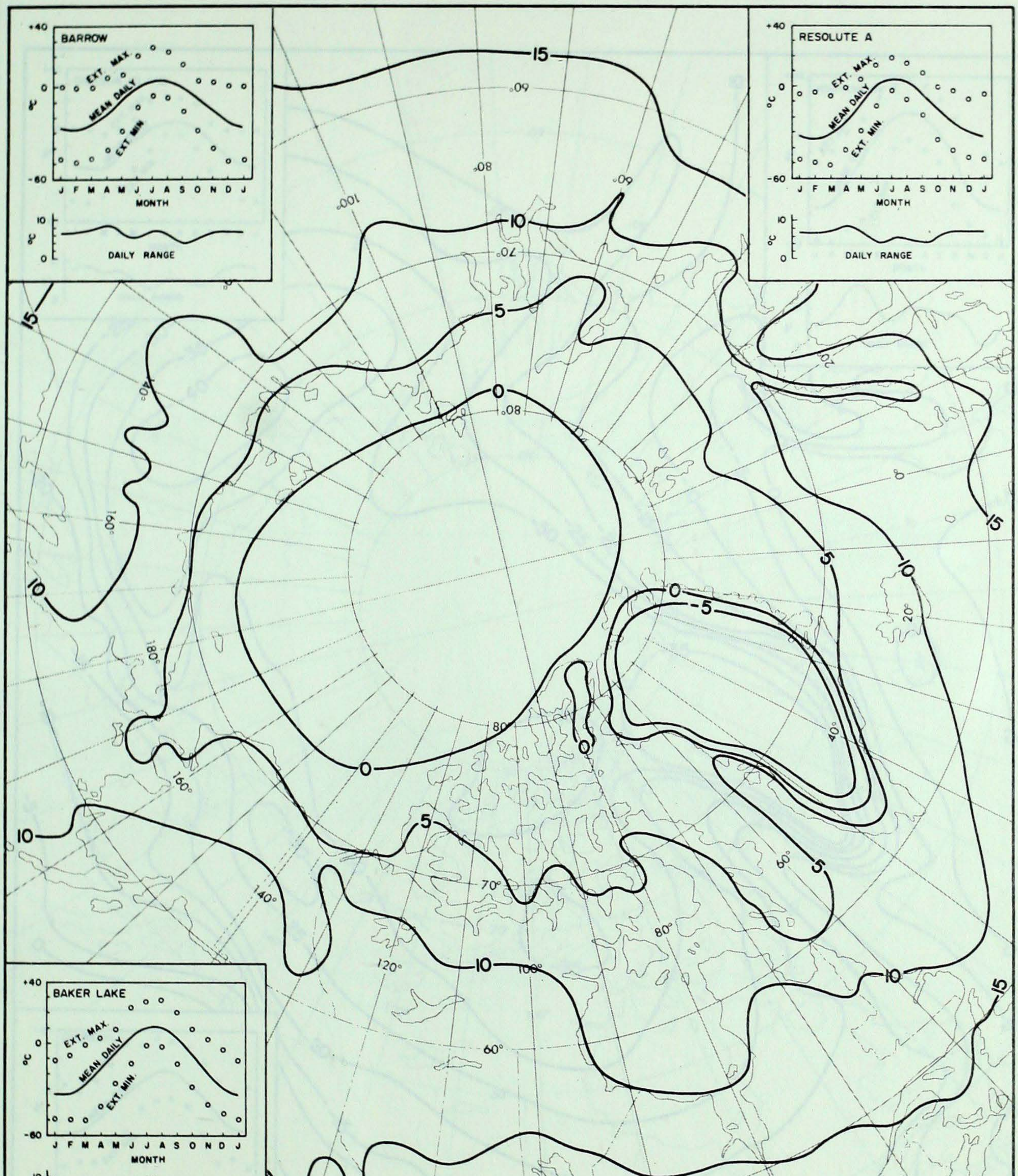


FIGURE 7 August mean daily temperature °C and the annual temperature regime (period 20-30 years during 1931-1960)

