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STUDY OF CLIMATIC CHANGE AND ITS IMPLICATIONS FOR NORTHERN PIPELINES PHASE I

C. Burn[1], B.E. Ryden[2], M.W. Smith[1], P.J. Williams[1]

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RESUME

ETUDE DU CHANGEMENT CLIMATIQUE ET DE SON IMPLICATION SUR LES PIPELINES DANS LE NORD

Des études ont montré qu'il y a eu des changements climatiques suffisamment importants dans le Yukon au cours des derniers siècles et décades, et durant la période post-glaciaire pour causer des modifications importantes dans le distribution du sol gelé. Des changements dans les conditions du sol en surface, ainsi que des caractéristiques hydrologiques du sol et d'autres conditions, provoquent des modifications du régime thermique du sol qui peuvent excéder celles causées par les variations climatiques. Des modèles sont en cours de développement pour prédire les modifications du régime thermique du sol qui sont susceptibles de se produire dans les prochaines décades. Ces modèles essaient de définir l'importance relative des effets de surface, des effets sous terrains et des effets atmosphériques. Il est nécessaire d'effectuer une étude compréhensive de ces effets lorsque la planification géotechnique d'un pipeline est interrelié aux conditions thermiques du sol.

Study of Climatic Change and Its Implications for Northern Pipelines Phase I

By

C. Burn, B.E. Ryden, M.W. Smith, P.J. Williams

FINAL REPORT

Study of Climatic Change and its Implications for Northern Pipelines Phase I

to the

Department of Energy, Mines and Resources
Earth Physics Branch

By

C. Burn, B.E. Ryden, M.W. Smith, P.J. Williams

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ABSTRACT

STUDY OF CLIMATIC CHANGE AND ITS IMPLICATIONS FOR NORTHERN PIPELINES

Studies based on the Yukon show that changes in atmospheric climate have occurred over recent decades and centuries, as well as through post-glacial time, of a magnitude sufficient to cause major modifications in the distribution of frozen ground. Changes in ground surface conditions, as well as in soil hydrological and other conditions, cause changes in ground thermal regime which may exceed those due to change of atmospheric climate. Models are being developed for the prediction of ground thermal regime modifications which may occur in the coming decades. The models seek to define the relative importance of ground surface and sub-surface, and of atmospheric, effects. Comprehensive studies of these effects are necessary where geotechnical designs for pipelines are closely related to thermal conditions in the ground.

PREFACE

This report describes an examination of the effect of climatic change on ground thermal regime in the Yukon. The research is prompted by concern that changes of the climate, of the kind well-documented elsewhere in the world, could necessitate significant modification of geotechnical designs for pipelines and other structures. The work involves several distinct thrusts and is being carried out by a team which also prepared the chapters of this report: Dr. M.W. Smith, Dr. B.E. Rydén, Christopher Burn (graduate research assistant), Dan Riseborough and Alan Dufour (undergraduate research assistants) and the undersigned. All are associated with the Geotechnical Science Laboratories; Dr. Rydén, on leave from the University of Sweden, Uppsala, is a consultant to the project. The work, which is being continued, illustrates the importance of a multi-disciplinary approach. It brings together the experience of the members of the team in climatology, microclimatology, statistical analysis, soil thermodynamics and geotechnical considerations.

P.J. Williams

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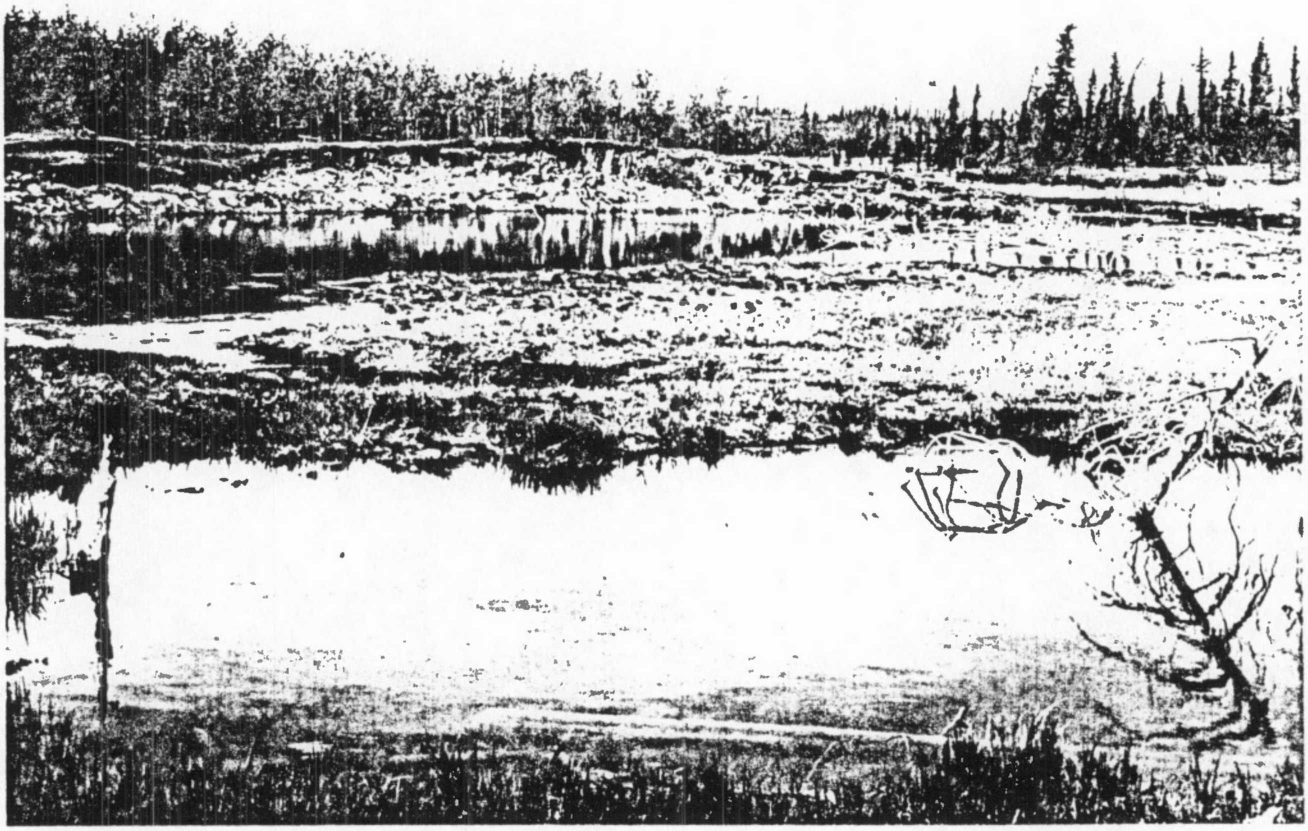

Plate 1 Thermokarst near Whitehorse
Melting of ice in the ground causes subsidence
(see also Pl.2).

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CHAPTER 1

CLIMATIC CHANGE AND GROUND THERMAL REGIME

Introduction: Geotechnical Implications

Although designs for major northern pipelines are not finalised, it appears that such designs will be matched closely to the ground thermal regime. If this regime were disturbed by natural causes, then designs based on the assumption of a stable permafrost environment could require modification. It becomes important, therefore, to attempt some prediction of the nature, rate and magnitude of ground thermal changes that might occur within the lifetime of a pipeline. The present study involves the natural environment. The thermal regime around a pipeline will depend on the natural conditions but will also be modified by the pipeline.

1.1 Climate, Microclimate and Permafrost Interaction

Changes in the ground thermal regime, and the thickness and extent of permafrost, may result from changes in climate or local conditions.

Changes in the local surface energy regime (i.e. the microclimate) can occur, for example, as a result of fire, changes in snow cover, etc. and can result in degradation or aggradation of permafrost. Large-scale climatic warming (or cooling) also has implications for the stability of permafrost conditions, although this has been generally ignored in northern geotechnical considerations. However, a warming trend could be quite significant in areas of discontinuous permafrost, for as the mean annual air temperature rises some permafrost at the southern limit could disappear and ground ice would melt. Thie (1974) has reported on the general melting and retreat of permafrost over the last century or so in Manitoba, and he believes that climatic warming has played a significant role.

Regional permafrost distribution is a function of climate, whereas the detailed local distribution is determined by micro-climatic conditions. Wide variations in ground thermal conditions are known to occur within a small area of uniform climate (e.g. Smith 1975a). In areas where mean ground temperatures are close to 0°C (discontinuous permafrost) local factors can determine whether permafrost is present or not. The specific effect of any climatic change on the ground thermal regime (and hence permafrost), then, will be modulated by local microclimatic conditions. Prediction of such effects is not necessarily simple or straightforward since variations in climatic conditions can be expected to invoke a range of responses in the ground thermal regime, due to the variety of local conditions. Thus, in addition to documenting the nature of climatic change (from weather records and proxy data), it is necessary to investigate the interactions between climate, microclimate and ground thermal conditions.

The work described in this report has several thrusts. Evidence concerning the climate in the past in the Yukon is examined. A brief analysis of the general atmospheric climate of the Yukon is given together with comments on the significance of relatively recent changes in atmospheric circulation. A detailed study of thermokarst (terrain formed by melting of ice in permafrost) emphasizes the effects of change of surface conditions; these effects are compared to those due to atmospheric climatic changes. Finally a predictive model is examined which seeks to take into account the significant factors, external to and within the ground, likely to modify the distribution of permafrost.

CHAPTER 2

THE PAST CLIMATE OF THE YUKON

Introduction

The identification of past climatic trends is a first step in the prediction of environmental conditions. Four aspects are considered in this section: (1) An introductory review of literature on the Holocene climatic history of this region. (2) An analysis of the meteorological records for the Yukon. (3) An examination of the spatial distribution of climatic fluctuations. (4) The relationship of snowfall and temperature.

2.1 Holocene Climatic History

The changing environmental conditions of the past 20,000 years have been reconstructed in the Yukon from three principal sources. For a continuous record, palynological results are used, which provide a general, coarse indication of vegetation history. Parts of the Yukon and much of Alaska were ice free in the last glaciation and provided *refugia* for several species; continuous pollen sequences have been found to date from pre-40,000 BP. Additionally, the fluctuation of glaciers in the St. Elias mountains has been reconstructed, however the response of individual glaciers to environmental fluctuation is not well understood. The mass balance of a glacier responds to changes in both winter snowfall and summer temperature, but simultaneous changes in these variables confuse interpretation. A third method is provided by dendrochronology. Such studies have not only involved tree ring analyses, but also tree line fluctuations, where evidence of fossil tree lines is available.

Although Clague and Rampton (1982) have recently documented the former shore lines of neo-glacial lake Alsek, there is little other information on either lake level fluctuations or the sedimentary record of lakes in the Yukon.

2.1.1 Palynology

The absence of Picea (spruce) from northwest North America from 30,000 to 11,500 BP is taken by Hopkins et al (1981) to indicate a very dry climate in this region during the last glaciation. Populus balsinifera (cottonwood) species survived in Beringia during this time, indicating a climate some 5° or 6°C cooler than at present. Rampton (1971) indicates a temperature depression from current values of over 12°F (6.6°C) for the period 27,000 to 10,000 BP from an analysis of pond sediments in the Snag-Klutan area of the South-West Yukon (Fig. 2.1).

Coincident with the recession of the Laurentide and Cordilleran ice sheets, a rise in temperature by 4°F

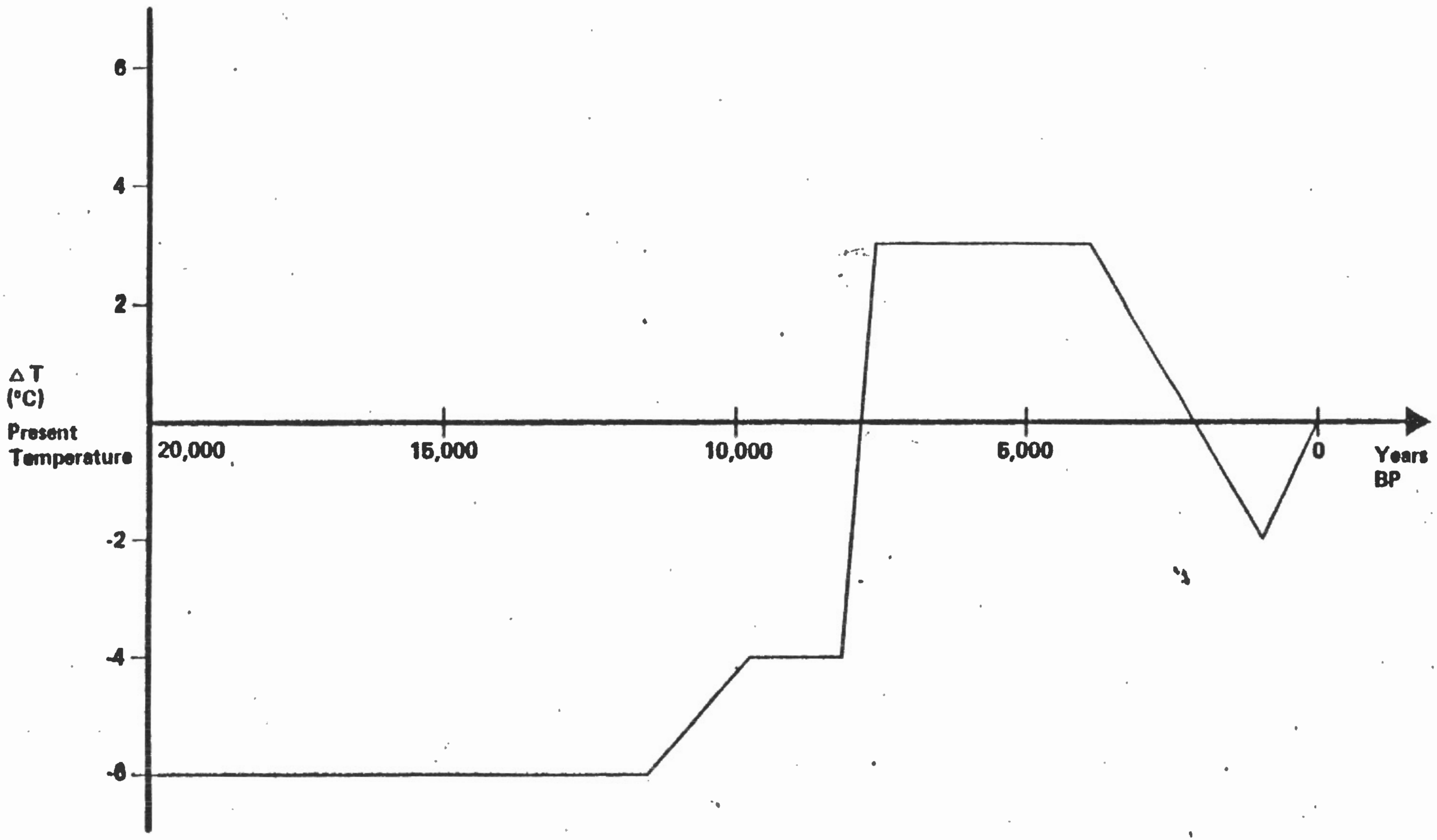


FIGURE 2.1
Holocene temperature changes in the Yukon reconstructed from pollen analysis (from Rampton 1971 and 1973, Ritchie and Hare, 1971, Hopkins, Smith and Matthews, 1981, and Birks, 1980).

(2.2°C) is postulated by Rampton (op cit), with the invasion of Populus sueviolata (poplar) from the south between 10,000 and 8,000 BP. The period 8,000 to 4,000 BP, is known as the hypsithermal period, and is agreed to be the warmest period of the past 10,000 years. Ritchie and Hare (1971) first suggested that this period may have been up to 5°C warmer than present climates, but Rampton (1973) disputes this, and feels that 1° or 2°C is a more appropriate figure (cf. Fig. 2.1). Picea is not traced in western Alaska until 5,300 BP, although Alnus (alder) appears in north Alaska around 6,000 BP.

In the latter half of the hypsithermal, a shift towards greater precipitation is noted by Hopkins et al (op cit), with an increase in peat accumulation. Temperatures after the hypsithermal dropped by about 2°C. However, Birks (1980) indicates that since 1220 14C BP there has been a considerable amelioration of climate in the southern Yukon, from examination of pollen assemblages close to the Klutan glacier.

Pollen data provide only coarse reference for palaeoclimatic reconstruction. Not only do species respond to fluctuation in several climatic parameters, but also pollen rain may be advected from other areas. Fig. 2.1 provides a coarse reconstruction of the Holocene climatic changes inferred from pollen analysis.

2.1.2 Glacial Evidence

Denton and Karlen (1973) found the two principal intervals of glacial expansion in the Yukon during the Holocene to be the cool period after the hypsithermal, for approximately 900 years after

3300 BP, and the 'Little Ice Age' of recent times from about 460 BP to the later half of the nineteenth century. Periods of recession were detected as 6175 to 5975 BP, 4030 to 3300 BP, 2400 to 1250 BP and 1050 to 460 BP. From this record, Denton and Karlen (op.cit.) note a recurrence of glacial activity every 2500 years, with a recent peak at 250 BP. Although there is evidence of some local glaciers extending to their Holocene limit during the Little Ice Age, (eg. Clague and Rampton, 1982), it does not appear that neo-glacial advances were as prolific in the Yukon as in other parts of the Cordillera.

The glacial chronology is not yet well established, and is of little use in an attempt at palaeoclimatic reconstruction.

2.1.3 Dendrochronology

Information about past climates derived from trees comes from two sources. Evidence of former treelines higher than at present is used by assuming a constant lapse rate over time, to infer the temperature at the fossil treeline. The climate is dated through the ^{14}C content of the wood. Rampton (1971) notes several shifts in the post-hypsithermal era that are not detectable in the pollen record, but are indicated by old tree lines in the Klutan area. In particular a departure of over +1^{o}C from present values (1970's) is noted for a period around 1000 BP and 7000 BP.

However, the principal thrust of dendroclimatology is through analysis of individual tree rings Fritts (1976) supplies a full discussion and appraisal of the technique. Essentially, dendroclimatology is useful where a single limiting parameter for tree growth is found. Jacoby and Cook (1981) indicate that, of several meteorological variables, June and July temperatures correlate best with the tree ring data from a site 125 km north of Dawson, Fig. 2.2. The variance explained by temperature in the chronology is not high ($r^2 = 0.36$), so it is suggested that only qualitative conclusions are drawn from the series, which extends back to 1550 AD.

The small ring width indices of the mid-19th century appear to correspond to a cold period documented elsewhere (Neatby, 1970), with particularly cold summer temperatures. Fluctuations in ring width index appear clearly in this record, but samples from Spruce Creek in the British mountains of the North Yukon (fig. 2.3) do not show such distinct fluctuation (Cropper and Fritts, 1981).

The difference between the near-Dawson chronology (fig. 2.2) and the Spruce Creek chronology is compatible with the results, discussed later, of an analysis of current Yukon climatic records. The North coast record does not exhibit climatic fluctuations that are synchronous with fluctuations in the southern Yukon. The fluctuations detected by tree growth provide records of annual temperature and precipitation. There does not appear to be much lag from the conditions of the previous growing season in the chronologies discussed here.

A principal problem with the work reported in the literature is an absence of examination of trees from sites close to meteor-

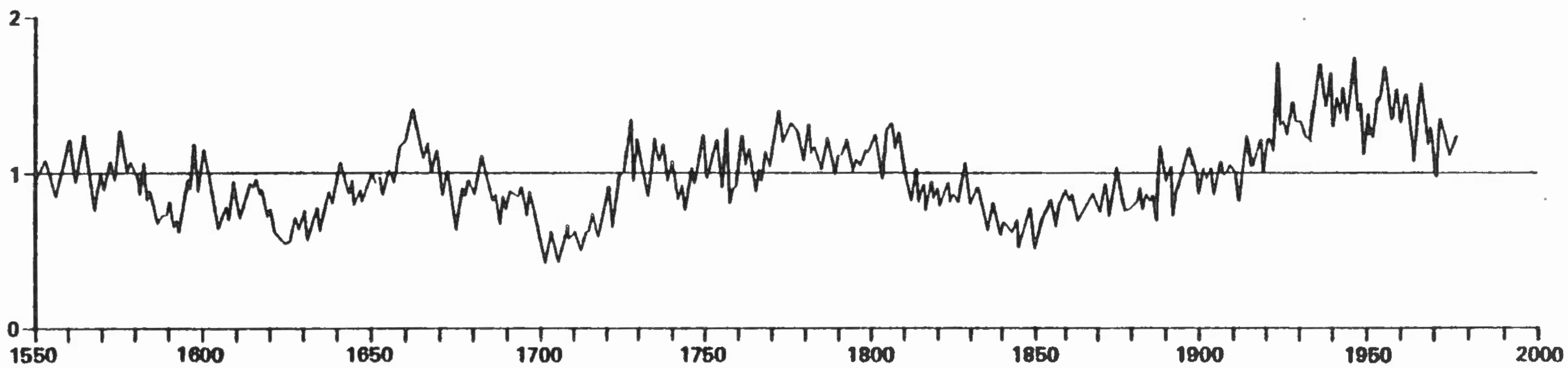


FIGURE 2.2
Tree ring width data; higher values represent faster growth. From site 125 km North of Dawson (from Jacoby and Cooke, 1981).

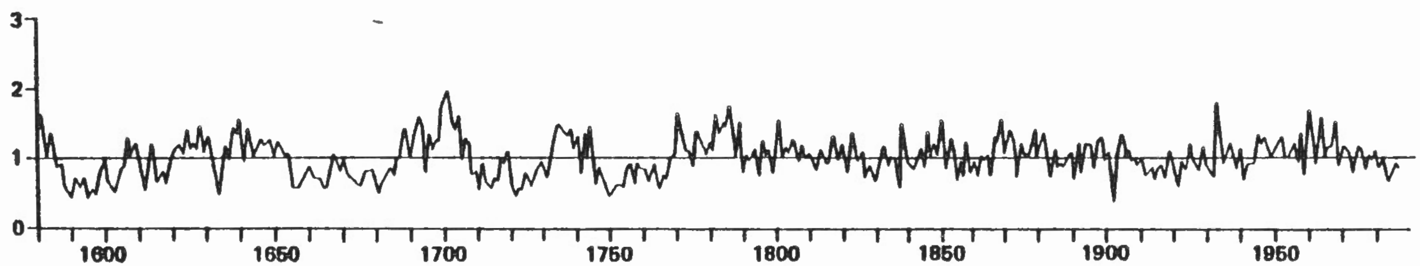


FIGURE 2.3
Tree ring width data for Spruce Creek (from Copper and Fritz, 1981).

ological stations, which would give an opportunity for calibration. There is also inadequate consideration of microclimatic and hydrologic influences on tree growth. This is a topic for later study in the project.

