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THE RELATIONSHIP BETWEEN SYNOPTIC-SCALE ATMOSPHERIC CIRCULATION AND GLACIER MASS BALANCE IN SOUTHWESTERN CANADA

by

Brenton M. Yarnal
A.B., University of California At Davis, 1973
M.Sc., University of Calgary, 1979

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
in the Department
of
Geography

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The Relationship Between Synoptic-Scale Atmospheric
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Abstract

Glacier-climate relationships in the Cordillera of southwestern Canada are investigated in terms of three interrelated objectives. The primary objective is to study the relationship between synoptic-scale atmospheric circulation and glacier mass balance. Objective synoptic typing techniques are applied to glaciometeorological data from Peyto Glacier, Alberta and Sentinel Glacier, British Columbia, and to climatological data from nearby weather stations. The second objective is to determine whether the results are affected by the scale and degree of generality of the synoptic patterns used in the analysis. Two scales of 500mb synoptic weather maps are analyzed and compared. One is smaller, with high-wavenumber patterns; the other is larger with more general circulation patterns. The third objective is to identify sources of error in the model and the effect these errors have on the results.

The results can be summarized in terms of the three objectives. First, the mass balances of Peyto and Sentinel Glaciers are shown to be related to the 500mb synoptic patterns passing over the area. Synoptic types with cyclonic curvature favor glacier accumulation, while anticyclonic types inhibit build-up of the regional snowpack. Ablation is suppressed by synoptic types associated with cloudy days and/or low temperatures, and is enhanced by types associated with warm, sunny days. Second, changes in the synoptic-scale used to analyze the climate-mass balance relationship do affect the results. Findings suggest that both the accumulation and ablation of Sentinel Glacier are controlled by high-wavenumber synoptic patterns. Conversely, Peyto Glacier accumulation is more closely related to large scale synoptic patterns, suggesting that much of the short wavelength variability imbedded in the long wave atmospheric flow may be dampened by the rough topography of the Canadian Cordillera. Ablation is predicted poorly by both synoptic-scales at Peyto. Third, much of the variability in the synoptic climatological model appears to be the result of errors introduced by methods used in this thesis and of problems inherent to the objective classification technique. Elimination of these errors would probably strengthen the statistical relationship between glacier mass balance and synoptic-scale circulation.

TO MY FATHER AND MOTHER,

DALE AND DORIS YARNAL,

AND TO MY FATHER-IN-LAW AND LATE MOTHER-IN-LAW,

ALISTAIR AND JOAN MACKAY

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1. Introduction

Scientists have long believed that the atmospheric environment controls the extent and behavior of glaciers (Figure 1.1). Glacier-climate research is plentiful, but has focused on either detailed micro- to local-scale relationships occurring over short periods of time (seconds to hours) or generalized global-scale atmospheric patterns accounting for long-term glacier changes (decades to millenia; Radok and Watts, 1975). Few glaciological studies have been done on the middle ground between these two extremes of the atmospheric continuum; that is, meso- and synoptic-scales with periods of days to years. One reason for the paucity of research has been the lack of suitable analytical tools making possible the linkage of glacier fluctuations to the atmospheric circulation. Recent advances in the field of synoptic climatology now provide the methodology needed to make these associations.

In recognition of the need to fill this gap in the understanding of glacier-climate systems, one goal of the Canadian contribution to the International Hydrological Decade, 1965-1974, was to link the synoptic-scale atmospheric circulation to the mass balance of a glacier (Loken, 1970). Although a few studies have applied the

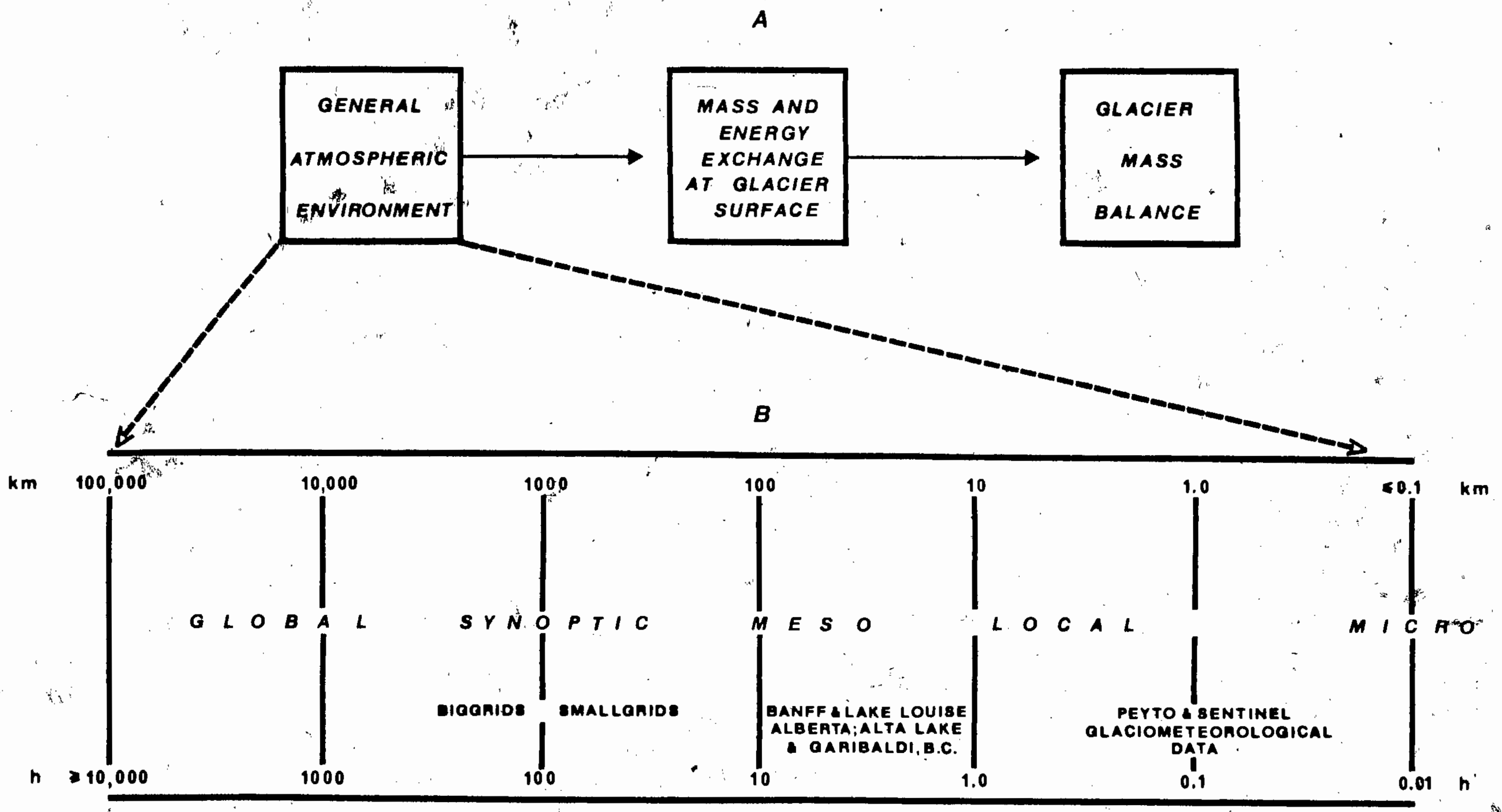


Figure 1.1. A. The relationship between climate and glacier mass balance (modified from Meier, 1965). The left-hand box of A, "General Atmospheric Environment," contains all of B.
B. Scales of atmospheric activity, including the scales of the present study (modified from Hanwell, 1980). Gradual changes take place from one scale to the next; overlap is to be expected in these areas. km = horizontal scale; h = time scale.

synoptic climatological approach to glacier mass balance in the Canadian High Arctic (Jacobs, et al, 1973; Alt, 1975, 1978, 1979), there are no comparable studies on glacierized areas of the topographically more complex Canadian Cordillera. In this thesis, a synoptic climatology of two mountain glaciers in southwestern Canada is presented. The results of the synoptic climatology are used to demonstrate the relationship between observed variations in mass balance and the atmospheric circulation over the region.

Because of the rapid progress in synoptic climatological methodology and the central role it plays in this thesis, synoptic climatology is briefly reviewed in the present chapter. Objectives of the study are then discussed and, finally, an outline of the thesis is presented.

1.1 Review of synoptic climatology

Synoptic climatology is concerned with understanding local or regional climate by examining the relationship between local weather elements and the circulation of the atmosphere over that area. Barry and Perry (1973) recognize two stages in any synoptic climatology:

1. categorization of features of the atmospheric circulation;
2. assessment of the relationship of these categories with

local weather elements.

Much of the work in synoptic climatology has been directed towards the formulation of effective synoptic type categories. Although there is a wide range of research dealing with this topic, the resulting classification techniques can be grouped under the headings of subjective and objective procedures.

Subjective classification procedures can be subdivided into kinematic and static views of the weather map (Barry and Perry, 1973). Kinematic methods subjectively categorize airflow, storm tracks or other dynamic features of weather movement. Subjective typing of the static weather map involves the identification of characteristic patterns of atmospheric pressure fields, such as the relative positions of highs and lows.

There are two major problems with subjective typing techniques. First, although some subjectively derived classifications are well established with accepted criteria for the determination of synoptic types, such as the surface airflow-type catalog for the British Isles (Lamb, 1972), most subjective classifications are unique, with typing criteria derived only for the research at hand. Consequently, the results of one study are not easily compared to the findings of another. Second, atmospheric features are continuous in time and space, so that the identification of synoptic type boundaries must be arbitrary. Even when clearly defined criteria are applied, replication of type categories and type member frequencies is difficult since the judgement of any two investigators will differ.

Because of the problems associated with subjective procedures, the development and application of objective classification techniques is the most important advance in synoptic climatology in the last few years (Barry, 1980). An objective synoptic climatology takes advantage of the large data handling capacity of modern computers, allowing the machine to determine statistically similar and significant synoptic groupings. When based on standardized criteria and data, results can be replicated and studies can be compared. Since standardized data are easily analyzed by computer methods, gridded climatological data sets, like those prepared by the National Center for Atmospheric Research (NCAR; Jenne, 1975) are ideally suited to objective synoptic typing (Barry, 1980).

Three main types of objective classification techniques have been developed and applied: the correlation method (Lund, 1963; Suckling and Hay, 1978; Singh, et al., 1978; Overland and Hiester, 1980), variable reducing procedures (Christiansen and Bryson, 1966; Kutzbach, 1967, 1970; Dixon, et al., 1972; Blasing, 1975; Rogers, 1978; Ladd and

Driscoll, 1980) and the sums of squares technique (Kirchhofer, 1973; Barry and Keen, 1978; Moritz, 1979; Bradley and England, 1979; Keen, 1980). The correlation method and variable reducing procedures typically classify 60% to 80% of the maps analyzed, although Petzold (1981) has developed a technique to improve significantly the percentage of maps classified by the correlation method. The sums of squares technique is an improvement over the above techniques, typically categorizing more than 90% of the weather maps. Due to the better categorizaton performance record of the sums of squares technique, this method is used with NCAR data in the present thesis.

The second stage in a synoptic climatology, evaluation of the relationships of synoptic type categories with local weather elements, has led to many diverse studies. In southwestern Canada, synoptic climatologies have been concerned with spatial distributions of precipitation (Walker, 1961), vertical distributions of precipitation (Fitzharris, 1975), solar radiation regimes (Suckling and Hay, 1978), frequencies of major avalanches (Fitzharris, 1981) and glacier katabatic winds (Stenning, et al., 1981). Studies specifically relating synoptic processes to glacier mass balance have been carried out for areas of Europe (Hoinkes, 1968), the Canadian Arctic (Jacobs, et al., 1973; Alt, 1975, 1978, 1979), the southern Indian Ocean (Radok and

Watts, 1975) and Alaska (Fahl, 1975). None of the glacier-climate studies use an objective synoptic typing methodology.

1.2 Objectives

The study has three interrelated objectives. The first is concerned with the physical environment, the other two with synoptic climatological methodology.

In accordance with the goals of the Canadian contribution to the International Hydrological Decade, the first objective is to study the relationship between synoptic-scale climate and the mass balance of two southwest Canadian glaciers. To do this, a chain of atmospheric scales of activity, from the synoptic-scale to the local-scale, must be linked to accumulation and ablation at these glaciers (Figure 1.1). Objective synoptic climatological techniques will be applied to this problem.

The second objective is to determine whether changes in the scale and the degree of generality of the synoptic patterns analyzed affects the results. Suckling and Hay (1978) hypothesized that their objective synoptic climatology of southwestern Canada would be improved if more detailed synoptic-scale patterns were used. To test this hypothesis in the context of the present work, two scales of synoptic weather maps are analyzed and compared. One is smaller with high-wavenumber patterns, similar in scale to the synoptic weather maps used by Bradley and England (1979). The other is larger with more general circulation patterns, similar in scale to the work of Suckling and Hay (1978). These weather maps are designated Smallgrids and Biggrids, respectively, in Figure 1.1.

The third objective is to identify sources of error in the synoptic climatological methodology and the effect these errors have on the results. Objective synoptic climatology is a relatively new field of research; many of its weaknesses are unknown or unstudied. For example, Bradley and England (1979) have suggested that internal (within-type) variation of the Kirchhofer sums of squares classification technique may have affected their results and is worthy of further study. Thus, within-type variation is investigated here, along with other problems inherent in the sums of squares classification technique or in its application in this thesis.

1.3 Organization of the study

After a discussion of the physical setting and of the data to be used (Chapter 2) and of the analytical techniques applied to these data (Chapter 3), the three main analytical chapters (4, 5 and 6) are presented. In chapter 4, a general synoptic climatology links local-, meso- and synoptic-scales of climate to one another. As mentioned above, two synoptic scales of atmospheric activity are analyzed and compared. In Chapter 5, the nature and strength of the relationship between glacier mass balance and climatological characteristics of both synoptic scales are analyzed. Chapter 6 follows with a look at the sources of error in the synoptic climatological model and their effects on the results. The thesis concludes with a summary of the results and suggestions for further research (Chapter 7).

2. The Study Area and Data

The relationship of southwestern Canada to the mid-latitude belt of westerly winds is presented in this chapter. Within that context, the glacierized areas of the Cordillera, of which Peyto and Sentinel Glaciers are believed to be representative, are discussed. Finally, the data used to relate synoptic-scale circulation to glacier mass balance are introduced.

2.1 Climatological setting

The climate of the southwestern Canadian Cordillera is dominated by the westerly flow of maritime airstreams (Bryson and Hare, 1974). The northerly portion of this flow crosses the Pacific Ocean from Asia and is most prominent in the winter, while the southern portion is associated with the Pacific Anticyclone and is most prominent in summer. Northern Pacific westerlies are cool, with a near-moist adiabatic lapse rate and a high moisture content through a considerable depth. The warm summer anticyclonic airstream is stable and arrives at the British Columbian coast with a shallow moist layer.

Eastward travelling cyclonic disturbances embedded in the westerly flow bring heavy precipitation to the southwestern coast of British Columbia. The core area affected by the storms varies from about 45^{0}N in the winter months to about 54^{0}N in summer. The cyclones are usually near the peak of their development upon reaching coastal British Columbia, especially in winter; hence the disturbed nature of the climate (Hare and Hay, 1974). Summer cyclones are less frequent and vigorous, and several warm anticyclonic spells may be expected during the summer months. The net result of the intense cyclonic activity and the rugged topography of the Coast Mountain Range is large annual deposits of snow that, because of sudden orographic uplift and frictional drag associated with the change from ocean to land surface, increase dramatically with elevation (Walker, 1961).

After a storm strikes the Coast Mountains, the mid-tropospheric trough associated with the surface fronts usually continues eastward across the Cordillera. Although it is difficult to follow surface fronts across the complex topography of the interior, the passage of a system shows itself in the observed weather (Hare and Hay, 1974). A front may produce little or no precipitation in the deep valleys or upland plateaus, but the higher mountain ranges (the Purcell, Monashee, Selkirk, Cariboo and Rocky Mountains) do receive heavy falls of rain and snow, especially in winter. Summer convective storms are common in all interior areas experiencing a mid-tropospheric disturbance.

2.2 Glaciological setting

Each year, heavy winter snowfalls blanket most upland areas of the Canadian Cordillera. In those locations where altitude or topography limit the amount of energy available for melting of the snowpack, excess accumulation has led to the formation of mountain glaciers.

During the International Hydrological Decade (IHD), five glacierized mountain basins were studied on an east-west transect from the Rocky Mountains to the Coast Range in southwestern Canada (Ostrem, 1966). Of these, Peyto and Sentinel Glaciers (Figure 2.1) received the most intense glaciological and meteorological study due to their accessibility and to their presumed representativeness of nearby glaciers. Summaries of the IHD programs at, and basic data for, Peyto and Sentinel are given by Young and Stanley (1976) and Mokievsky-Zubok and Stanley (1976), respectively.

2.2.1 Peyto Glacier

Peyto Glacier is influenced by a relatively continental climate. It is located in the Waputik Ranges of the Rocky Mountains of Alberta at 51°40′N latitude, 116°35′W longitude (Figures 2.1 and 2.2). Peyto has an area of approximately

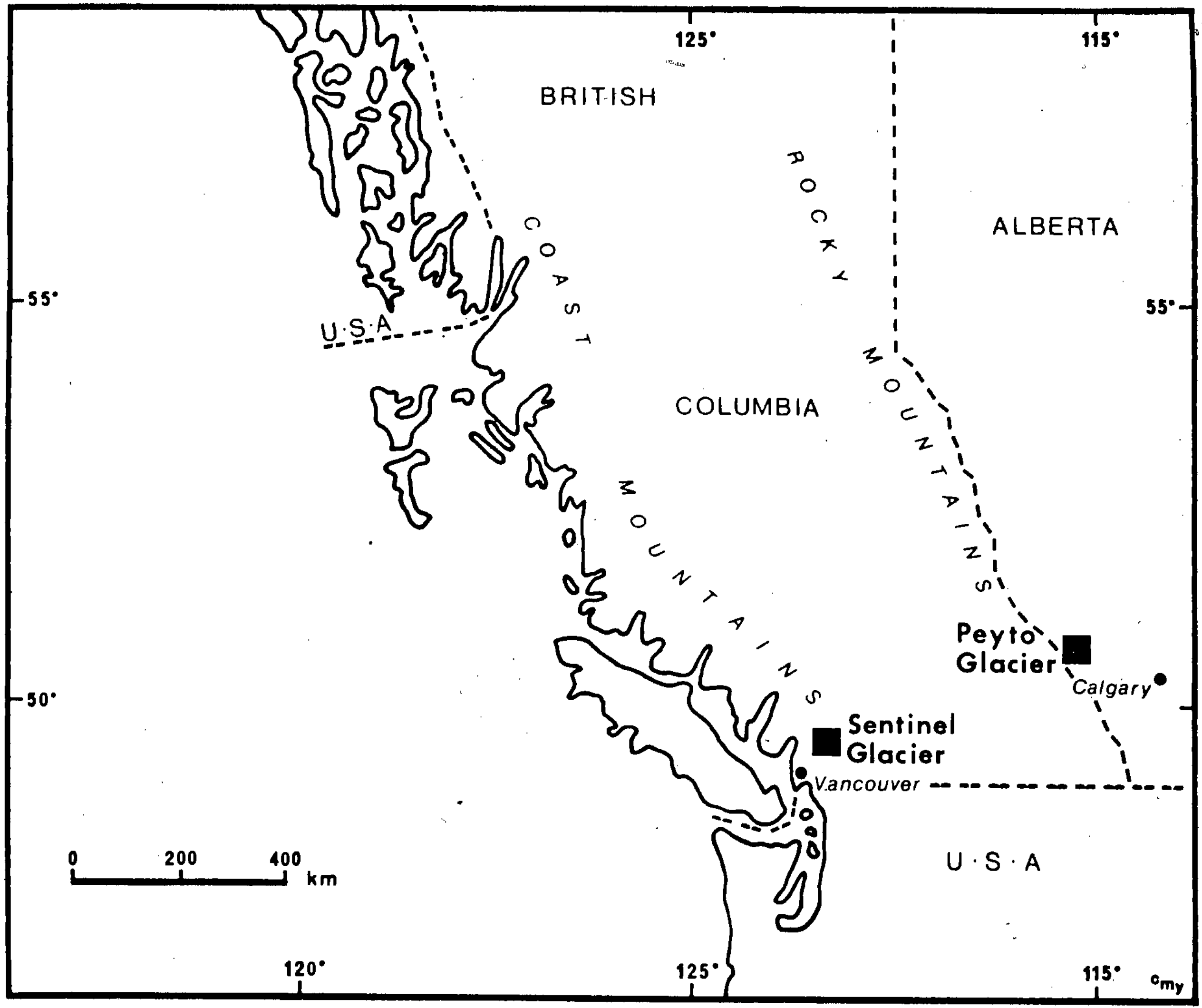


Figure 2.1. Locations of Peyto and Sentinel Glaciers.