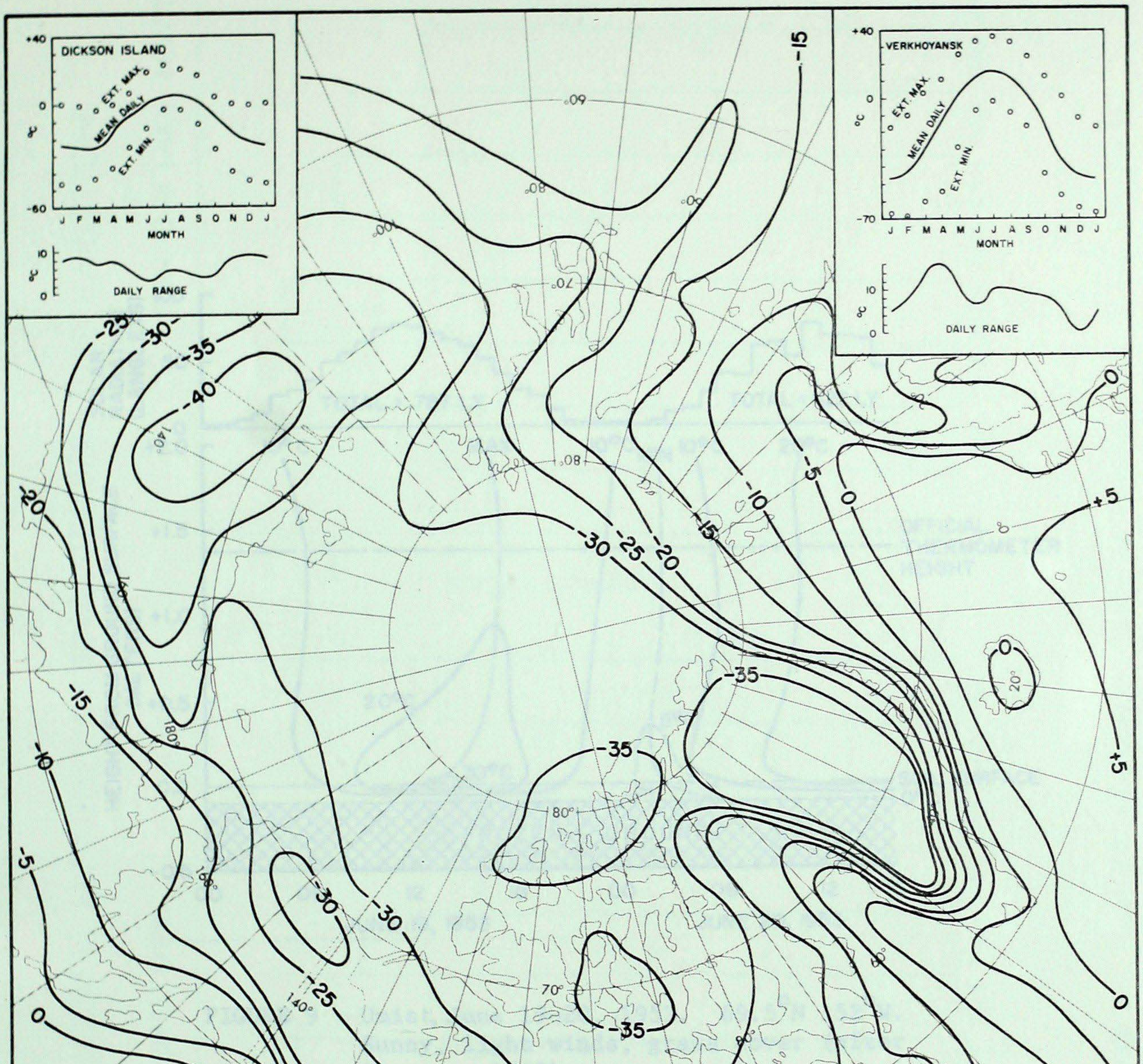


FIGURE 8 February mean daily temperature °C and the annual temperature regime (period 20-30 years during 1931-1960)

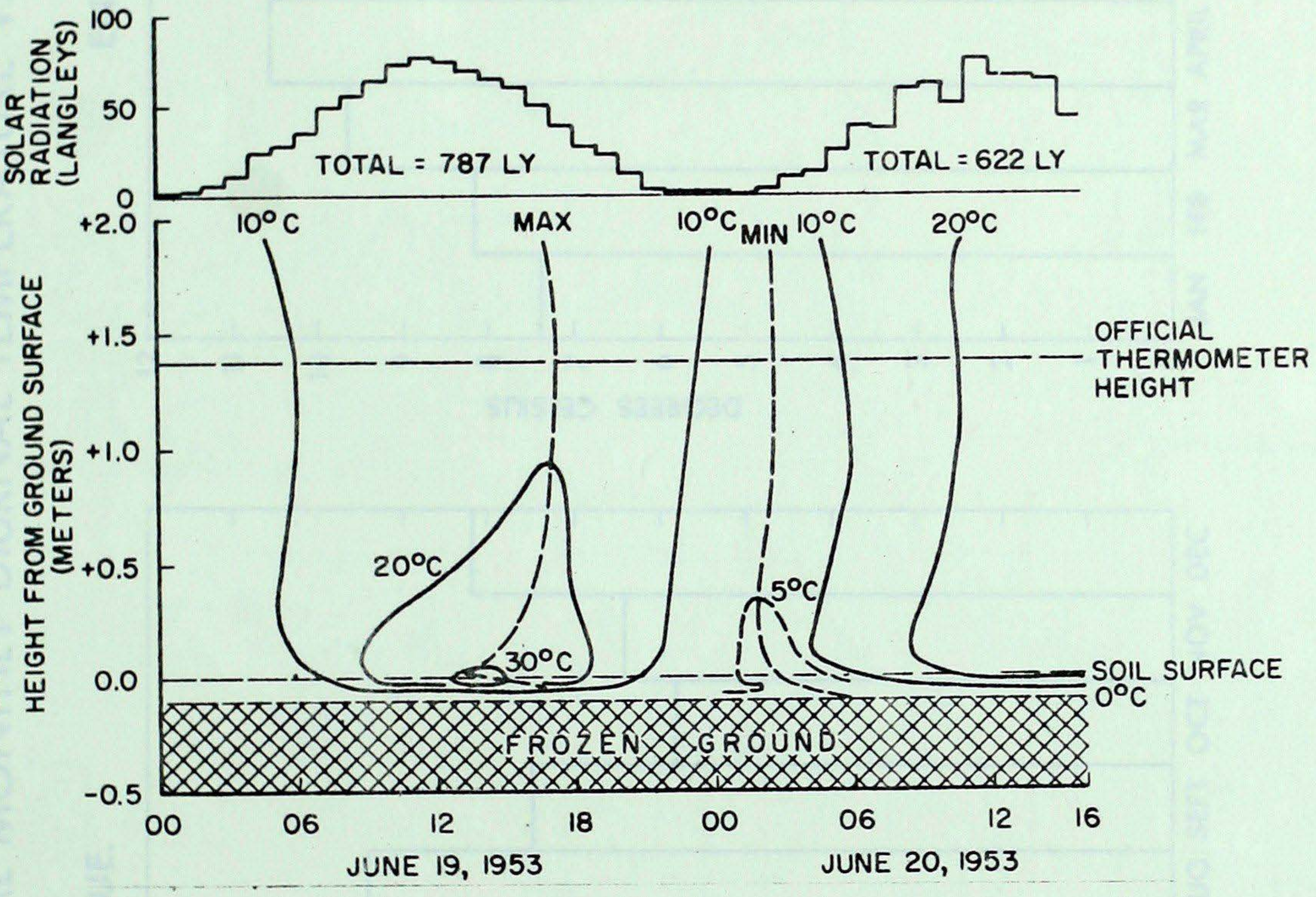


FIGURE 9 Umiat, June 19-20, 1953. 69.5°N 152°W. Sunny, light winds, grass cover (after Conover, 1960)