Figure 2.4 is an attempt at a generalised assessment of the changing temperature of the Yukon, with information drawn from the sources noted above.

2.2 Analysis of Meteorological Records

2.2.1 Data Preparation

Data for thirteen climatic stations in the Yukon (fig. 2.5 and Tables 1a,1b) have been analysed.* The earliest record available is from 1899 (at Dawson). The data refer to mean annual, mean winter (December - March), mean January and mean July temperatures, and total annual, winter (November - April), and January snowfall. Where monthly data are missing from the record they have been interpolated to be the median of the enclosing six years' records for the same month. If more than five months records are missing from any one calendar year then this year has been ignored. For the purposes of this report, the climatic year begins in September and ends in August, taking the value of the second half of the year - e.g. the climatic year September 1948 to August 1949 is regarded as the year 1949. The length and quality of the records from each station are shown in Tables 2.1a and 2.1b.

The data have been smoothed to recognize underlying trends, and to display these graphically. An analysis of variance has been carried out on the smoothed data.

*Appreciation is expressed to the Atmospheric Environment Service, Environment Canada, for generous assistance with data compilation.

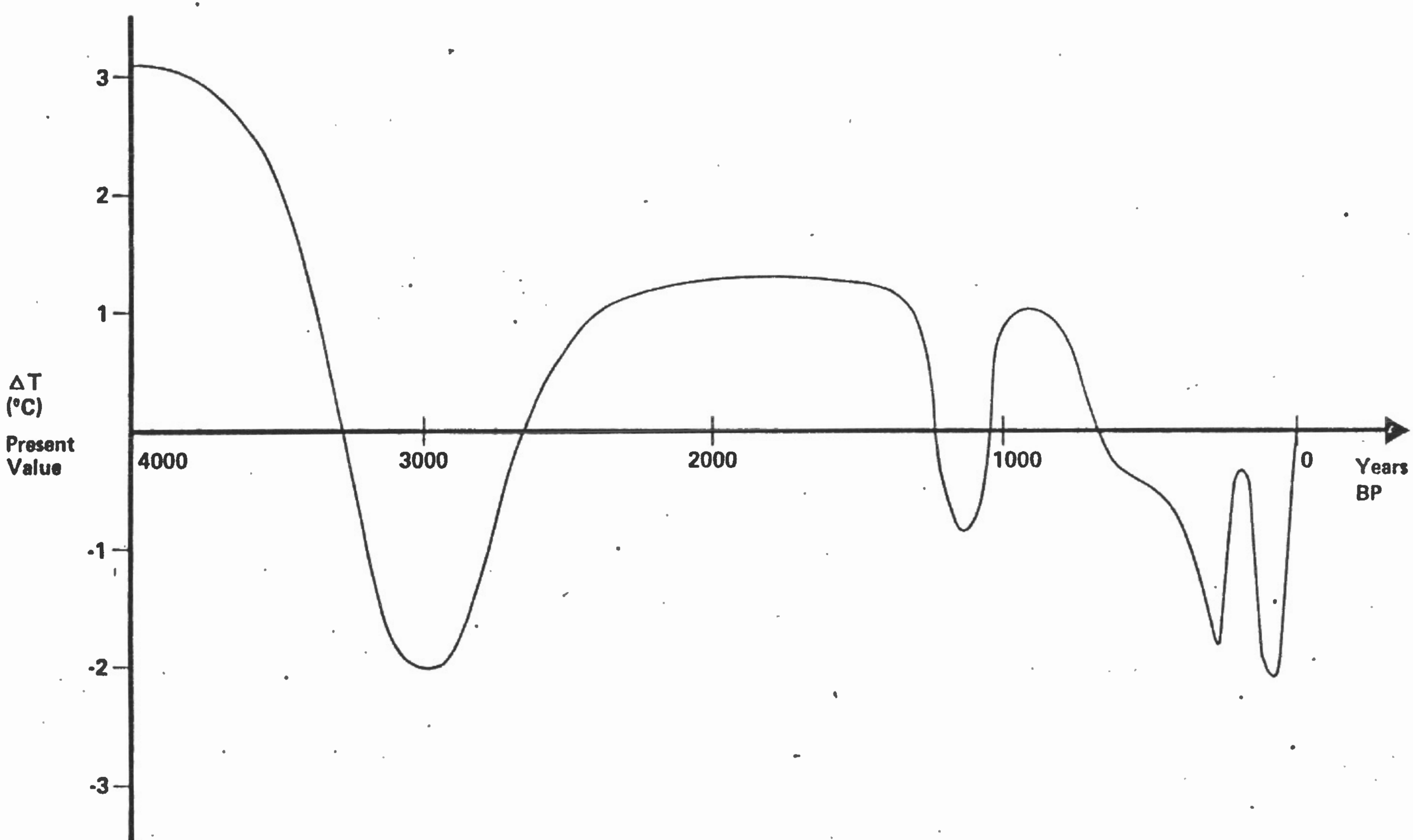


FIGURE 2.4
A generalized assessment of post-hypsithermal Yukon temperatures.

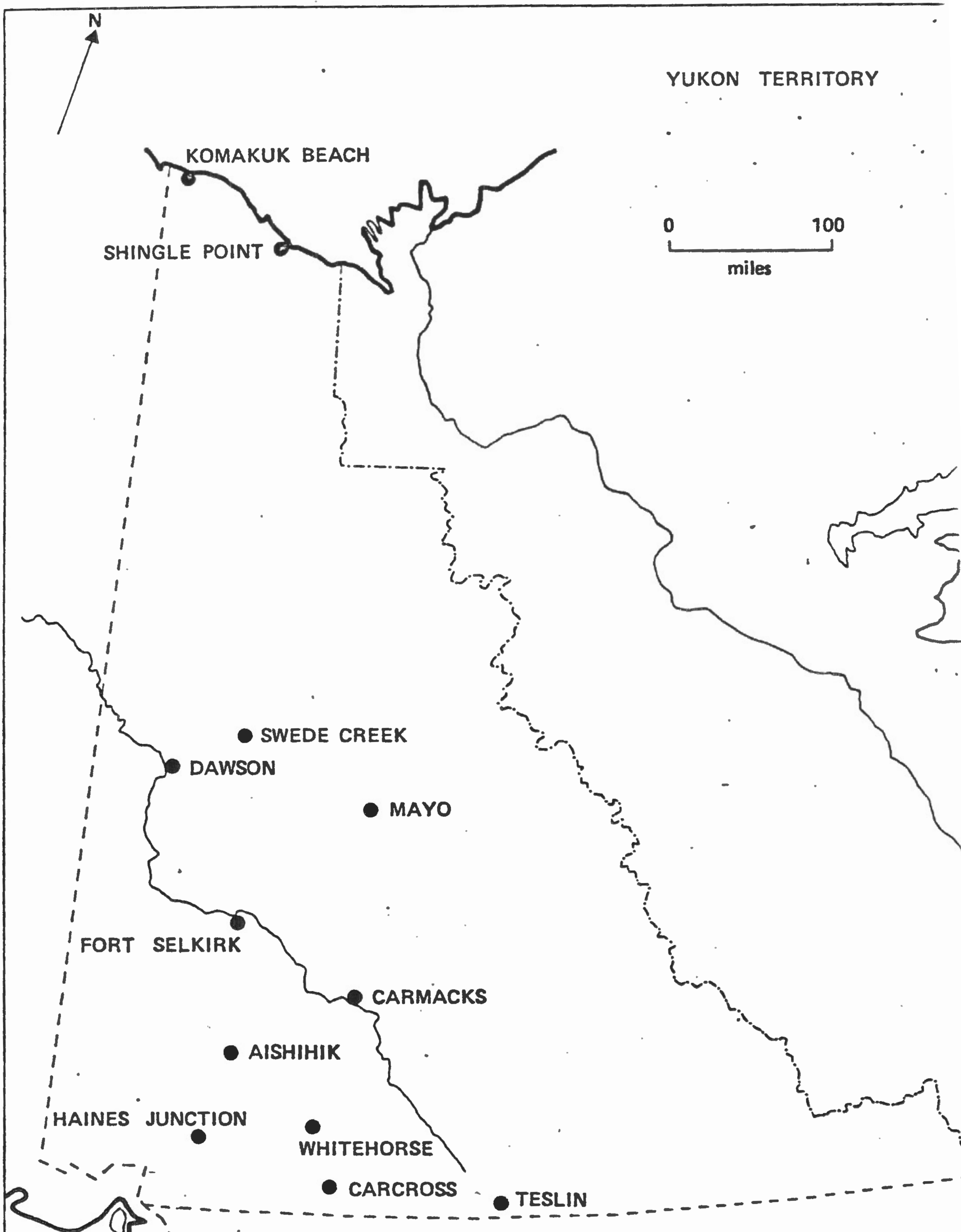


FIGURE 2.5
Location of Stations

Statistical Packages

The package programs used are the Scattergram and Pearson Corr of the SPSS library (Nie *et al*, 1975), and the P1M program of the BMDP library (Hartigan, 1981). Preparation of data for the programs has been in Fortran 77.

Units

All temperature data are in degrees Celsius (°C), while snowfall data are recorded in cm of accumulation throughout the winter.

2.2.2 Smoothing

The data series for mean annual temperature have been smoothed using a robust non-linear filter. The model followed in the smoothing is that:

data = signal + noise,

and in particular,

data = [long term trend] + [short term 'random' fluctuation]

Non-linear smoothing filters are preferred for three reasons. First, any linear regression implies *a priori* assumptions about the structure of the data. In an exploratory analysis such as this, such assumptions are undesirable. Second, the analysis is supposed to retain cycles or thresholds present in the data, which are explicitly of interest. Finally, linear methods are not resistant to extreme or outlying values - non-linear smoothing will not be unduly "swung" by one or two very large or very small values. A comprehensive discussion of exploratory smoothing is provided by McNeil (1976).

The smoothing function 3R is used here, taking running

Table 2.1a Length of Yukon mean annual temperature records.

STATION NAME	PERIOD OF DATA AVAILABILITY	YEAR WITH POOR* RECORD	YEARS MISSING+
Aishihik	1944-66	1	0
Carcross	1909-28	3	0
	1935-40,73-80	0	1
Carmarks	1964-80	1	0
Dawson	1899-78	2	3
Fort Selkirk	1954-80	2	0
Haines Junction	1944-80	1	0
Komakuk Beach	1961-80	1	0
Mayo Landing	1926-80	1	0
Shingle Point	1961-80	4	0
Swede Creek	1918-29	2	0
Teslin Airport	1943-80	3	0
Whitehorse Airport	1944-80	0	0
Whitehorse Riverdale	1959-80	0	0

* Six or more months of missing data.
\+ Missing from within period of observation.

Table 2.1b Length of Yukon snowfall records.

STATION NAME	PERIOD OF DATA AVAILABILITY	YEARS WITH POOR* RECORD	YEARS MISSING+
Aishihik	1944-66	1	0
Carcross	- -	- -	- -
Carmarks	1964-80	1	0
Dawson	1899-78	2	3
Fort Selkirk	1954-80	2	3
Haines Junction	1945-80	1	0
Komakuk Beach	1959-80	1	0
Mayo Landing	1926-80	1	0
Shingle Point	1961-80	4	0
Swede Creek	1919-28	2	0
Teslin Airport	1944-80	3	0
Whitehorse Airport	1942-80	0	0
Whitehorse Riverdale	1973-80	0	0

* Six or more months of missing data.
\+ Missing from within period of observation.

medians of 3 years' records and repeating the smoothing until the series is unaltered by repetition. This serves to create a smoothed series that consists entirely of original data points, and which has reached a final position as a result of the relations betwen the data points themselves, and not some arbitrary cut-off value imposed on the number of passes involved in the smoothing. End values are a problem with this procedure. One can either produce an artificial function to cater for them, or ignore them. The latter course is followed here.

The operation 3R (5R, 7R and 9R have also been used) is followed by the operation H, Hanning. This operation is a non-resistant smoothing operation, where the i^{th} data point in each series, x_i, is replaced by $\frac{1}{4}x_{i-1} + \frac{1}{2}x_i + \frac{1}{4}x_{i+1}$. This operation, repeated three times (HHH) makes the curve more comprehensible for interpretation. The smoothed curve is not altered greatly by the operations HHH, having achieved its principal position through 3R.

2.2.3 Analysis of variance

An analysis of variance inspects the residuals from a fitted curve in a raw data set, and relates the variance of the residuals to the variance of the raw data. It assumes that the residuals are distributed about the smoothed fit with mean 0. An interpretation of the method is presented by Erickson and Nosanchuk (1977, p. 235).

In the case of a linear fit, we calculate the residuals Y', where Y - (bX+a) = Y', for "raw" values Y. Applying this to the

Table 2.2 Statistics for smoothing operations 3RHHH on stations displayed.

TEMPERATURE

STATION	NUMBER OF PASSES	VARIANCE DUE TO RESIDUALS (%)	VARIANCE DUE TO SMOOTHED FIT (%)	MEAN OF RESIDUALS	MEAN OF DATA
Dawson	4	67.26	32.74	0.09	-4.93
Mayo	4	68.51	31.49	0.13	-3.79
SNOWFALL					
Dawson	4	61.6	38.40	-4.27	138.96
Whitehorse	4	76.59	23.41	-3.37	130.88

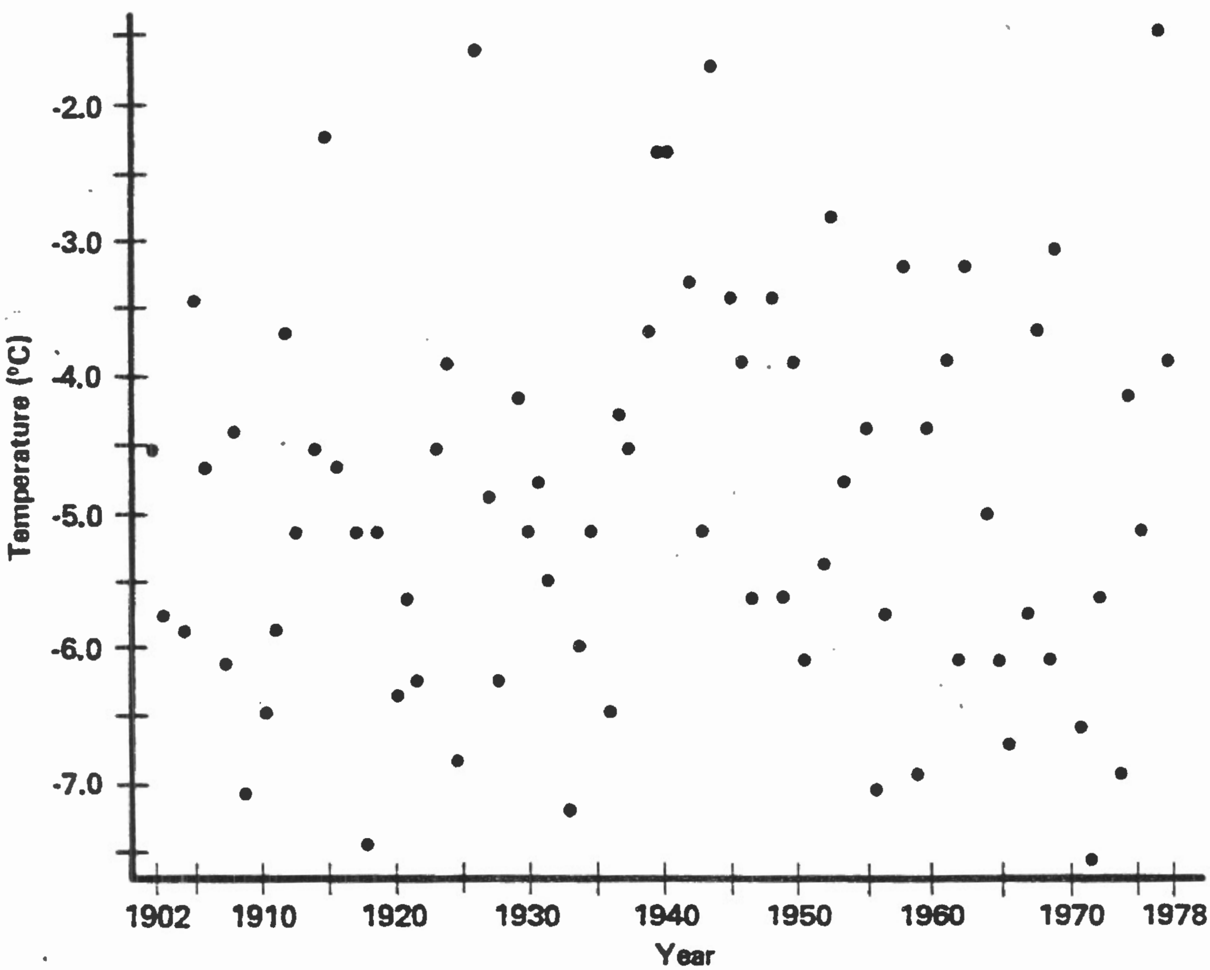


FIGURE 2.6
Mean annual temperatures by year for Dawson.

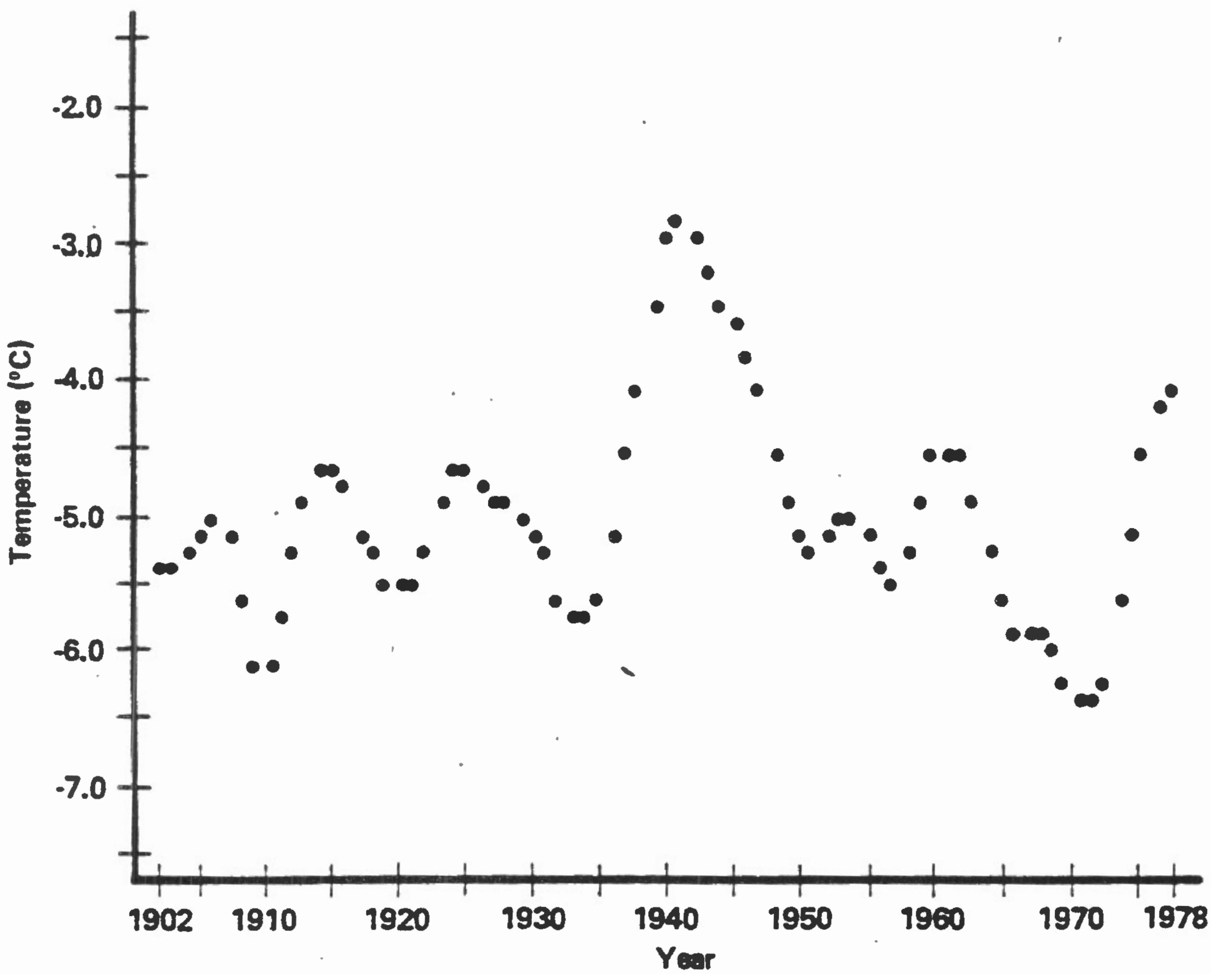


FIGURE 2.7
Data from Fig. 2.6 smoothed 3RHHH (see text).