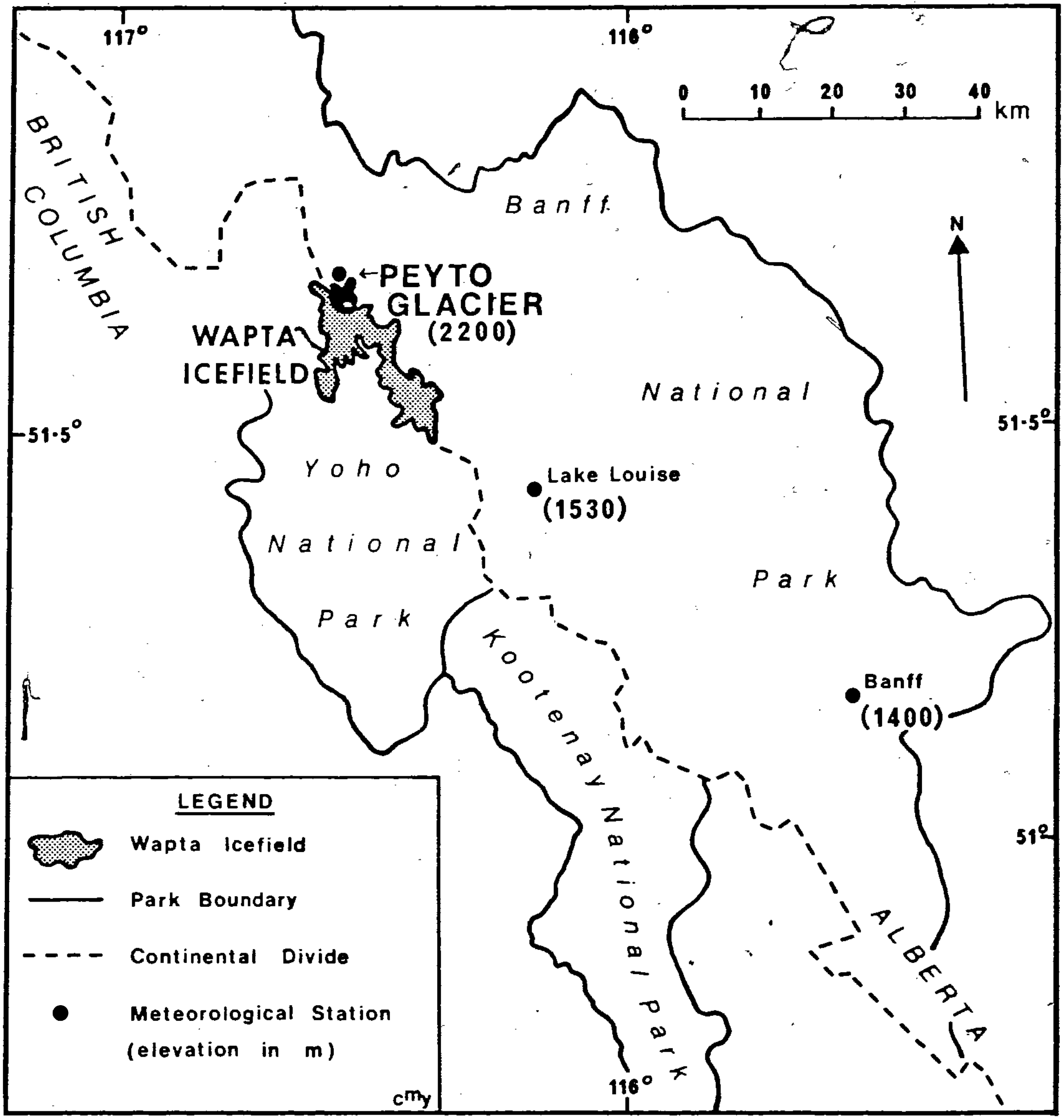


Figure 2.2. Peyto Glacier and vicinity.

13.4 square km, ranges in altitude from 2100m to 3200m a.s.l. and has an average slope of 13^0. It is a major outlet for the Wapta Icefield.

The basic mass balance program at Peyto Glacier involved monitoring mass balance changes at 38 stakes on the glacier and extrapolating these point measurements to the whole glacier (Young, 1976). An approximate fixed date measurement system was used (Anonymous, 1969), with winter balance usually being measured in mid to late May and annual balance in mid to late September. Accounting for errors in measurement and errors in the extrapolation algorithm, a conservative standard error of estimate for winter and annual balances in the ablation zone of the glacier is 0.02m water equivalent (Young, 1981). In the accumulation zone, conservative standard errors of estimate are 0.03m for winter balances and 0.05m for annual balances. 1% to 2% of the area of Peyto Glacier was lost during the IHD, but no account of the change was taken in the calculation of mass balance (Young, 1977). Specific accumulation, ablation and annual mass balance results are shown in Figure 2.3.

During the summer months of the IHD, a meteorological station was maintained at Peyto Glacier base camp, located on a lateral moraine at 2200m a.s.l. and about 100m from the glacier. Weather conditions at the base camp appear to reflect local-scale conditions for the basin as a whole.

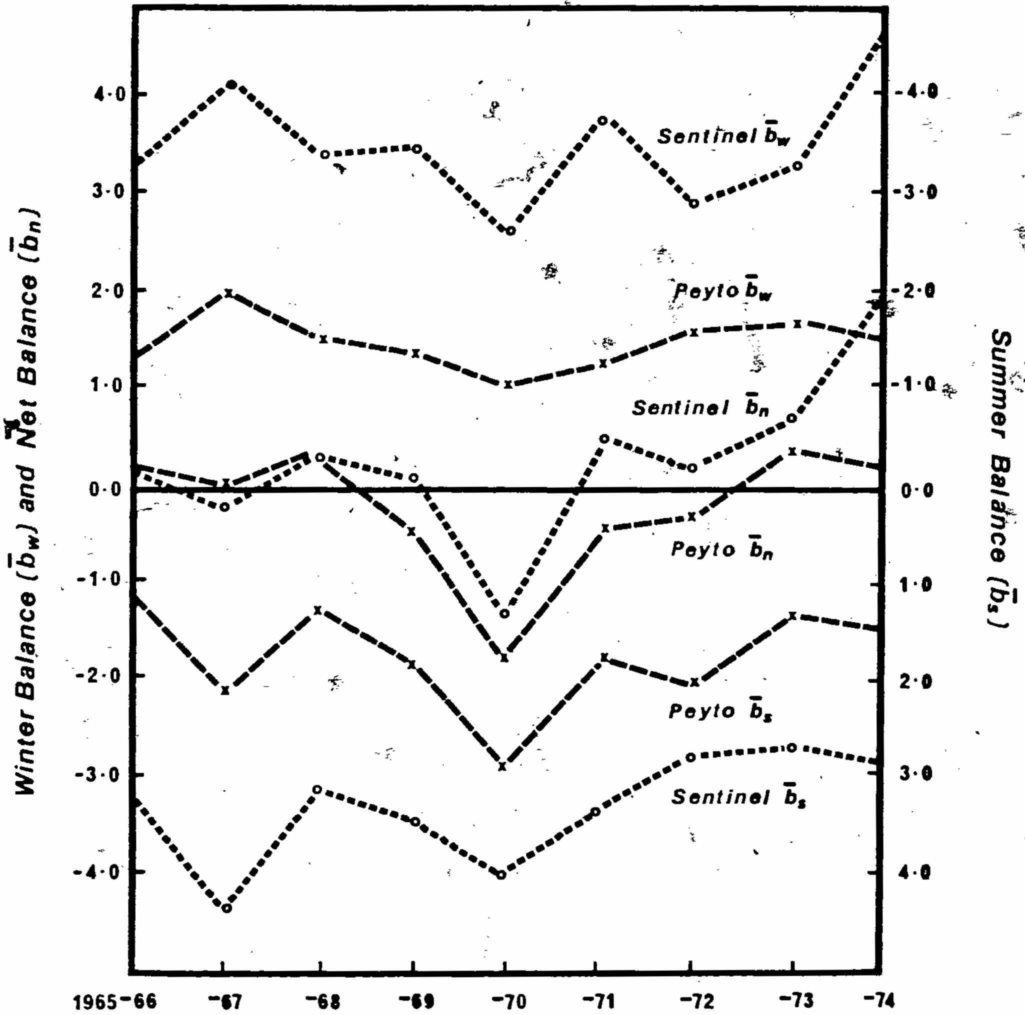


Figure 2.3. Winter balance, summer balance and net mass balance in meters of water equivalent at Peyto and Sentinel Glaciers during the International Hydrological Decade. Data from Young and Stanley (1976) and Mokievsky-Zubok and Stanley (1976).

Young (1977) has performed a factor analysis on the 11 meteorological variables routinely monitored at Peyto. Not unexpectedly, approximately 70% of the total variance in these data is described by a temperature factor and a precipitation factor, thereby suggesting that common daily temperature and precipitation data are useful measures of Peyto's meteorological environment.

2.2.2 Sentinel Glacier

Sentinel Glacier is located at 49°54′N latitude, 122°59′W longitude in the Coast Mountains of British Columbia (Figures 2.1 and 2.4). The maritime climate of the region produces winter snow cover on the glacier that usually exceeds 9m at higher elevations. The relatively small, uneven glacier covers about 2 square km, ranges from 1550m to 2100m a.s.l. and has an average gradient of 17°. The constantly diminishing surface area throughout the IHD was not accounted for in mass balance calculations.

The combination of steep gradient, small area, heavy snow cover and variability in surface topography present difficulties in assessment of mass balance at Sentinel Glacier (Mokievsky-Zubok, 1973a, 1974). However, three methods of mass balance determination consistently produced similar results (Mokievsky-Zubok, 1973b). Standard errors of estimate are not given for Sentinel, but are probably

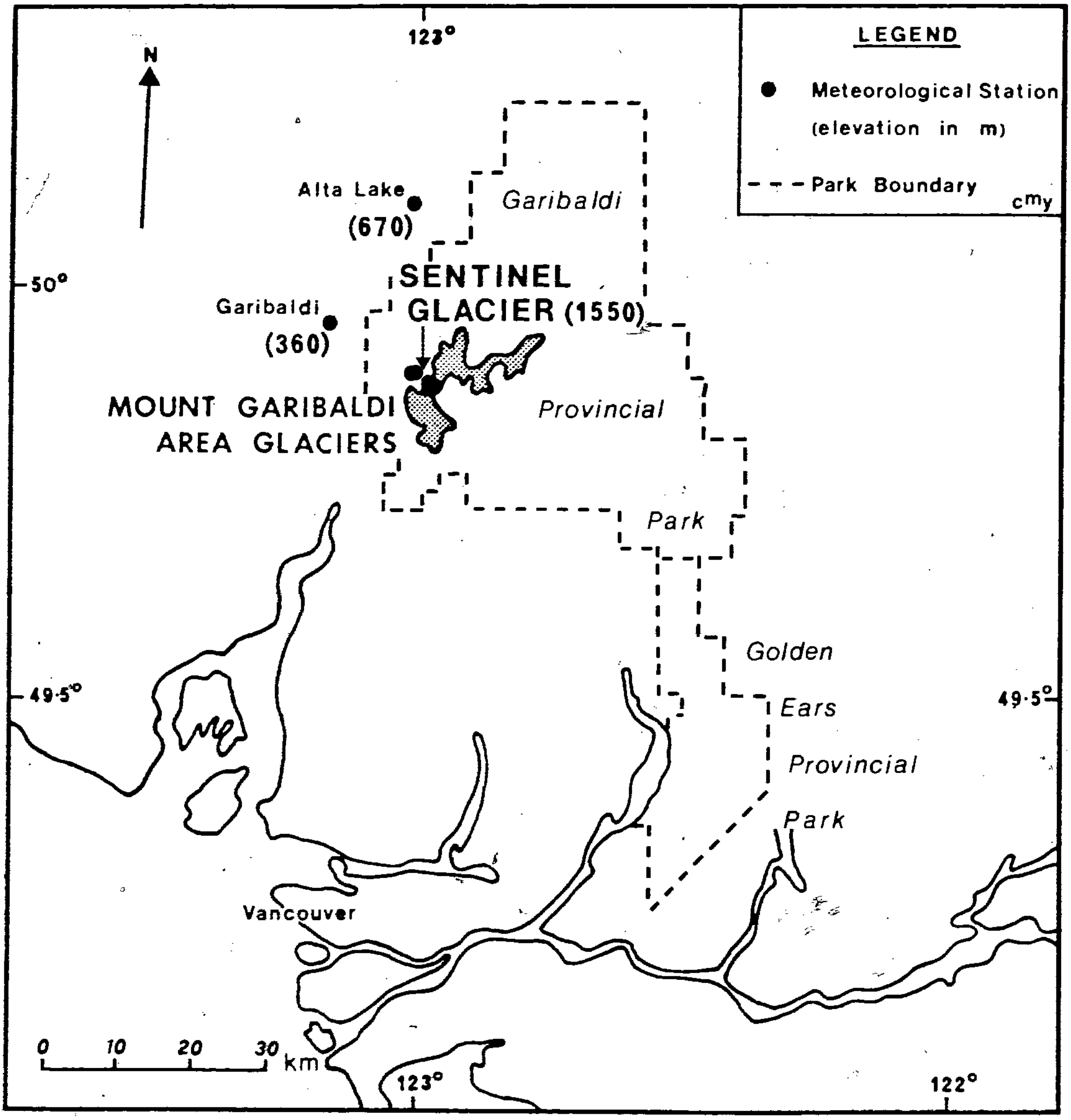


Figure 2.4. Sentinel Glacier and vicinity.

greater than those of Peyto Glacier because of measurement problems and high accumulation and ablation totals. Approximate fixed dates for winter balances (mid May) and annual balances (late September to early October) were used. Mass balance results are presented in Figure 2.3.

A meteorological program similar to the one at Peyto Glacier was carried out. The main base camp weather station is located at 1550m a.s.l. and about 400m downvalley from the glacier. Like Peyto, a principal components analysis suggests the expected association between glacier melt and temperature and precipitation events in the basin (Fogarasi and Mokievsky-Zubok, 1978).

2.3 Data

The primary goal of synoptic climatological research is to associate local climate with atmospheric circulation. In this study, elements of the mass balance and climate of Peyto Glacier and Sentinel Glacier are compared to objectively determined synoptic-scale features of circulation over southwestern Canada. Mass balance, daily mean temperature and daily precipitation data from the 9 glaciological years (1 October 1965 to 30 September 1974) of the IHD programs at Peyto and Sentinel are used to represent local conditions. Unfortunately, the meteorological data from the glaciers are for warm seasons only and the length of record varies from year to year. Therefore, it is necessary to use weather data from nearby meso-scale stations (Figure 1.1) to represent the meteorological environment of the glaciers (Young, 1977). Daily temperature and precipitation data from Banff and Lake Louise, Alberta (Figure 2.2) and Alta Lake and Garibaldi, British Columbia (Figure 2.4) are linked to the data from the glaciers and used throughout the analysis. For association with these ground-based data, daily 1200 GMT synoptic-scale 500mb pressure grids are compiled from the 1977-point National Meteorological Center (NMC) grid of the Northern Hemisphere produced by NCAR (Jenne, 1975). The mid-tropospheric 500mb pressure surface is used because it is above the topographic influence of the Cordillera of southwest Canada.

3. Analytical Techniques

In this chapter, the analytical techniques used in Chapters 4 and 5 are described. The objective synoptic type classification procedure is discussed, followed in turn by crosstabulaton and multiple linear regression techniques. In the latter section, special attention is given to the procedure known as ridge regression. The chapter concludes with a note on the choice of significance levels used in the linear regressions.

3.1 Synoptic type classification procedure

The objective technique proposed by Kirchhofer (1973) is used to classify the synoptic types. This approach has also been employed by Barry and Keen (1978), Moritz (1979), Bradley and England (1979) and Keen (1980) for areas of the North American Arctic.

The classification procedure is applied to two data sets compiled from NCAR 1200 GMT 500mb data. First, a synoptic-scale set of 27 contiguous NMC grid points is used to synthesize 30 equally spaced points of latitude and longitude (Smallgrids; Figure 3.1). Then, a larger, more generalized synoptic-scale set is created in which every other grid point from an 11 by 10 section of the NMC grid is

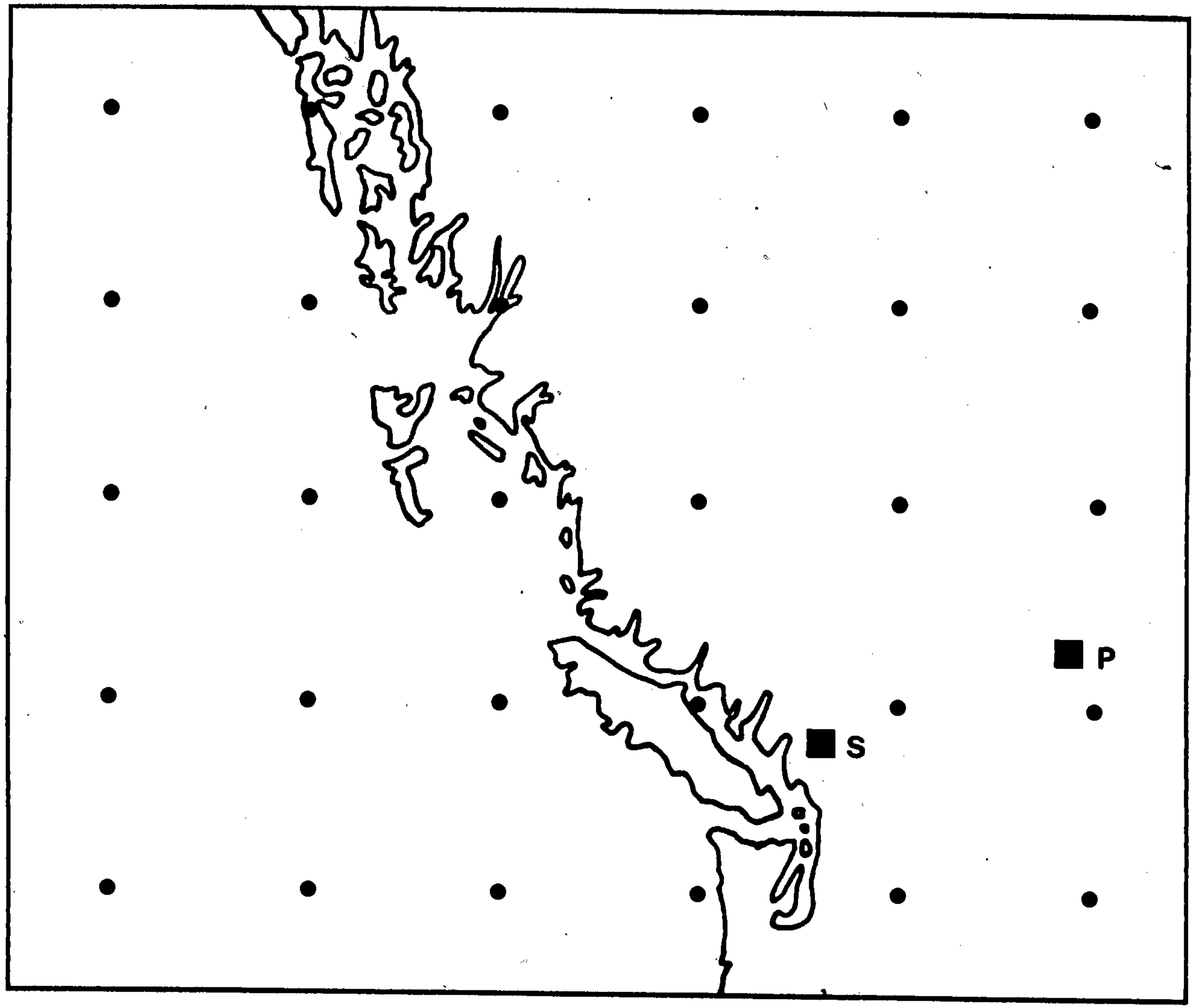


Figure 3.1. Smallgrids.

extracted to produce another 30-point matrix (Biggrids; Figure 3.2). Latitude and longitude are not considered for Biggrids. By using 5 by 6 matrices for both Smallgrids and Biggrids, the same computer algorithm is applied to both data sets, thus facilitating comparison of the resulting climatologies for each synoptic-scale.

To apply the Kirchhofer technique, the gridded pressure data sets are first normalized using the z-transformation:

$$Z_i = \frac{(x_i - \bar{x})}{s} \qquad (3.1)$$

where Z_i = normalized value of grid point i;
x_i = data value at grid point i;
$\bar{x}$ = mean of the N-point grid;
s = standard deviation of the grid.

Each normalized grid is compared to all other grids by the sums of squares equation:

$$S = \sum_{i=1}^{N} (Z_{ai} - Z_{bi}) \qquad (3.2)$$

where S = Kirchhofer score;
Z_{ai} = normalized grid value of point i on day a;
Z_{bi} = normalized grid value of point i on day b;
N = number of data points.