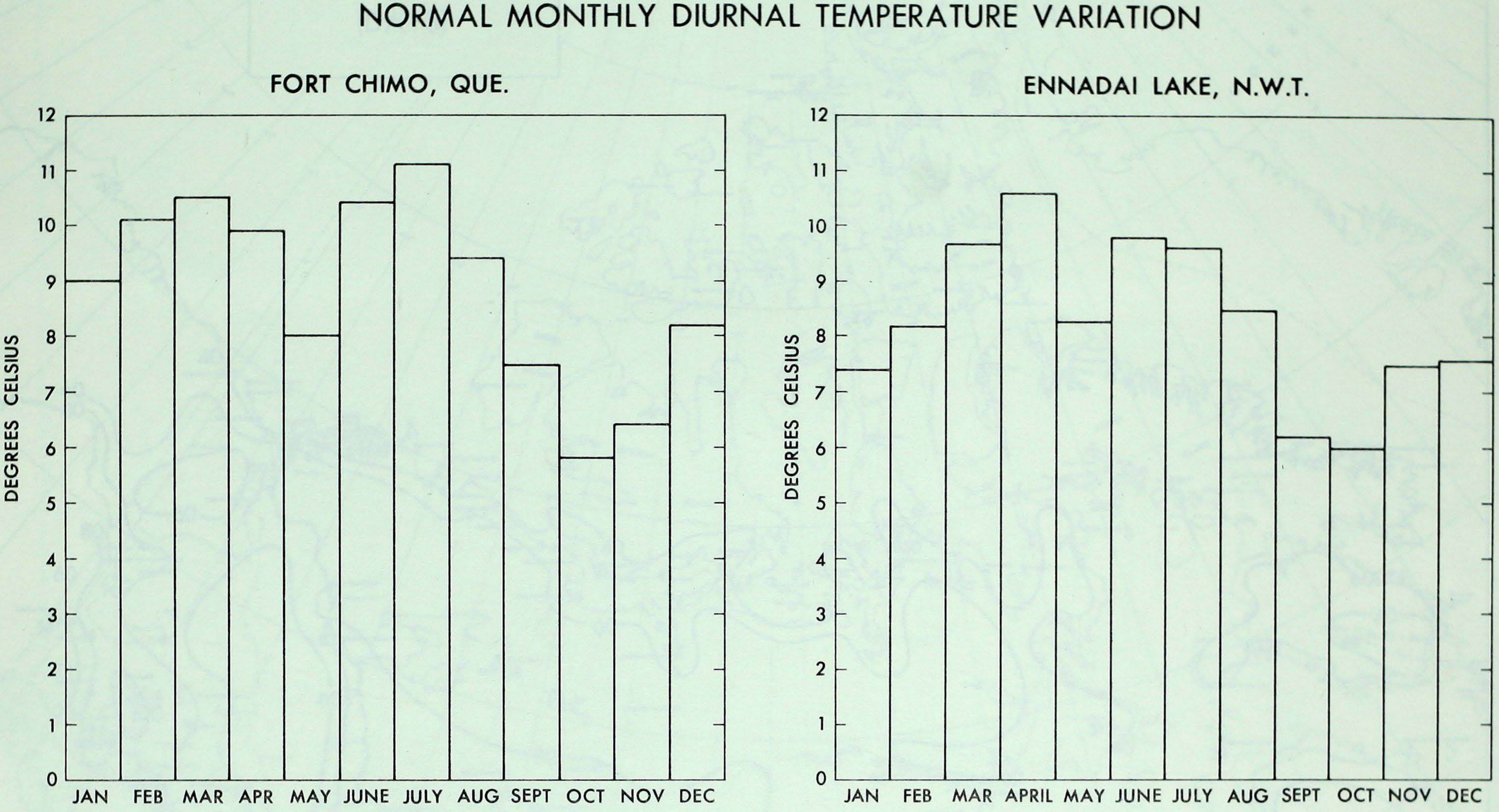


FIGURE 10 Mean monthly diurnal range of temperatures at two sub-arctic locations

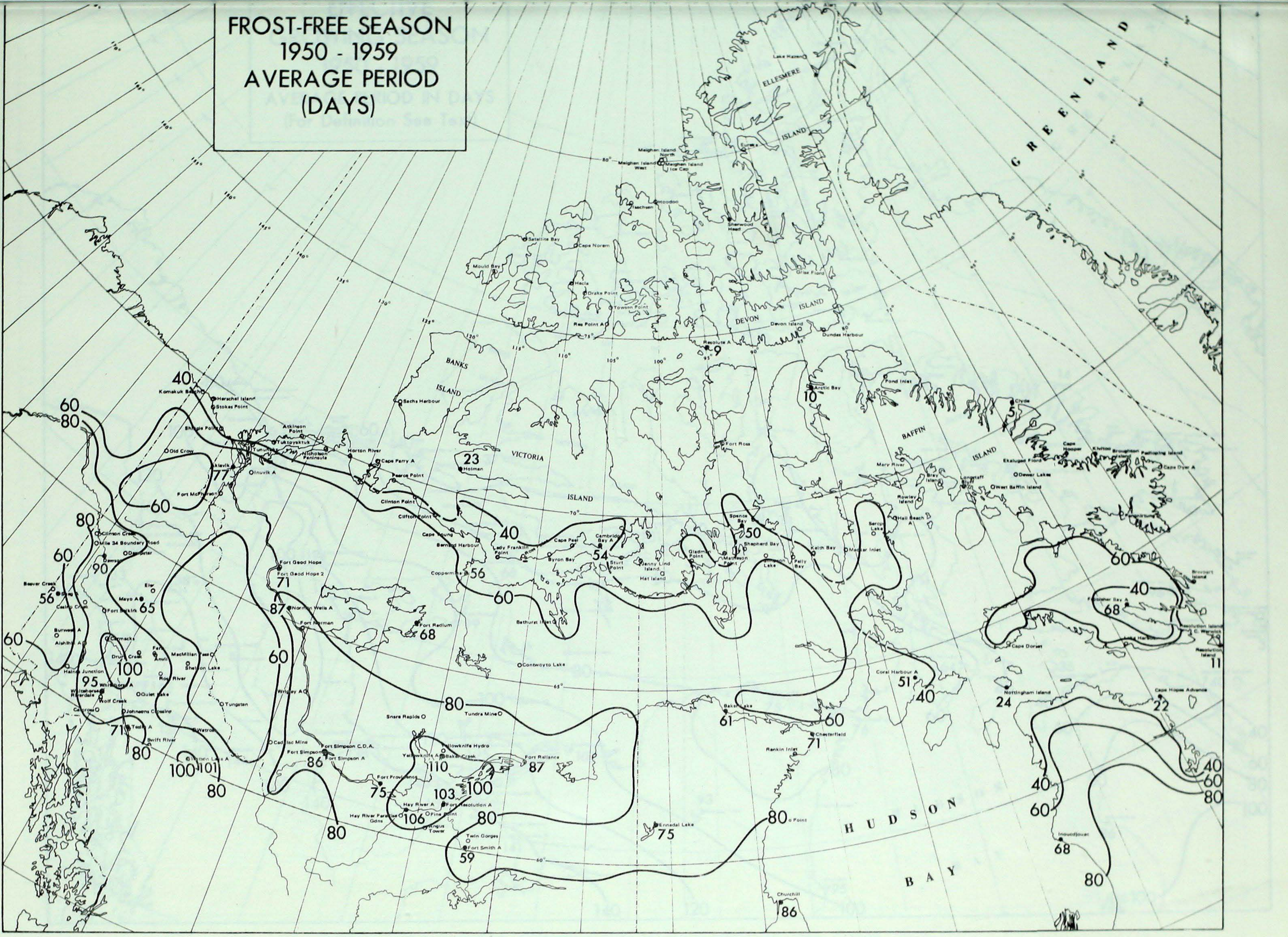