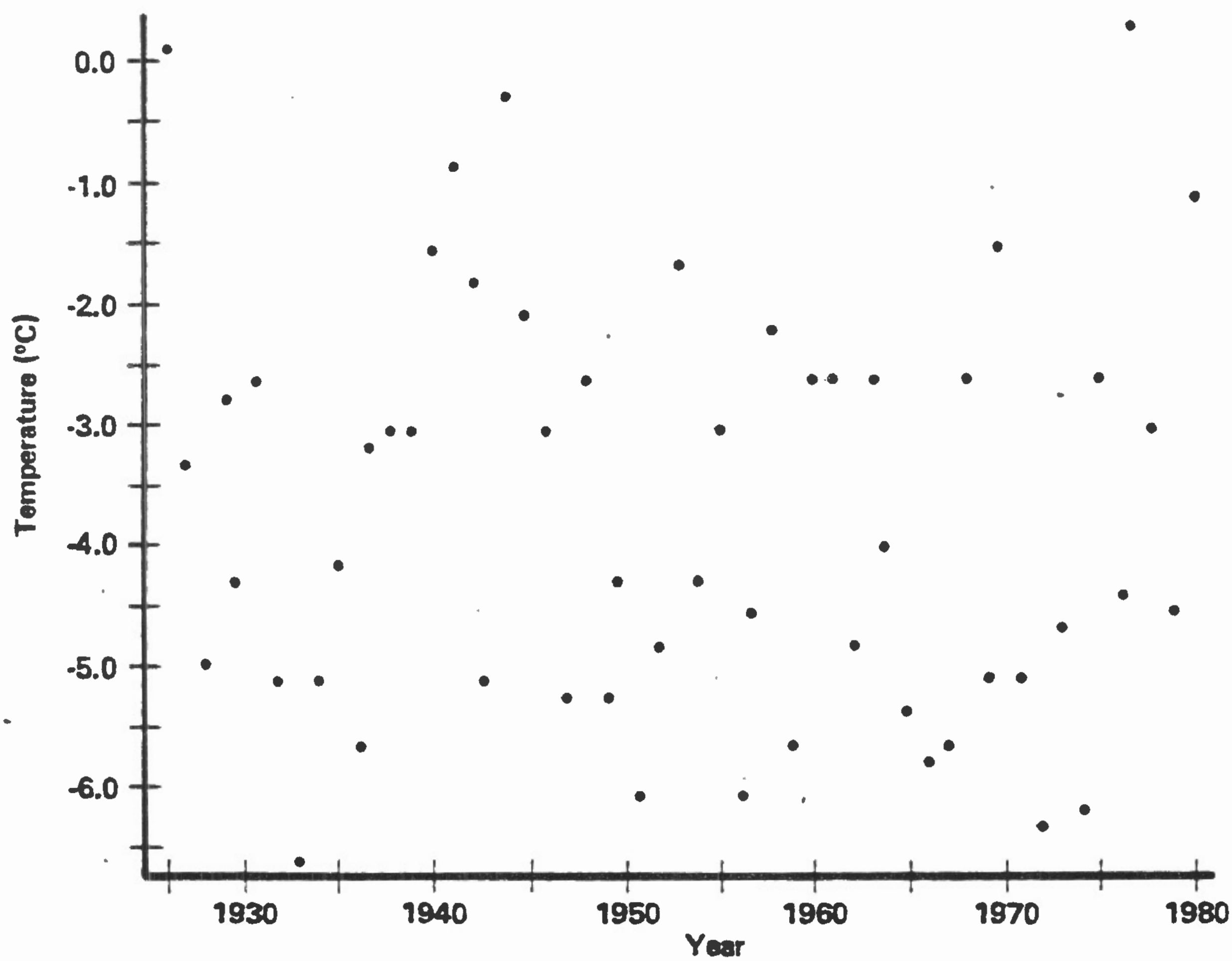


FIGURE 2.8
Mean annual temperatures for Mayo Landing.

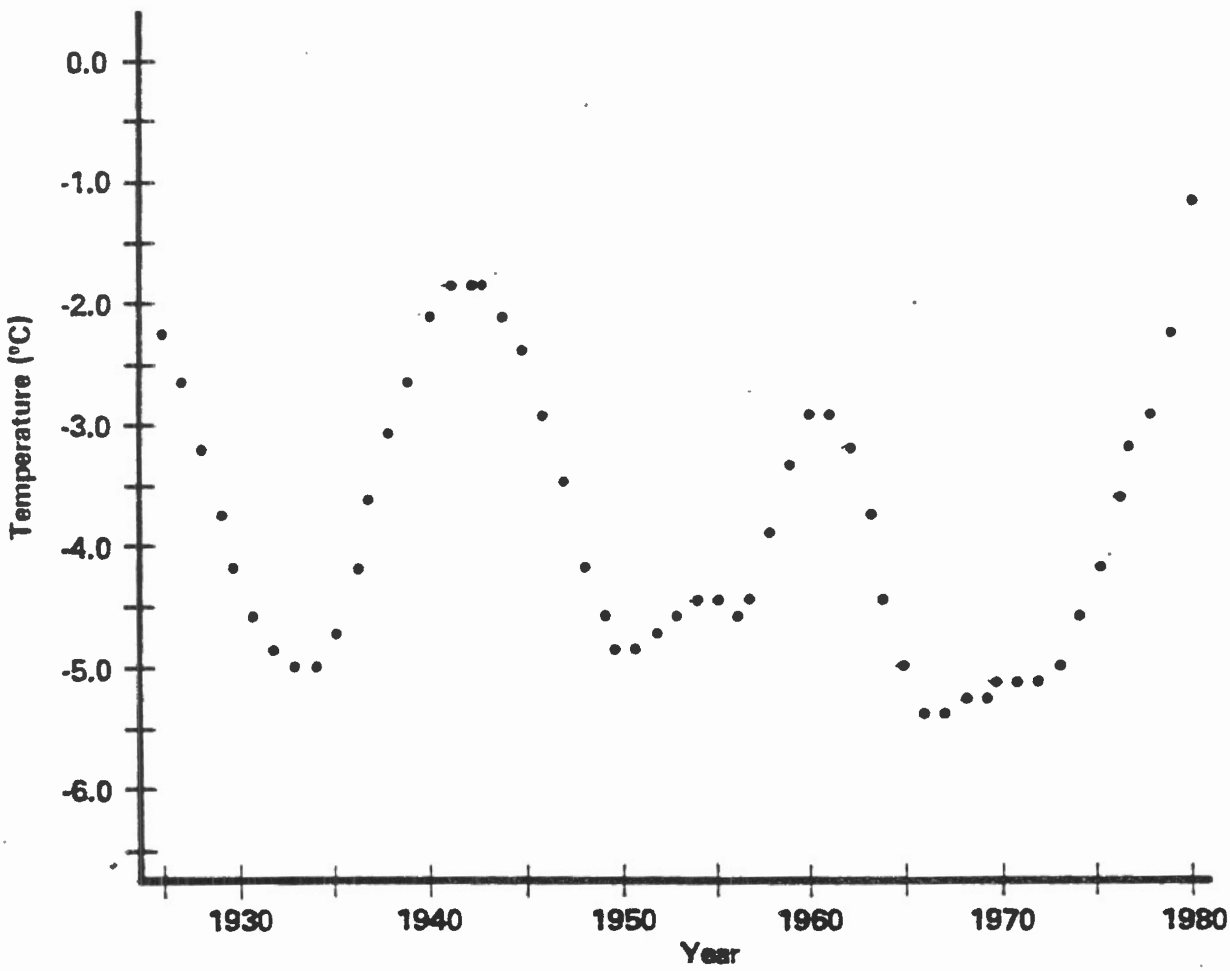


FIGURE 2.9
Data in Fig. 2.8 smoothed 3RHHH (see text).

smoothed curve, we calculate residuals Y', where

$$Y - (S(Y)) = Y',$$

S(Y) being the smoothed function of the series. Now, we have

$$\text{proportion of Y unexplained by } S(Y) = \frac{\text{variance } Y'}{\text{variance } Y}$$

Therefore, if the proportion explained by S(Y) is r^2,

$$r^2 = 1 - \frac{\text{variance } Y'}{\text{variance } Y}$$

2.2.4 Results

Raw and smoothed data from Dawson and Mayo (fig. 2.6 to 2.9) indicates how effectively the smoothing procedure tidies the data. However, the smoothing would be misleading if it accounted for little of the total variance. Inspection of the smoothing statistics (Table 2.2) indicates how much of the variance is preserved within the smoothed data; the residual means are not great, indicating that the analysis is valid.

The smoothed series for temperature from Dawson and Mayo (Figs. 2.7,2.9 both indicate that considerable oscillation in mean annual temperature has occurred during this century. The coolest period was the late 1960's and early 1970's, with temperatures at Dawson and Mayo more than 3.5°C cooler than at the warmest point since 1900. Before 1940, Dawson experienced two 12-year period temperature oscillations, but there does not appear to have been any observable trend at this time. Hamilton (1965) also noted the 1940's warming, but he used a non-resistant technique of data smoothing (running means of 8 years), which turned the data series into a pre-1940's warming trend, and obscured the cyclic oscillation. The pronounced difference in temperature in the 1940's period was also obscured, Hamilton giving a peak of 2°F (1.1°C) above the local trend, while 2.5°C is, perhaps, a better estimate. As noted elsewhere (e.g. Hechdt, 1981), there has been a noticeable global cooling trend since 1941. This cooling appears to have occurred in the Yukon as well.

Lengthening the smoothing filter dampens the amplitude of oscillation, and noticeably, alters the 1970's warming. The effect of, for example, a seven-year period as the basis for the smoothing is illustrated in Fig. 2.10.

Broadly speaking, we can see a cyclic pattern to the mean annual temperature, and a rise in the past decade to a level higher than at any other post-1945 period. However, if the current cycles continue, we would expect a cooling during the 1980's, of 2° to 3°C.

Smoothed snowfall series exhibit fluctuations of period approximately 14 years. The fluctuation for Whitehorse since 1960 and for Dawson over the years of the record (Fig. 2.11 to 2.14) appear in anti-phase with the fluctuations of mean annual temperature. In particular a marked 1970's decline in snowfall was simultaneous with the rise in temperature. The amplitude of oscillation appears to be of the order of 60 cm of snow over the year.

The interaction of snowfall and temperature is considered further later (section 2.4).

2.3 Spatial Distribution of Recorded Changes

The spatial heterogeneity of the climate in the Yukon was

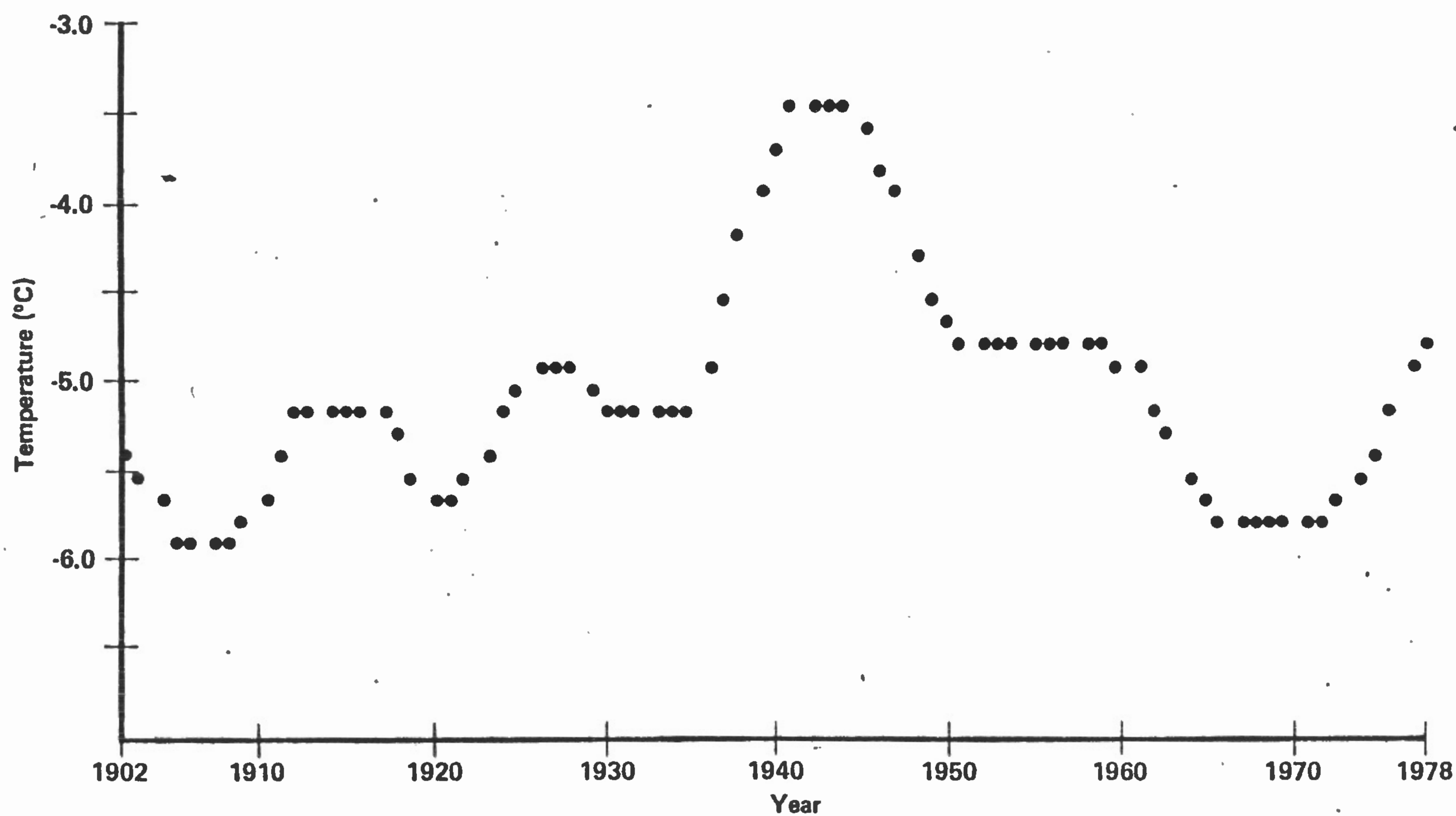


FIGURE 2.10
Data from Fig. 2.6, smoothed 7RHHH.

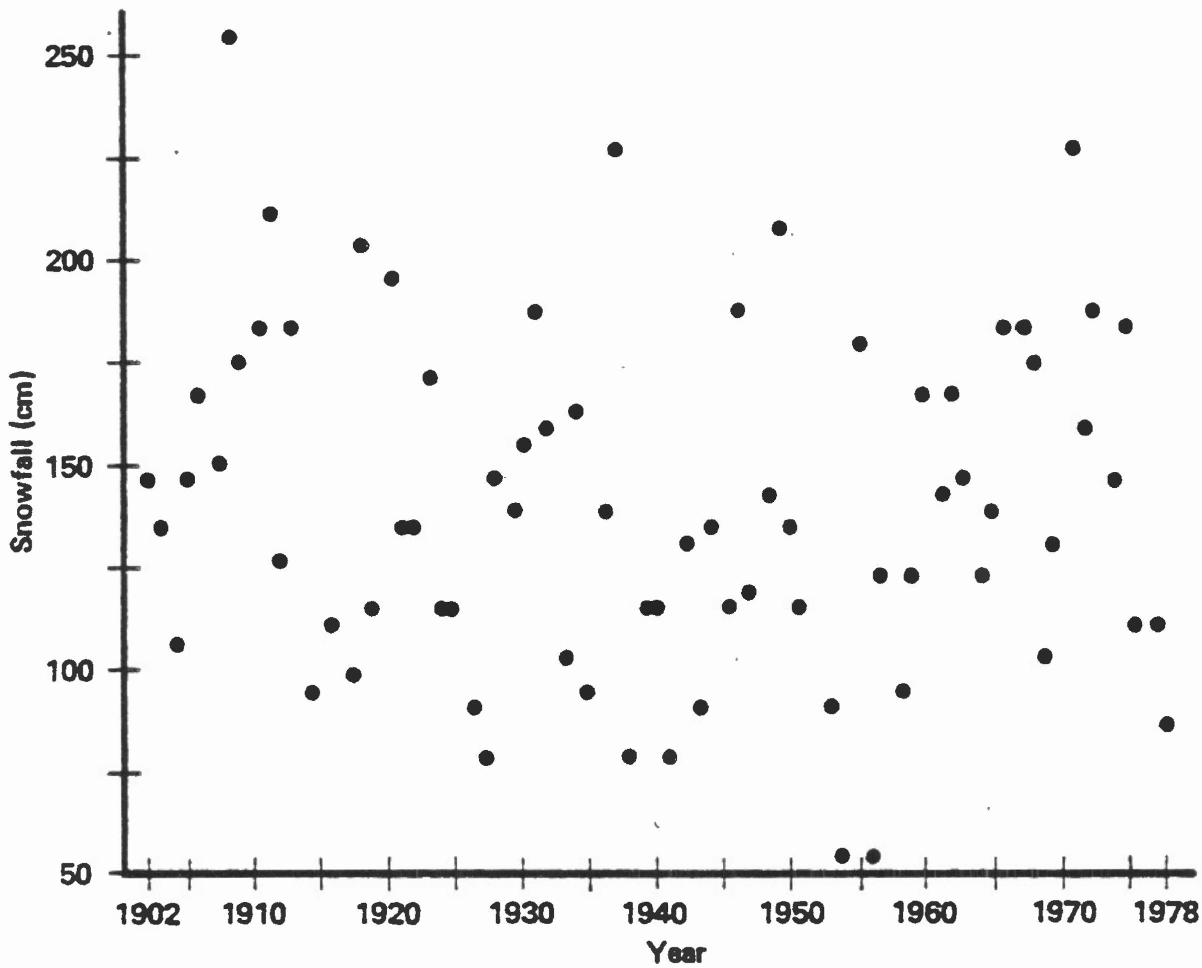


FIGURE 2.11
Total annual snowfall for Dawson.

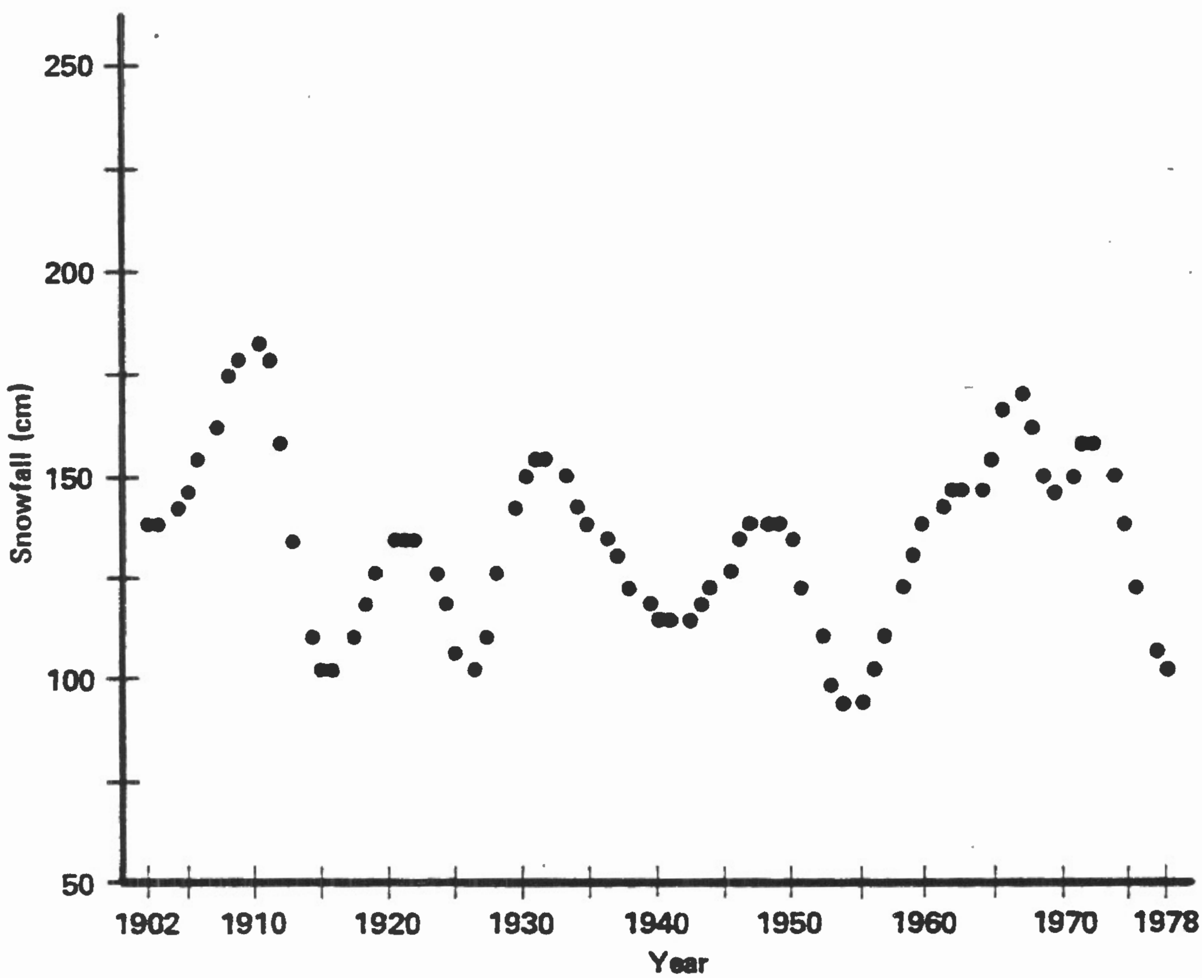


FIGURE 2.12
Data from Fig. 2.11, smoothed 3RHHH.

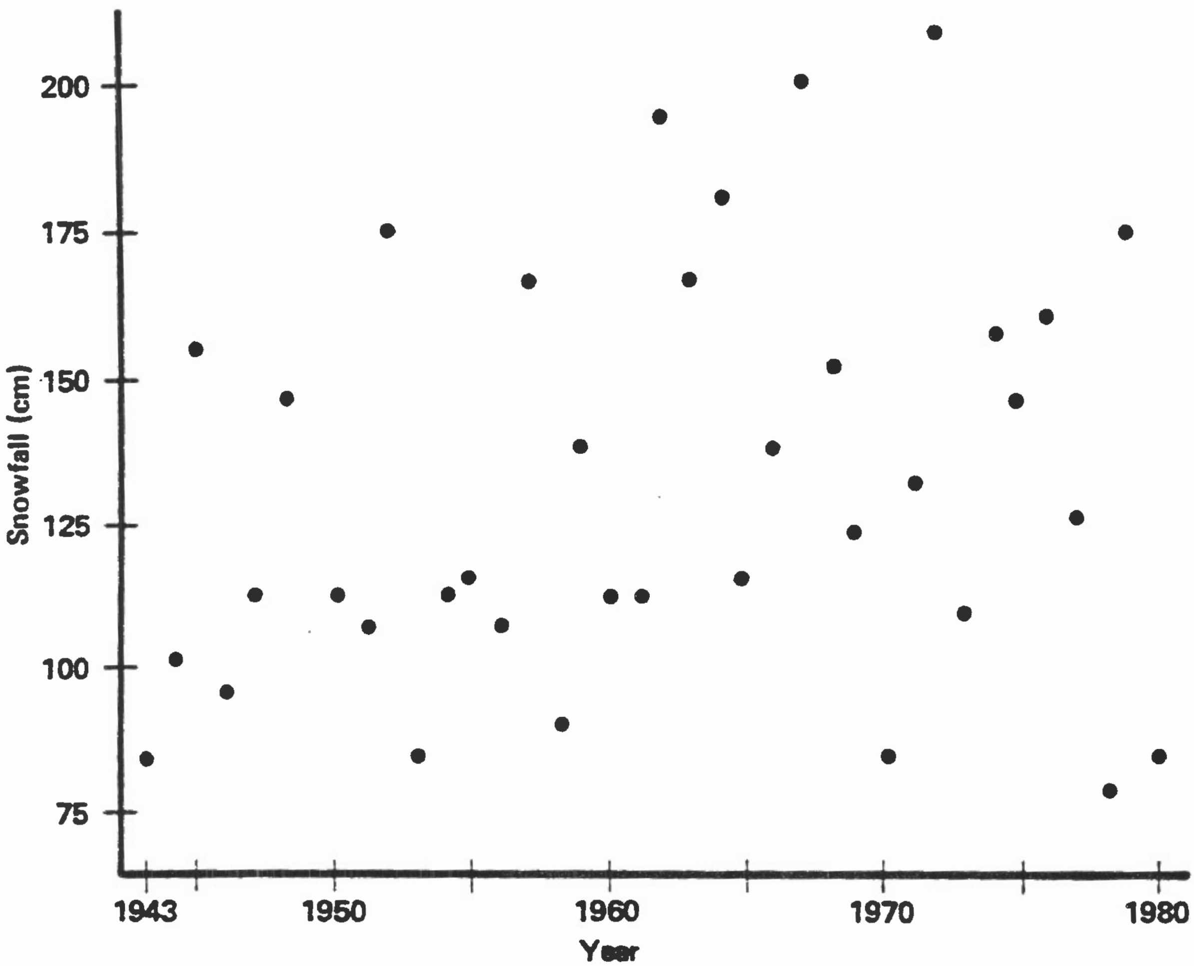


FIGURE 2.13
Total annual snowfall for Whitehorse.