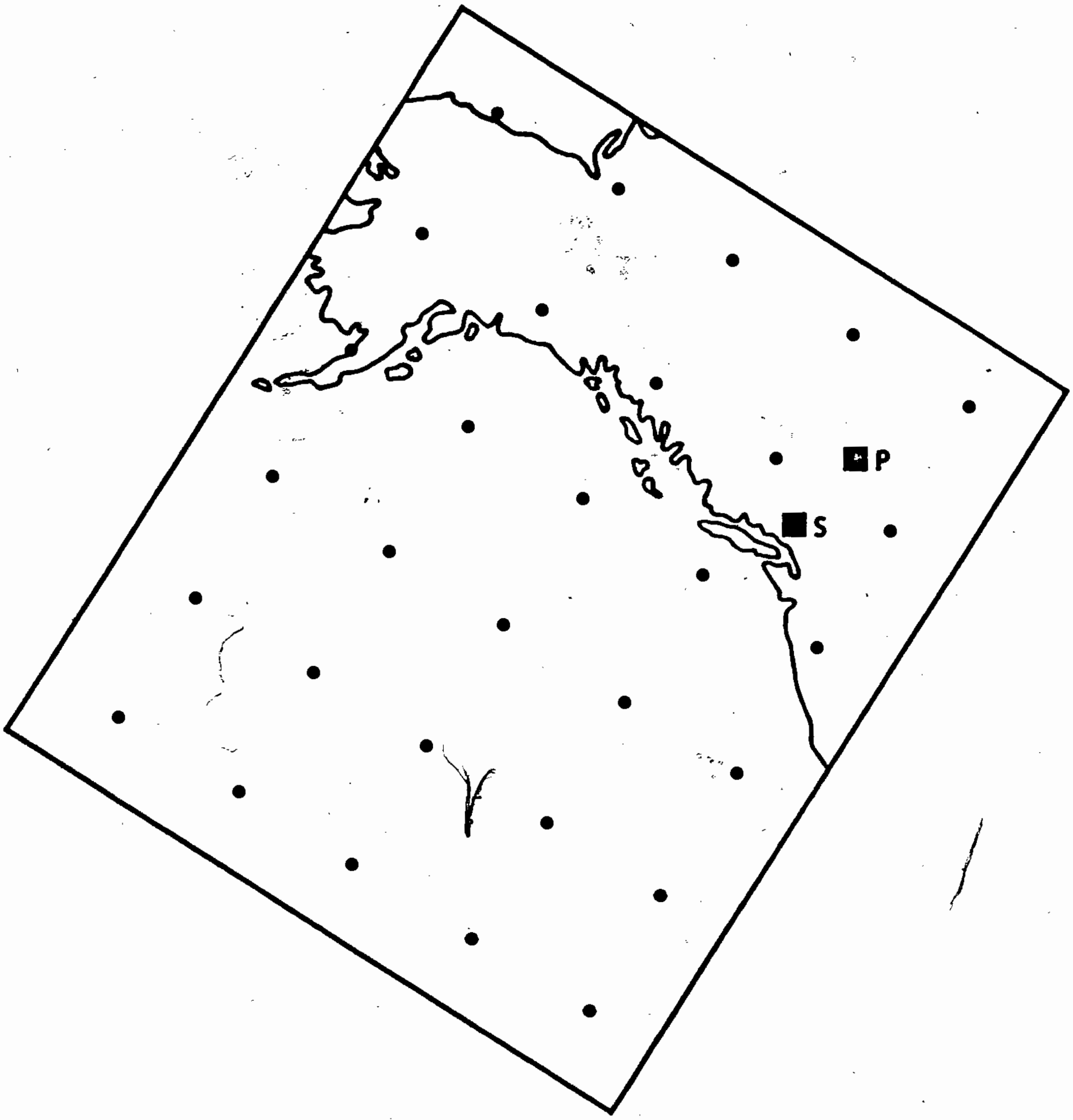


Figure 3.2. Biggrids.

It is possible for a comparison of any two grids to generate a low S value, denoting overall statistical similarity, and yet have widely varying patterns in specific sectors of the map. Therefore, to ensure pattern similarity in all areas of the grids, subscore values for each row and column of the 5 by 6 matrices are calculated using Equation 3.2.

Grids are considered similar if $S < 15$ (in other words, $0.5N$) and row and column scores S_R and $S_C < 1.0N_R$ and N_C, where N_R and N_C equals the number of points in the row or column, respectively. Previously cited studies using the Kirchhofer method (such as Moritz, 1979) have used thresholds for S of 1.0N and for row and column scores of $1.8N_R$ and $1.8N_C$. In the present work, however, the relatively stringent thresholds provide greater similarity within characteristic synoptic patterns while providing a comparably high percentage of classified days and a manageable number of patterns.

Due to computer storage limitations (see below) and cost considerations, it is necessary to use a sample of the days of the 9-year study period. When dealing with an infinite population, sample size is determined (Dixon and Leach, 1978):

$$n = \left(\frac{z\ v}{c}\right)^2 \qquad (3.3)$$

where n = required sample size;

z = confidence level z-score;

v = expected variability of the sample standard deviation relative to the sample mean;

c = confidence limits.

The present study sets the confidence level at 95%, confidence limits at ± 2%, and estimated variability at 50%, so that:

$$n = \left(\frac{1.96*50}{2}\right)^2 \doteq 2401$$

Because 2401 is a large proportion of the population of the 3287 daily grids of the study period, an adjusted sample can be obtained (Dixon and Leach, 1978):

$$n' = \frac{n}{1 + (n/N)} \tag{3.4}$$

$$= \frac{2401}{1 + (2401/3287)}$$

$$\doteq 1387$$

4 years of the study period includes approximately 1460 grids and is therefore taken as a suitable sample size. The glaciological years 1 October to 30 September 1965-66, 1966-67, 1969-70 and 1973-74 are chosen as the 4 sample years following a subjective assessment of the mass balance characteristics of Peyto and Sentinel Glaciers (Table 3.1). It is assumed that the widest range of synoptic weather patterns occured during these years.

87 of the 3287 daily grids are eliminated because of missing or bad data in the NCAR 500mb data set. 39 of the

Table 3.1. Subjective assessment of selected winter balance and summer balance seasons at Peyto and Sentinel Glaciers during the International Hydrological Decade. Parenthetical figures refer to the percentage of mean winter balance or mean summer balance for the 9 year study period.

	PEYTO		SENTINEL	
ASSESSMENT	Winter Balance	Summer Balance	Winter Balance	Summer Balance
very low	1969-70 (70%)	1965-66 (64%)	1969-70 (74%)	------
low	1965-66 (81%)	1973-74 (81%)	------	1973-74 (83%)
average	1973-74 (106%)	------	1965-66 (92%)	1965-66 (97%)
high	------	1966-67 (121%)	1966-67 (118%)	1969-70 (121%)
very high	1966-67 (134%)	1969-70 (163%)	1973-74 (135%)	1966-67 (135%)

deleted days come from the 4 sample years, leaving 1424 sample grids for analysis. The algorithm used to determine Kirchhofer scores requires:

$$\text{space} = \frac{n(n-1)}{2} \qquad (3.5)$$

$$= \frac{1424*1423}{2}$$

$$= 1{,}013{,}176$$

where space = number of bytes in central memory.

The computer facility used for the analysis imposes a 1.6 million byte memory limit per user, thereby restricting the number of sample years available for treatment to 4 in most cases.

S, S_R and S_C values are calculated for every pair of grids in the sample. If the previously mentioned threshold requirements are met, the pair of grids is considered significantly similar and the S value is entered into memory. The daily grid with the most S values associated with it is designated Keyday 1. That keyday is then removed from the analysis along with all grids associated with the keyday and all days associated with those days. This process is repeated to determine subsequent keydays until all days are classified into m groups of 5 days or more. Remaining days are termed "unclassified."

In the final step, S, S_R and S_C values are again calculated, this time for each of the m keydays with each day of the total population (3200) of daily grids. The lowest significant Kirchhofer score is recorded for each daily grid, with the associated keyday denoting the synoptic type of the day. Because it is possible for any day to be significantly related to more than one keyday, days misclassified by early removal during the keyday determination procedure described above are reclassified. Results of the synoptic type classification appear in Appendices I and II and are summarized in Sections 4.2 and 4.3.

3.2 Crosstabulation

A crosstabulation is a joint-frequency distribution of cases according to two or more classificatory variables (Nie, et al., 1975). These joint frequency distributions can be analyzed by the chi-square statistic (Siegel, 1956; Blalock, 1972) to determine the statistical independence of the variables. However, chi-square does not tell the investigator how strongly the variables are related. The strength of the association must be analyzed by one of a number of specialized measures which describe the degree to which the values of one variable predict or vary with those of another. The choice of measure used is determined by sample size, table size and data level.

Asymmetric lambda (λ_b) is a measure of association for crosstabulations based on nominal-level data (Mueller, _et al_., 1977). This statistic measures the percentage improvement in prediction of the value of the dependent variable given knowledge of the value of the independent variable. Asymmetric lambda is calculated (Nie, _et al_., 1975):

$$\lambda_b = \frac{\Sigma \max f_C - \max f_R}{N - \max f_R} \tag{3.6}$$

where $\Sigma \max f_C$ = sum of the maximum values of the cell frequencies in each column;

$\max f_R$ = maximum value of the row totals;

N = number of cases.

The maximum value of lambda is 1.0, which occurs when each independent variable category can be predicted by each category of the dependent variable. A value of zero indicates no improvement in prediction is afforded by knowledge of the independent variable. A crosstabulation using chi-square and asymmetric lambda is performed in Section 4.4 of this thesis to determine the nature and strength of the relationship between Smallgrids and Biggrids synoptic types.

3.3 Multiple linear regression

Multiple linear regression analysis is used extensively in the following chapters. In several cases, the normally straightforward ordinary least squares estimation technique is complicated by a lack of independence among the predictor variables (collinearity).

Consider the standard multiple regression model:

$$y = \mathbf{X}\beta + \varepsilon \qquad (3.7)$$

where y = criterion variable vector;

$\mathbf{X}$ = vector of true regression parameters; β_0 is the regression constant and β_i $(i = 1,2,\ldots,k)$ are the partial regression coefficients;

ε = vector of error terms.

Let:

$$\hat{\beta} = \mathbf{R}^{-1}g \qquad (3.8)$$

where $\hat{\beta}$ = least squares estimate of β;

$\mathbf{R}^{-1} = (\mathbf{X}^T\mathbf{X})^{-1}$ = inverse of the correlation matrix of predictor variables; $\mathbf{X}^T$ = transpose of $\mathbf{X}$;

$g = \mathbf{X}^T y$ = vector of correlation coefficients between y and each X variable.

The difficulties arising from correlated predictor variables are a direct result of the average distance between β and $\hat{\beta}$. Specifically:

$$L^2 = (\hat{\beta} - \beta)^T (\hat{\beta} - \beta) \qquad (3.9)$$

where L^2 = measure of goodness of fit of the estimated regression coefficients (Jones, 1972).

If $\hat{\beta}$ is near β, then L^2 is small and the fit is good. A large L^2 denotes a poor fit. Hoerl and Kennard (1970a) have shown that:

$$E(L^2) = \sigma^2 \operatorname{trace}(R^{-1})$$

$$= \sigma^2 \sum_{i=1}^{k} (1 - \lambda_i) \qquad (3.10)$$

where $E(L^2)$ = expected value of L^2;

σ^2 = variance of ε;

λ_i = "i"th eigenvalue of R.

In other words, as the predictor variables become increasingly correlated, λ_i becomes smaller, L^2 gets larger and $\hat{\beta}$ will be farther from β. Therefore, from the above it can be demonstrated that ordinary least squares estimates from correlated predictor variables may be too large in absolute value and may even have the wrong sign. Additionally, the least squares solution may be unstable with replicate samples producing widely differing regression coefficients.

One solution to the problem of correlated predictors is ridge regression (Hoerl, 1962; Hoerl and Kennard, 1970a, 1970b; Jones, 1972; Stone and Conniffe, 1973; Smith and Goldstein, 1975). In ridge regression, instead of unbiased least squares estimates, the fitting criterion stresses minimum mean square deviation between true and estimated regression coefficients. Although the new coefficients minimize L^2, thus decreasing mean squares, error sums of squares must be allowed to increase slightly. Biased estimation is done by adding a small constant to each of the diagonal elements:

$$\hat{\beta}^* = (R + KI)^{-1}g \tag{3.11}$$

where $\hat{\beta}^*$ = ridge estimate of β;

K = a constant within the range $0.0 \leq K \leq 1.0$;

I = identity matrix.

The ridge trace, a plot of K against $\hat{\beta}^*$, is used to determine the best estimate of $\hat{\beta}^*$ and the nature of the relationships among the variables. The following hypothetical ridge regressions and their ridge traces (Figures 3.3 and 3.4) illustrate use of the technique to remove correlated predictor variables from the full

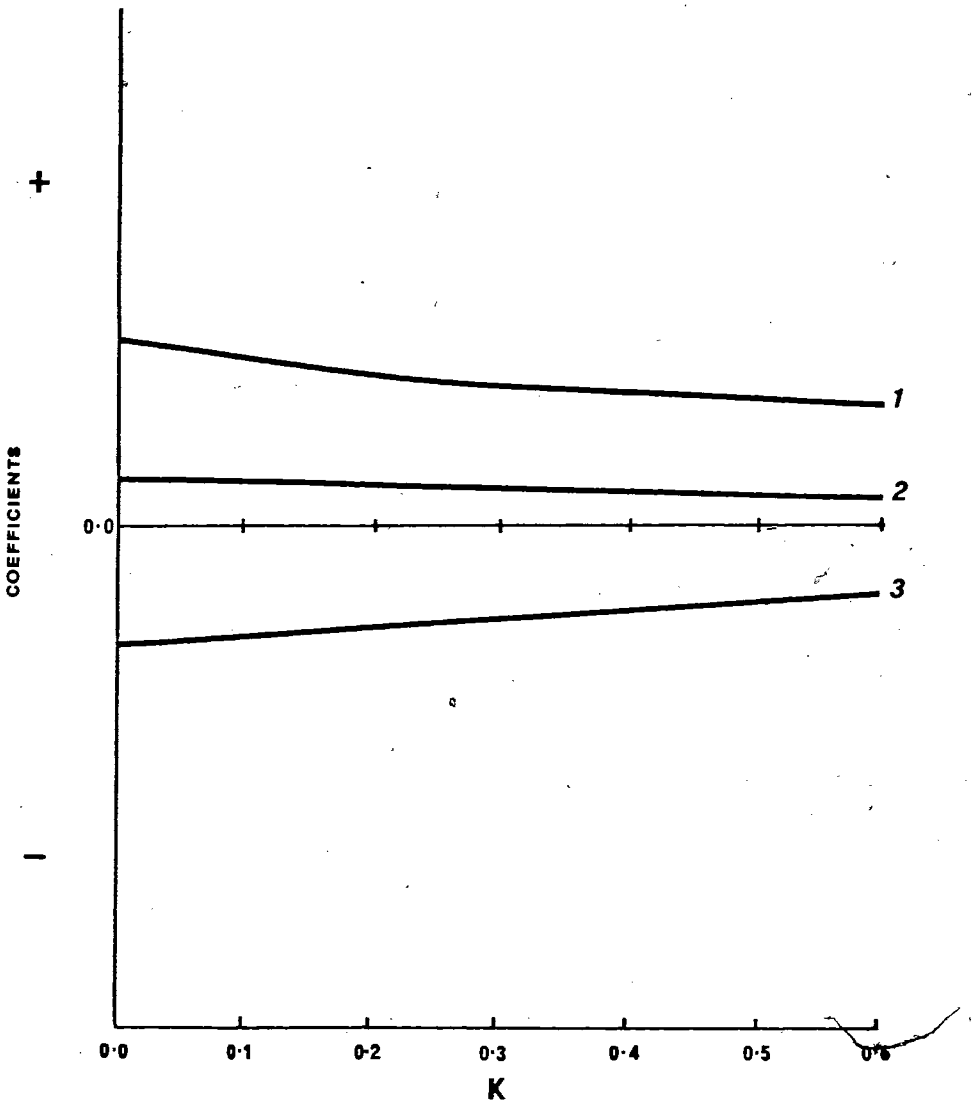


Figure 3.3. Hypothetical ridge trace of uncorrelated predictor variables (after Jones, 1972).

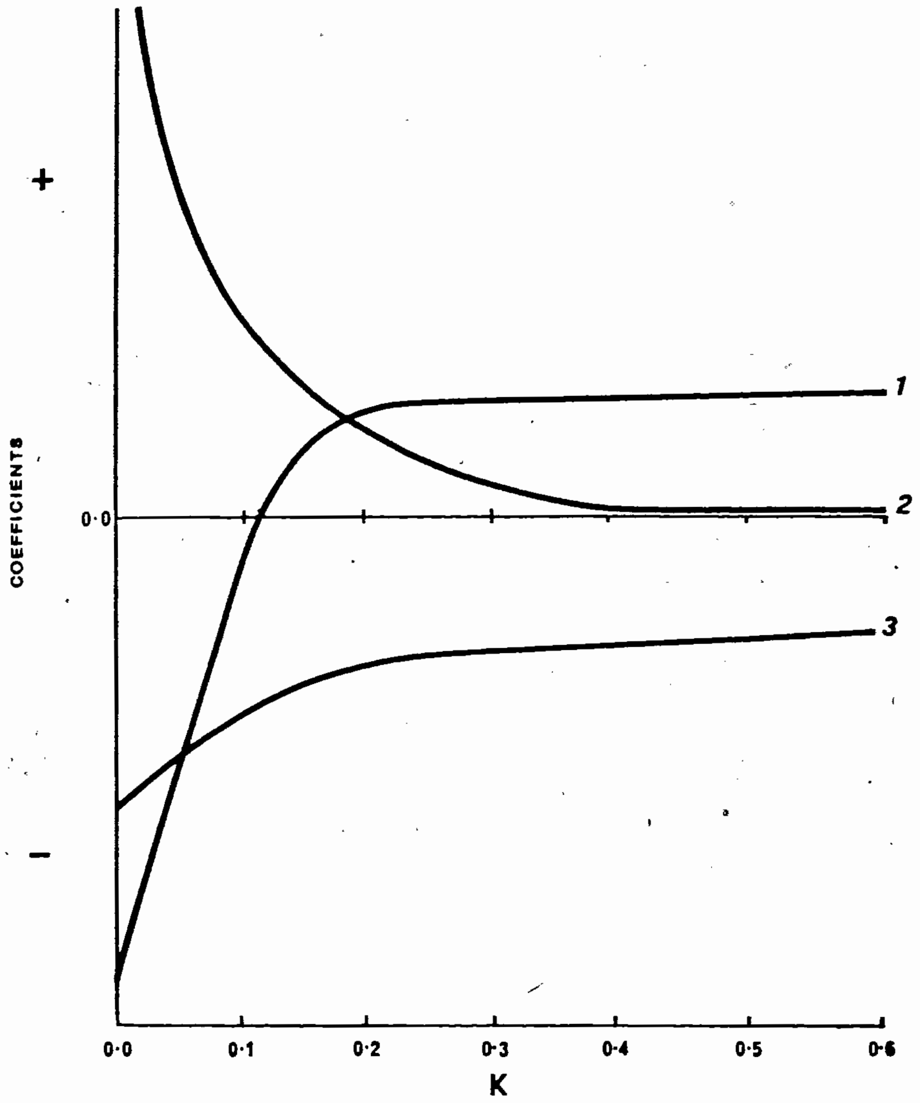


Figure 3.4. Hypothetical ridge trace of correlated predictor variables (after Jones, 1972).

regression model (after Jones, 1972).

In Figure 3.3, there are no correlations between variables and the coefficient values vary little with K. Because this is a stable situation, ridge regression is not needed and the uncorrected least squares coefficients at K = 0.0 are good estimates of β. In Figure 3.4, the predictor variables are strongly correlated and the regression coefficients are sensitive to changes in K. Variable 1 has a high negative coefficient value at K = 0.0, but reverses signs and stabilizes as K increases. Variable 2 starts with a strongly positive coefficient value, but decreases to near-zero values with increasing K. Variable 3 is relatively stable.

Figure 3.4 demonstrates that ordinary least squares estimates (K = 0.0) for Variables 1 and 2 are not reliable because of collinearity. However, as K increases, their ridge traces stabilize. In this thesis, when two variables are collinear, the weaker predictor is removed from the analysis. The rapid movement of Variable 2 to the zero-line as K increases suggests that it does not hold its predictive power (Hoerl and Kennard, 1970b) and is therefore a suitable choice for removal. After Variable 2 is removed, another ridge regression is run with just Variables 1 and 3 to check the presumed stability of the remaining regression coefficients (not shown).

In the present thesis, a technique for applying the stepwise linear regression computer program BMDP2R (Dixon and Brown, 1979) to ridge regression as suggested by Hill (1975) is used. The ridge traces are constructed by computing $\hat{\beta}*$ for several values of K, with emphasis on those values less than K = 0.3. BMDP2R is also used for ordinary least squares regression.

3.4 Significance levels

In hypothesis testing, Type I errors occur when a researcher rejects a null hypothesis that, in fact, is true. Type II errors take place when a null hypothesis is accepted that, in fact, is false. It is traditionally argued that Type I and Type II errors are minimized by setting rejection levels at a "happy medium" of 0.01 to 0.05. Thus, much of the scientific literature reports experiments with results that are significant at the 0.01 or 0.05 levels. Unfortunately, automatic use of these conventional significance levels can set artificial limits that largely ignore the character of the data set and the practical consequences of the research design.

Skipper, et al. (1967) question the conventional wisdom that Type I and Type II errors are best avoided by the use of 0.01 and 0.05 significance levels. They demonstrate that there are no standard significance levels that are satisfactory for all statistical tests. The authors also show that in any case it is impossible to minimize Type I and II errors without increasing the number of observations recorded. Based on the above, they recommend that significance levels should be adjusted as research demands and that the level of significance should be reported to the reader. In support of their views, Labovitz (1968) suggests criteria for selecting significance levels, including the use of relaxed levels of significance when sample sizes are small.

In Chapter 5 of the present thesis, hypothesis testing of the linear regressions is applied to situations with extremely small sample sizes (N = 6, 7 or 8). Strict adherence to conventional significance levels is inappropriate: the small sample sizes promote a tendency towards committing Type II errors. Furthermore, relaxed levels of significance are in order because of the bias towards Type II errors and because of the exploratory nature of the analysis. Therefore, shifting significance levels are used, with results reported at the 0.001, 0.01, 0.05, 0.10 and 0.20 levels of significance. Data that are not significant at the relaxed 0.20 level are listed as "not significant."

4. General Synoptic Climatology

Results of the synoptic type classifications are reported and basic associations between pressure patterns and the climate of the Peyto and Sentinel Glacier areas are discussed in this chapter. The relationship between Smallgrids and Biggrids synoptic types is also analyzed. First, an analysis of glacier seasons and meso-scale data selection is carried out.