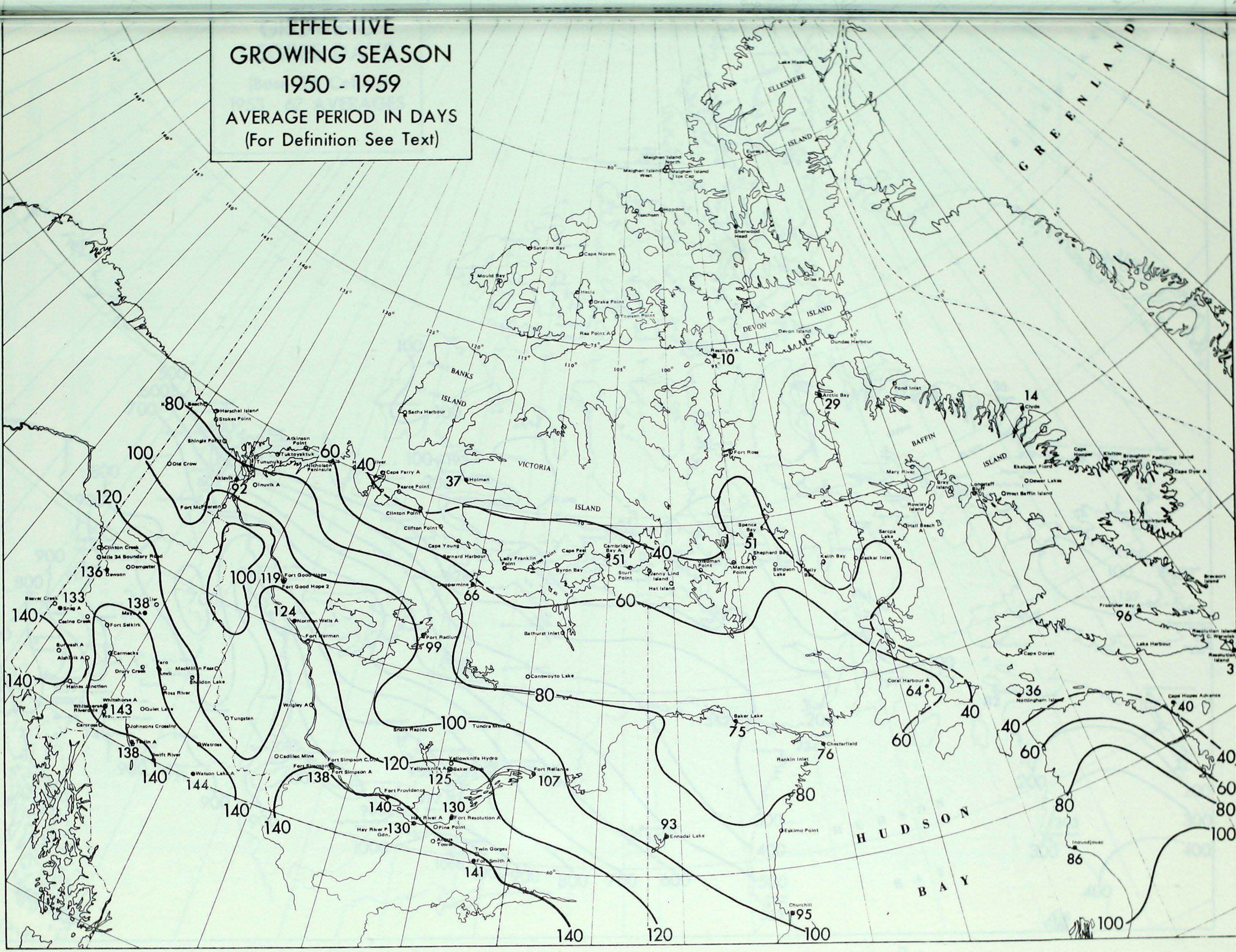


FIGURE 11 Frost-free season in northern Canada

 EFFECTIVE GROWING SEASON 1950 - 1959 AVERAGE PERIOD IN DAYS (For Definition See Text)