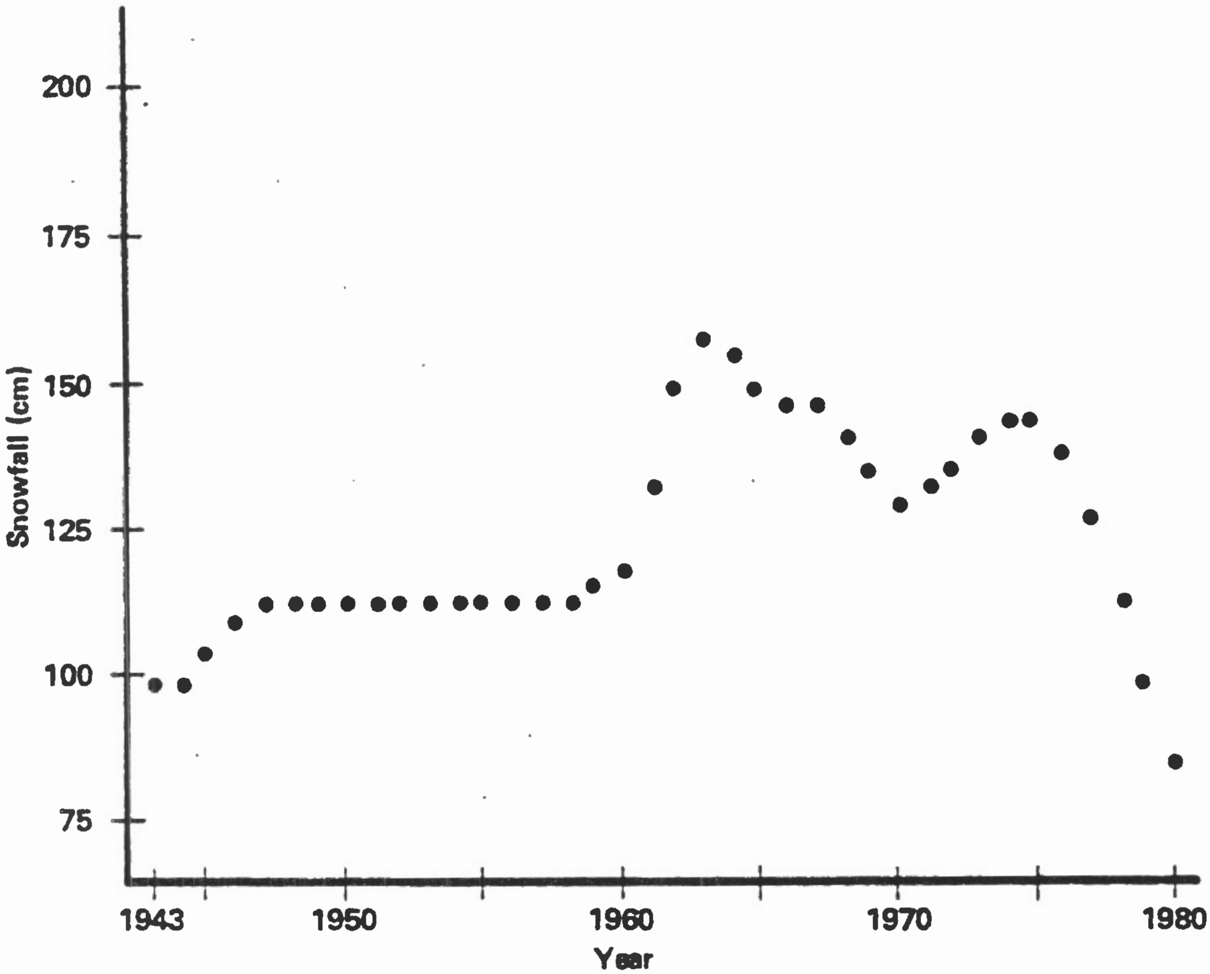


FIGURE 2.14
Data from Fig. 2.13, smoothed 3RHHH.

	Aishihik	Carcross	Carmacks	Dawson	Ft.Selkk.	Haines	Komakuk	Mayo	Shingle	Swede	Teslin
Aishihik	1.0000										
Carcross	-	-									
Carmacks	.9534,3	-	1.0000								
Dawson	.0775,22	-	.5406,15	1.0000							
Ft.Selkirk	-.2125,12	-	.5435,17	.2671,24	1.0000						
Haines Jn.	.0055,21	-	-.3401,17	-.0008,33	-.1273,26	1.0000					
Komakuk B.	.9067,6	-	.2064,17	-.2983,18	-.1551,20	.5069,20	1.0000				
Mayo Ln.	-.2022,22	-	.2510,17	.5422,53	.4552,26	.0913,35	-.3069,20	1.0000			
Shingle P.	.0137,6	-	.0540,17	-.1551,18	-.2924,20	.3156,20	.3441,19	-.3452,20	1.0000		
Swede Cr.	-	-	-	.5004,9	-	-	-	-	-	1.0000	
Teslin A.	.3387,22	-	.7142,15	.1883,34	.4469,24	.1593,33	.6025,18	.2461,34	-.3842,18	-	1.0000
Whitehorse: Airport	.2801,22	-	.5173,17	.2300,36	.7769,26	.2245,35	-.0126,20	.3442,38	-.3157,20	-	.6881,34
Riverdale	-	-	.1934,7	.5489,5	.7089,7	.6359,7	.0262,7	.6940,7	.0608,7	-	.7843,7

Whitehorse:	Airport	Riverdale
Airport	1.0000	
Riverdale	.8883,7	1.0000

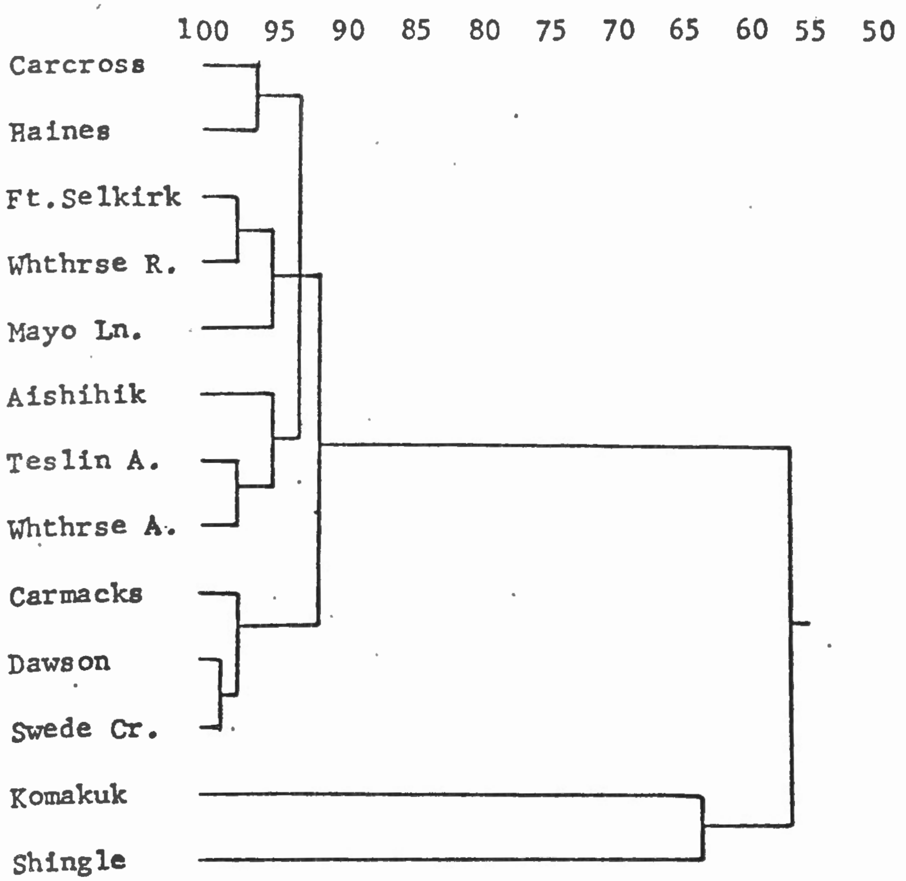
Table 2.3b Correlation coefficients and years of simultaneous record for total annual snowfall records from Yukon stations.

noted earlier in the dissimilarity of the Spruce Creek and near-Dawson dendrochronologies (Figs. 2.2 and 2.3). In the present study, a cross-correlation between records from the various stations has been carried out to identify regions with homogeneous climatic characteristics.

The records from the various stations have been grouped into clusters using the correlation coefficient as the measure of similarity between variables, and average distance between clusters (distance between the means) as the amalgamation criterion. A matrix of correlation coefficients is input to a BMDP package program (Hartigan 1981) to do this. Kendall (1980, Ch. 3) describes the clustering process in more detail. In the program, each station is initially considered to be a separate cluster; then the two most similar stations are joined to form a cluster. The amalgamation continues in a stepwise fashion joining stations or clusters of stations, until a single cluster is formed containing all the stations (Hartigan, 1981, p. 448).

2.3.1 Cluster Analysis

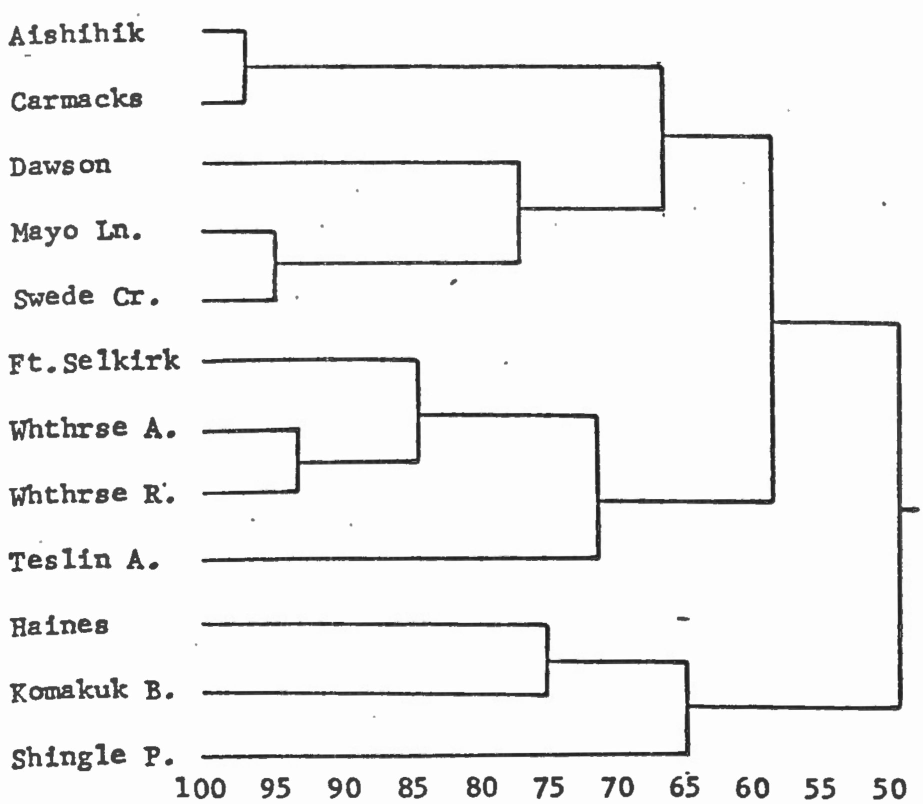
The cluster tree for mean annual temperature in the Yukon is presented in Fig. 2.15, and the correlation matrix in table 2.3a. Three principal groups of stations are evident. Aishihik has little overlapping record with some stations, and therefore was not incorporated into the routine; it is tentatively grouped with the cluster containing Mayo, since it loads most heavily on that station. Swede Creek was handled similarly. The station with longest record in each group is selected for further analysis.



Scale

50 - 54 $0 \leq r^2 < .1$
55 - 69 $.1 \leq r^2 < .2$
.
.
95 -100 $.9 \leq r^2 \leq 1.0$

FIGURE 2.15 Grouping of Mean Annual Temperatures. (Scaled)



Scale
as in fig.2.15

FIGURE 2.16 Grouping of Total Annual Snowfall. (Scaled)

Komakuk Beach and Shingle Point, on the Beaufort Sea coast, have been omitted from further analysis because of their low association with other groups or each other. Their location places them in the Arctic rather than the Boreal zone (Hare & Thomas 1979). However, since the correlation between these two stations is also low the microclimates of the stations appear dissimilar. These microclimates do not respond in the same way to climatic changes.

The clustering of stations by snowfall is not as well defined as that by mean annual temperature. The cluster diagram is presented in Fig. 2.16 and the correlation matrix in table 2.3b The Aishihik-Carmacks cluster is the densest, but the generating correlation coefficient is only based on three observations. Dawson and Whitehorse appear at the center of two looser groups. Again the Northern coastal stations are not closely linked to any others; the fact that Haines is grouped there testifies to both low strength of the clustering, but more importantly the locally variable nature of snowfall.

Indeed, micro- and meso-scale variables concerning climate have more effect on snowfall than temperature on at least two counts. First, the difficulties of using instrumentation that does not affect the environment are more pronounced; local turbulence and deposition conditions are created by snow measurement structures. Second, the distance from a source of moisture, in this case the ocean, and topographic wind barriers affect precipitation variables more than temperature, precipitation being dominantly an advected variable, with little local component.

The smoothed data from Haines and Whitehorse (not shown here)indicate that historic changes across the Yukon have been synchronous, since the correlation coefficients are high. However, the amplitude of oscillation has not been constant over space. Again, one may look to the reactions of microclimates to climatic change to help understand this situation.

Although annual temperature fluctuations in the Yukon are more synchronous over space than changes in snowfall, it is important to investigate how uniform the climatic regime is in the Yukon over one year. Fluctuations in summer temperature are likely to have more effect on ground thermal regime than fluctuations in winter temperature, since a snow cover acts as an efficient insulator. Under a snow cover of approximately 1 m, Kerby (1979) recorded ground surface temperatures no lower than -4°C, while air temperatures below -40°C were measured. Hence a homogeneous summer regime will mean less spatial variation in ground thermal conditions.

The cluster diagrams for January and July temperatures are presented in Figs. 2.17 and 2.18. These indicate that summer conditions are more variable than winter conditions. The July clusters fall more closely into groups that can be divided topographically. The increased variability in the summer temperature regime may be accounted for by the sporadic passage of Pacific air masses over this region, and the local energy balance of abundant insolation during the long northern summer day. Fig.2.19

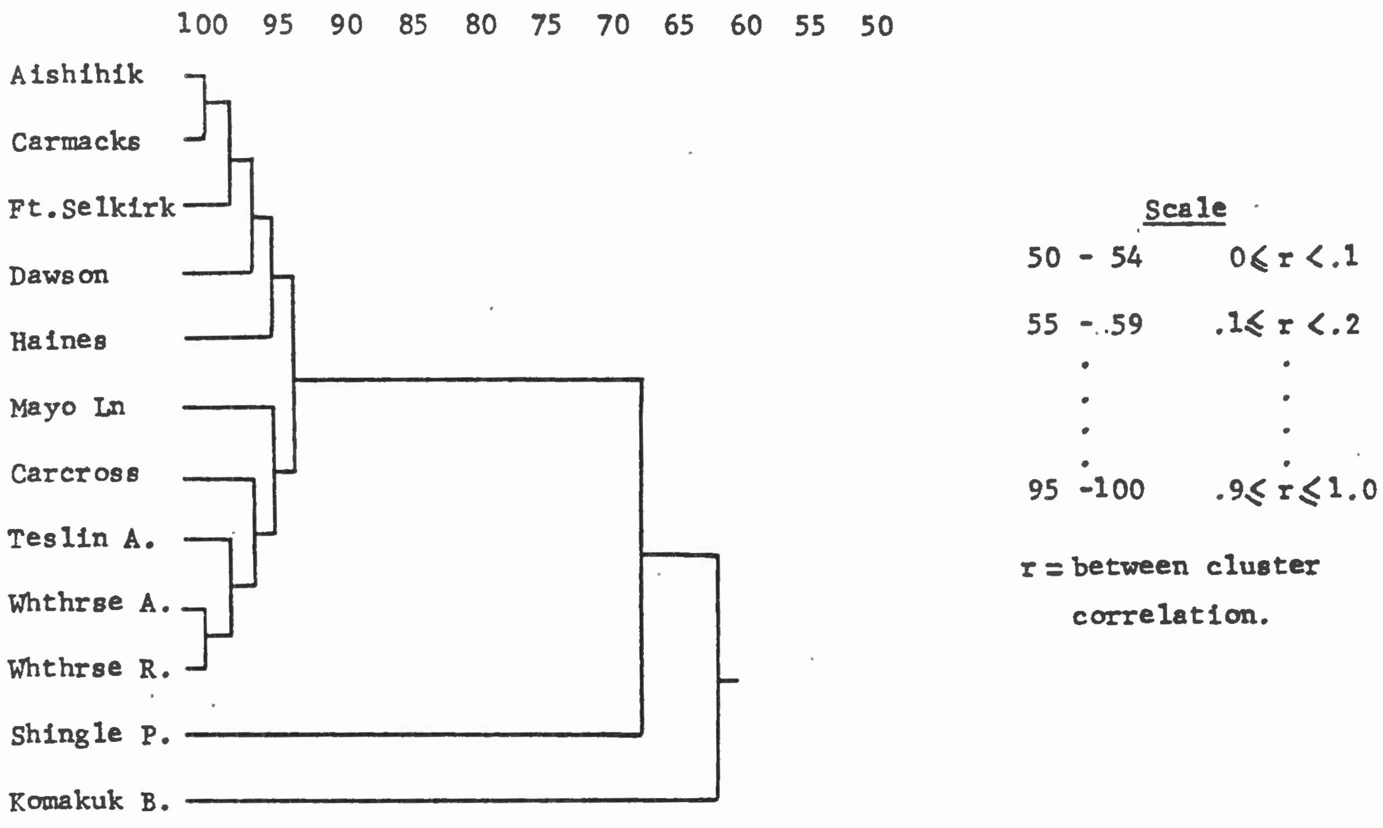


FIGURE 2.17 Grouping of Mean January Temperatures (Scaled)