4.1 Analysis of seasons and selection of meso-scale data

Climatological and glaciological analyses generally use fixed-length seasons or key months to represent seasons. However, interannual variability in the length, first day and last day of a season are important elements of the climate that affect glacier mass balance. Therefore, in this thesis the natural seasons at Peyto and Sentinel Glaciers are used for analysis.

To establish the natural glacier seasons, arbitrary cut-offs must be established that mark the end of one season and the beginning of another. Here, Winter is defined as that period where all mean daily temperatures at the glacier meteorological station are below 0^{0}C, while Summer mean daily temperatures are always above freezing. The shoulder seasons, Fall and Spring, are those periods when mean daily temperatures fluctuate above and below 0°C.

Since temperature records at Peyto and Sentinel Glaciers are incomplete, daily temperature data from nearby meso-scale stations (Figure 1.1) are used to establish season cut-off dates. Stepwise linear regression shows that daily maximum temperatures from Banff and Alta Lake enter first into the regression equations and explain more than 80% of the variation in mean daily temperatures at Peyto and Sentinel Glaciers, respectively (Tables 4.1 and 4.2). An analysis of variance (not shown) demonstrates that subsequent entries into the regression do not add significantly to the variance explained by daily maximum temperature at Banff and Alta Lake. Using the equations derived from the first step of these regressions, daily mean temperatures and glacier seasons for Peyto and Sentinel can be predicted.

Tables 4.3 and 4.4 list the resulting natural glacier seasons. Cross-checking these dates with cases where seasonal transitions were recorded at the glacier meteorological stations find~~s~~ predicted dates are usually accurate within approximately ± 1 day. Inspection of the tables reveals that Peyto Winters are generally much longer than Peyto Summers, whereas Summer is the dominant season at

Table 4.1. Regression analysis of the relationship of warm season mean daily temperature at Peyto Glacier with temperatures at Banff and Lake Louise. All data are considered as a single group for significance testing.

CRITERION VARIABLE: Peyto Glacier mean daily temperature

PREDICTOR VARIABLE	CUMULATIVE R^2	R^2 CHANGE	REGRESSION COEFFICIENT
Banff Tmax	83.4	83.4	0.385
Banff Tmin	86.9	3.5	0.177
Lake Louise Tmax	88.1	1.2	0.212
Lake Louise Tmin	88.3	0.2	0.101
		(y-intercept)	-6.984

F observed = 1891.74

F critical (at 4 and ∞ degrees of freedom and with $\alpha = 0.001$) = 4.62 .

Table 4.2. Regression analysis of the relationship of warm season mean daily temperature at Sentinel Glacier with temperatures at Alta Lake. All data are considered as a single group for significance testing.

CRITERION VARIABLE: Sentinel Glacier mean daily temperature

PREDICTOR VARIABLE	CUMULATIVE R^2	R^2 CHANGE	REGRESSION COEFFICIENT
Alta Lake Tmax	81.5	81.5	0.553
Alta Lake Tmin	84.8	3.3	0.259
		(y-intercept)	-5.602

F observed = 2778.83

F critical (at 2 and ∞ degrees of freedom and with $\alpha = 0.001$) = 6.91

Table 4.3. Peyto Glacier seasons during the International Hydrological Decade.

GLACIOLOGICAL YEAR	FALL			WINTER			SPRING			SUMMER		
	Length	First Day	Last Day	Length	First Day	Last Day	Length	First Day	Last Day	Length	First Day	Last Day
1965-66	67	0828#	1102	140	1103	0323	59	0324	0523	123	0524	0923
1966-67	33	0924	1026	176	1027	0423	37	0424	0531	122	0601	0930
1967-68	31	1001	1031	115	1101	0226	78	0227	0514	126	0515	0917
1968-69	42	0918	1029	148	1030	0329	50	0330	0519	117	0520	0913
1969-70	39	0914	1022	182	1023	0429	12	0430	0512	118	0513	0907
1970-71	55	0908	1101	148	1102	0404	58	0405	0604	101	0605	0913
1971-72	29	0914	1012	153	1013	0315	70	0316	0525	103	0526	0905
1972-73	45	0906	1020	163	1021	0409	54	0410	0602	89	0603	0830
1973-74	58	0831	1027	145	1028	0326	64	0327	0530	99	0531	0906
MEAN	44	0912	1026	152	1027	0331	54	0401	0525	111	0526	0912
STANDARD DEVIATION (DAYS)	13	11	7	20	7	28	19	28	8	13	8	13

Outside the study period.

Table 4.4. Sentinel Glacier seasons during the International Hydrological Decade.

	FALL			WINTER			SPRING			SUMMER		
GLACIOLOGICAL YEAR	Length	First Day	Last Day	Length	First Day	Last Day	Length	First Day	Last Day	Length	First Day	Last Day
1965-66	27	1016	1111	---	1112	*	--	*	0414	---	0415	*
1966-67	--	*	*	---	*	0331	17	0401	0417	184	0418	1018
1967-68	20	1019	1107	108	1108	0223	71	0224	0505	152	0506	1004
1968-69	47	1005	1120	110	1121	0310	53	0311	0502	169	0503	1018
1969-70	26	1019	1113	99	1114	0220	64	0221	0425	177	0426	1020
1970-71	16	1021	1105	133	1106	0318	35	0319	0422	177	0423	1016
1971-72	7	1017	1023	144	1024	0315	46	0316	0430	144	0501	0921
1972-73	33	0922	1024	123	1025	0220	66	0221	0427	167	0428	1011
1973-74	17	1012	1028	150	1029	0319	38	0320	0426	187	0427	1030#
MEAN	24	1015	1105	124	1106	0309	49	0310	0425	170	0426	1013
STANDARD DEVIATION (DAYS)	12	10	11	19	11	16	18	16	7	15	7	12

* Missing Alta Lake data.
\# Outside the study period.

Sentinel. On average, Spring is the longer shoulder season at both glaciers. Falls at Peyto Glacier are nearly twice the length and half the variability of those at Sentinel Glacier. Fall of 1965-66 at Peyto and Summer of 1973-74 at Sentinel extend beyond the bounds of the study period (1 October 1965 to 30 September 1974) and will not be used in many of the subsequent analyses. Missing daily maximum temperature values at Alta Lake during periods of 1965-66 and 1966-67 prevent determination of several seasons at Sentinel Glacier.

The stratigraphic system of mass balance determination (Anonymous, 1969) uses natural glacier seasons like those described above. However, approximate fixed dates were used to determine the mass balances of Peyto and Sentinel Glaciers (Young and Stanley, 1976; Mokievsky-Zubok and Stanley, 1976). Mixing of the two measurement systems introduces error (Anonymous, 1969), but is unavoidable in this thesis unless annual climatic variation is artificially constrained by using the approximated fixed dates as seasonal boundaries. Demonstrating this source of error and using the most extreme example possible, the Summer season began on 18 April 1967 at Sentinel Glacier (Table 4.4), but the winter balance was not measured until 31 May 1967. Considerable variation in synoptic-scale weather, ablation and accumulation was possible in that 44 day period. In this case, use of the approximate fixed date without consideration of the natural seasons moves ablation season synoptic type and climate data into the Accumulation season (see Section 5.1.3). The measured winter balance will probably differ slightly from the figure that would have been obtained using the stratigraphic method. Fortunately, in all other cases, the dates when winter or annual balances were measured were much closer to the natural season transition so that discrepancies between actual and measured mass balance data are considered to be small (R.B.Sagar, personal communication, after O. Mokievsky-Zubok, March, 1982).

Choice of the best meso-scale daily precipitation data is treated in the same manner as temperature. Stepwise linear regression reveals that Lake Louise and Alta Lake daily precipitation better predict warm season precipitation at the glaciers than data from Banff or Garibaldi, respectively (Tables 4.5 and 4.6). Disappointingly, only about 15% and 50% of the variance in precipitation at Peyto and Sentinel, respectively, is explained by these data. These low levels of statistical explanation are believed to be the result of the high spatial variability of summer convective activity in mountainous regions (World Meteorological Organization, 1972). The greater explanation provided by the Alta Lake data suggests that during summer

Table 4.5. Regression analysis of the relationship of warm season precipitation at Peyto Glacier with precipitation at Banff and Lake Louise. All data are considered as a single group for significance testing.

CRITERION VARIABLE: Peyto Glacier daily precipitation

PREDICTOR VARIABLE	CUMULATIVE R^2	R^2 CHANGE	REGRESSION COEFFICIENT
Lake Louise precip.	15.0	15.0	0.307
Banff precip.	20.7	5.7	0.254
		(y-intercept)	0.963

F observed = 129.83

F critical (at 2 and ∞ degrees of freedom and with $\alpha = 0.001$) = 6.91

Table 4.6. Regression analysis of the relationship of warm season precipitation at Sentinel Glacier with precipitation at Alta Lake and Garibaldi. All data are considered as a single group for significance testing.

CRITERION VARIABLE: Sentinel Glacier daily precipitation

PREDICTOR VARIABLE	CUMULATIVE R^2	R^2 CHANGE	REGRESSION COEFFICIENT
Alta Lake precip.	51.5	51.5	1.218
Garibaldi precip.	53.6	2.1	0.313
		(y-intercept)	0.332

F observed = 574.20

F critical (at 2 and ∞ degrees of freedom and with $\alpha = 0.001$) = 6.91

months the Coast Range is influenced by the passage of weak weather fronts that have not yet been fragmented by the mountainous terrain of the interior. It is assumed that the winter precipitation of both regions is the result of vigorous, deep fronts, thus providing the spatial coherence needed to relate meso-scale precipitation to glacier accumulation. Subsequent analysis supports this assumption.

4.2 Smallgrids analysis

4.2.1 Smallgrids synoptic types

Table 4.7 summarizes the results of the Smallgrids synoptic type classification. The 18 synoptic types recognized account for 93.7% of the days in the study period. The first eight types account for over 77% of the days, with higher order types being much less important in terms of frequency. Mean Kirchhofer scores are well below the threshold value of 15.0, and Kirchhofer score standard deviations are relatively small, suggesting the classification fit is good. Kirchhofer scores are related inversely to frequency, indicating greater pressure pattern diversity in less frequent types (Bradley and England, 1979). The keyday maps for each of the 18 synoptic types are shown in Figures 4.1 to 4.3. A catalog of synoptic types for all 9 years of the study is presented in Appendix I.

Table 4.7. Summary of the Smallgrids synoptic type classification, 1 October 1965 to 30 September 1974.

TYPE	FREQUENCY (%)	MEAN KIRCHHOFER SCORE	KIRCHHOFER SCORE STANDARD DEVIATION
1	24.2	4.5	2.4
2	14.2	5.3	2.8
3	6.5	7.0	2.7
4	10.5	4.9	2.7
5	7.1	5.4	2.9
6	8.3	6.7	2.5
7	2.0	7.7	2.8
8	4.8	6.6	2.4
9	1.7	8.3	3.2
10	2.0	7.7	3.2
11	1.2	8.7	3.6
12	2.5	8.4	2.8
13	0.6	9.4	3.3
14	1.7	8.3	3.3
15	2.6	6.5	2.9
16	2.7	6.9	2.7
17	0.3	10.6	4.2
18	0.8	8.4	3.6
UNCLASSIFIED	3.7	---	---
MISSING DATA	2.6	---	---

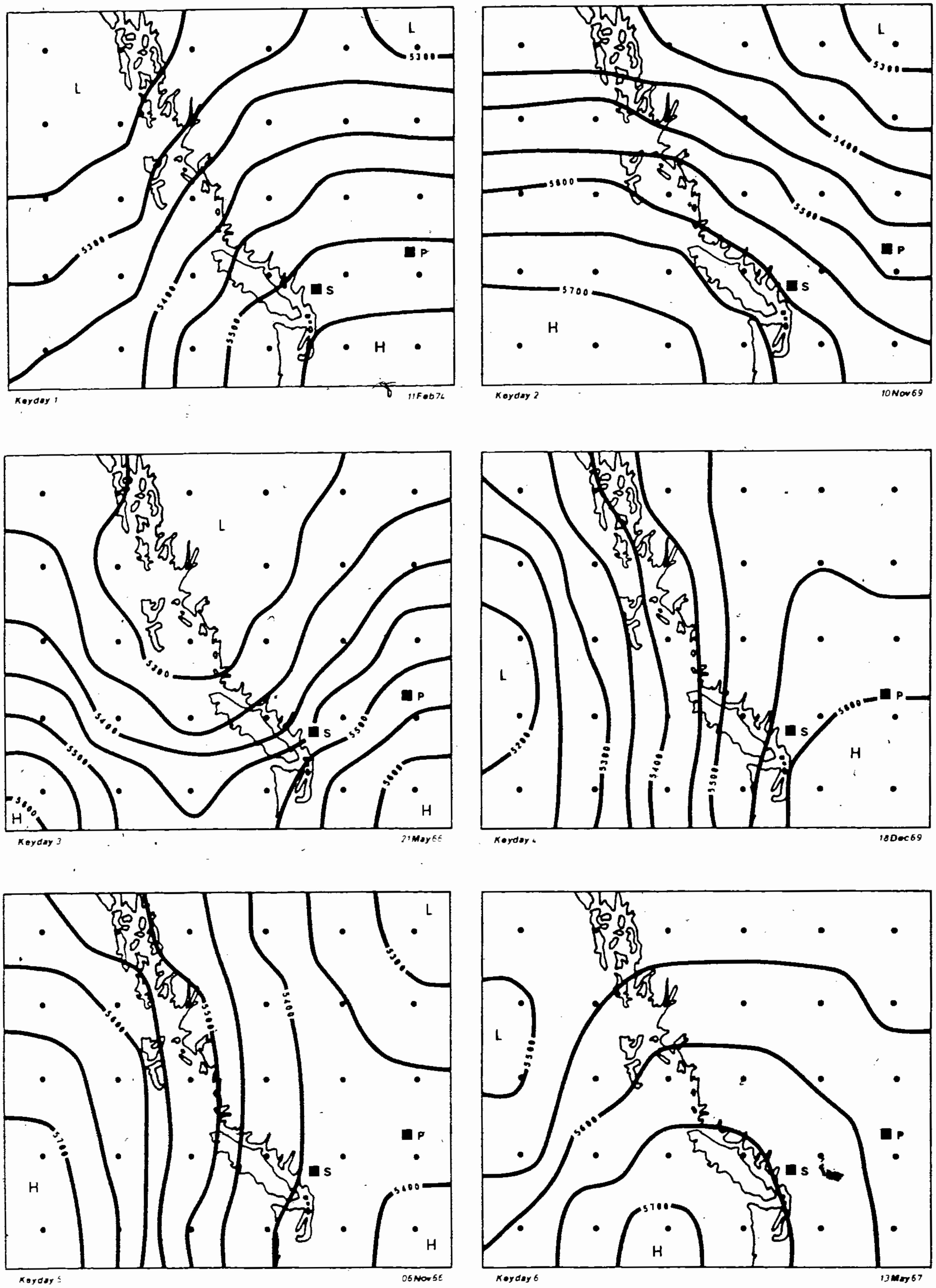


Figure 4.1. 500mb pressure distributions on Smallgrids Keydays 1 to 6.

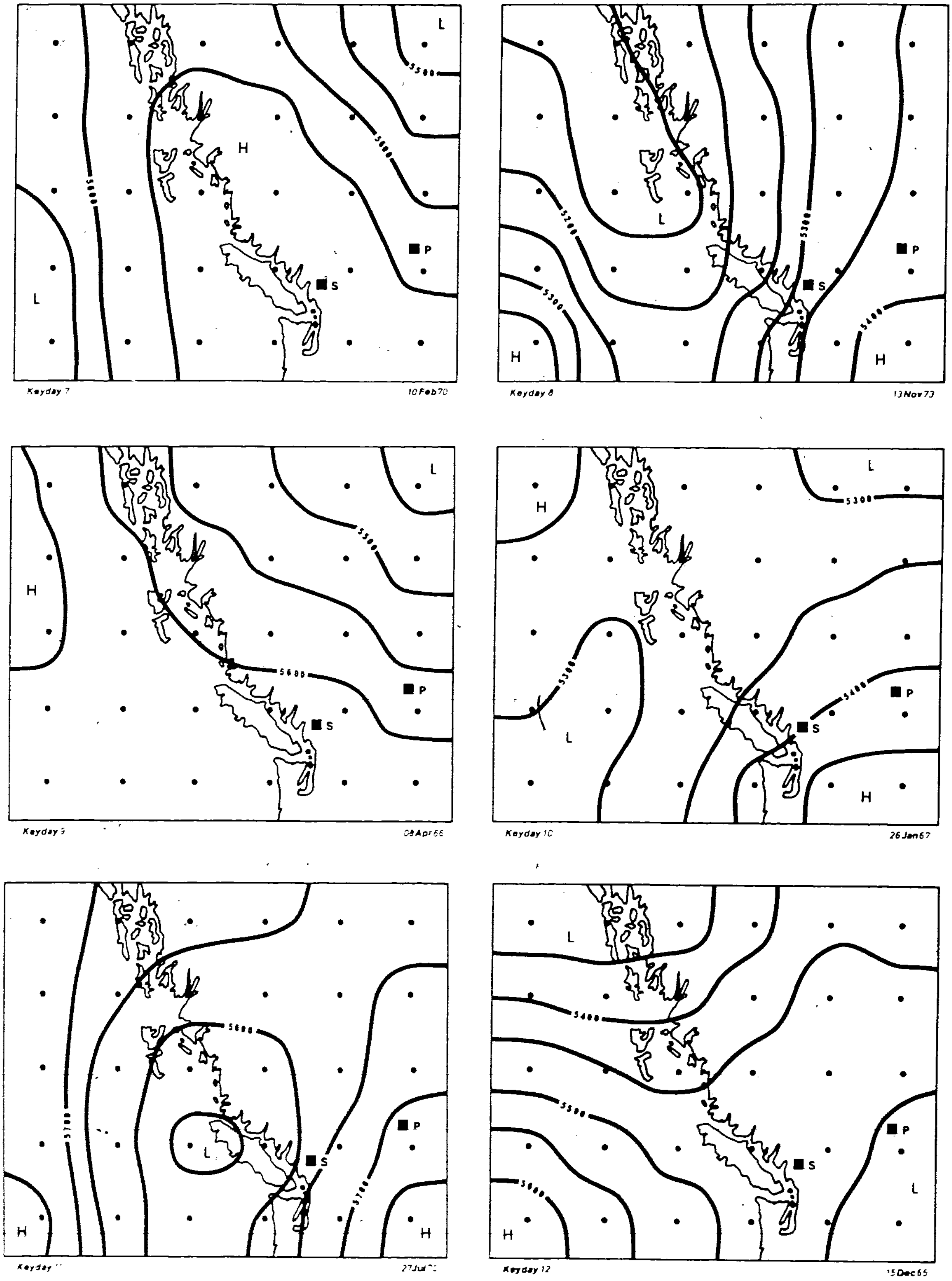


Figure 4.2. 500mb pressure distributions on Smallgrids Keydays 7 to 12.

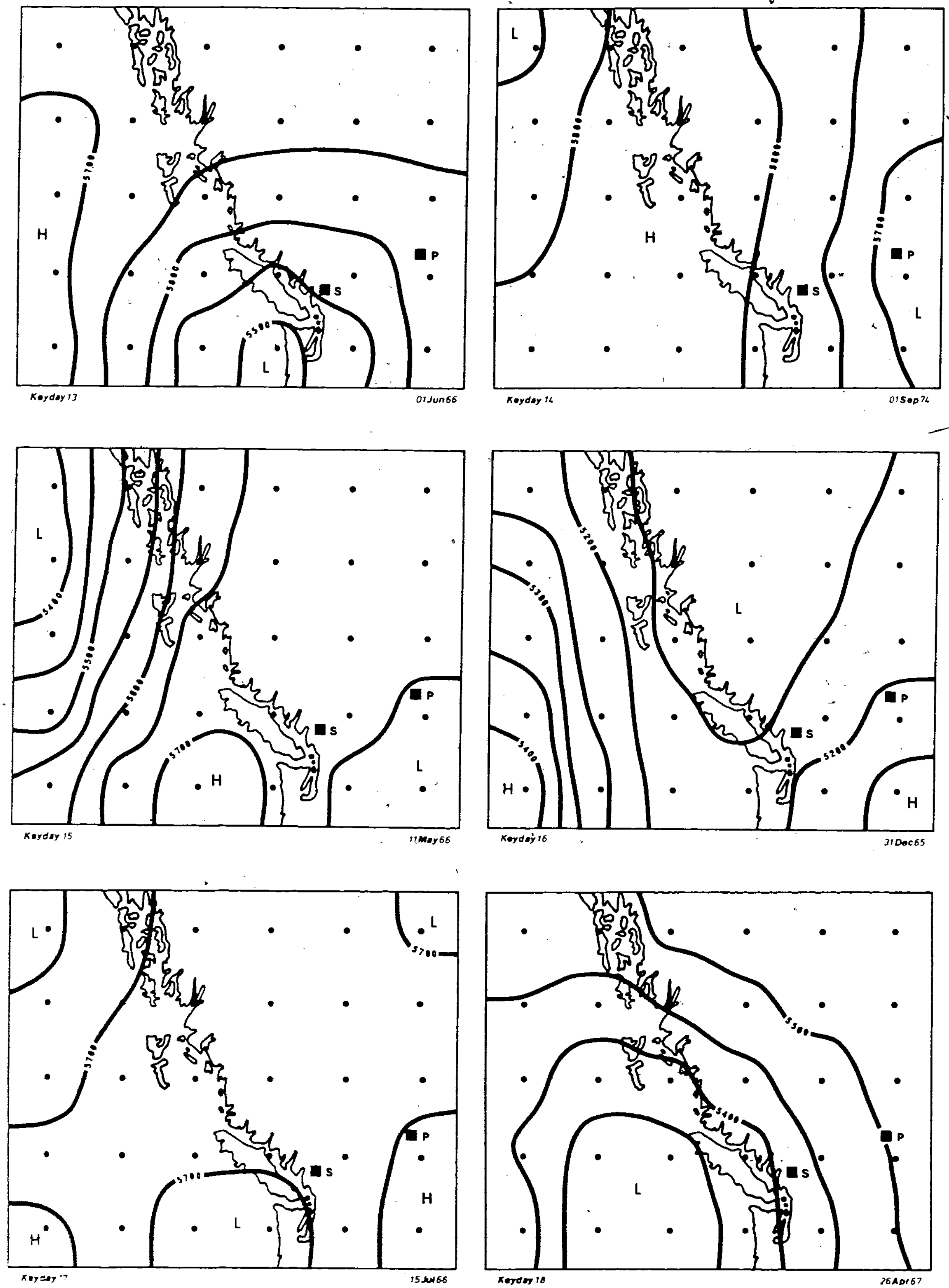


Figure 4.3. 500mb pressure distributions on Smallgrids Keydays 13 to 18.