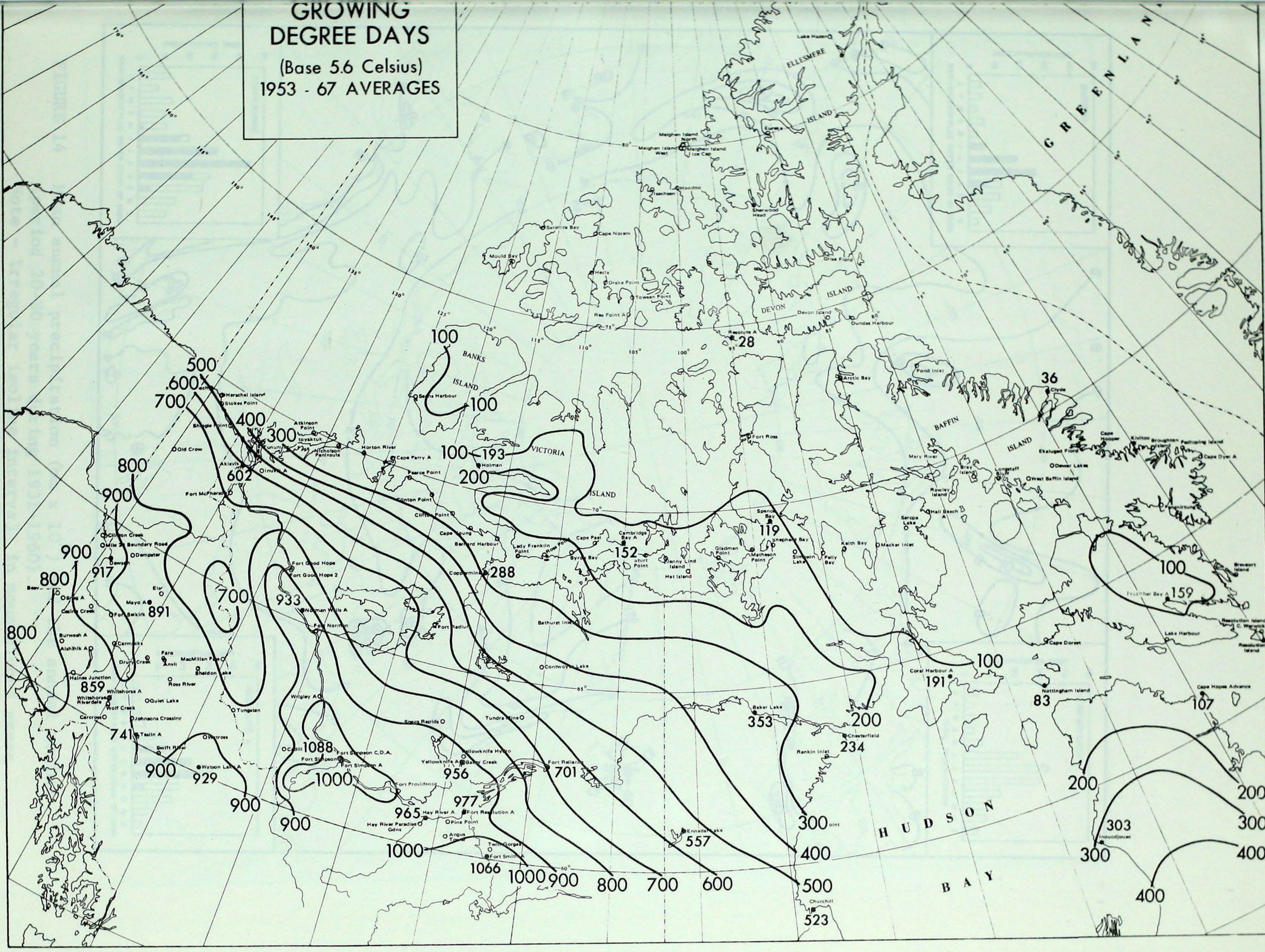


FIGURE 13 Growing degree-days in northern Canada (base 5.6°C)

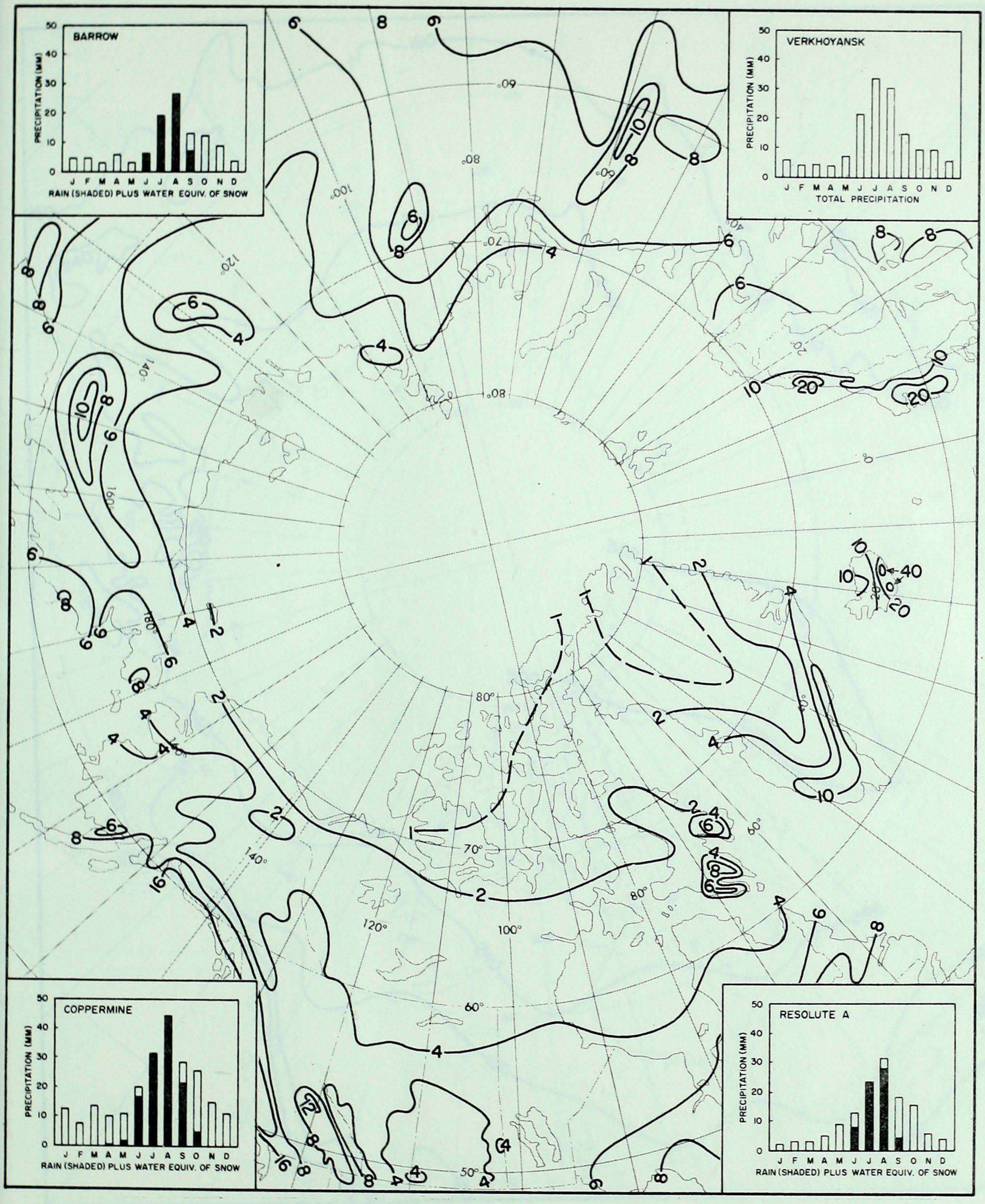


FIGURE 14 Mean annual precipitation (mm x 10^2) and the annual regime (period 20-30 years during 1931-1960).
Note - Irregular isoline intervals in mountainous areas