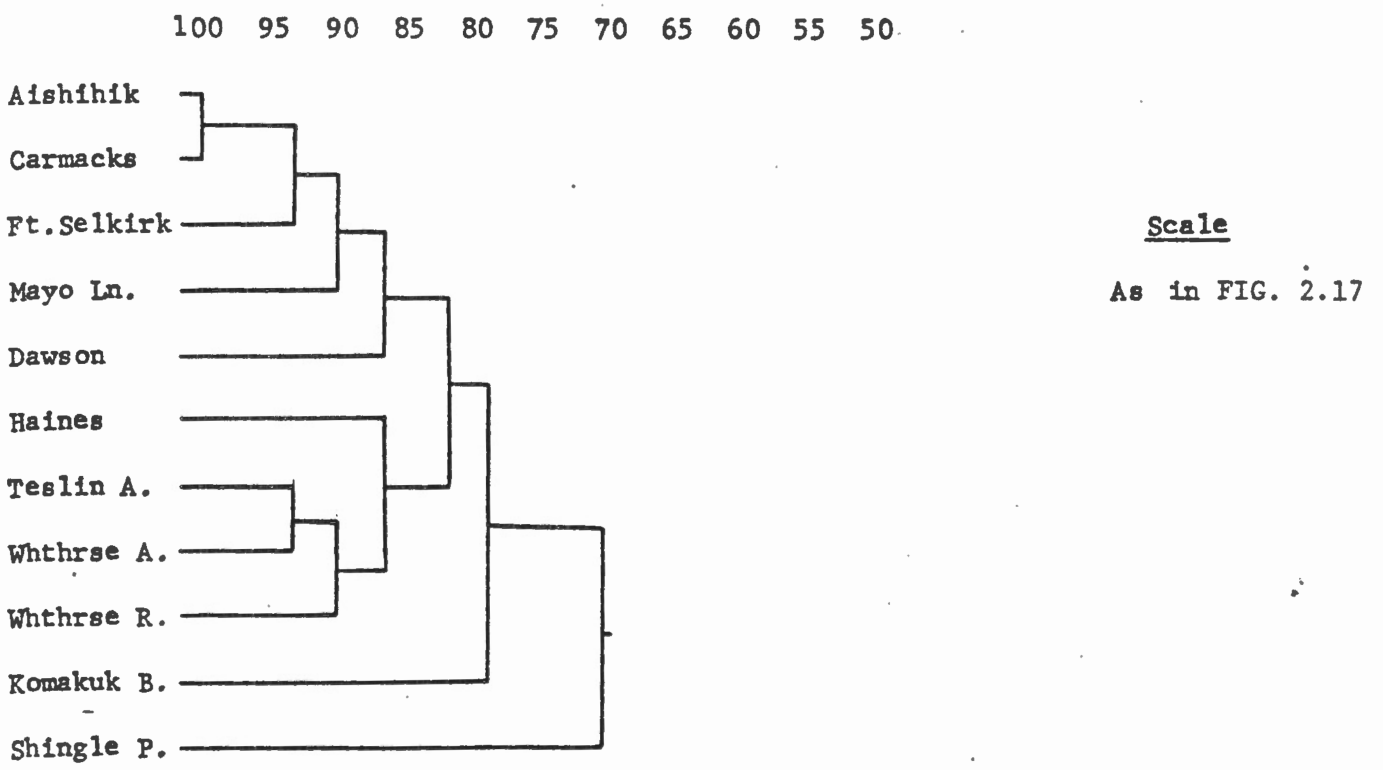
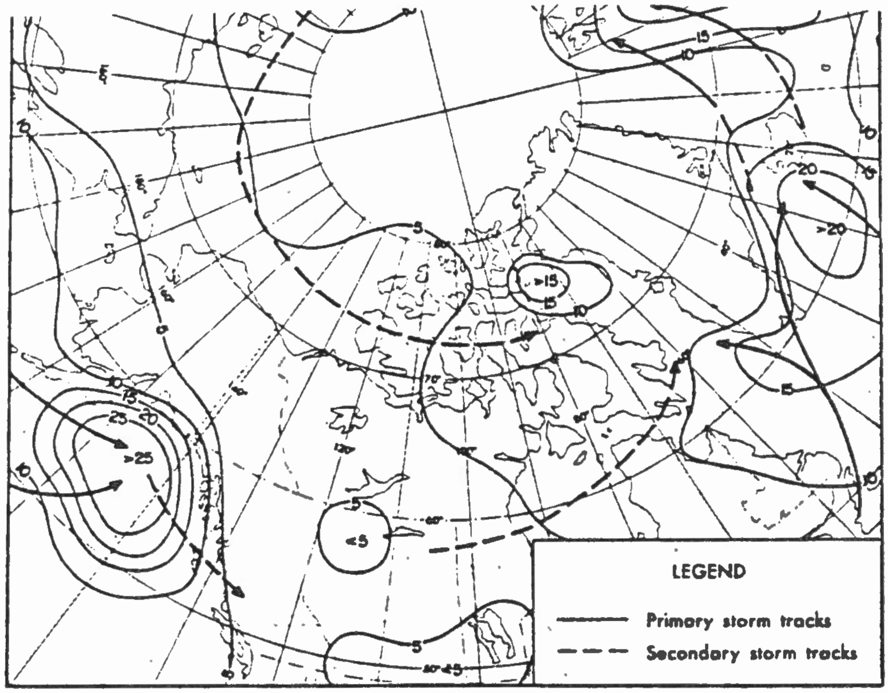
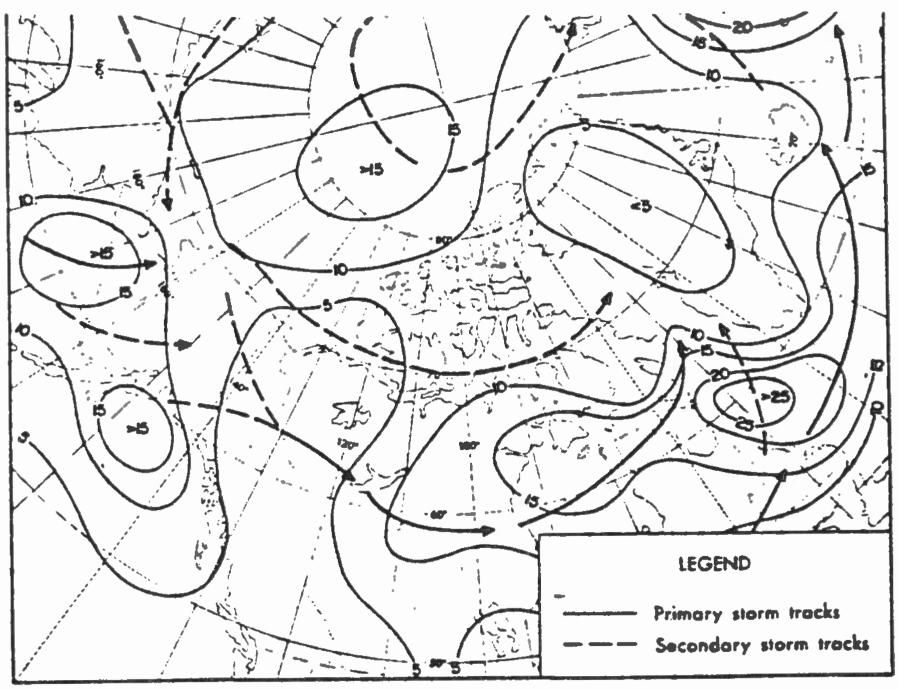


FIGURE 2.18 Grouping of Mean July Temperatures (Scaled).



(a)



(b)

FIGURE 2.19
Seasonal variation in frequency of cyclonic centres and storm track locations. (a) Percentage frequency of cyclonic centres in a 650,000 km^2 area and principal storm tracks, in February and (b) the same for August. from McKay et al (1973).

indicates the changing distribution of storm tracks over the Yukon between summer and winter.

2.4 Snowfall Temperature Relationships

It was previously noted that fluctuations in temperature and snowfall at Dawson appear in anti-phase, (Fig. 2.20 is a plot of smoothed temperature and snowfall. A distinct trend is visible, but the low r^2 (=0.297) is produced by the considerable scatter present.

In order to produce useful relationships between snowfall and temperature, when the data display such scatter, the maximum and minimum (raw) snowfall values for discrete temperature intervals were considered. The range of mean annual temperature was divided into intervals of 0.25°C from the warmest temperature downwards. Each temperature value was paired with the snowfall value recorded during the same year. For each interval the maximum and minimum values of snowfall are plotted against the lower boundary. The statistics produced by such plots are given in Table 2.4.

The r^2 values generated for maximum snowfall and temperature show improvement over the value of 0.297 for the smoothed data. However, minimum snowfall does not exhibit as strong a linear relationship with temperature. Expansion of temperature intervals by a factor of 2 was attempted in order to make the intervals more general. The statistics for this are also reported in Table 2.4. The improvement in r^2 was again noticed for maximum snowfall, although it is not replicated with the minimum snowfall data.

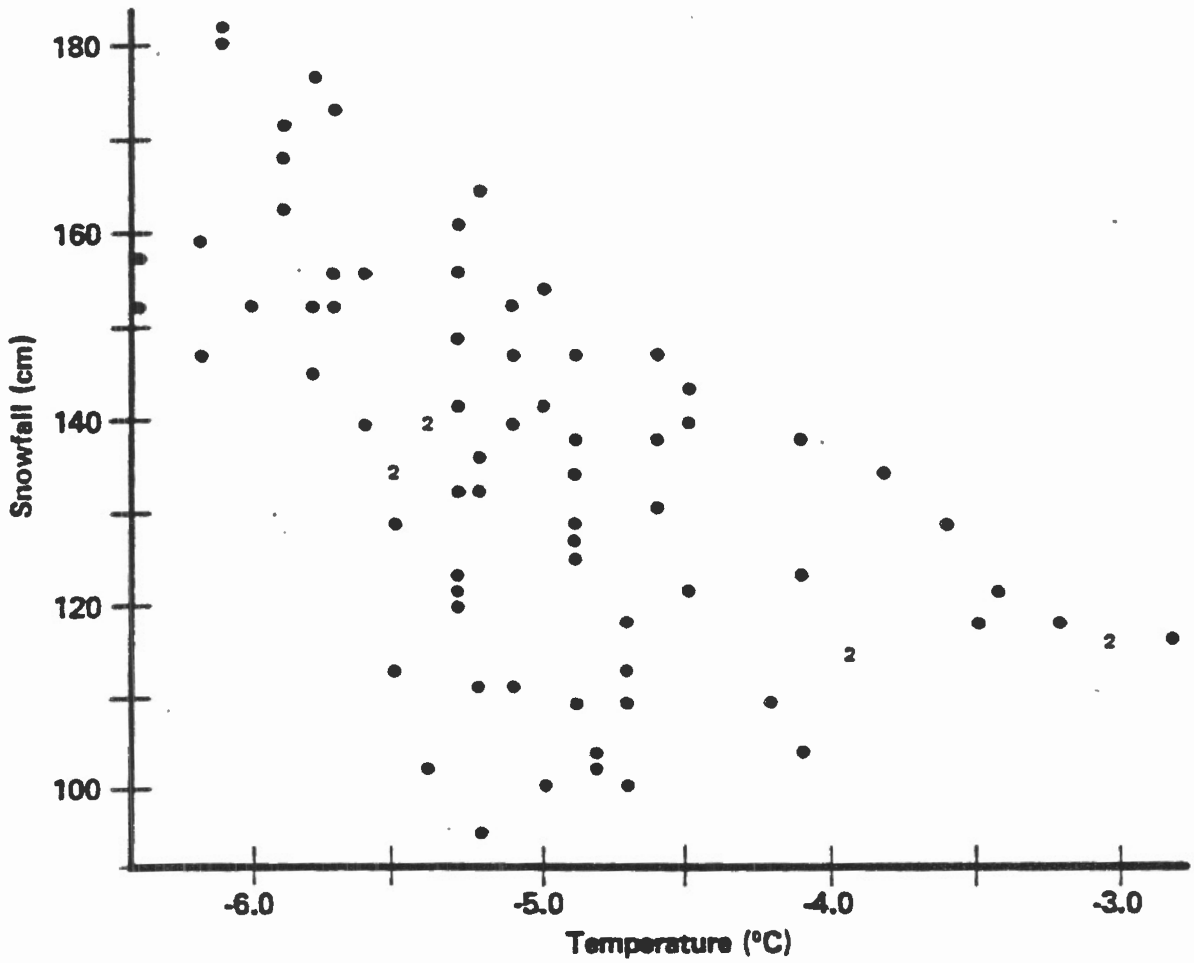


FIGURE 2.20
Plot of temperature and snowfall, smoothed 3RHHH, for Dawson. '2' represents two overlapping points.

Table 2.4 Snowfall and Temperature Linear Statistics at Dawson

	Intercept	Slope	r^2
Temperature segregated by 0.25°C			
Maximum snowfall	87.71	-15.15	0.349
Minimum snowfall	76.41	- 7.69	0.148
Temperature segregated by 0.5°C			
Maximum snowfall	98.06	-15.84	0.437
Minimum snowfall	65.11	- 5.68	0.137

Table 2.5 Statistics for Maximum Snowfall with Temperature at 0.5°C segregation.

	Intercept	Slope	r^2
Maximum snowfall, all values	98.06	-15.84	0.437
Maximum snowfall, outlier excluded	85.79	-16.86	0.674

Additionally, the plot of maximum snowfall against temperature segregated at 0.5°C level (Figure 2.21) contains one outlier, in the interval -4.5°C to -4.0°C. If this outlier is eliminated, then the r^2 value improves to 0.647 (Table 2.5). Both r^2 values are significant at the 99% level.

It is concluded that reliable linear relationships can only be obtained from the snowfall and temperature data after considerable statistical manipulation. The usefulness of these relationships as a predictive tool is therefore limited. Additionally, the efficiency of the snowcover is dampening air temperature effects on the ground surface depends on depth, so it is important to know the limits of snowcover depth. In this case one can only predict the upper limit with any confidence.

It should also be noted that, as documented previously, snowfall variations are more localized than temperature variations. Dawson is grouped with other stations in the Yukon only at a level with $r^2 = 0.4$. When using the relationships described above, it is important to be aware not only of the low r^2 values of these linear relationships, but also the low level of association of Dawson with other stations.

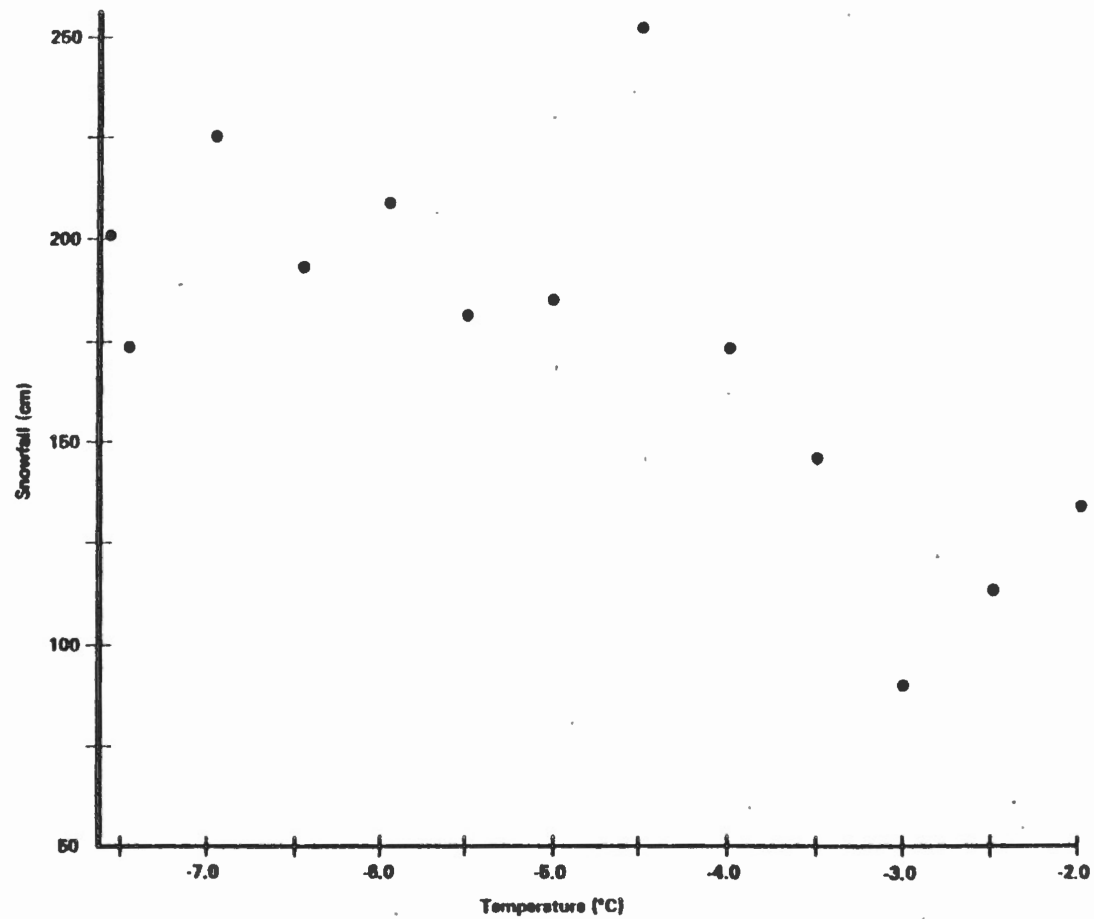


FIGURE 2.21
Maximum snowfall versus temperature for Dawson (see text).

2.5. Conclusions

To conclude this section we can note several points:

i) Mean annual temperature fluctuations in the southern and central Yukon are quite uniform over space. Winter temperature fluctuations are more uniform than those of summer.

ii) Fluctuations in total snowfall do not exhibit such homogeneity but clustering does not show any inverse relationships between regions.

iii) A series of temperature cycles is visible in the data, with a marked warm period peaking in the early 1940's, and the coolest period so far of the 20th century occurring in the early 1970's. A sharp, rapid recovery from this cooling has occurred, at a rate similar to the pre-1940's warming.

iv) Some evidence for a weak inverse relationship between total annual snowfall and mean annual temperature exists. The relationship between maximum snowfall and temperature is considerably stronger. It seems that the heterogeneity of snowfall fluctuations and the weak snowfall-temperature relationship prevent a general identification of annual change in ground thermal regime. This appears to be controlled by more site-specific factors.

CHAPTER 3

THE ATMOSPHERIC CLIMATE IN THE YUKON

3.1 Yukon in the General Atmospheric Circulation

The major part of the Yukon Territory is located within the Boreal climatic region of Canada, which region extends from coast to coast; and only a small part of northernmost Yukon belongs to the zone of Arctic climate (Hare & Thomas, 1979). Accordingly, climatic conditions of Yukon resemble very much those of the interior of Alaska.

Averages of 50-year records of atmospheric pressure at sea level for January, April, July, and October (Figs. 3.1 through 3.4) reveal the main pattern of winds and cyclone paths (Liljequist, 1970). In January a high pressure ridge is generally located over Western Canada from SE to NW. Cyclones pass mainly parallel to the Rocky Mountains and seldom enter the Yukon Territory, which is thereby shielded from influence of Pacific air masses. The Territory acts instead as part of a source region for Arctic air masses. Cyclones pass W to E north of the coast.

In April, the high pressure centre is, on the average, located over the Polar region, causing a moderate flow over the Yukon Territory from E and SE. Modified Polar and dry Arctic air masses thereby enter the Territory. The weakening of the high pressure system continues into the summer, and July pressure pattern shows very weak winds, on the average, from NW into the Territory. The Polar Front over the area fluctuates about an

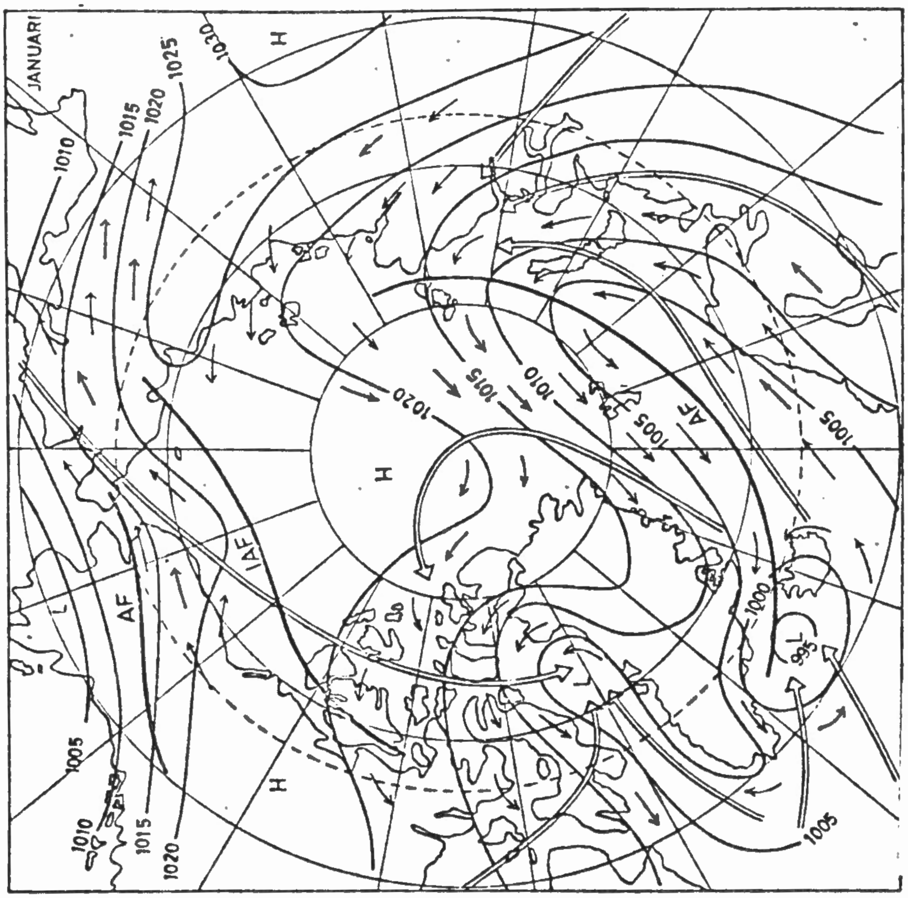


FIGURE 3.1
Sea level pressure winds, fronts and cyclone paths Arctic regions, for January.

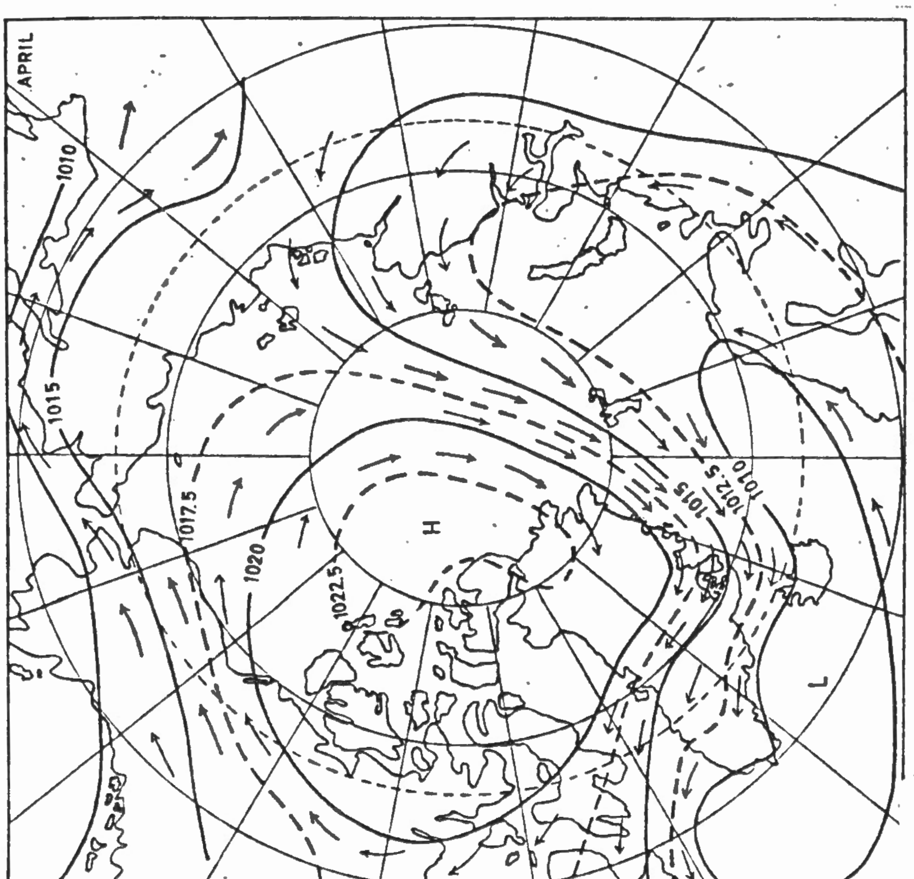


FIGURE 3.2
As for Figure 3.1, for April.