4.2.2 Synoptic type frequencies

An index of seasonal differences in synoptic type frequencies is computed (Moritz, 1979):

$$\Delta f = \sum_{i=1}^{N} |f_{ij} - f_{ik}| \qquad (4.1)$$

where f = mean seasonal percentage frequency of synoptic type i in season j or k;

N = number of synoptic types.

The relative size of Δf denotes the degree of difference in the synoptic type regimes of the periods being compared. Δf is used to compare the seasonal synoptic type regimes of Peyto and Sentinel Glaciers and the relative season-to-season regime differences at each glacier.

Because season length and time of occurrence varies between Peyto and Sentinel, the seasonal Smallgrids synoptic type regimes at each glacier also vary. Table 4.8 shows that although Winter type regimes at Peyto and Sentinel are similar, Fall regimes are quite different. Spring and Summer synoptic type regime differences are moderate, but are sufficiently large to warrant the differentiation of Peyto and Sentinel in subsequent analysis.

Δf provides insight into the nature of the season-to-season Smallgrids synoptic type regime differences

Table 4.8. Relative seasonal differences (Δf) between the Smallgrids synoptic type frequency regimes at Peyto and Sentinel Glaciers.

	Δf
Fall	31.8
Winter	6.6
Spring	17.3
Summer	13.5

at each glacier (Table 4.9 and 4.10). At Peyto, the Fall synoptic type regime is distinct, with the transition from Summer to Fall Regimes being most pronounced (Figure 4.4). At Sentinel, the Δf patterns are similar to those of Peyto, with the exception of the sharper difference between Fall and Winter regimes. These data, taken with the brevity of the Fall season at each glacier (Tables 4.3 and 4.4) suggest that the arrival of winter is abrupt in southwestern Canada. Harmon (1971) states that autumn is a period of considerable variability in the atmospheric circulation of the Northern Hemisphere, with changing latitudinal and longitudinal distributions of heat sources leading to an intensification of the westerlies. Δf calculations also suggest that Spring is a time of atmospheric variability over the study area, again agreeing with Harmon (1971). Based on the above Δf comparisons, subsequent analyses are stratified by glacier, season when appropriate.

Smallgrids synoptic type frequencies are summarized in Tables 4.11 and 4.12, respectively. Type 1 is the preponderant circulation pattern in all seasons, but is least dominant in Winter. Types 2, 3, 4, 5, 6 and 8 are all important annually, but change the order of their frequency rankings with season and region. For example, Type 2 is the second most dominant pattern in most seasons, but Type 4 is second most frequent at Peyto in Spring and Summer and at

Table 4.9. Relative seasonal differences (Δf) of the Smallgrids synoptic type frequency regimes at Peyto Glacier.

	Fall	Winter	Spring	Summer
Fall	0.0			
Winter	33.5	0.0		
Spring	38.2	34.5	0.0	
Summer	38.9	25.9	24.1	0.0

Table 4.10. Relative seasonal differences (Δf) of the Smallgrids synoptic type frequency regimes at Sentinel Glacier.

	Fall	Winter	Spring	Summer
Fall	0.0			
Winter	45.7	0.0		
Spring	36.6	26.9	0.0	
Summer	33.0	22.0	16.2	0.0

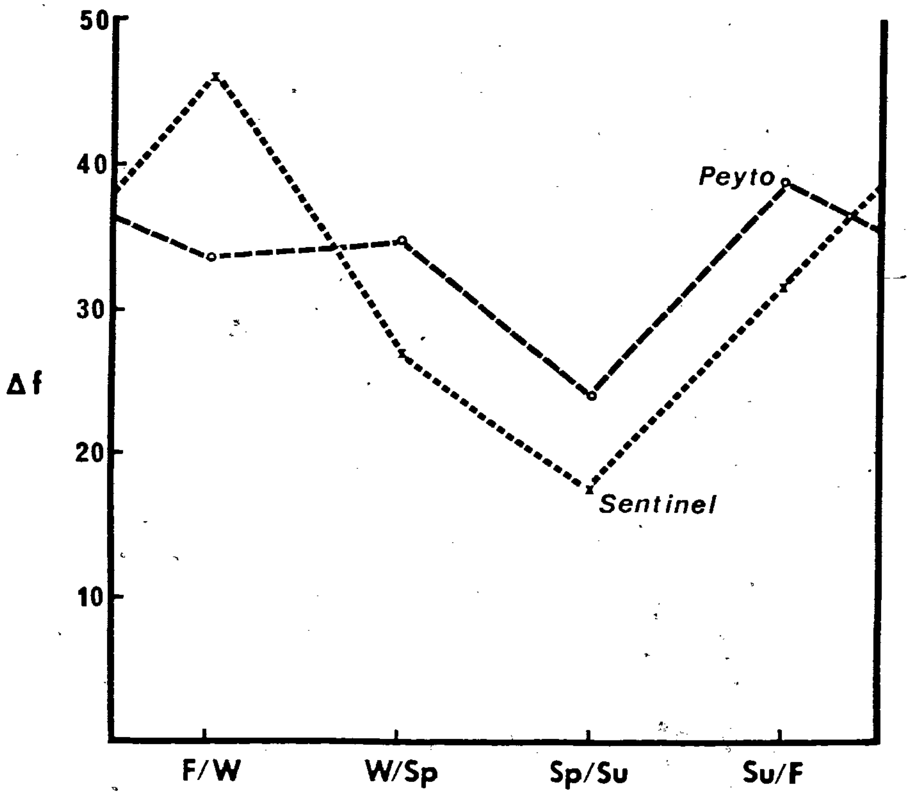


Figure 4.4. Smallgrids Δf comparisons for consecutive seasonal pairs at Peyto and Sentinel Glaciers (after Moritz, 1979).

Table 4.11. Smallgrids synoptic type frequencies at Peyto Glacier in mean days per season.

ANNUAL		FALL		WINTER		SPRING		SUMMER	
Type	Days	Type	Days	Type	Days	Type	Days	Type	Days
1	88.6	1	12.0	1	36.4	1	11.6	1	26.8
2	51.9	2	5.4	2	27.0	4	7.3	4	13.9
4	38.3	6	5.2	5	15.6	2	5.9	2	13.3
6	29.9	5	3.2	4	14.4	6	4.9	6	8.0
5	26.3	3	2.5	6	12.2	3	3.6	3	7.6
3	23.8	4	2.5	3	10.3	8	3.4	8	6.3
8	17.4	8	2.2	8	5.6	15	2.9	5	4.8
16	9.8	16	1.6	16	4.4	12	2.7	7	3.0
15	9.6	12	1.5	10	4.1	5	2.4	9	2.8
12	9.1	15	0.8	15	3.9	16	1.5	10	2.7
7	7.2	14	0.6	7	3.3	14	1.0	11	2.7
10	7.2	18	0.4	12	3.3	9	0.9	16	2.3
9	6.3	9	0.2	14	3.0	13	0.9	15	2.1
14	6.2	7	0.1	9	2.5	18	0.7	12	1.7
11	4.2	10	0.1	11	1.4	7	0.5	14	1.6
18	2.9	11	0.0	18	0.8	10	0.2	18	1.1
13	2.2	13	0.0	13	0.4	17	0.2	13	0.9
17	1.0	17	0.0	17	0.2	11	0.1	17	0.7

Table 4.12. Smallgrids synoptic type frequencies at Sentinel Glacier in mean days per season.

ANNUAL		FALL		WINTER		SPRING		SUMMER	
Type	Days	Type	Days	Type	Days	Type	Days	Type	Days
1	88.6	1	7.9	1	29.0	1	11.1	1	39.6
2	51.9	4	3.1	2	22.4	2	6.2	2	20.9
4	38.3	6	2.5	5	13.1	4	6.2	4	18.1
6	29.9	2	2.1	4	10.4	6	3.9	6	13.6
5	26.3	3	1.6	6	8.7	5	3.5	3	10.0
3	23.8	8	1.2	3	8.0	3	3.4	5	9.3
8	17.4	5	0.9	8	4.1	8	2.4	8	8.6
16	9.8	10	0.6	16	3.9	12	2.2	16	4.9
15	9.6	16	0.5	15	3.4	15	2.2	15	4.7
12	9.1	12	0.4	10	2.9	7	1.2	12	4.1
7	7.2	15	0.4	7	2.4	9	1.0	7	3.4
10	7.2	14	0.2	14	2.4	16	1.0	14	3.3
9	6.3	18	0.2	9	2.0	14	0.8	9	3.1
14	6.2	7	0.1	12	2.0	10	0.5	11	3.0
11	4.2	9	0.1	11	0.9	11	0.2	10	2.9
18	2.9	11	0.1	13	0.4	13	0.2	18	2.6
13	2.2	13	0.0	18	0.4	17	0.2	13	1.0
17	1.0	17	0.0	17	0.1	18	0.1	17	0.1

Sentinel in the Fall. Less frequent, higher order synoptic types are not important on average, but can be significant factors in any given glaciological year.

4.2.3 Smallgrids climatological characteristics

In the following, keyday maps are analyzed and climatic data from each meso-scale station are stratified by Smallgrids synoptic type to determine the climatic characteristics of each circulation pattern. Regional airflow, temperature and precipitation characteristics of the Smallgrids types are discussed.

The predominant 500mb airflow over Peyto and Sentinel Glaciers on the Smallgrids synoptic type keydays is presented in Table 4.13. Westerly flows are most common, confirming earlier work demonstrating that marine or modified marine air dominates the climate of both glacier regions (Walker, 1961). Inspection of the keyday maps also suggests that in general the least frequent, higher orderstop synoptic types have meridional airflow, whereas lower order types are more likely to be zonal in nature.

The Smallgrid synoptic types are ranked in order of increasing mean daily maximum temperatures (Tables 4.14 and 4.15). Above average temperatures are generally associated with south to southwesterly 500mb flows, such as Types 1 and 4, or with atmospheric ridging, such as Type 7. Cold

Table 4.13. Predominant 500mb airflow over Peyto and Sentinel Glaciers on the Smallgrids synoptic type keydays.

TYPE	AIRFLOW	
	Peyto	Sentinel
1	W	SW
2	NW	NW
3	SW	SW
4	W	S
5	N	N
6	NW	NW
7	NW	?
8	S	S
9	NW	NW?
10	SW	SW
11	S	S
12	?	?
13	S	SE
14	N	N
15	?	N
16	SW	SW
17	S	S
18	S	S

Table 4.14. Mean daily maximum temperature (Tmax) at Banff by Smallgrids synoptic type and Peyto Glacier season.

ANNUAL		FALL		WINTER		SPRING		SUMMER	
Type	Tmax	Type	Tmax	Type	Tmax	Type	Tmax	Type	Tmax
17	19.1	7	18.9	4	2.2	17	16.1	7	23.6
4	12.4	4	13.9	15	2.2	8	13.4	1	23.3
1	11.5	1	13.5	17	2.2	4	13.1	17	23.0
8	11.5	9	12.5	1	1.7	15	12.9	8	22.2
7	11.1	15	11.8	12	1.3	1	12.5	10	22.2
15	10.4	18	11.1	6	0.5	6	11.5	4	22.1
18	10.2	6	11.0	18	0.4	7	10.8	15	21.1
6	9.5	8	10.7	8	-1.4	12	9.7	6	20.5
11	8.6	14	10.6	7	-1.5	9	9.1	9	20.4
9	8.2	3	10.0	3	-2.2	3	8.7	11	20.4
12	7.8	2	9.9	2	-2.6	16	7.9	3	20.0
3	7.7	12	7.6	10	-3.4	2	7.8	2	19.2
10	6.5	5	7.1	14	-5.1	14	7.5	18	18.5
13	6.5	16	6.3	9	-6.5	18	7.3	12	18.0
2	5.7	10	2.8	16	-6.5	10	6.7	16	17.8
14	4.2	11	---	13	-9.1	13	4.7	13	17.6
16	3.5	13	---	5	-9.2	5	4.6	14	16.9
5	-1.3	17	---	11	-12.7	11	2.8	5	15.8
$\bar{x}$	8.6	$\bar{x}$	11.1	$\bar{x}$	-1.6	$\bar{x}$	10.7	$\bar{x}$	20.9

Table 4.15. Mean daily maximum temperature (Tmax) at Alta Lake by Smallgrids synoptic type and Sentinel Glacier season.

ANNUAL		FALL		WINTER		SPRING		SUMMER	
Type	Tmax	Type	Tmax	Type	Tmax	Type	Tmax	Type	Tmax
17	18.5	7	10.4	17	4.4	14	12.3	7	29.1
7	17.3	1	9.5	15	3.6	15	9.8	9	23.5
9	14.7	6	9.0	7	3.2	2	9.2	14	21.4
6	13.4	9	8.3	1	2.7	6	9.2	1	21.2
15	13.0	4	7.8	4	2.5	7	8.7	6	21.2
1	12.5	18	7.8	18	2.2	9	8.7	10	21.2
4	12.3	2	7.6	6	2.0	18	8.3	2	20.3
14	12.2	10	7.0	3	1.5	16	8.2	4	19.9
11	11.1	15	7.0	12	1.0	4	7.7	15	19.9
18	10.9	3	6.9	2	0.1	1	7.6	17	18.9
2	10.7	14	6.9	8	0.0	5	7.5	11	17.7
12	10.5	12	6.6	10	-0.4	12	7.5	5	17.4
8	10.4	16	6.0	16	-2.6	11	6.9	3	16.1
13	10.0	8	5.9	14	-2.7	3	6.4	8	16.1
3	9.7	11	4.4	9	-5.0	8	6.3	12	16.1
10	9.0	5	-1.1	5	-5.2	10	5.8	16	14.3
16	7.3	13	---	11	-8.0	13	5.8	18	13.6
5	5.9	17	---	13	-8.3	17	5.3	13	13.1
$\bar{x}$	11.4	$\bar{x}$	8.4	$\bar{x}$	0.5	$\bar{x}$	8.0	$\bar{x}$	19.6

synoptic types can be the result of northerly airflow trajectories over water (Type 2) or land (Type 5), or of the superposition of an atmospheric trough (Type 16) or cold low (Type 13). Rankings do change from season to season, but most synoptic types maintain their relative position above or below the seasonal mean. Notable exceptions occur, however. In Winter, Type 18, a cold low pattern, advects relatively warm marine air over cold land surfaces, producing slightly above average temperatures. In Summer, temperatures associated with this type are well below the mean because cool marine air is advected over relatively warm land. These temperature reversals are especially evident at Sentinel, where the proximity of the glacier to the Pacific Ocean does not provide the time needed for modification of the marine air.

Temperature ranking discrepancies between glaciers usually can be explained in terms of relationships to synoptic-scale features of circulation. For example, in Summer, Type 14 is associated with a ridge of high pressure and above average temperatures at Sentinel Glacier, while it is associated with 500mb low pressure and low temperatures at Peyto Glacier. Notable discrepancies in the shoulder season rankings may be caused by small sample size and time of occurrence. In Spring, Type 17 is the warmest type at Peyto Glacier, while it is the coldest at Sentinel Glacier.

This is the result of a few late Spring occurrences of this type at Peyto and only one early season occurrence at Sentinel.

Smallgrids synoptic types are also ranked in terms of the relative precipitation totals of each glacier season (Tables 4.16 and 4.17). At Peyto, six types (1, 2, 3, 4, 5 and 8) are associated with about 74% of the annual total. Only five types (1, 2, 3, 4 and 8) are needed to account for nearly 85% of the annual precipitation at Sentinel. For the most part, these figures reflect the frequency with which the types occur. However, important characteristics of the synoptic types, such as trough and ridge position, precipitation efficiency and temperature, may affect accumulation and ablation at each glacier.

Differences between seasonal precipitation percentages for Peyto and Sentinel Glaciers often can be attributed to their positions relative to synoptic-scale troughs and ridges. For example, higher seasonal precipitation percentages are associated with Type 1 at Sentinel because it lies closer to the zone of maximum vorticity advection and upward vertical motions ahead of the trough than does Peyto (see Figure 8 in Harmon, 1971; after O'Connor, 1963).

Precipitation efficiency refers to the amount of precipitation brought to an area by a given synoptic type relative to its frequency (Bradley and England, 1979). It is

Table 4.16. Percentage of total precipitation (P) at Lake Louise by Smallgrids synoptic type and Peyto Glacier season. Expected precipitation is 5.6% per type. Asterisks indicate types that are efficient bearers of precipitation.

ANNUAL		FALL		WINTER		SPRING		SUMMER	
Type	P	Type	P	Type	P	Type	P	Type	P
1*	28.1	1*	37.0	1*	36.6	3*	15.3	1	14.2
3*	11.6	8*	14.7	3*	12.4	4*	13.9	4*	13.2
2	10.7	3*	9.2	2	11.7	1	11.6	2*	12.3
4	9.8	16*	8.4	4	8.5	8*	9.6	3*	9.5
8*	7.4	6	8.3	8*	6.2	2	6.6	5*	7.8
5	6.3	2	7.1	5	6.1	12*	6.3	8*	6.8
6	4.7	5	5.2	6	5.1	16*	4.9	12*	5.0
15*	4.6	10*	2.8	10*	4.5	5*	4.3	16*	4.3
10*	3.0	12	2.6	9*	2.1	6	2.4	6	3.5
16*	2.9	4	2.2	7	1.6	9*	1.8	11*	3.3
12*	2.8	18	0.3	11*	1.5	15	1.6	18*	3.1
14*	2.3	9	0.1	16	0.9	13	0.7	13*	2.1
9	1.7	7	0.0	12	0.8	18	0.7	10	1.5
11*	1.7	14	0.0	13*	0.3	10*	0.5	9	1.4
18*	1.0	15	0.0	14	0.3	11*	0.5	15	0.6
7	0.9	11	---	15	0.2	7	0.0	7	0.2
13*	0.8	13	---	17	0.0	14	0.0	14	0.2
17	0.0	17	---	18	0.0	17	0.0	17	0.0

Table 4.17. Percentage of total precipitation (P) at Alta Lake by Smallgrids synoptic type and Sentinel Glacier season. Expected precipitation is 5.6% per type. Asterisks indicate types that are efficient bearers of precipitation.

ANNUAL		FALL		WINTER		SPRING		SUMMER	
Type	P	Type	P	Type	P	Type	P	Type	P
1*	46.9	1*	65.4	1*	49.7	1*	54.4	1*	30.4
4*	16.1	8*	10.6	2	11.8	4*	22.2	4*	21.7
3*	7.7	4	8.7	4*	11.8	8*	5.6	8*	14.2
8*	7.3	6	5.2	3*	8.6	3	5.2	3*	10.7
2	6.8	3	5.0	6	5.8	2	2.6	6	3.6
6	4.8	16	1.3	10*	4.3	12	1.8	16	2.9
10*	3.3	2	0.9	8*	4.0	10*	1.7	2	2.5
16	1.4	10	0.7	16	1.2	6	1.6	18*	1.9
5	0.8	5	0.4	5	0.6	16	1.5	11*	1.8
12	0.7	11	0.4	7	0.6	17*	1.2	10	1.6
7	0.5	12	0.4	9	0.5	15	0.6	12	1.3
18	0.5	7	0.4	15	0.4	7	0.2	5	0.8
9	0.4	18	0.3	12	0.3	5	0.1	13*	0.7
11	0.4	15	0.2	11	0.1	11	0.1	9	0.6
15	0.4	9	0.0	13	0.0	9	0.0	15	0.6
13	0.2	14	0.0	14	0.0	13	0.0	7	0.0
17	0.1	13	---	17	0.0	14	0.0	14	0.0
14	0.0	17	---	18	0.0	18	0.0	17	0.0

calculated:

$$R_{ij} = \frac{P_{ij}}{f_{ij}} * 100 \qquad (4.2)$$

where R_{ij} = precipitation efficiency index of type i in period j;

P_{ij} = percentage of the total precipitation of type i in period j;

f_{ij} = percentage type frequency of type i in period j.

A synoptic type that occurs 10% of the time and delivers 10% of the period's precipitation scores an R value of 100. In this thesis, a synoptic type is considered an efficient bearer of precipitation if R>100 (Tables 4.16 and 4.17). For example, Type 1 is efficient in all seasons at Sentinel and in the Fall and Winter at Peyto. On the other hand, Type 2 is never efficient at Sentinel and only in Summer at Peyto. This agrees with previous findings (Harmon, 1971) that areas of southwesterly flow between a trough and the next downstream ridge receive above normal precipitation, while areas of northwesterly flow between a ridge and the next downstream trough receive subnormal precipitation. Efficiency ratings also suggest that the presence or absence of infrequently occurring, efficient synoptic types can be important to the interannual climatic variability of an area. For instance, Type 13 is relatively rare, but brings heavy precipitation to Peyto in all seasons of occurrence. In summary, efficient precipitation bearing Smallgrids types are usually associated with southwesterly cyclonic flow (Types 1, 3, 4, 8 and 10) or cold lows (Types 11, 13 and 18).