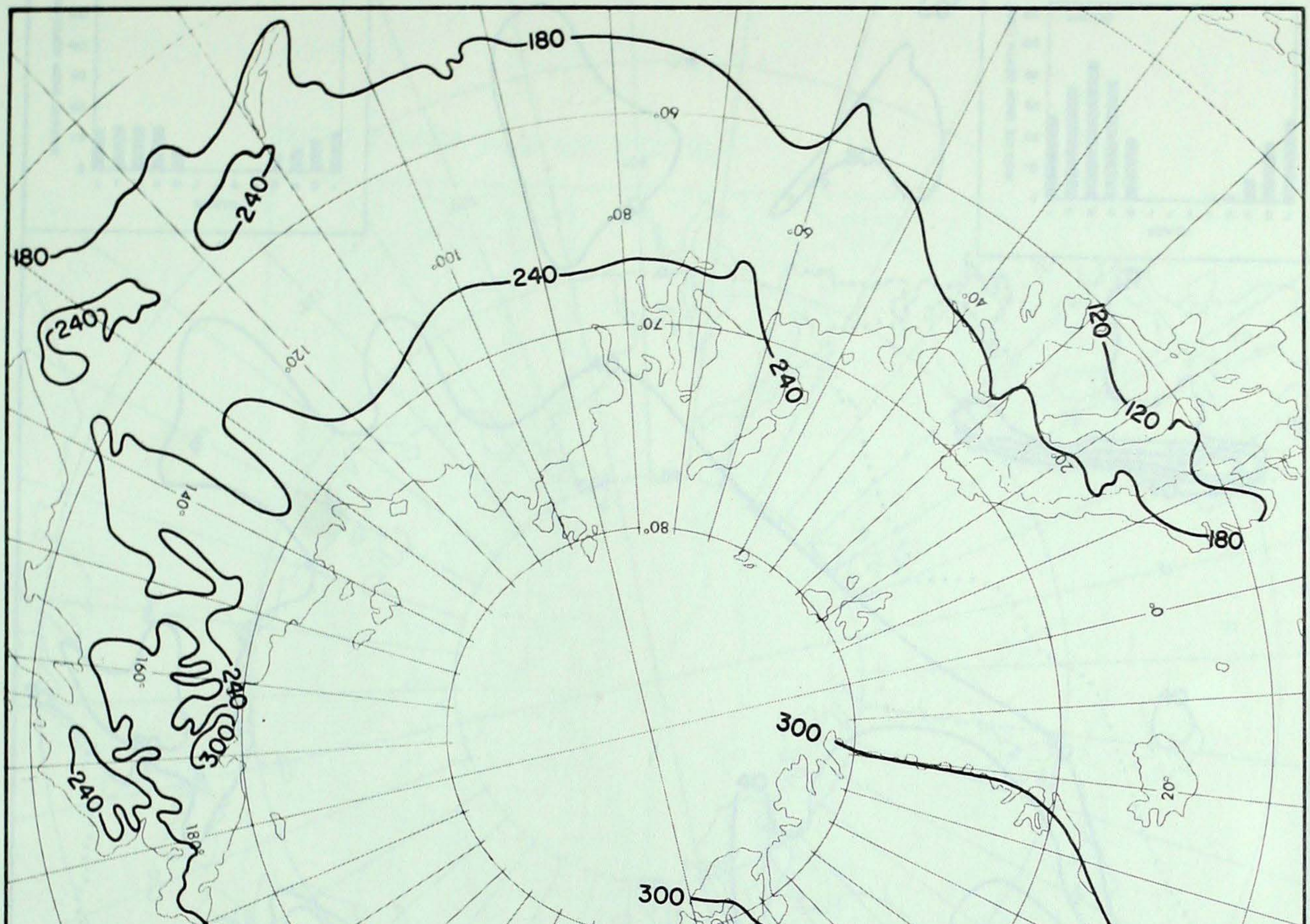


FIGURE 15 Mean annual number of days with snow cover

FIGURE 16 Mean depth of late winter snow cover (cms) and annual regime (period 20-30 years during 1931-1960). Note - Dotted line shows average extent of sea ice in April