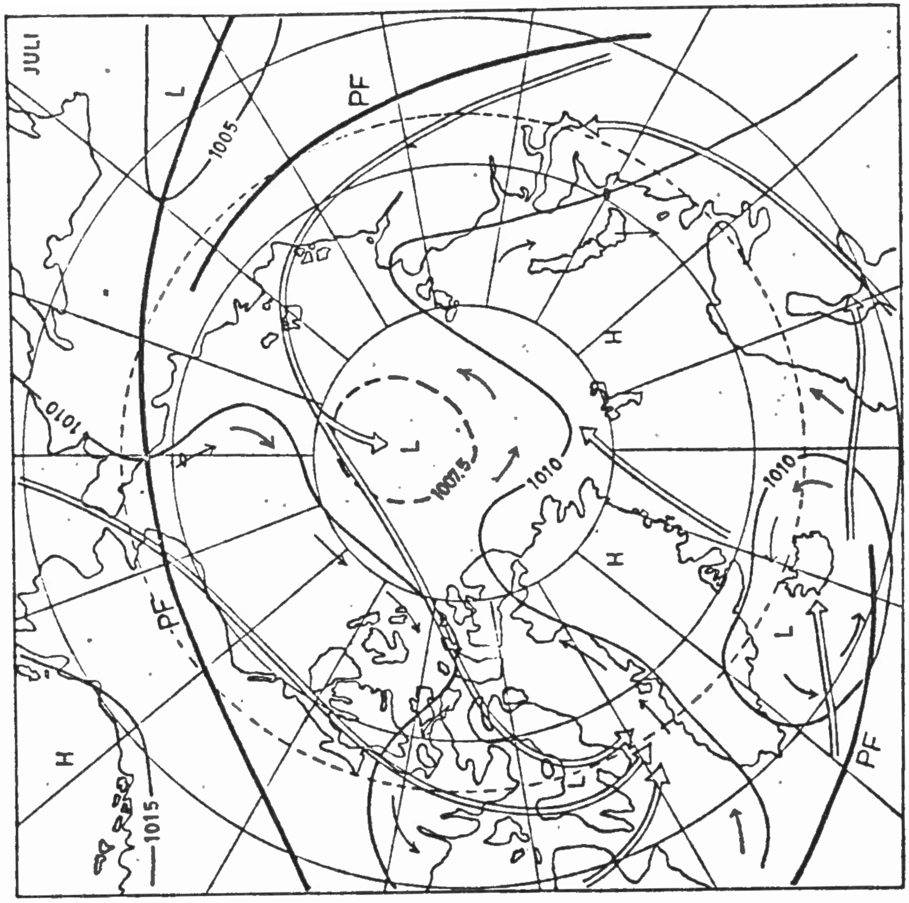


FIGURE 3.3
As for Figure 3.1,
for July.

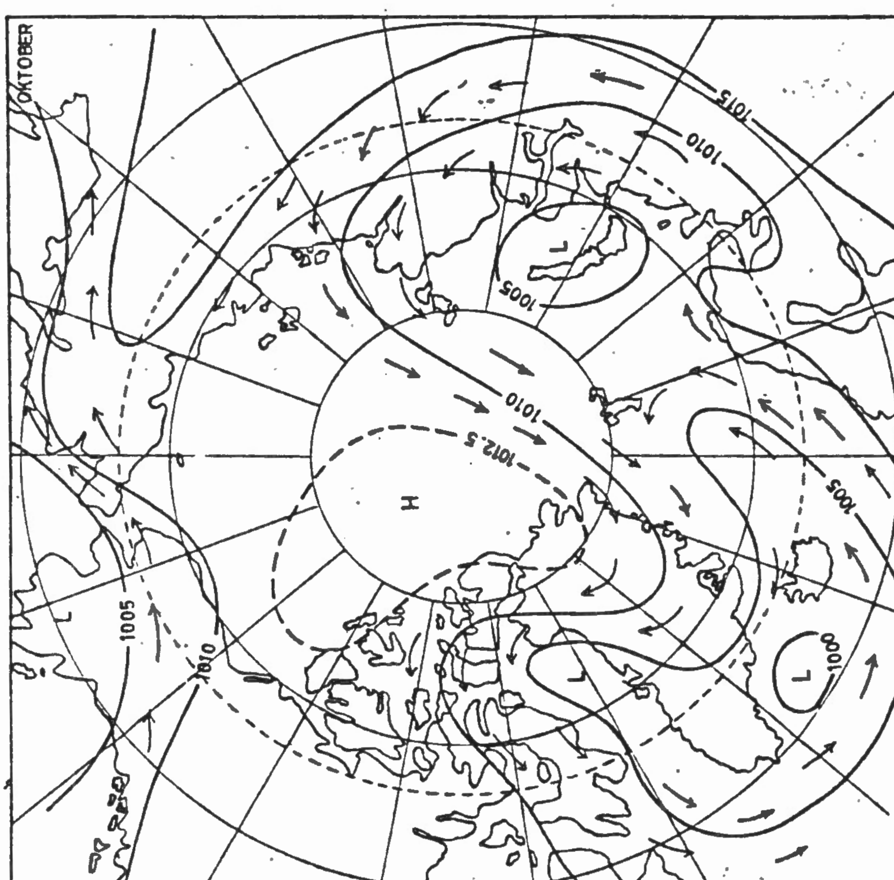


FIGURE 3.4
As for Figure 3.1,
for October.

average position NW to SE. Polar and modified Pacific air masses enter the Territory. The Polar region shows generally a low pressure system.

Gradually during the autumn through October, a high pressure system is created over the Polar region extending south into central Canada. The main flow is again from SE to NW over the Territory, but relatively weak. Pacific air masses may enter the area, carrying precipitation that starts to form the winter snow cover over the Territory. The pressure gradient towards the Pacific is gradually increased over the winter months, culminating in January.

In conclusion, for most of the year the mean wind over the Yukon, is a flow from south or southeast that in winter may be very strong. Thereby, maritime Arctic air may make the cold over the interior plateaus less severe for shorter or longer periods. However, the inflow of continental Arctic air masses causes often the reverse effect. In summer, the flow pattern is the opposite, the Polar and Arctic air masses then keeping the temperature fairly moderate over the Territory. This is also expressed by a relatively high average cloud coverage (7 tenths for July) (Hare & Thomas, 1979).

For the flow of air masses and for the temperature regime during weak pressure gradients, the macrogeography is an important controlling factor. Transects through the Yukon Territory at four locations (Fig. 3.5) show the topography from the Rocky Mountains eastwards into the interior and the main plateau (Figs. 3.6 through 3.8), and from the coast of Beaufort Sea south into the northern plateau (Fig. 3.9). It is evident that

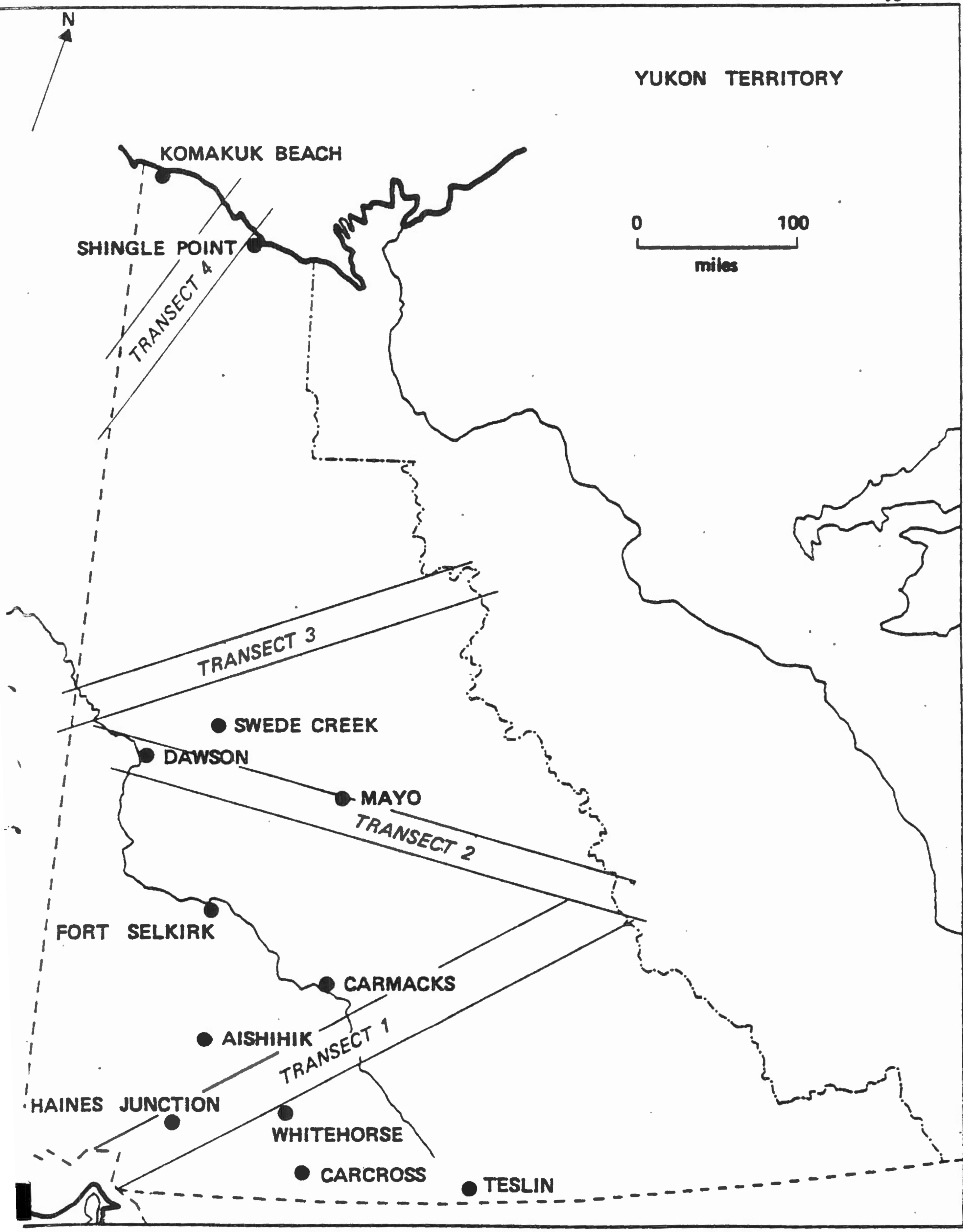
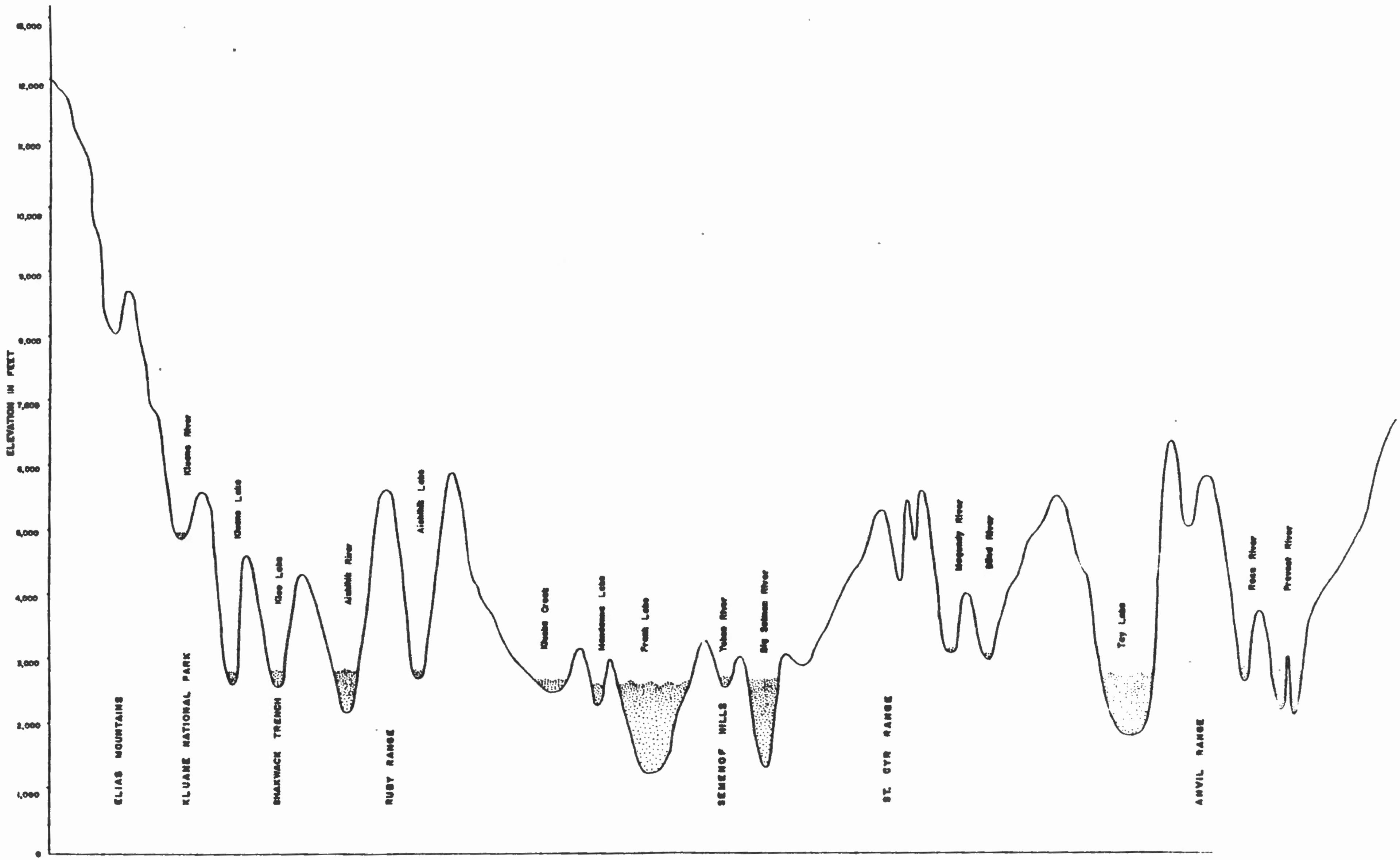


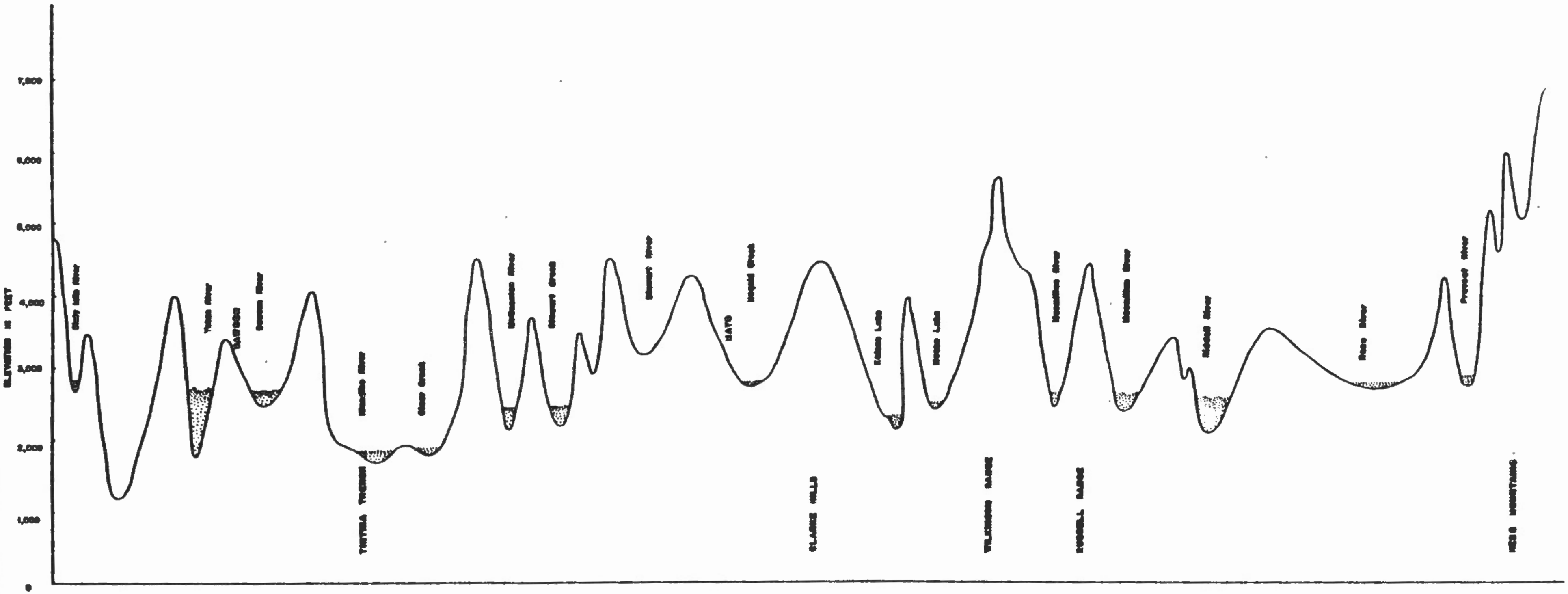
FIGURE 3.5

Location of transects, shown in Figure 6-8.



TRANSECT FROM MT. CAIRNES(SW)—MT. WILSON(NE)
YUKON, CANADA

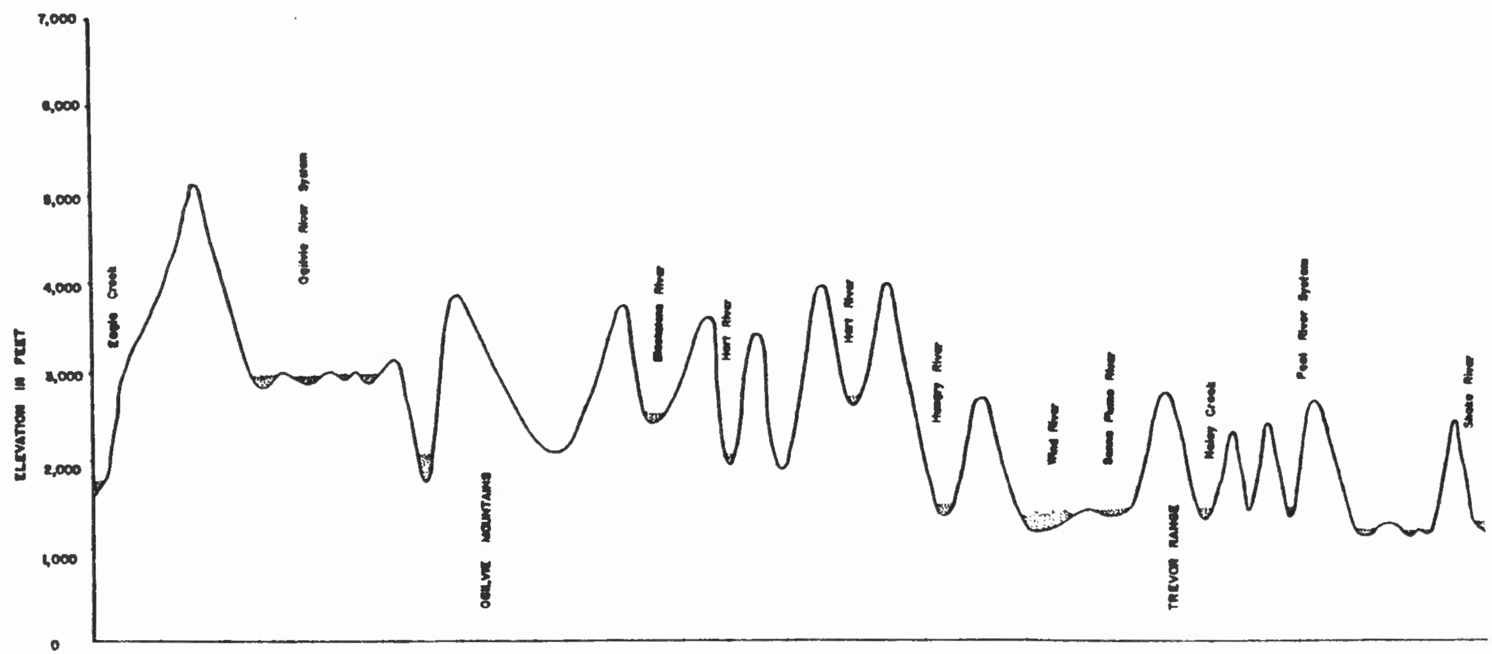
FIGURE 3.6



TRANSECT FROM SIXTYMILE (NW)—North of MT. PIKE (SE)

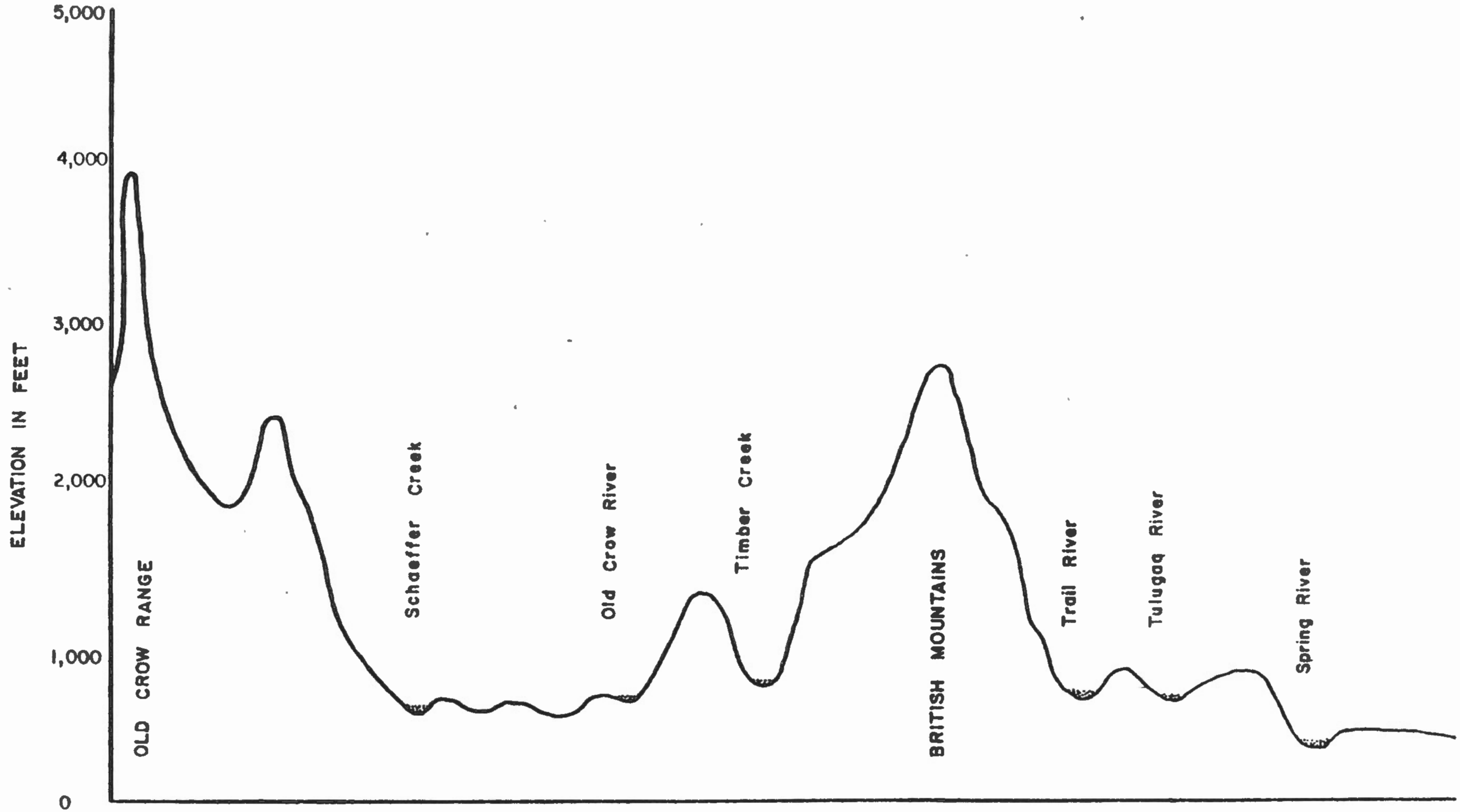
YUKON, CANADA

FIGURE 3.7



TRANSECT FROM MT. GLADMAN(SW) — BALD HILL(NE)