When temperature and precipitation characteristics are taken together, the occurrence of certain types are seen to be important to glacier mass balance. For example, in Summer at Peyto, Type 5 is associated with below average temperatures and precipitation efficiency, thereby suppressing ablation. In Fall, Types 16 and 8 bring cool temperatures and large quantities of precipitation to Peyto and Sentinel, respectively, to help initiate the new accumulation season. Likewise, Type 3 at Peyto and Type 8 at Sentinel bring relatively large snowfalls in Spring to prolong accumulation. The appearance of a persistent Type 15 ridge brings very dry, warm conditions to both glaciers, thus adding very little to annual accumulation.

4.3 Biggrids analysis

4.3.1 Biggrids synoptic types

The results of the Biggrids synoptic type classification are summarized in Table 4.18. 8 synoptic types accounting for 94.5% of the 3287 days are identified.

Table 4.18. Summary of the Biggrids synoptic type classification, 1 October 1965 to 30 September 1974.

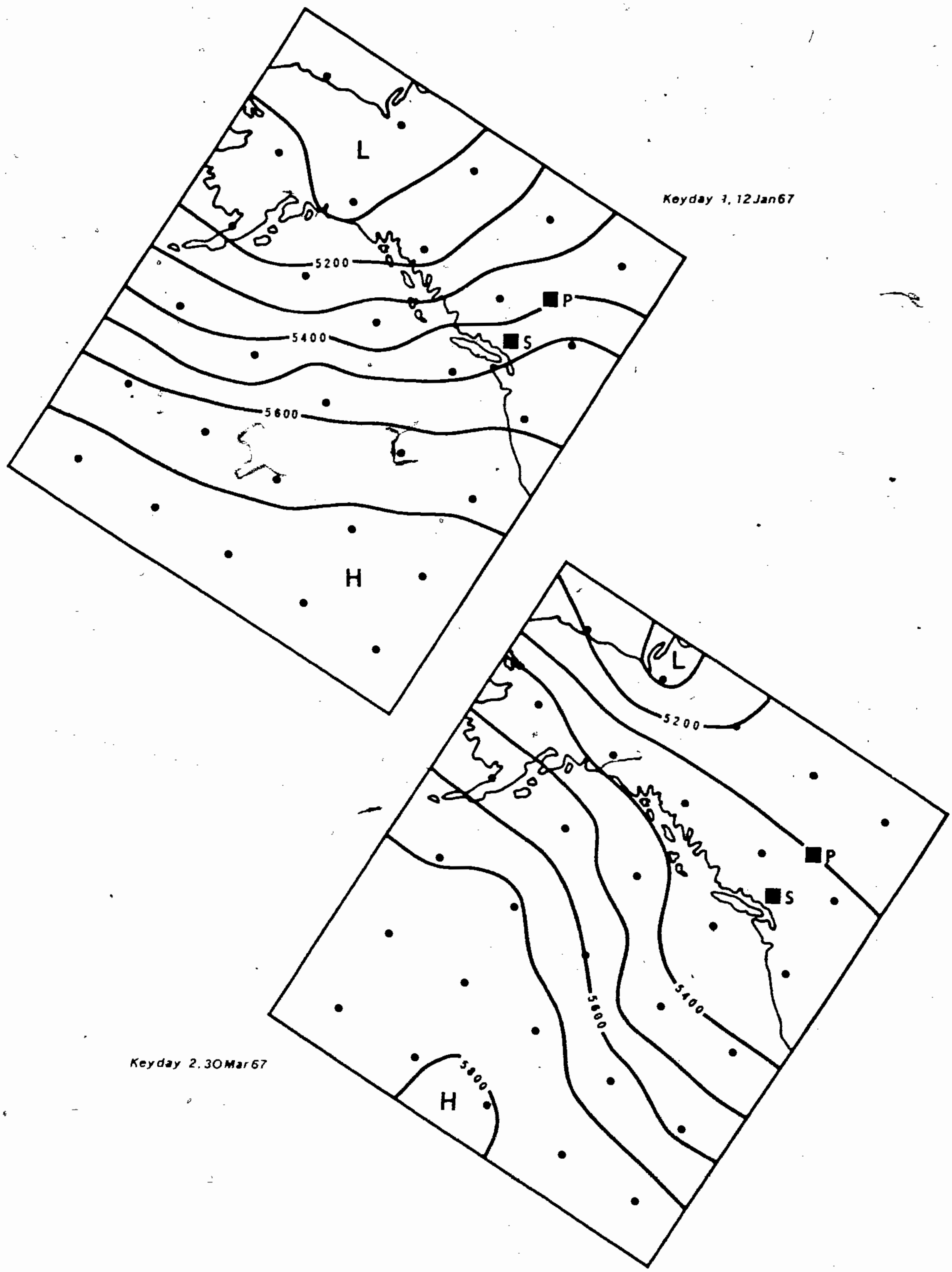
TYPE	FREQUENCY (%)	MEAN KIRCHHOFER SCORE	KIRCHHOFER SCORE STANDARD DEVIATION
1	60.0	5.5	2.5
2	12.0	7.0	2.6
3	7.2	7.3	2.8
4	7.8	7.6	2.7
5	3.3	8.4	2.4
6	2.9	8.4	2.6
7	0.6	10.5	3.7
8	0.7	9.7	3.5
UNCLASSIFIED	2.9	---	---
MISSING DATA	2.6	---	---

The first 4 types account for 87.0% of the days. Type 1, with the lowest Kirchhofer score and standard deviation, has the best statistical fit, while Types 7 and 8 have the greatest internal diversity. Keydays for the Biggrids synoptic types are shown in Figures 4.5 to 4.8, and a catalog of Biggrids types for the study period is presented in Appendix II.

4.3.2 Synoptic type frequencies

Relative differences between Biggrids synoptic type regimes at Peyto and Sentinel Glaciers (Table 4.19) are not as great as those of Smallgrids (Table 4.8). This is at least in part a result of the diminished detail in the 8 Biggrids synoptic types. Additionally, because Δf is only a relative index, it is difficult to determine whether the regime differences warrant differentiation between glacier regions in subsequent analysis. In order to keep the Biggrids analysis in line with that of Smallgrids and to determine if regional differentiation is, in fact, justified, Peyto and Sentinel Glacier data are analyzed separately for Biggrids.

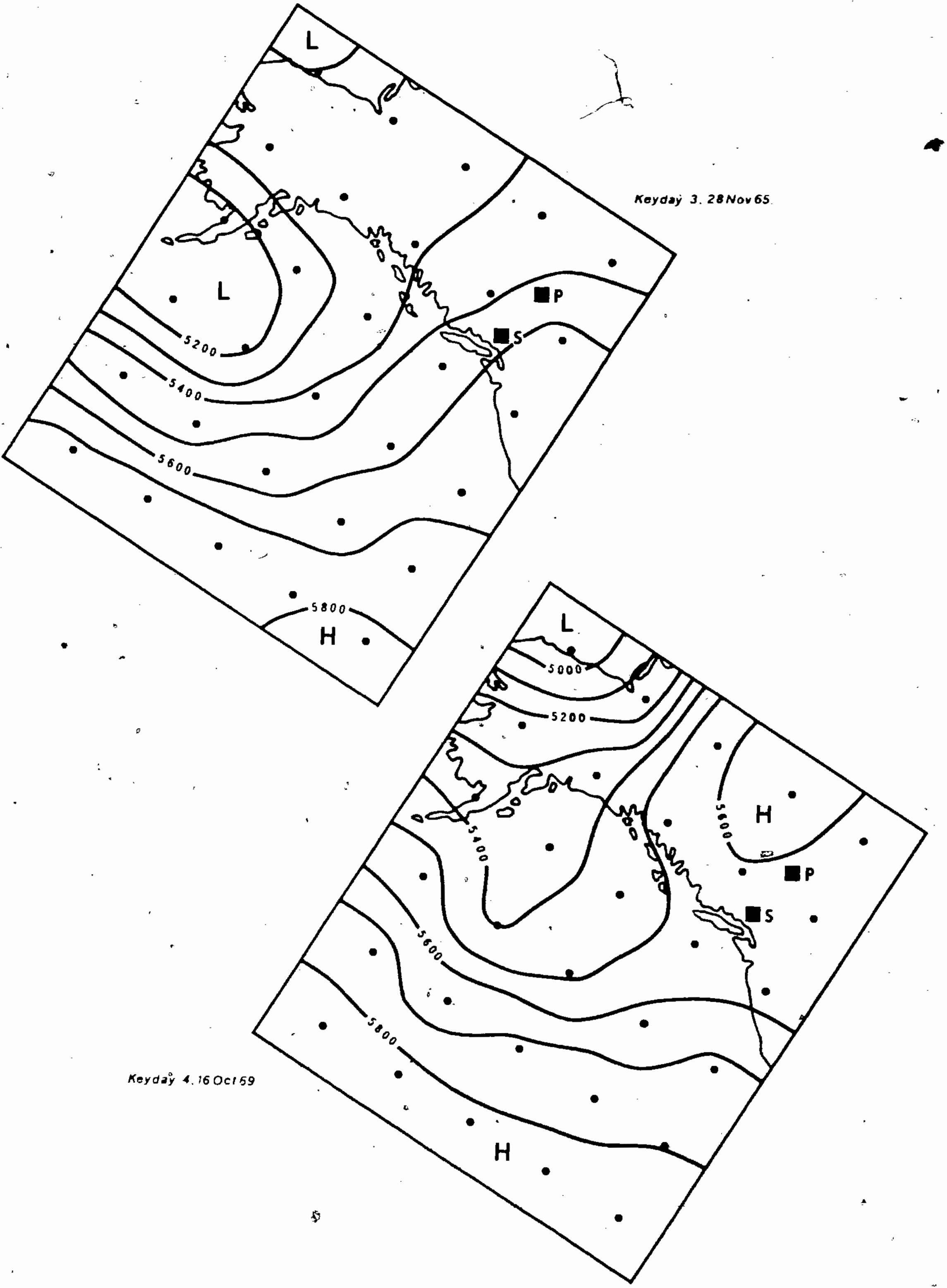
Although season-to-season synoptic regime differences at each glacier are more discernible (Tables 4.20 and 4.21), observed Δf values are not easily explained. For example, Fall and Spring are not distinct seasons, as is the case for



Keyday 1, 12Jan67

Keyday 2, 30Mar67

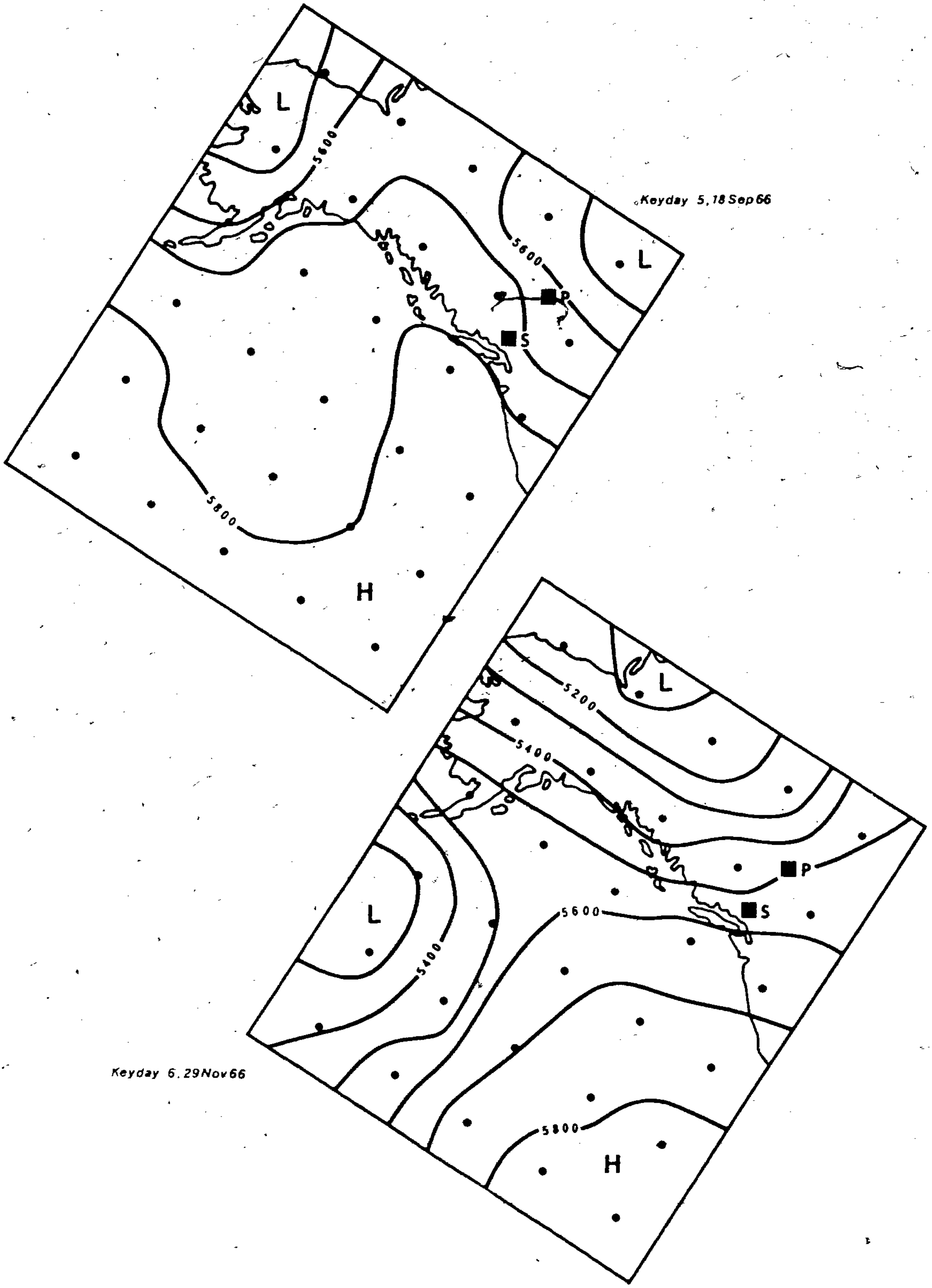
Figure 4.5. 500mb pressure distributions on Biggrids Keydays 1 and 2.



Keyday 3. 28Nov65

Keyday 4. 16Oct69

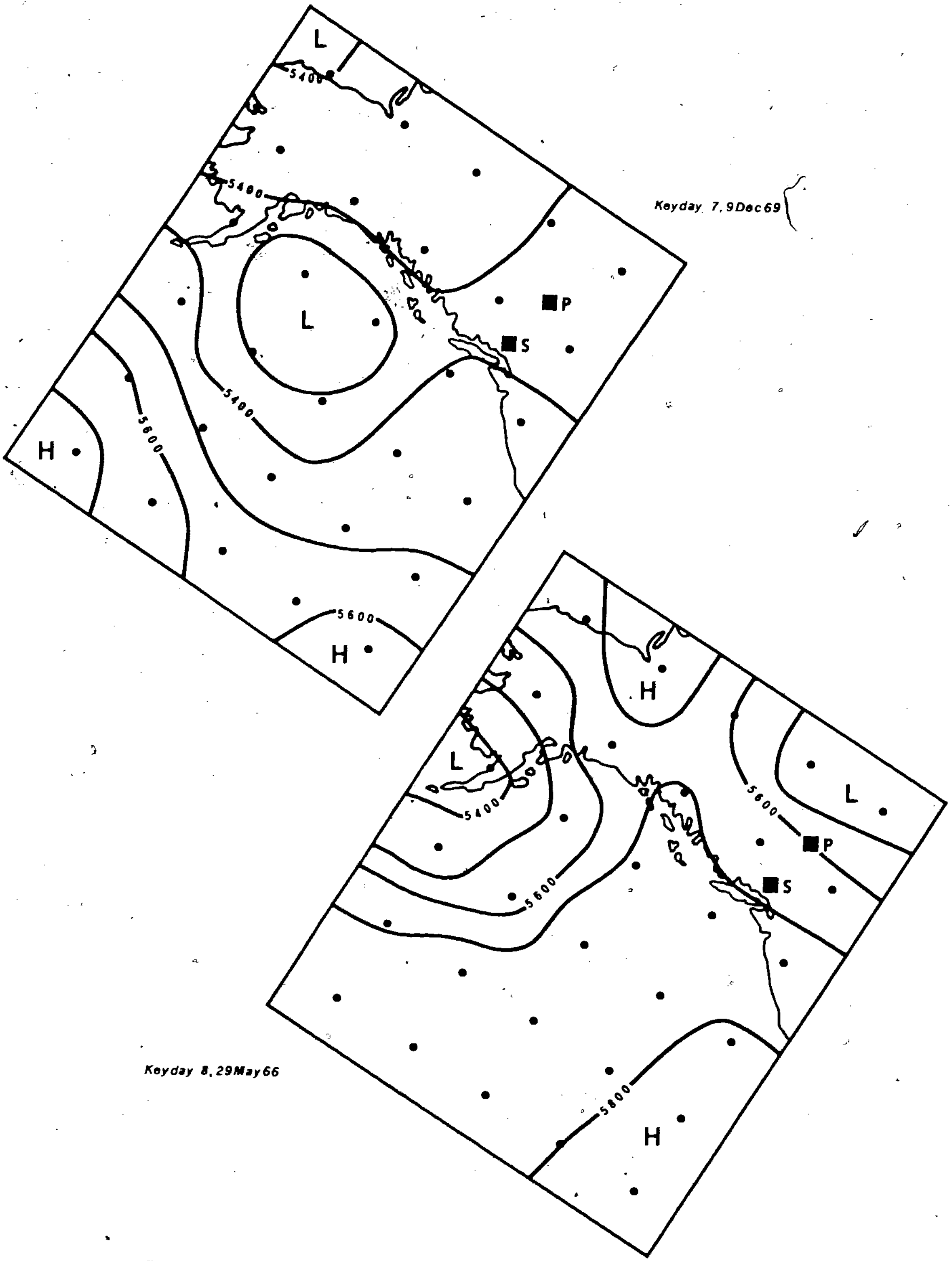
Figure 4.6. 500mb pressure distributions on Biggrids Keydays 3 and 4.



Keyday 5, 18 Sep 66

Keyday 6. 29Nov66

Figure 4.7. 500mb pressure distributions on Biggrids Keydays 5 and 6.



Keyday 7, 9Dec69

Keyday 8, 29May66

Figure 4.8. 500mb pressure distributions on Biggrids Keydays 7 and 8.

Table 4.19. Relative seasonal differences (Δf) between the Biggrids synoptic type frequency regimes at Peyto and Sentinel Glaciers.

	Δf
Fall	18.9
Winter	5.9
Spring	12.8
Summer	11.0

Table 4.20. Relative seasonal differences (Δf) of the Biggrids synoptic type frequency regimes at Peyto Glacier.

	Fall	Winter	Spring	Summer
Fall	0.0			
Winter	23.6	0.0		
Spring	40.0	24.5	0.0	
Summer	23.8	20.4	29.9	0.0

Table 4.21. Relative seasonal differences (Δf) of the Biggrids synoptic type frequency regimes at Sentinel Glacier.

	Fall	Winter	Spring	Summer
Fall	0.0			
Winter	28.0	0.0		
Spring	12.2	25.2	0.0	
Summer	25.9	27.1	16.9	0.0

Smallgrids (Tables 4.9 and 4.10). Furthermore, a plot of consecutive seasonal pairs (Figure 4.9) reveals no sharp contrasts in seasonal regimes relative to those of Smallgrids (Figure 4.4). Again, these patterns may possibly be attributed to the results of the Biggrids classification procedure, where much of the variation in the data is suppressed, and not necessarily to physical phenomena. Tightened S, S_R and S_C threshold values (Section 3.1) would increase the number of synoptic types and might bring out the expected distinctions in Fall and Spring regimes. As with Smallgrids, the Δf values of Tables 4.20 and 4.21 are sufficiently large to allow stratification by glacier season when appropriate.

A summary of Biggrids synoptic type frequencies shows an overwhelming preponderance of Type 1 in all seasons (Tables 4.22 and 4.23). Types 2 and 4 are of moderate importance in each season, while Type 3 is only important in Winter. Type 5 frequencies increase modestly in Summer at both glaciers, as does Type 6 in Winter at Peyto. Types 7 and 8 are rare.