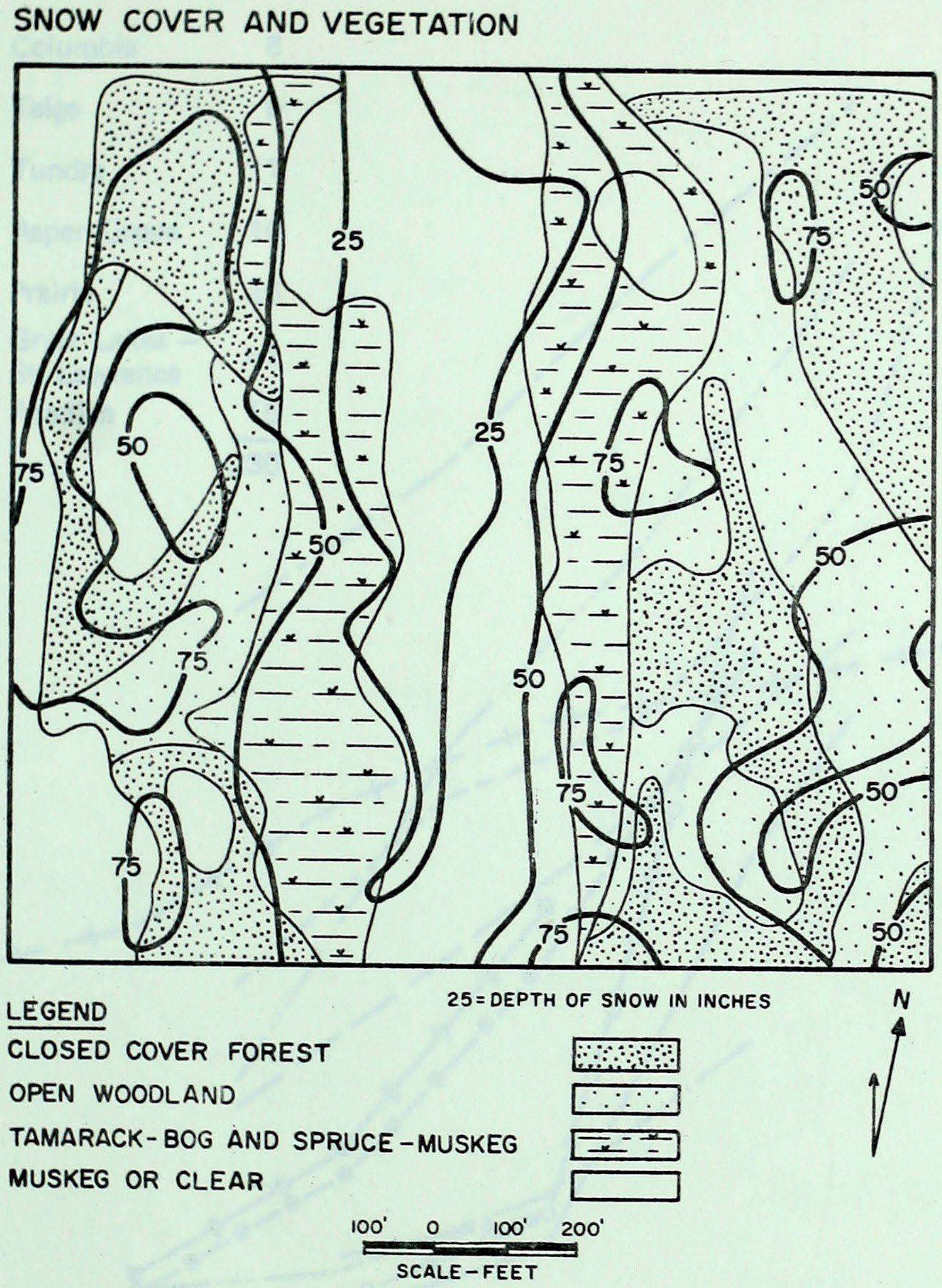


FIGURE 17 Depth of snow as found within different types of vegetation (after Adams and Findlay)

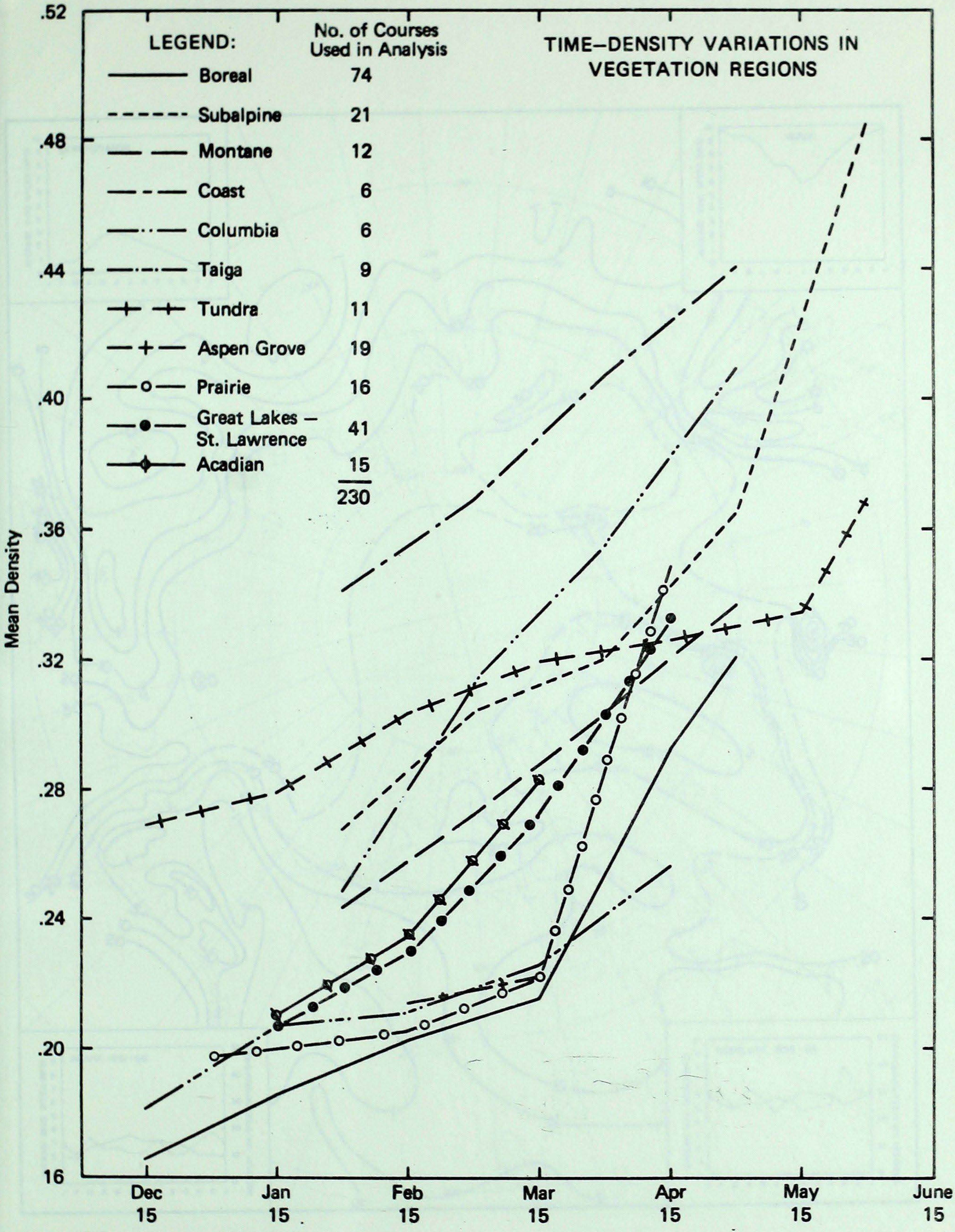


FIGURE 18 Temporal variations of snow density in Canadian vegetation regions (after Findlay and McKay 1972)