YUKON, CANADA



TRANSECT from OLD CROW RANGE(NW)-STOKES PT.(N)

YUKON , CANADA

FIGURE 3.9

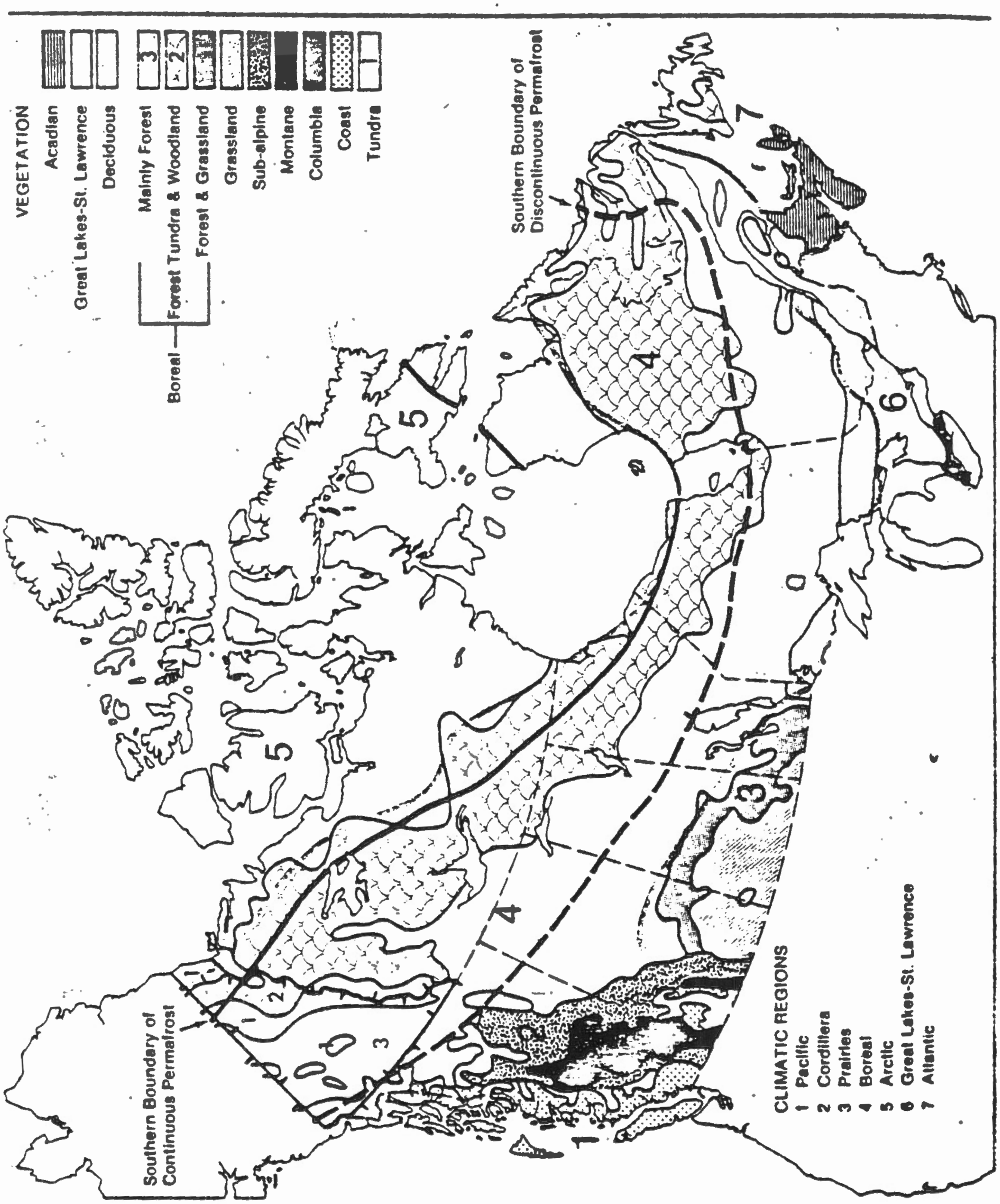


FIGURE 3.10
Canada's macrogeography (modified after L.E. Hamelin).

3.2 Atmospheric Circulation as a Cause of Climatic Fluctuation

The recent climatic fluctuations, i.e. during the 20th century, appear to have one immediate cause in the strength of the global atmospheric circulation. The cyclone path over the North Atlantic is located more to the North than earlier, at the same time as the westerlies in this area show a pronounced increase in strength. The high-pressure cell over Siberia has moved westwards towards Scandinavia, and the North American high-pressure cell seem to have moved eastwards (Barry & Chorley, 1968).

However, the period for which records of atmospheric pressure exist over north-western North America is limited to not more than about five decades. Analyses of these very recent records may indicate, on the other hand, what type of climatic changes earlier centuries may have experienced. Individual stations (Fig. 3.11) show trends in sea level pressure (Jan.) that have a certain interest in comparison with the winter flow pattern (Fig. 3.1). Since World War II Vancouver records show a marked decrease (5 mb), Winnipeg is relatively constant (Fig. 3.12) whereas Whitehorse, Fort Smith and Resolute show increases (3 - 5 mb), (Fig. 3.13) (Thomas, 1975). Since the difference between Whitehorse and Vancouver is the greatest, it indicates shortly that the pressure gradient, found in Fig. 3.1, has increased, and thus the atmospheric circulation is strengthened - in this case along and off the western coast of North America.

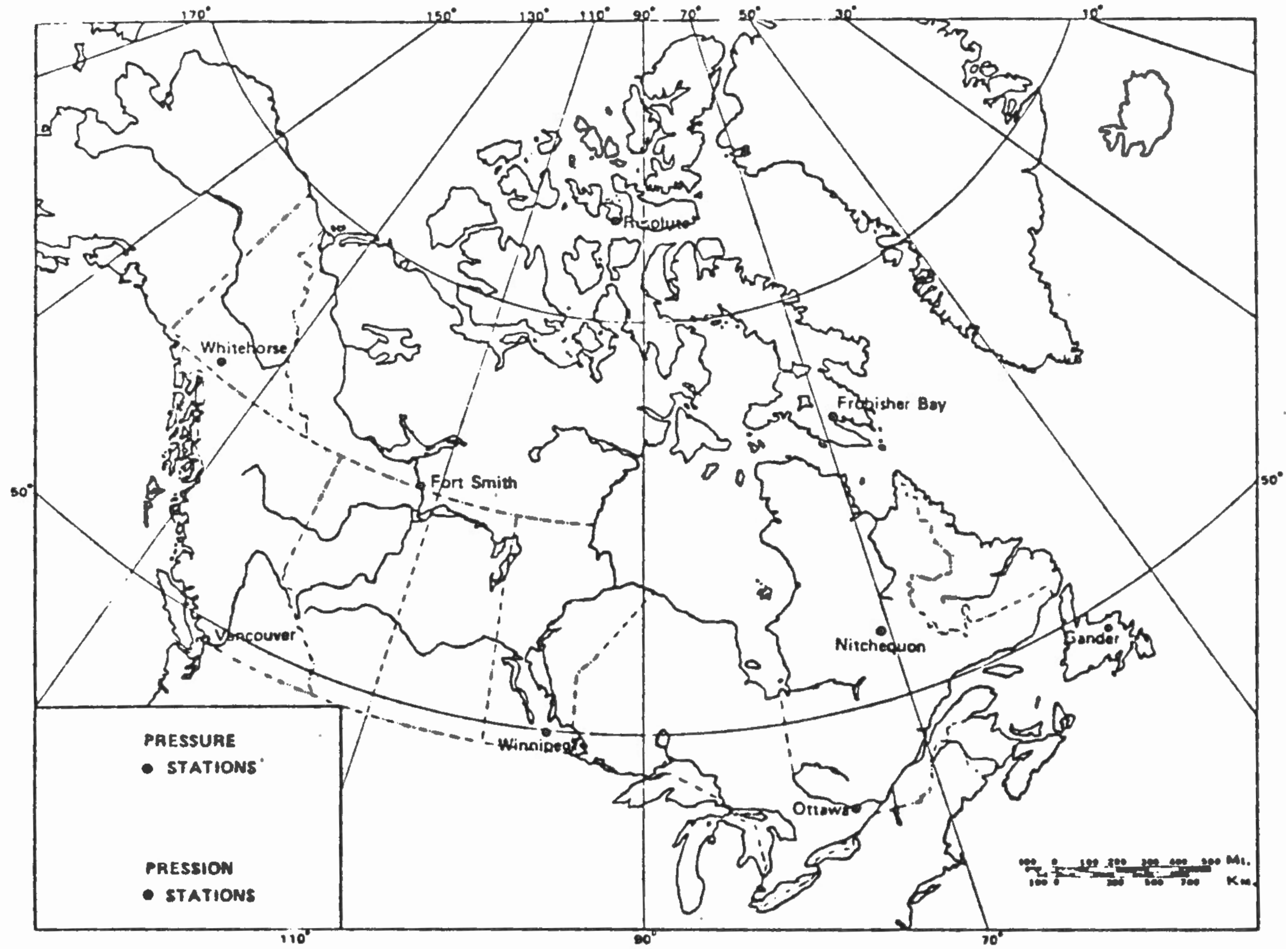


FIGURE 3.11
Stations recording air pressures shown in Figure 3.12

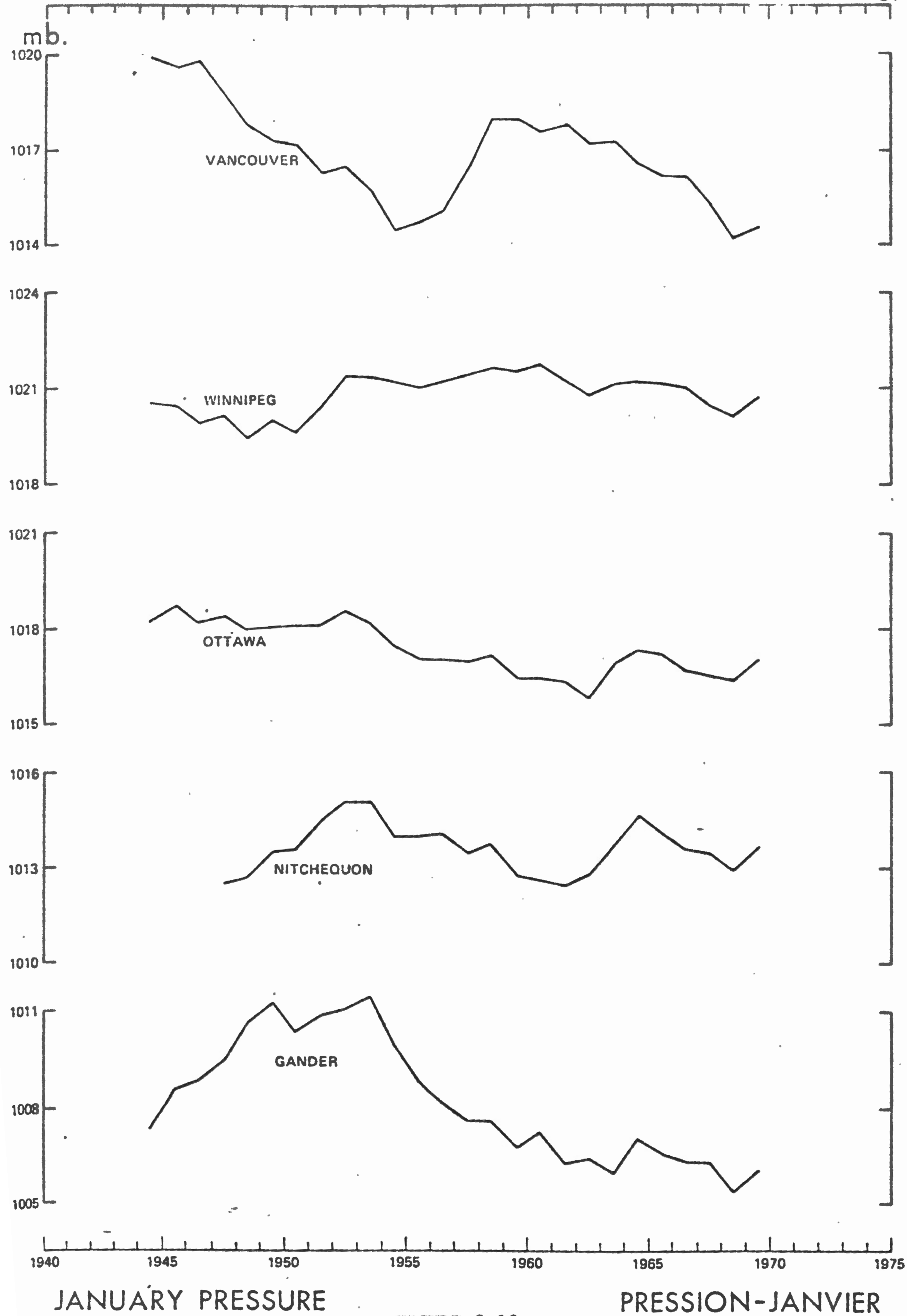
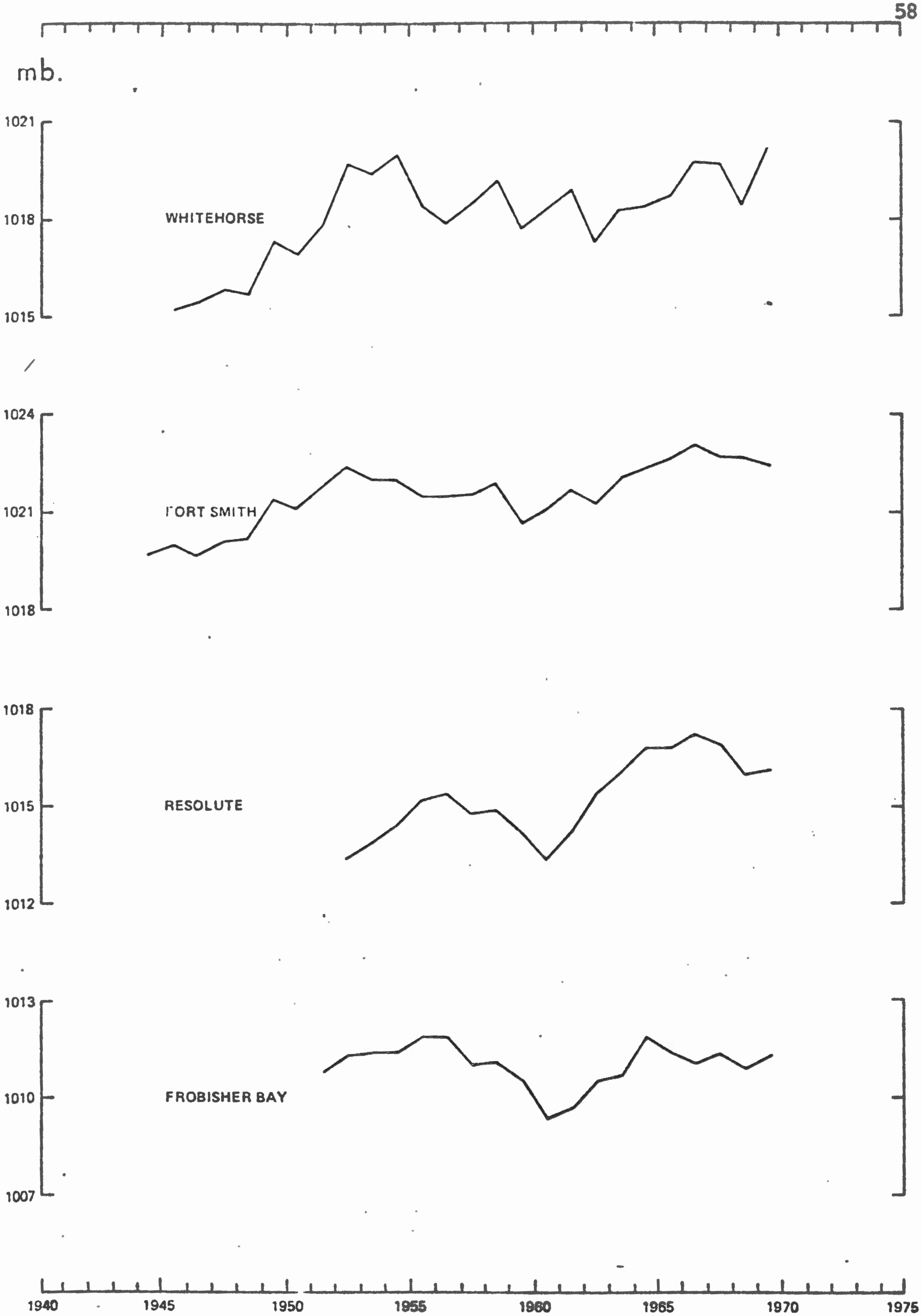


FIGURE 3.12
January air pressures, southern Canadian stations.



JANUARY PRESSURE FIGURE 3.13 PRESSION-JANVIER

January air pressures, northern Canadian stations (Thomas, 1975).

Since the other three stations show increasing trends, the implication is threefold. The winter high-pressure cell over North America has increased in pressure, and stability; the centre of the cell seems to have moved eastwards, or the cell has expanded eastwards; the blocking effect of the cell has been strengthened towards the West.

The conclusions to be drawn for Yukon, are, among others, a reduced cyclonic activity during winters over the interior of Yukon, and a possible increase in wind over the southwestern part of Yukon.

CHAPTER 4

TERRAIN STUDIES

Introduction

Elsewhere in this report climatic changes in the Yukon are discussed. It is now important to consider how much effect these changes can have on the ground thermal regime and permafrost conditions. A superficial expression of such changes is thermokarst, the pitted relief that develops in permafrost terrain due to localized melting of ground ice.

Investigations of thermokarst have been pursued on two fronts. First a literature search was undertaken, since writings about this subject are scattered and no principal reference source exists. Second, air photographs of thermokarst features, taken at different periods, were examined in order to investigate recent development of ponds in the Takhini Valley and near Mayo, Yukon Territory. Preparations were made for fieldwork to be carried out in the summer of 1982.

In addition, a computer simulation study was carried out to examine and compare the effects on ground thermal conditions of changes in micro-climate with changes of a general climatic nature.

Before the results of these investigations are presented, a brief summary of the physical processes involved in the formation of thermokarst features is given.

4.1 Thermokarst Processes

Two distinct processes are involved in the formation and development of thermokarst features: thermal subsidence and thermal erosion.

4.1.1 Subsidence

Subsidence occurs when water drains from the ground after the melting of excess ice due to a rise in ground temperature.

Nixon and McRoberts (1973) present a simplified approach to determining the rates of thaw in frozen ground. Much of the following is derived from their work.

In general, the depth of thaw (x) is related to the time (t) after a change in surface temperature, by the equation:

$$x = \alpha\sqrt{t}, \tag{1}$$

where α is a constant, determined as a root of the transcendental equation:

$$\frac{e^{-\frac{\alpha^2}{4\kappa_u}}}{\operatorname{erf}\frac{\alpha}{2\kappa_u}} - \frac{T_g\lambda_f}{T_s\lambda_u}\sqrt{\frac{\kappa_u}{\kappa_f}} \times \frac{e^{-\frac{\alpha^2}{4\kappa_u}}}{\operatorname{erfc}\left(\frac{\alpha}{2\sqrt{\kappa_f}}\right)} = \frac{L\sqrt{\pi}\,\alpha}{2\sqrt{\kappa_u}\,c_u\,T_s} \tag{2}$$

where erf ( ) is the error function

erfc ( ) = 1- erf ( )

κ_u, κ_f are diffusivities of unfrozen and frozen soil ($cm^2 s^{-1}$)

$\lambda u, \lambda f$ are thermal conductivities of unfrozen and frozen soil (cal cm^{-1} K^{-1} s^{-1})

c_u, c_f are volumetric heat capacities of unfrozen and frozen soil (cal $K^{-1} cm^{-3}$)

L is volumetric latent heat of soil (cal cm^{-3} soil)

Tg is the (uniform) initial ground temperature (°C)

Ts is the applied constant surface temperature.

This equation can be simplified by assuming that Tg = 0, and by introducing the Stefan number Ste, where

$$Ste = \frac{C_u T_s}{L} \tag{3}$$

Then,

$$\pi \frac{\alpha}{2\sqrt{\kappa_u}} \, e^{\frac{\alpha^2}{4\kappa_u}} \, \mathrm{erf}\left(\frac{\alpha}{\sqrt{\kappa_u}}\right) = Ste, \tag{4}$$

or, on a semi-empirical basis,

$$\frac{\alpha}{2\sqrt{\kappa_u}} = \sqrt{\frac{Ste}{2}} \left(1 - \frac{Ste}{8}\right) \tag{5}$$

We have, therefore, $\alpha = f(\kappa_u, c_u, L, Ts)$.

Four controlling variables for α can therefore be identified, λu, c_u, L and T_s ($k_u = \lambda u/c_u$).

The thermal solution, by defining α, helps define the rate of production of excess pore fluids. However the rate of subsidence also depends on the coefficient of consolidation, Cv, which governs the rate of excess fluid elimination from a soil. Cv is a unique geotechnical property of a soil. McRoberts and Morgenstern (1974) indicate that the rate at which water is produced by thawing is determined by the thaw consolidation ratio thaw consolidation ratio R, where

$$R = \alpha/2 \quad Cv \tag{6}$$

The rate of subsidence depends, therefore, principally on the surface temperature and the moisture content of the thawed soil.

4.1.2 Thermal Erosion

Thermal erosion is the retreat of surfaces due to the melting of the ice content of the constituent materials by running water. Kerfoot (1973) does not consider this process significant in tundra areas as a whole, since irregular subsidence, due to the heterogeneous ice content of surficial materials precludes the development of an integrated drainage system. Additionally, the surface gradient of many areas is low, and the amount of available water small, except in coastal areas and where drainage is inhibited.