4.3.3 Biggrids climatological characteristics

Inspection of the 500mb patterns on the Biggrids synoptic type keydays shows the importance of westerly marine airflow over Peyto and Sentinel Glaciers (Table

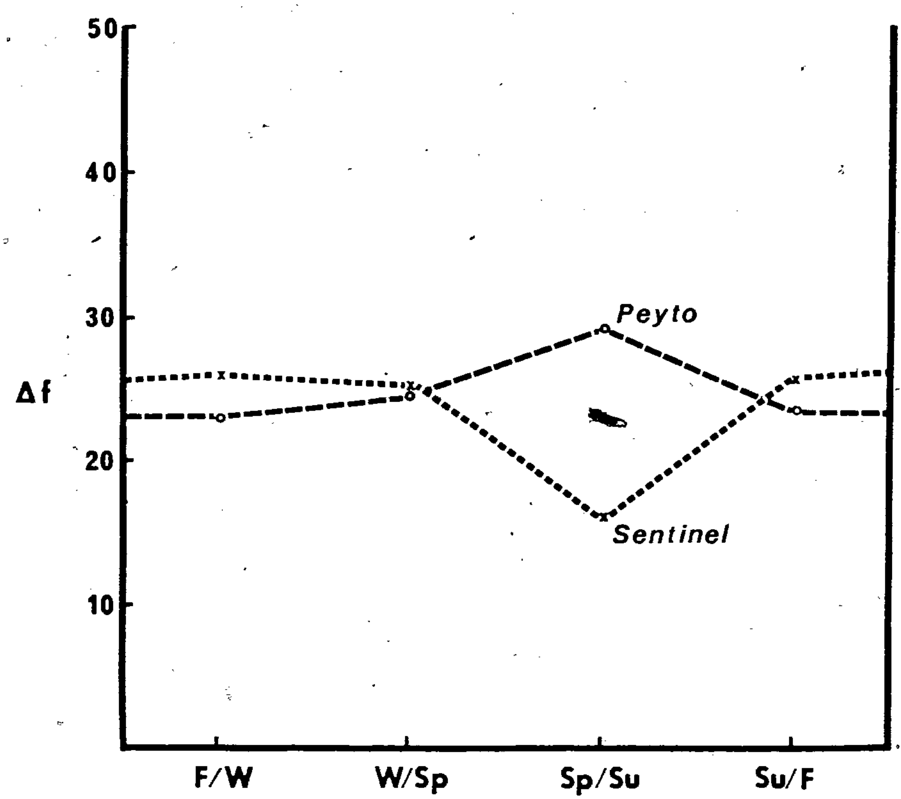


Figure 4.9. Biggrids Δf comparisons for consecutive seasonal pairs at Peyto and Sentinel Glaciers (after Moritz, 1979).

Table 4.22. Biggrids synoptic type frequencies at Peyto Glacier in mean days per season.

ANNUAL		FALL		WINTER		SPRING		SUMMER	
Type	Days	Type	Days	Type	Days	Type	Days	Type	Days
1	213.3	1	25.0	1	97.1	1	27.2	1	68.0
2	42.7	2	8.2	3	16.0	2	6.8	2	13.4
4	27.7	4	2.0	2	15.8	4	6.3	4	9.3
3	25.6	3	1.8	4	10.4	3	5.7	5	7.8
5	11.7	5	0.9	6	4.8	6	2.1	6	3.4
6	10.3	6	0.1	5	1.8	5	1.7	3	1.7
8	2.5	7	0.1	7	1.6	8	0.8	8	1.3
7	2.1	8	0.0	8	0.6	7	0.4	7	0.0

Table 4.23. Biggrids synoptic type frequencies at Sentinel Glacier in mean days per season.

ANNUAL		FALL		WINTER		SPRING		SUMMER	
Type	Days	Type	Days	Type	Days	Type	Days	Type	Days
1	213.3	1	12.4	1	78.1	1	26.1	1	98.6
2	42.7	2	4.2	3	12.0	2	7.0	2	23.3
4	27.7	3	2.0	2	9.6	4	4.5	4	17.1
3	25.6	4	1.1	4	8.4	3	4.1	5	7.7
5	11.7	5	0.6	6	4.0	5	1.2	3	5.6
6	10.3	6	0.6	7	1.3	6	1.2	6	4.0
8	2.5	7	0.1	5	1.1	8	0.8	8	0.9
7	2.1	8	0.0	8	0.6	7	0.5	7	0.3

4.24). Type 1 displays a high zonal index flow, whereas Types 2 and 3 represent increased oscillation in the upper westerlies. Types 4 through 8 illustrate low zonal index situations with meridional exchange of cold and warm air. In Types 3 through 8, Peyto and Sentinel sit under transitional areas between upper level cyclonic and anticyclonic flow, thus making considerable temperature and precipitation diversity within types a possibility.

Despite this potential source of error, clear relationships between synoptic types and temperature are evident (Tables 4.25 and 4.26). Type 1 westerly conditions bring moderate temperatures to the Peyto and Sentinel areas. This type is associated closely with the seasonal mean temperatures because of its high frequency and its zonal flow (Harmon, 1971). A northwestely trajectory maintains cool conditions at the glaciers during all Type 2 situations, while southwesterly flow, sometimes reinforced by ridging, keeps Type 3 temperatures above average. Because Peyto and Sentinel are positioned under two connecting ridges and experience southerly airflow on Type 4 days, temperatures are relatively warm. Although Types 5 and 6 are usually warm, reversals of form may possibly be explained by slight seasonal pressure pattern shifts from the keyday "mean" positions, as suggested above. Type 7 cold lows generally advect cold air into the Peyto and Sentinel

Table 4.24. Predominant 500mb airflow over Peyto and Sentinel Glaciers on the Biggrids synoptic type keydays.

TYPE	AIRFLOW	
	PEYTO	SENTINEL
1	W	W
2	NW	NW
3	SW	SW
4	S?	S?
5	N	N
6	W	W
7	W?	W?
8	N	N

Table 4.25. Mean daily maximum temperature (Tmax) at Banff by Biggrids synoptic type and Peyto Glacier season.

ANNUAL		FALL		WINTER		SPRING		SUMMER	
Type	Tmax	Type	Tmax	Type	Tmax	Type	Tmax	Type	Tmax
5	17.1	3	14.6	6	2.0	3	14.6	3	24.8
4	12.0	5	13.4	5	1.9	4	13.3	4	24.0
6	10.6	4	12.9	3	1.0	7	12.3	5	22.4
1	8.4	7	12.2	4	-0.1	6	11.3	6	22.2
8	8.4	1	11.9	1	-2.1	5	11.0	1	21.1
3	7.3	2	8.0	2	-3.6	1	9.7	8	17.9
2	6.3	6	5.6	7	-4.0	8	9.3	2	16.0
7	0.3	8	---	8	-15.5	2	8.4	7	---
$\bar{x}$	8.6	$\bar{x}$	11.1	$\bar{x}$	-1.6	$\bar{x}$	10.7	$\bar{x}$	20.9

Table 4.26. Mean daily maximum temperature (Tmax) at Alta Lake by Biggrids synoptic type and Sentinel Glacier season.

ANNUAL		FALL		WINTER		SPRING		SUMMER	
Type	Tmax	Type	Tmax	Type	Tmax	Type	Tmax	Type	Tmax
4	15.0	7	11.1	6	4.2	4	10.4	4	22.3
5	14.2	5	9.2	3	2.1	3	9.6	3	21.0
6	11.7	1	9.0	5	1.8	7	8.3	1	20.4
1	11.5	6	8.4	4	1.1	2	7.9	6	19.9
2	9.6	3	7.9	1	0.5	6	7.6	5	16.9
3	9.6	4	7.7	2	-2.6	1	7.5	2	15.2
8	9.4	2	6.4	7	-2.9	5	6.4	8	14.4
7	4.1	8	---	8	-6.4	8	4.4	7	13.3
$\bar{x}$	11.4	$\bar{x}$	8.4	$\bar{x}$	0.5	$\bar{x}$	8.0	$\bar{x}$	19.6

regions, and Type 8 is associated with outbreaks of Arctic air.

The Biggrids precipitation summaries are dominated by Type 1 (Tables 4.27 and 4.28). Although in part this reflects frequency, high efficiency ratings mean consistently high precipitation totals are associated with Type 1 at both glaciers. On the other hand, Type 4 is usually very dry. Other Biggrids synoptic types are not as consistent as Types 1 and 4 in their precipitation characteristics. Type 2 is relatively dry in Winter, but quite wet in Summer. Type 3 is an efficient bearer of precipitation during Sentinel Winters, while it is inefficient at Peyto. Type 5 has low absolute totals in Winter, but is an important contributor to Summer totals at both glaciers. Due to positive efficiency ratings, Types 6, 7 and 8 are important to the precipitation of some seasons.

As in the case of Smallgrids synoptic types, Biggrids precipitation statistics can usually be explained in terms of mid-tropospheric wave patterns. For example, Type 1 days at Peyto and Sentinel are associated with moist southwesterly cyclonic flows, upward vertical motion and maximum vorticity advection ahead of the main trough axis. On the other hand, Type 2 days are associated with divergence and subsidence of relatively less moist northwesterly flows behind the main trough axis.

Table 4.27. Percentage of total seasonal precipitation (P) at Lake Louise by Biggrids synoptic type and Peyto Glacier season. Expected precipitation is 12.5% per type. Asterisks indicate types that are efficient bearers of precipitation.

ANNUAL		FALL		WINTER		SPRING		SUMMER	
Type	P	Type	P	Type	P	Type	P	Type	P
1*	68.4	1*	66.3	1*	79.5	1*	50.5	1	54.8
2	10.7	2*	26.8	3	7.5	4	11.8	2*	16.5
5*	5.4	3*	4.5	2	4.9	2	10.8	5*	13.4
3	4.6	5	1.7	6*	4.4	5*	4.6	4	5.4
6*	3.4	4	0.7	5*	1.8	6	3.6	8*	3.1
4	3.1	6	0.0	8*	0.9	3	2.7	6	2.4
8*	1.4	7	0.0	4	0.6	7*	1.7	3	0.1
7	0.2	8	---	7	0.0	8	0.5	7	---

Table 4.28. Percentage of total seasonal precipitation (P) at Alta Lake by Biggrids synoptic type and Sentinel Glacier season. Expected precipitation is 12.5% per type. Asterisks indicate types that are efficient bearers of precipitation.

ANNUAL		FALL		WINTER		SPRING		SUMMER	
Type	P	Type	P	Type	P	Type	P	Type	P
1*	70.3	1*	64.9	1*	75.0	1*	69.4	1*	66.0
3*	8.9	2	14.2	3*	11.4	2	6.9	2	13.5
2	8.4	3*	9.1	2	6.1	6*	5.5	5*	9.9
5*	4.2	6*	5.9	6	2.3	4	5.3	4	3.0
6*	3.2	5*	2.7	4	1.9	3	5.0	3	2.4
4	2.4	4	1.6	5	0.8	8*	3.2	6	2.0
8*	0.9	7	0.0	8*	0.7	5*	2.6	8*	1.0
7*	0.6	8	---	7	0.5	7*	1.1	7	0.0

4.4 The relationship between Smallgrids and Biggrids

Table 4.29 shows the results of a crosstabulation of Smallgrids and Biggrids synoptic types. Although no clear relationships emerge upon inspection of the contingency table, a chi-square analysis of the first six rows and columns suggests that observed frequencies are not chance variations. However, using asymmetric lambda to measure the ability to predict Smallgrids types given knowledge of the Biggrids type frequencies shows only a 2.87% improvement in prediction. No improvement is found using Smallgrids to predict Biggrids types. Therefore, there is clearly very little direct statistical relationship between the two synoptic type classifications used in the present study.

The above results are due to the filtering of data during the compilation of Biggrids, when approximately 73% of the original 110 data points were removed. Consequently, a great deal of small-scale synoptic variation may take place over southwestern Canada without these changes being evident in the Biggrids types. Biggrids are related to the long wave patterns of the Northern Hemisphere, while Smallgrids are high-wavenumber, migratory perturbations imbedded in the Biggrids flow.

Table 4.29. Crosstabulation comparing Smallgrids and Biggrids synoptic types.

	BIGGRIDS								
SMALLGRIDS	1	2	3	4	5	6	7	8	UNCLASSIFIED
1	564	41	87	41	19	34	0	2	7
2	329	70	26	19	2	9	0	3	8
3	143	34	7	1	14	10	0	3	0
4	167	19	42	52	21	14	5	4	19
5	137	55	4	16	2	4	2	0	11
6	178	33	25	17	3	9	1	0	6
7	41	2	8	9	0	1	1	0	1
8	70	24	9	9	29	3	2	6	3
9	47	3	4	1	0	0	0	1	0
10	49	6	2	1	3	4	0	0	0
11	25	7	0	0	4	1	0	1	0
12	31	32	2	5	4	1	2	0	5
13	11	0	0	4	0	0	0	2	2
14	23	4	3	15	0	0	1	0	10
15	27	12	9	28	1	0	1	0	9
16	50	25	1	3	2	2	3	1	0
17	6	0	1	2	0	0	0	0	0
18	6	4	2	9	1	0	0	0	3
UNCLASSIFIED	59	22	2	24	3	2	0	0	10

χ^2 observed* = 253.02

χ^2 critical (at 25 degrees of freedom and $\alpha = 0.001$) = 52.62

λ_b (Smallgrids dependent) = 0.0287

λ_b (Biggrids dependent) = 0.0000

* Due to the presence of many expected values <5 in the high order synoptic types, χ^2 was only calculated for Smallgrids and Biggrids Types 1 to 6.

4.5 Summary

General synoptic climatologies of Peyto and Sentinel Glaciers using Smallgrids and Biggrids synoptic type classifications were presented in this chapter. Although the resulting data are sufficiently detailed for the analysis of glacier mass balance with synoptic type characteristics to follow in Chapter 5, a few generalizations can be derived from these results.

The relative differences between seasonal synoptic type regimes at Peyto and Sentinel Glaciers are much greater for Smallgrids than for Biggrids. Also, relative season-to-season differences at each glacier are more clearly discriminated by Smallgrids than Biggrids synoptic type frequencies. The greater detail provided by the 18 Smallgrids types relative to the 8 Biggrids types accounts for these results. Nonetheless, it has been demonstrated that Biggrids temperature and precipitation characteristics are physically reasonable when stratified.

Features of synoptic-scale circulation identified by both Smallgrids and Biggrids synoptic types influence the climate of southwestern Canada. Airflow trajectories, isobaric curvature and positions of troughs and ridges of the 500mb synoptic types appear to be directly related to the temperature and precipitation characteristics of the Peyto and Sentinel Glacier areas.

No direct statistical association exists between Smallgrids and Biggrids synoptic types. The generalization imposed on the data during compilation of Biggrids eliminated much of the high-wavenumber synoptic-scale information contained in Smallgrids. However, it is demonstrated in Chapter 5 that Biggrids, as well as Smallgrids, are useful in predicting elements of mass balance at Peyto and Sentinel.

5. The Relationship between Glacier Mass Balance and Synoptic Type Characteristics

5.1 Introduction

In this chapter, the first two thesis objectives are addressed. The first objective is to determine the association betweeen glacier mass balance and synoptic-scale circulation in southwestern Canada. This will be achieved by an examination of the nature and strength of the relationships shown by winter balance and by Summer temperature with some simple climatological characteristics of the synoptic types. The second objective is to determine the effect that changes in the information level and scale of the synoptic features have on the results. A comparison of Smallgrids and Biggrids synoptic type characteristics is used for this purpose. Before the main analysis, the criterion variables (winter balance and Summer mean daily maximum temperature), the predictor variables (the synoptic type characteristics frequencies), and the seasons to be analyzed are introduced.

5.1.1 Criterion variables: winter balance and Summer temperature

Annual glacier mass balance is a simple combination of annual accumulation and annual ablation. Annual accumulation consists of the solid precipitation entering a glacier basin during a mass balance year, including direct snowfall, wind drifted snow and avalanching. Up to 15% of the annual accumulation on a typical mountain glacier can be attributed to drifting and avalanching (Kotlyakov, 1973). For the purposes of the present study, this percentage is unknown but considered to be stable over time and proportional to the annual snowfall of the region. Annual ablation consists of the mass lost from the glacier during the mass balance year, including ice and snow melt, evaporation, wind drifting and calving (see below).

The measures annual accumulation and annual ablation are not used in the present study. Part of the snow accumulation on a glacier may have been removed by melting, evaporation or wind prior to measurement. Likewise, snow falling during the ablation period alters the melt rate and is part of the annual accumulation, although it is not counted as such. Thus, measured accumulation and ablation differ from the "true" annual accumulation and ablation totals. These measured quantities are denoted <u>winter balance</u> and <u>summer balance</u> (Anonymous, 1969). All values are presented in meters of water equivalent averaged over the entire glacier area.

Winter balance measurements from Peyto and Sentinel Glaciers are used as the criterion variables representing annual accumulation in the regression analysis of Section 5.2. Mass lost to melting, evaporation and wind drifting is considered negligible (Ostrem and Stanley, 1969).

Choice of an appropriate variable or variables to represent either "true" annual ablation or measured summer balance is not straightforward. Energy for annual ablation is provided by a complex combination of energy sources that change over time and space (Paterson, 1969). Synoptic types are not directly linked to annual ablation, but do affect the components of the energy balance (Vowinckel and Orvig, 1969, 1971; Alt, 1975, 1979). At Peyto, Föehn (1973) has monitored the energy balance over a snow surface, while Derikx (1975) and Munro and Davies (1977, 1978) have done so over ice. Munro and Young (1982) have modelled net shortwave radiation over the entire Peyto basin for July and August, 1978. No such studies have been implemented at Sentinel. Because the energy balance is difficult and costly to measure or model, the above studies are all short-term and therefore of little use to the present research.

Fortunately, temperature can be used to represent the variables of the energy balance and estimate annual ablation (Braithwaite, 1981). Models of summer balance using meso-scale temperature data have been developed by Hoinkes and Steinacker (1975), Braithwaite (1977) and Tangborn (1980). All such models use a form of melting degree day to describe the total energy input for ablation. In addition, adjustments for the surface conditions (i.e. presence or absence of snow over ice) can be included (Hoinkes and Steinacker, 1975).

Based on the above, a multiple linear regression of summer balance with Banff and Alta Lake Summer mean daily maximum temperature, Summer season length and winter balance are presented in order to identify potential criterion variables to represent annual ablation (Tables 5.1 and 5.2). Summer temperature and length of the Summer are included because total melting degree days for a summer balance season can be expressed as a function of the seasonal mean temperature and the number of days available for melting. Winter balance serves as a rough descriptor of the glacier surface: high winter balance totals imply a prolonged period of high surface albedo and relatively low melt rates, while low totals have a converse association. At Peyto, Summer temperature and season length together explain 50% of the variance in summer balance. Annual changes in the winter balance account for 10% of the explained variance. At Sentinel, season length explains over 58% of the variance, while temperature accounts for an additional 21%, for a total of 79%. Winter balance does not enter the equation. Therefore, melting degree days, expressed as a function of Summer temperature and season length, are very important in

Table 5.1. Stepwise linear regression of Peyto Glacier summer balance with Banff Summer mean daily maximum temperature, Summer length and winter balance.

CRITERION VARIABLE: Peyto Glacier summer balance

PREDICTOR VARIABLE	CUMULATIVE R^2	R^2 CHANGE	REGRESSION COEFFICIENT
temperature	39.7	39.7	0.358
winter balance	53.9	14.2	-0.634
length	64.2	10.3	0.013
		(y-intercept)	-6.261

F observed = 2.98

F critical (at 3 and 5 degrees of freedom and with $\alpha = 0.20$) = 2.25

Table 5.2. Stepwise linear regression of Sentinel Glacier summer balance with Alta Lake Summer mean daily maximum temperature and Summer length. The F-level of winter balance is too low for inclusion.

CRITERION VARIABLE: Sentinel Glacier summer balance

PREDICTOR VARIABLE	CUMULATIVE R^2	R^2 CHANGE	REGRESSION COEFFICIENT
length	58.8	58.8	0.033
temperature	79.7	20.9	0.374
		(y-intercept)	-9.500

F observed = 7.87

F critical (at 2 and 4 degrees of freedom and $\alpha = 0.05$) = 6.94

predicting summer balance at Sentinel, but only moderately so at Peyto.

Of the three variables tested above, maximum temperature at Banff and Alta Lake is used as the criterion variable to be predicted by changes in the frequencies of the synoptic type characteristics. Summer season length is implicitly related to the synoptic type frequencies; inclusion of this variable would provide redundant information and is not necessary. Summer synoptic types do not control the winter balance of the previous season and must be excluded from the analysis. Only the Summer temperature component of summer balance can be influenced by synoptic type frequencies.

5.1.2 Predictor variables: synoptic type characteristics frequencies

Due to degrees of freedom limitations, multiple linear regression cannot be carried out if:

$$P > N-1 \qquad (5.1)$$

where P = number of predictor variables;

N = number of cases of the criterion variable.

In this study, the m synoptic types (P) exceed the (N - 1) seasons available for analysis in nearly every situation.

Thus, the synoptic types must be collapsed into climatologically reasonable groups. The frequencies of certain synoptic type characteristics, based on criteria extablished by Bradley and England (1979), are used for this purpose. Wet synoptic types are those types associated with more precipitation than the expected amount in a given season. Any Smallgrids type providing more than 5.6% (Tables 4.12 and 4.13) and any Biggrids type providing more than 12.5% (Tables 4.23 and 4.24) of the seasonal total precipitation are considered wet. For example, for Peyto Smallgrids Winters, Types 1, 2, 3, 4, 5 and 8 are wet synoptic types (Table 4.12). Dry types are those with seasonal totals below 5.6% for Smallgrids and 12.5% for Biggrids. As explained in Section 4.2.4, efficient bearers of precipitation are types associated with larger seasonal precipitation totals than their relative frequency of occurrence. Ineffficient bearers of precipitation are associated with lower seasonal precipitation totals than their relative frequencies. Efficient synoptic types are asterisked in Tables 4.12, 4.13, 4.23 and 4.24. Cool and warm types are synoptic types that fall below or above the seasonal mean daily maximum temperature (Tables 4.10, 4.11, 4.21 and 4.22). For example, for Sentinel Smallgrids Summers, Types 1, 2, 4, 6, 7, 9, 10, 14 and 15 are warm synoptic types (Table 4.11). Physical reasons for the climatological characteristics of the synoptic types were presented in Sections 4.2 and 4.3.