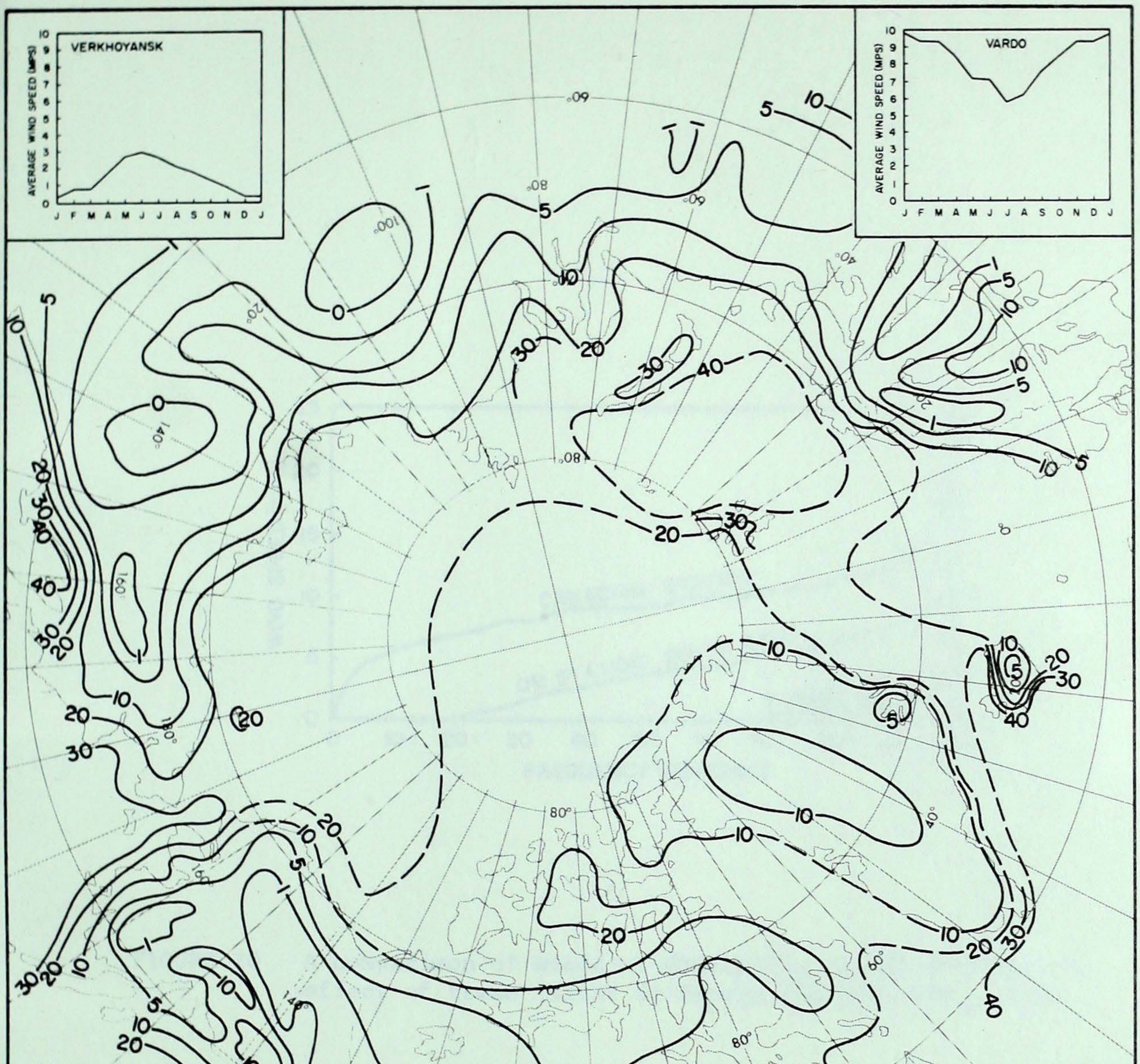


FIGURE 19 Mean percentage of winds over 11 mps (24 mph), December–February, and annual wind regime (portion outside Canada after Hastings, 1961)

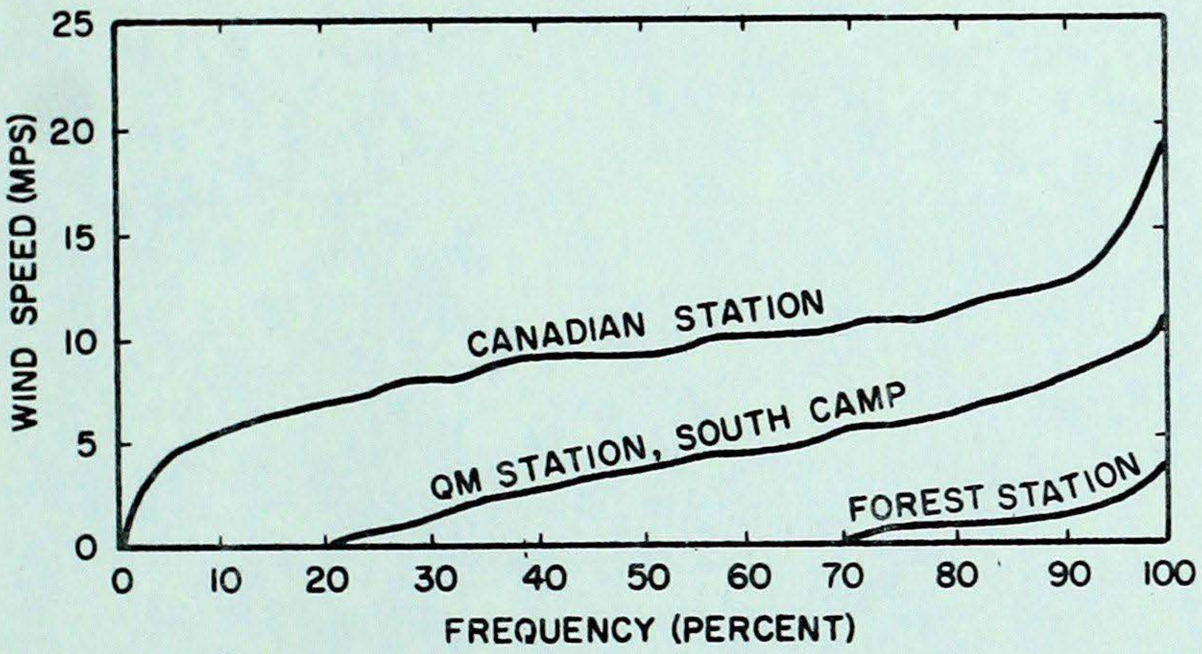


FIGURE 20 A comparison of winds at Churchill, Canada showing the effect of trees (after de Percin and Falkowski, 1956)