Hughes (pers. comm., 1982) believes that thermokarst is limited to valley bottoms of ice-rich glaciolacustrine silts, and indicates that the distribution of thermokarst reveals ground ice distribution in the Yukon today.

4.2 Analysis of Microchange vs Macrochange for Thermokarst Initiation

A change in Ts can be produced by either altering the surface conditions, or by altering the ambient air temperature. It appears that much of the active thermokarst in the Yukon has been initiated by an alteration of the surface conditions. Indeed, if thermokarst were sensitively related to climatic conditions, then apparently natural thermokarst features should be distributed with density uniformly decreasing with increasing latitude. This would mean that the density of features in the Bell or Bluefish basins of the Northern Yukon should be less than that in the Takhini Valley near Whitehorse, which is about some 400 miles to the south. This is not the case. Additionally, the considerable variation in meteorological conditions from summer to summer means that the depth of the active layer will not be constant. The shock to the ground thermal system to initiate thermokarst must, therefore, be greater than a large proportion of the experienced warmer deviations from the standard mean.

In order to clarify the differing effectiveness of local change in surface conditions and climatic change, a simulation of the effects of fire disturbance and climatic warming on ground surface temperature was carried out. A modified version of the ALUR one-dimensional model of ground thermal regime (Smith, 1977) was used. Mean monthly temperature data for Whitehorse were supplied to a model of an arbitrary ground surface, with simulated vegetation, the ground thermal profile being initially isothermal at 0°C. The same surface was retained, but the temperature data increased by 2°C, in the subsequent model. Snowfall data were held constant. In a final model the original temperatures were retained, but a fire was simulated by decreasing the surface roughness from 10 cm to 1 cm, the albedo from 0.2 to 0.15 and wetness (gravimetric water content) from 0.6 to 0.3. The results of this disturbance on the depth of active layer and mean annual ground surface temperature are presented in Table 4.1. The change in surface conditions is seen to be considerably more effective in altering the ground thermal regime than the change in air temperature. It should be noted that the magnitude of air temperature change simulated is equivalent to some estimates of how much warmer the warmest Holocene period was compared to today (Rampton, 1971). Furthermore, the change is simulated by a step change, which is not realistic for the climatic simulation, where any warming will be gradual and therefore likely to cause less disturbance than the fire simulation, which does occur abruptly in the real world.

4.3 The Development of Thermokarst and Climatic Change

The initiation of thermokarst is principally due to local factors. However, it is realistic to assume that in a period of climatic warming, less alteration to surface conditions is required to initiate the feature. In general, a positive feedback during the development of thermokarst depressions can be identified. The depression results in preferential snow accumulation which acts as a more effective insulator for the retention of summer heat than in the surrounding terrain. This additional snow provides water which accumulates heat in the summer to maintain a talik beneath the depression.

Once the depression is formed, it can enlarge by thaw-induced collapse of the surrounding banks. At this stage, the rate of development of the feature may be related to climatic conditions. The rate of retreat of a thawing slope depends largely on the heat flux conducted into the ground from the surface, Q_G which is a component in the energy balance equation:

$$Q^* = Q_H + Q_E + Q_G$$

Q^* = net all-wave radiation incident at surface

Q_H = sensible heat exchanged at surface by convection

Q_E = latent heat exchanged at surface by convection

Q_G = conduction to or from the underlying soil

(Oke, 1977)

We assume that in summer, overall, Q_G is positive in a direction downwards from the soil surface. In particular, McRoberts and Morgenstern (op.cit.) note:

$$V = \frac{Q_G}{L + cT}$$

where V = velocity of thaw ablation surface (cm/day)

Q_G = energy flux conducted into the ground (cal cm^{-2} day^{-1})

L = latent heat per volume frozen soil (cal cm^{-3})

C = volumetric heat capacity (cal cm^{-3} $^{o}C^{-1}$)

T = ground temperature (^{o}C)

and since CT at surface temperature is much less than L, we can approximate $V = \frac{Q_G}{L}$. Q_G depends on the surface conditions. If ground is exposed, Q_G is high, so V is high. If the ground ice is covered by either mineral soil or a peat blanket, then Q_G is lower.

Monthly Temperatures °C	Albedo %	Wetness gg^{-1}	Roughness cm	Mn.Ann.Sur Temperature °C	ΔT_s °C	Depth of warmth penetration m	ΔZ m
Normal	20	0.6	10.0	4.6	0	8.4	0
Normal + 2°C	20	0.6	10.0	6.9	2.3	13.0	4.6
Normal	15	0.3	1.0	8.3	3.7	20.0	11.6

Table 4.1 ALUR simulation of relative changes to ground thermal characteristics; Whitehorse meteorological data but assuming an originally isothermal profile at 0°C. Temperature and warmth penetration after 16 months as predicted by model.

4.4 Observations of Recent Thermokarst Development

Few records exist of thermokarst development over long periods of time, but post-war air photography can provide some information. Two sites were investigated, one in the Takhini Valley and the other near Mayo. Sedimentological studies are not yet helpful since the deposition processes of the ponds are not understood. For the Takhini River Valley, 14 miles west of Whitehorse, air photographs have been taken in 1964, 1971 and 1979. A concentration of ponds close to the Takhini River bridge was investigated. These have been described briefly by Klassen (1979). It is clear that these ponds are actively enlarging. In particular three types of pond decline, or growth drainage can be identified. Drainage, or capture; coalescence; and lateral expansion may occur either through evaporation, or erosion of a bank between two ponds at different levels (capture). Coalescence is joining of two ponds at the same level. Lateral expansion is due to uninterrupted bank recession.

It was impossible to make any accurate measurements from photographs at the scale available, particularly since the ponds are not all situated in the same part of the images.

Also, at least 4 ponds have been captured by other ponds. Hence the development of the ponds here appears in part to be due to their location relative to each other, rather than purely to climatic, local ground ice or surface conditions. Such a factor only confuses the rate of development and reduces the ability to relate rate of pond enlargement to external factors.

More dramatic activity can be seen at Mayo, in the Stewart River Valley. Photographs taken in 1949, 1965, 1961 and 1977 were studied. Both pond activity and the development of retrogressive thaw flow slides are visible. One bimodal flow is located at the southern elbow of the river meander, in a position where debris from the headscarp can be flushed out by the river (Figure). The headscarp retreated sufficiently, about 60 m between 1950 and 1961, to drain the lake to the south of it in that time.

The distribution of lakes in this cluster may partly be determined by the availability of groundwater, or the former distribution of ground ice with the greatest pond density situated adjacent to the bottom of the valley side scarp, where most through flow would be available. The adjacent area at the west of the cluster that is pond-free is elevated, and hence better drained.

Including the drained lake as an area of thermokarst, we find that between 1949 and 1965 the percentage of this small basin that was pitted increased from 7.8% was to 13.4%. This gives an annual rate of increase in pitted area of 3.5%.

Photography is also available of an area of thermokarst ponds east of the Mayo airstrip. The 1961 photography reveals that 23.1% of the surface area marked on Figure was pitted. In 1977 this had grown to 35.7%. An annual rate of growth at 2.8% can be obtained, if a constant rate of growth is assumed. The rate of increase of real coverage of this thermokarst can be compared to that of the features south of the river. If we assume that environmental conditions at Mayo between 1949 and 1965 and 1961 and 1977 were similar (in terms of mean annual temperatures at Mayo, this has earlier been shown to be the case), then from a comparison of average annual development rates we can generate an hypothesis about rates of development at different stages of growth. The rate of growth of the southern bank features was 3.5% yr^{-1}, whilst it is 2.8% yr^{-1} for the northern cluster. There was a total coverage of 13.4% in 1965 for south bank thermokarst, and 35.7% in 1977 for the northern features. We might hypothesize that as thermokarst develops, the rate of development declines due to a reduction in the ratio of feature circumference to talik volume. Absolute growth is larger in the northern features of course.

4.4.1 Chronology

Chatwin (1981) concludes that the permafrost degradation near Fort Simpson, NWT has only been occurring within the past 250 years, especially within the last 120 years. If the annual rate of development of thermokarst, as with the southern features, has been 3.5%, and in the year of initiation 1% of the land was pitted, then logarithmic calculation indicates that the features appeared 60 years before 1949, i.e. about 1890. Similarly, assuming a constant growth rate for the other examples, we can estimate date of initiation 115 years before 1961, that is 1845. Moreover, if the rate of development decreases with time from initiation, than 1845 is an estimate of the oldest possible date of initiation. Both these dates would indicate that this thermokarst is a contemporary feature, which has formed in the warmer period after the "Little Ice Age".

It should be noted that the different scales of the air photography and the lack of time control points prohibit a finer analysis. A more general chronology is discussed next.

As noted above, there appears to be little known about the relative rates of thermokarst development over time. It is often assumed that the rate of thermokarst development increases with the temperature but humidity may also be an important variable of climatic change. A drier environment not only leads to more evaporation and sublimation of snowmelt, with less surface wash for thaw flow slide debris removal, but also will lead to more evaporation of surface water in summer. This will raise the normal effective stress on slopes (Carson and Kirkby, 1972) increasing stability, and also result in a shallower depth of pond water. This reduces the size of the depression talik. Nevertheless, while the general pattern of temperature fluctuations in the Yukon this century has been established (Hamilton, 1965; Burn, 1982), there is no evidence to suggest that these fluctuations are significant for thermokarst development in a region such as this, where microclimatic factors are important.

Jacoby and Cook (1981), as noted earlier, inferred that since the mid-17th Century the climate has been significantly warmer. This supports Chatwin's (op. cit) conclusions about the recent development of permafrost degradation, although his use of isotopic techniques to produce a date of 250 years since degradation of the permafrost began, is marred by the absence of discussion of the fractionation problems associated with $\delta^{18}O$ in frozen ground. Thie (1974) also found that melting has exceeded permafrost aggradation in the past 150 years in northern Manitoba and has been accompanied by collapse of peat plateaus.

It has been proposed by Rampton (1973) that the hypsithermal interval was that of maximum thermokarst initiation and development in the Arctic coastal plain. Under his hypothesis, since the basal temperature of the ice sheets was near 0°C, conditions for permafrost aggradation were not present during the glacial periods. However, deglaciation was rapid and accompanied by ground ice formation, mostly post 14,000 BP. The rapidity of formation is deduced from the incision of glacial meltwater channels into a landscape already containing ground ice. The massive ice formed rapidly from abundant glacial meltwater and because of high hydrostatic pressure in the groundwater due to glacial overburden. Rampton obtained basal dates from some thermokarst ponds, and found that the earliest originated in 22,400 ± 240 BP, although the modal date is 8000 BP (i.e. at the beginning of the hypsithermal interval). Brown (1973) argues that most thermokarst post-dates 11,500 BP.

There is a general consensus in the Soviet literature, too, that the thermokarst lakes of Yakutia are hypsithermal features. Soloviev (1973a,b) and Are (1973) indicate that the lakes are 7,000 years old, but there is some confusion about the age of individual lakes. Solviev (1973a) gives evidence of artifacts 4,000 to 6,000 years old being found at the bottom of some lakes, while in a different paper (1973b) he estimated the age of artifacts to be 2,000 to 4,000 years old.

Conclusions

We can note four points.

1. Three conditions are necessary for the formation of thermokarst: there must be ground ice present; the general climate must support a permafrost environment;

but a microclimate must be established that initiates the melting of ground ice.

2. Once initiated, the depression enhances such a microclimate effect by retaining a greater snow cover in winter and because of the standing water in summer.
3. Thermokarst initiation appears to occur at random. A local microclimatic change, induced naturally or artificially, is required. Initiation should be more frequent under warmer climatic regimes.
4. It appears that the amelioration of climate after the recent 'Little Ice Age' has been sufficient to induce considerable permafrost degradation and the development of associated thermokarst features.

CHAPTER 5

PREDICTIVE MODELLING

This part of the study is concerned with the development of a generalised predictive model to estimate the expected magnitude and rate of microclimatic and ground thermal response associated with a climatic change. A suitable strategy for such problems is outlined in Figure 5.1. The local surface energy regime (microclimate) is modelled as the interaction between atmospheric (climate) surface and subsurface conditions. This, in turn, provides the boundary conditions governing the ground thermal regime. Hence, ground temperatures are explicitly linked to the microclimate, which, in turn, is linked to the climate.

A model originally developed by Outcalt (1972) synthesized the local energy regime from standard climatological data, such as that collected by the Atmospheric Environment Service. Based upon this, Smith (1975b, 1976) developed the computer simulation model for the investigation of permafrost regimes. The model proved useful in predicting, amongst other things, daily ground temperatures and active layer development. The model was subsequently used for predicting frost penetration beneath highways (Smith and Tvede, 1977).

For the present application it was necessary to introduce a number of modifications into the model:

1) The rate of response of ground temperature conditions to

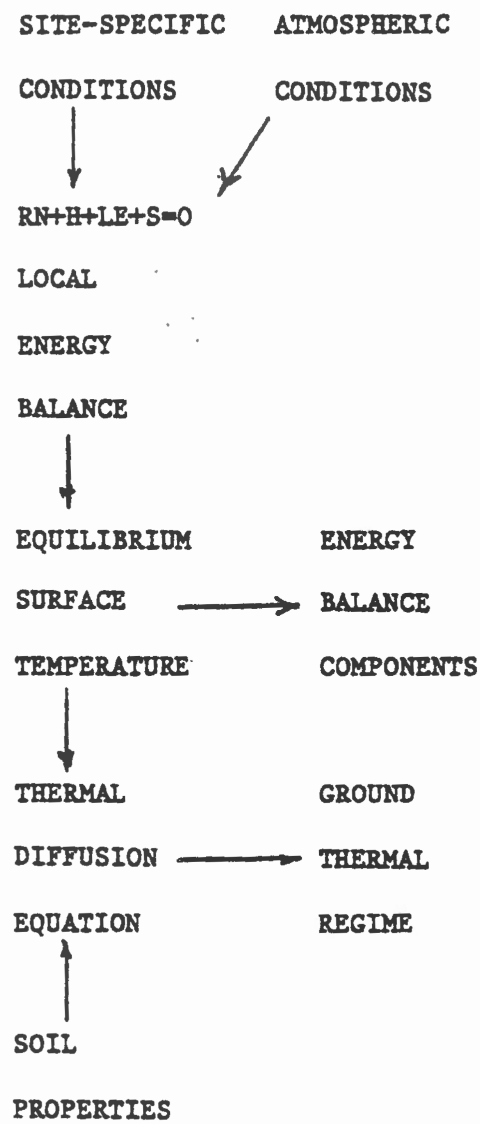

SITE-SPECIFIC CONDITIONS
ATMOSPHERIC CONDITIONS
RN+H+LE+S=0
LOCAL ENERGY BALANCE
EQUILIBRIUM SURFACE TEMPERATURE
ENERGY BALANCE COMPONENTS
THERMAL DIFFUSION EQUATION
GROUND THERMAL REGIME
SOIL PROPERTIES

FIGURE 5.1

any change at the surface is determined by the ground thermal properties. Since these are strongly temperature dependent, it is most important to represent this as realistically as possible.

i) The phase change effects of freezing and thawing are handled in terms of the apparent heat capacity, C_a:

$$C_a(T) = C_m(T) + \rho_w \left(\frac{d\theta_{uf}}{dT}\right)_T L$$

where C_m is the volumetric heat capacity of the soil-ice-water mixture, L is the latent heat of freezing (0.334 MJ/kg), ρ_w is the density of water, and $\left(\frac{d\theta_{uf}}{dT}\right)_T$ the slope of the freezing characteristic curve at temperature T.

Freezing characteristic data are now becoming routinely available for a variety of soils via Time Domain Reflectometry (see Patterson and Smith, 1982).

ii) The temperature dependence of thermal conductivity is described by experimental results obtained in the Geotechnical Science Laboratories using a new needle probe.

2) The grid for ground temperature calculations has been extended to a depth of 100 metres. Since the bottom temperature is held constant in the model, such a bottom depth is necessary to avoid numerical distortions in calculated temperatures for long time periods (decades). The grid spacing is approximately exponential, allowing fine resolution near the surface and becoming coarser with depth.

3) The geothermal gradient term has been incorporated, allowing a more realistic simulation of permafrost degradation from below.

4) Climatic data are normally input on a monthly basis. However, in the case of snowfall, which exerts the most significant influence upon winter ground temperature conditions, a more realistic approach was considered desirable. Therefore, snow accumulation is now handled on a daily basis. Further, snow density can be varied through the season.

In addition, a number of other minor changes have been made, including an improved ground heat flux calculation.

Since the principal modifications to the model have involved the ground thermal diffusion routine, and since these modifications have only recently been completed, the preliminary investigations reported here of climatic effects on ground thermal regime are restricted to a discussion of surface temperature. Nonetheless, the results serve as a good indication of the sensitivity of different sites to climatic conditions and climatic change. The discussion of computer modelling results has two main aspects:

1) A sensitivity analysis, carried out to reveal the range of possible microclimatic conditions, created by variations in local (site-specific) factors, within a uniform climate. These local factors include albedo, slope, aspect, surface wetness, aerodynamic roughness, snow cover characteristics, and ground thermal properties. For example:

   i) A wet site will experience more evaporation and therefore less sensible heating than a dry site;

   ii) At a site with deep snow cover, the ground is insulated from the full impact of winter cooling; etc.

   By varying these individual local factors in the model, their effect on surface temperature was examined.

2) The range of response at different microclimatic sites to a climatic warming was examined, by repeating the analysis above[1], but with the climatic normal temperatures were increased by 2°C for all months. The surface temperature response at a site will depend upon the way in which energy is dissipated there. For

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[1] Climate data for Ottawa were used in preliminary analyses (for a sensitivity analysis, the actual location is not very important). For the ground thermal studies now underway, Whitehorse data are being used.

example, at a wet site, additional (new) energy would result largely in increased evaporation, thus having increased evaporation, thus having little effect on sensible heating. At a very dry site, however, additional energy input would result substantially in sensible heating.

The two-part analysis revealed several characteristics of the response of microclimates to variations in climatic and microclimatic conditions (Table 5.1).

1) Variations in every microclimatic parameter result in some variation in surface temperature. The variation is smallest for aerodynamic roughness (0.7°C for three orders of magnitude) and albedo (0.9°C for a five-fold change). However, such variations could be significant enough in the discontinuous permafrost zone to determine whether permafrost was present or not. The most sensitive factor is the surface wetness, since evaporation is such an important term in the energy balance.

2) The difference in surface temperature due to the variation within a single microclimatic factor is, in some cases, greater than the change caused by air temperature warming. For example, variations in surface wetness, snow cover, wind speed and slope angle result in differences in surface temperature greater than that due to air temperature warming.

3) The range in response to the 2°C warming among all microclimatic sites simulated was 0.2° to 2.8°C (column ΔT, Table 5.1). Thus a simple correlation between air temperature changes and ground temperature changes is not likely.

4) In most cases, the variation in surface temperature due to a single microclimatic factor, is similar for both the "normal" and "+2°C" cases. Exceptions to this are found for wind speed, wetness and snow cover. In the case of snow cover, the difference in response for the two cases may be attributed to the melting of some snow at the higher temperature regime. Hence, increased snowfall has less effect on ground temperatures in a warmer climate.

MEAN ANNUAL AIR TEMPERATURE:		MEAN ANNUAL SURFACE TEMP. NORMAL	'+2°C'	ΔT
SFC LAYER	PEAT	8.9	10.5	1.6
	SILT	7.5	8.9	1.4
WIND SPEED	½ NORMAL	3.8	5.9	2.1
	NORMAL	7.5	8.9	1.4
	2xNORMAL	7.4	8.7	1.3
Zo SURFACE ROUGHNESS				
	.01	8.0	9.5	1.5
	0.1	7.7	9.2	1.5
	1.0	7.5	9.0	1.5
	10.0	7.3	8.6	1.3
ALBEDO	.1	7.7	9.1	1.4
	.2	7.5	8.9	1.4
	.3	7.3	8.7	1.4
	.4	7.0	8.4	1.4
	.5	6.8	8.2	1.4
WETNESS	0.0	14.8	17.6	2.8
	0.2	10.8	13.2	2.4
	0.4	8.5	10.6	2.1
	0.6	7.5	8.9	1.4
	0.8	5.9	7.0	1.1
	1.0	4.5	6.3	1.8
SLOPE, N/S ASPECT				
	30°N	6.5	7.8	1.3
	10°N	7.1	8.5	1.4
	0°	7.5	8.9	1.4
	10°S	7.5	9.4	1.9
	30°S	8.4	10.4	2.0
SNOWCOVER	¼ NORMAL	5.1	6.8	1.7
	½ NORMAL	5.3	7.1	1.8
	NORMAL	5.9	7.0	1.1
	2XNORMAL	7.0	7.2	0.2

Table 5.1 Simulation of changes to ground thermal regime, showing effect on mean annual surface temperature of changing various microclimatic factors. '+2°C' column shows mean annual surface temperatures when mean annual air temperature is increased by 2°C.

The results of such an analysis demonstrate the sensitivity of sites to variations in microclimatic and climatic conditions. In the zone of discontinuous permafrost, such an analysis will allow the characterisation of sites at which permafrost is now present, and thence to identify those sites which would be liable to permafrost degradation under a warmer climatic regime. This work will be carried out next. In addition, the analysis will be expanded to examine variations in more than one factor at a time. The effect of climatic change which is not uniform throughout the year will also be examined.

After those permafrost sites which are sensitive to climatic change have been identified, an analysis will be carried out to establish the rate of permafrost degradation that may be expected.

CONCLUSIONS

Assessing the significance of climatic change for geotechnical engineering requires the careful examination of several facets of the natural environment. Details of conclusions reached in this study, with respect to the climatic change in the past; to the effects of modification of ground surface conditions on ground thermal regime; and with respect to predictive modelling, are given at the ends of Chapters 2,4 and 5.

The following general conclusions apply:

1. There is ample evidence to show that changes of climate in the past, including those in recent decades or centuries, were such as to modify the distribution of frozen ground substantially. These changes, and by implication, future changes have a magnitude that could necessitate adaptation of geotechnical designs for various constructions.
2. Meteorological records and other data for the Yukon are limited but there are sources of information which are not yet fully examined.
3. The understanding of the geotechnical consequences of climatic change requires detailed examination of ground thermal regime including the surface energy exchange. It is demonstrated that natural changes of cover are important in changes of ground thermal regime and may mask effects due to changes of atmospheric climate.

4. Predictive methods must take into account a range of factors controlling ground thermal regime in addition to the atmospheric climatic elements. These methods can indicate the probable extent of the effects within the life of a pipeline or other construction.

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