5.1.3 Accumulation and Summer seasons

In the following sections, Accumulation and Summer season synoptic type characteristics will be analyzed. Pilot regressions (not shown) tested annual winter balance with Winter synoptic type characteristics and with Accumulation season type characteristics (a simple additive combination of Fall, Winter and Spring type characteristics frequencies). Accumulation season synoptic types provided consistently stronger statistical explanation than did the Winter season data. Similar pilot studies using Summer and Ablation season data (an additive combination of Spring, Summer and Fall type characteristics and a weighted combination of seasonal mean daily maximum temperatures) found Summer temperature was far better predicted by Summer synoptic type characteristics than Ablation season temperature was predicted by Ablation season synoptic types.

5.2 Winter balance

Regression analyses of Peyto and Sentinel Glacier winter balance with Accumulation season Smallgrids and Biggrids synoptic type characteristics frequencies are carried out here. Each situation, Peyto Smallgrids, Sentinel Smallgrids, Peyto Biggrids and Sentinel Biggrids, is analyzed separately.

5.2.1 Peyto Smallgrids

Table 5.3 shows simple correlations of Peyto winter balance with Smallgrids synoptic type characteristics. Wet, efficient and cool synoptic types are positively correlated with winter balance, while dry, inefficient and warm types are negatively correlated. The strongest correlation is between cool synoptic types and winter balance; the weakest is between inefficient types and the criterion variable.

It appears that the ideal way to determine the total variance in winter balance provided by the synoptic type characteristics frequencies is by multiple linear regression. Such an analysis for the Peyto Smallgrids data (Table 5.4) suggests that 98% of the explained variance is accounted for by four synoptic type characteristics. However, the regression coefficient of ~~the~~ efficient predictor variable has a sign that is opposite in direction to that of the simple r of Table 5.3. This spurious result is caused by severe collinearity in the predictor variable set (Table 5.5). The correlation matrix of these variables shows extremely high positive correlations among wet, efficient and cool synoptic types. Dry, inefficient and warm

Table 5.3. Simple two-variable regressions of Peyto Glacier winter balance with Smallgrids synoptic type characteristics.

CRITERION VARIABLE: Peyto Glacier winter balance

PREDICTOR VARIABLE	r	r^2	F OBSERVED	F CRITICAL*	SIGNIFICANCE LEVEL
wet	0.5501	30.3	2.60	2.07	0.20
dry	-0.5076	25.8	2.08	2.07	0.20
efficient	0.5806	33.7	3.05	2.07	0.20
inefficient	-0.1030	1.1	0.06	----	not significant
cool	0.7110	50.6	6.13	5.99	0.05
warm	-0.5321	28.3	2.37	2.07	0.20

* At 1 and 6 degrees of freedom.

Table 5.4. Stepwise linear regression of Peyto Glacier winter balance with Smallgrids synoptic type characteristics. All data are considered as a single group for significance testing. The F-levels of the wet and dry synoptic types are too low for inclusion.

CRITERION VARIABLE: Peyto Glacier winter balance

PREDICTOR VARIABLE	CUMULATIVE R^2	R^2 CHANGE	REGRESSION COEFFICIENT
cool	50.6	50.6	0.041
warm	75.1	24.5	-0.008
inefficient	82.8	7.7	-0.020
efficient	98.2	15.4	-0.029
		(y-intercept)	3.834

F observed = 44.37

F critical (at 4 and 3 degrees of freedom and $\alpha = 0.01$) = 28.71

Table 5.5. Correlation matrix of Peyto Glacier Accumulation season Smallgrids synoptic type characteristics.

	WET	DRY	EFFICIENT	INEFFICIENT	COOL	WARM
WET	1.0000					
DRY	-0.3290	1.0000				
EFFICIENT	0.9412	-0.4290	1.0000			
INEFFICIENT	-0.2231	0.7867	0.0026	1.0000		
COOL	0.8803	-0.0986	0.8382	0.4084	1.0000	
WARM	-0.0462	0.3978	-0.1185	0.2923	-0.0520	1.0000

synoptic types are also positively correlated, especially dry and inefficient types.

The net result of this nonindependence is shown at K = 0.0 in the ridge trace of Peyto winter balance with the six predictor variables (Figure 5.1). The regression coefficient of the cool synoptic types is too high, whereas the efficient type also starts out very high and with the wrong sign. Wet types show erratic coefficient behavior and are indistinguishable from the efficient types at higher values of K. The inefficient variable loses predictive power as it approaches a coefficient value of zero. The warm type trace is relatively stable, and the dry type does not enter the equation until K = 0.02.

Figure 5.2 demonstrates the behavior of the variable coefficients when wet and dry synoptic types are removed from the analysis. It appears that the correlations between the cool and efficient variables and between the warm and inefficient variables result in only slightly dampened coefficient instability over the full regression model. If efficient and inefficient type variables are removed, but wet and dry types are allowed to remain, the resulting ridge trace (not shown) is virtually identical to Figure 5.2. Removal of all but cool and warm synoptic type characteristics from the ridge regression results in stable traces (Figure 5.3).

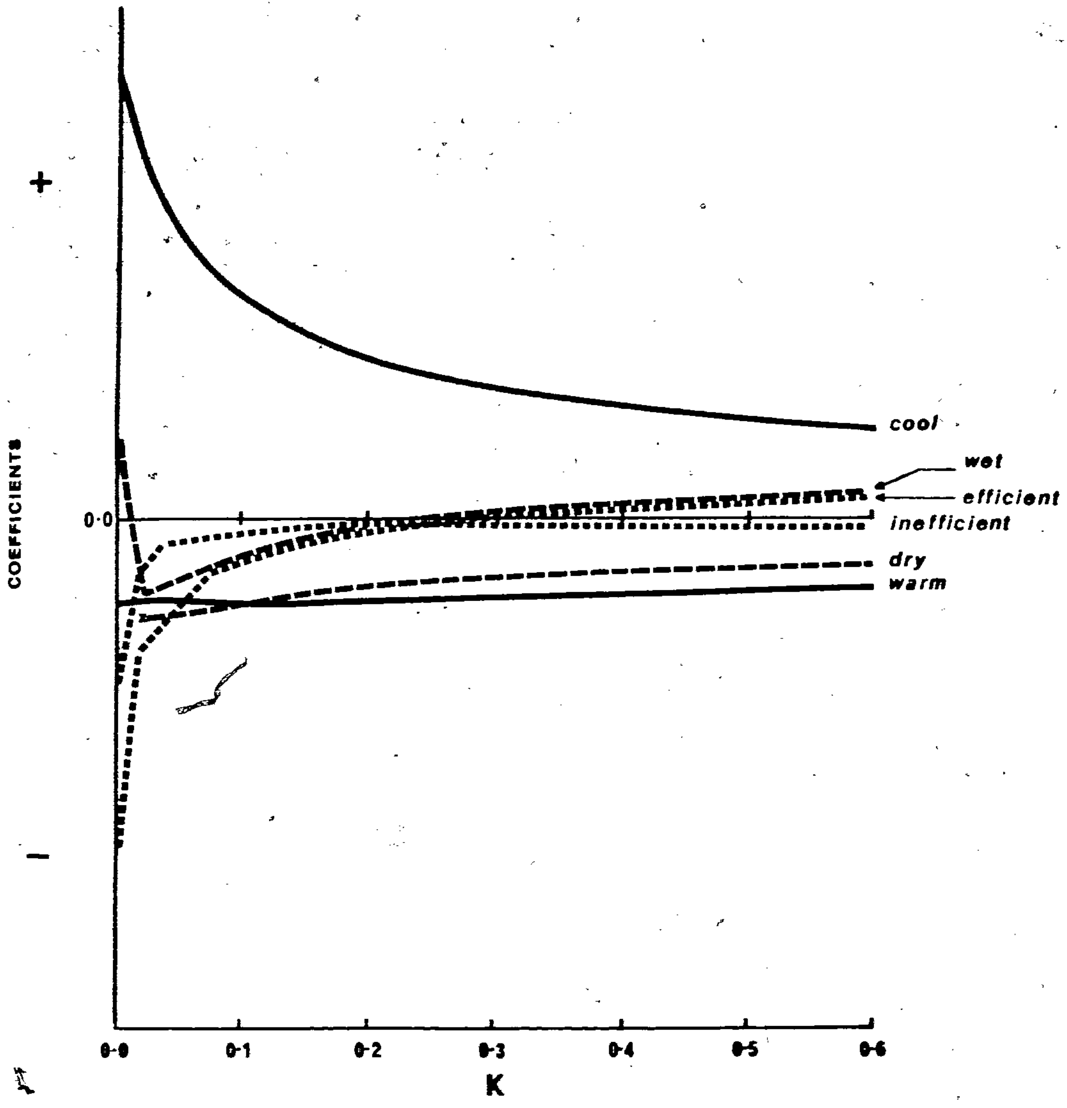


Figure 5.1. Ridge trace of Peyto Glacier winter balance with Smallgrids synoptic type characteristics.

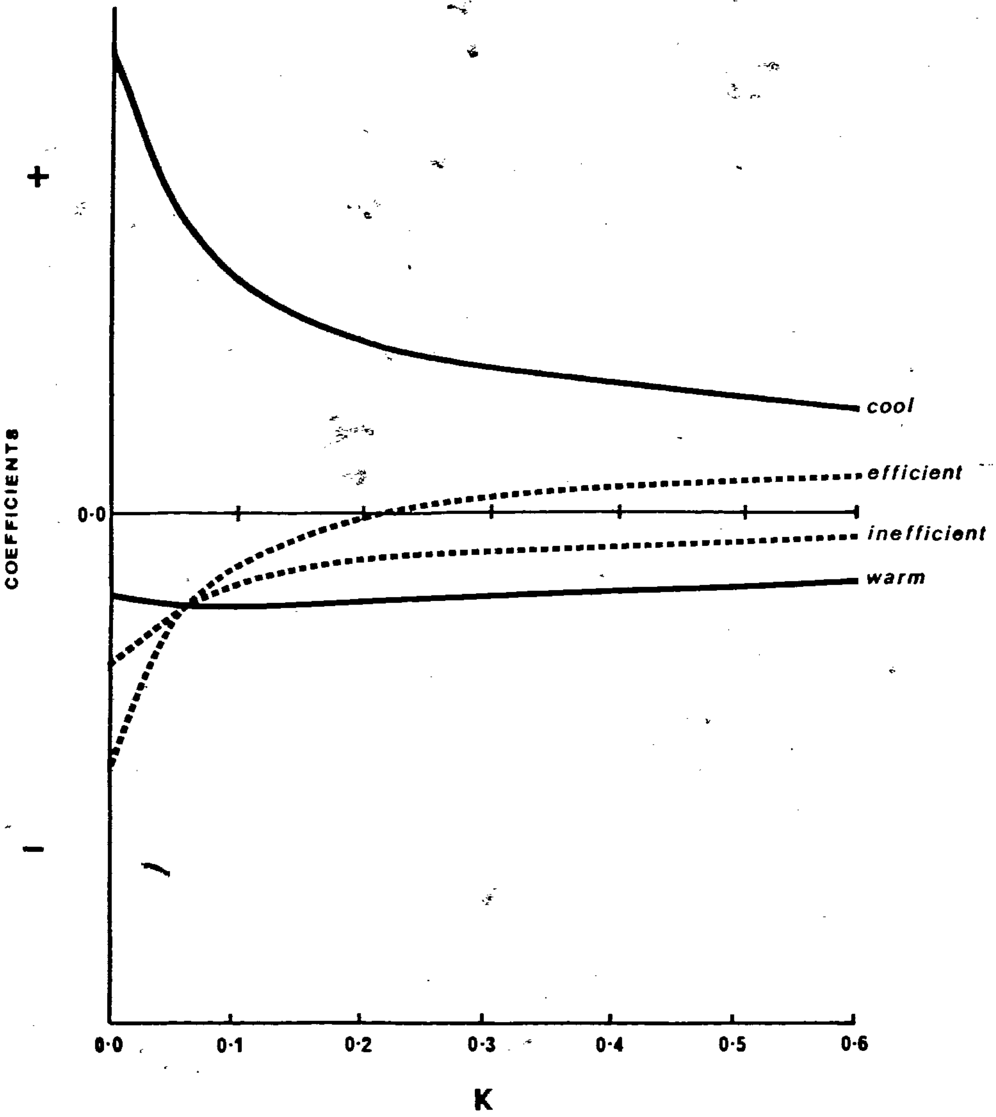


Figure 5.2. Ridge trace of Peyto Glacier winter balance with Smallgrids efficient, inefficient, cool and warm synoptic types.

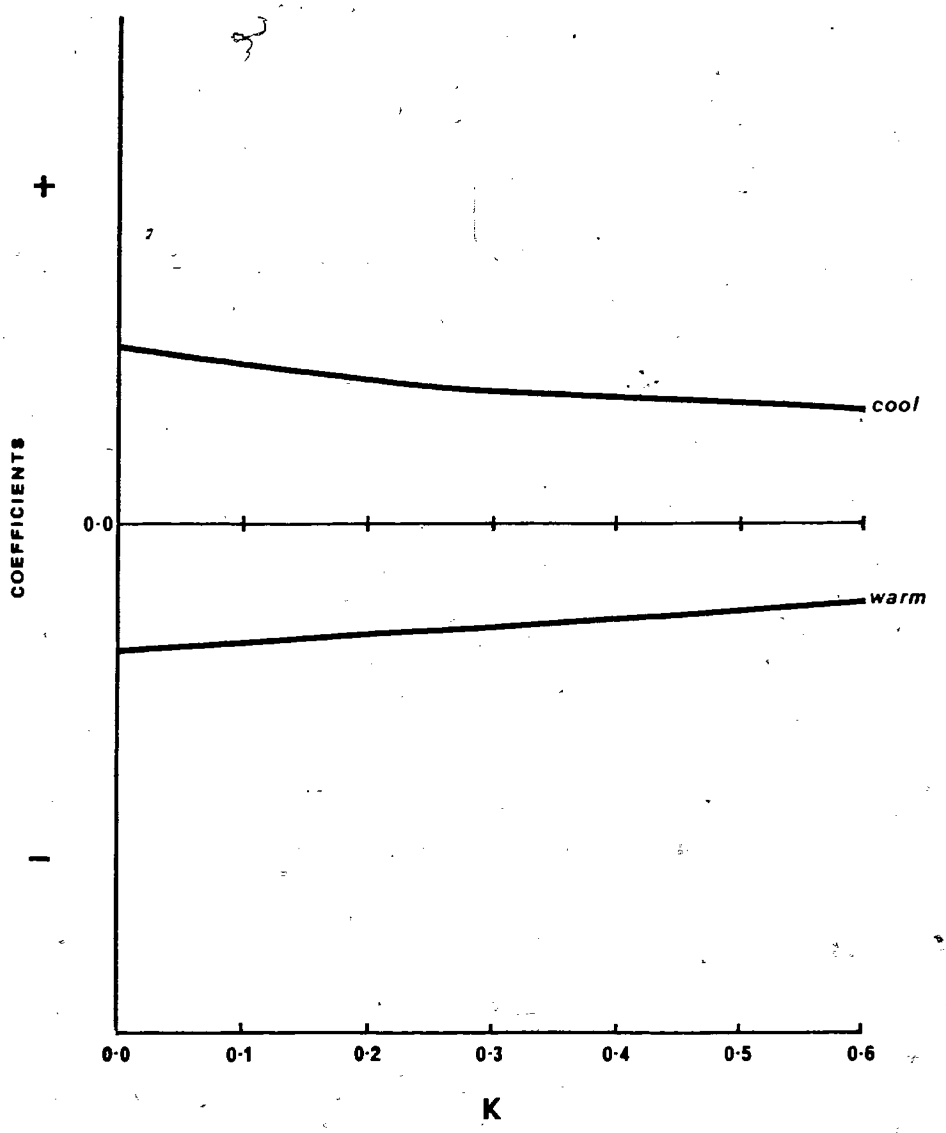


Figure 5.3. Ridge trace of Peyto Glacier winter balance with Smallgrids cool and warm synoptic types.

Based on these results, a stepwise linear regression entering just the cool and warm Smallgrids synoptic type characteristics explains 75% of the variance in Peyto Glacier's winter balance (Table 5.6). This may be called a "minimum reliable estimate" of the explained variance. For example, some of the warm/wet and warm/efficient synoptic types, such as Winter Types 1, 4 and 8, make positive contributions to accumulation and account for some of the unexplained variance but are removed because of collinearity with the cool predictor variable. Unfortunately, present regression techniques do not provide for the decomposition needed to sort out collinear variables. A statistically significant example of this source of unexplained variance in the present model is presented in Section 6.1.3.

Peyto Smallgrids cool synoptic types explain 50% of the variance in winter balance. These pressure patterns either have northerly airflows or bring cool polar air into the area. Cool types include many important wet and efficient synoptic types, thus explaining much of the collinearity. Types 2 and 5 are wet patterns with northerly airflow trajectories, whereas Types 10, 11 and 13 are efficient cold low patterns pumping cool unstable air into the region. Cool Type 3 brings maritime polar air to Peyto with wet and efficient moisture bearing properties, meaning that it occurs often and brings heavy precipitation when it does.

Table 5.6. Stepwise linear regression of Peyto Glacier winter balance with Smallgrids cool and warm synoptic types.

CRITERION VARIABLE: Peyto Glacier winter balance

PREDICTOR VARIABLE	CUMULATIVE R^2	R^2 CHANGE		REGRESSION COEFFICIENT
cool	50.6	50.6		0.015
warm	75.1	24.5		-0.013
			(y-intercept)	1.484

F observed = 7.55

F critical (at 2 and 5 degrees of freedom and with $\alpha = 0.05$) = 5.79

Smallgrids warm synoptic types explain 25% of the variance in Peyto winter balance. They include the warm/wet and warm/efficient types mentioned above (Types 1, 4 and 8), each associated with damp southerly airflow. It would be more appropriate to group these three types with positive contributors to winter balance and not with negative contributors. More important to low accumulation totals are the dry and/or inefficient warm types associated with prominent ridges over Peyto (Types 6, 7, 15 and 17). Some years, such as 1969-70, have a sharp increase in these ridge types and a concomitant decrease in all moisture bearing synoptic types.

5.2.2 Sentinel Smallgrids

Positive correlations exist between Sentinel Glacier winter balance and wet, efficient and cool Smallgrids synoptic type frequencies (Table 5.7). Negative correlations are seen between winter balance and dry, inefficient and warm synoptic types. Although cool and warm types were the most highly correlated for Peyto Smallgrids, they are very weak predictors at Sentinel.

The stepwise linear regression for Sentinel Smallgrids produces an outlier seen in the residual plots and confirmed by the Dixon Criteria outlier test for small samples (Younger, 1979). One assumption of the linear regression

Table 5.7. Simple two-variable regressions of Sentinel Glacier winter balance with Smallgrids synoptic type characteristics.

CRITERION VARIABLE: Sentinel Glacier winter balance

PREDICTOR VARIABLE	r	r^2	F OBSERVED	F CRITICAL*	SIGNIFICANCE LEVEL
wet	0.6320	39.9	3.33	2.18	0.20
dry	-0.5796	33.6	2.53	2.18	0.20
efficient	0.7338	53.8	5.83	4.06	0.10
inefficient	-0.5260	27.7	1.91	----	not significant
cool	0.3086	9.5	0.53	----	not significant
warm	-0.2181	4.8	0.25	----	not significant

* At 1 and 5 degrees of freedom.

model is that all residual terms are normally distributed; an outlier is a residual value significantly beyond the range of the normal distribution. As a result, the year 1967-68 is removed from the analysis, decreasing the already limited degrees of freedom by one. The results of the subsequent regression show a high percentage of explained variance, but also reveal coefficients of the wrong sign for inefficient and wet synoptic types (Table 5.8). Inspection of the correlation matrix of predictor variables suggests collinearity (Table 5.9).

Because of the limited degrees of freedom available, a full model ridge regression is not possible. Thus, the weakest predictors, cool and warm synoptic type characteristics, are removed. The ridge trace for the remaining variables shows strong collinearity between efficient and wet types and between inefficient and dry types (Figure 5.4). Wet and inefficient synoptic types reverse signs and the absolute coefficient values at K = 0.0 are much too high. The weaker predictors, inefficient and wet types, are removed resulting in a stable ridge trace of the efficient and dry synoptic types (Figure 5.5). A stepwise linear regression of Sentinel Glacier winter balance with efficient and dry type characteristics explains 80% of the variance in the data (Table 5.10). This is the only case in which the set of best predictor variables does

Table 5.8. Stepwise linear regression of Sentinel Glacier winter balance with Smallgrids synoptic type characteristics. Data for the year 1967-68 are removed because the residual value violates the normality assumption of the linear regression model. All remaining data are considered as a single group for significance testing. Only the first four variables are entered due to degrees of freedom limitations.

CRITERION VARIABLE: Sentinel Glacier winter balance

PREDICTOR VARIABLE	CUMULATIVE R^2	R^2 CHANGE	REGRESSION COEFFICIENT
efficient	59.3	59.3	0.103
dry	80.0	20.7	-0.074
inefficient	94.4	14.4	0.082
wet	100.0	5.6	-0.025
		(y-intercept)	-5.201

F observed = 480.5

F critical (at 4 and 1 degrees of freedom and with $\alpha = 0.05$) = 224.6

Table 5.9. Correlation matrix of Sentinel Glacier Accumulation season Smallgrids synoptic type characteristics. Data for the year 1967-68 are removed.

	WET	DRY	EFFICIENT	INEFFICIENT	COOL	WARM
WET	1.0000					
DRY	-0.6403	1.0000				
EFFICIENT	0.4364	-0.1772	1.0000			
INEFFICIENT	-0.3525	0.6382	-0.6576	1.0000		
COOL	0.4743	0.3016	0.5069	0.1667	1.0000	
WARM	-0.7981	0.2532	-0.2190	0.0755	-0.6859	1.0000

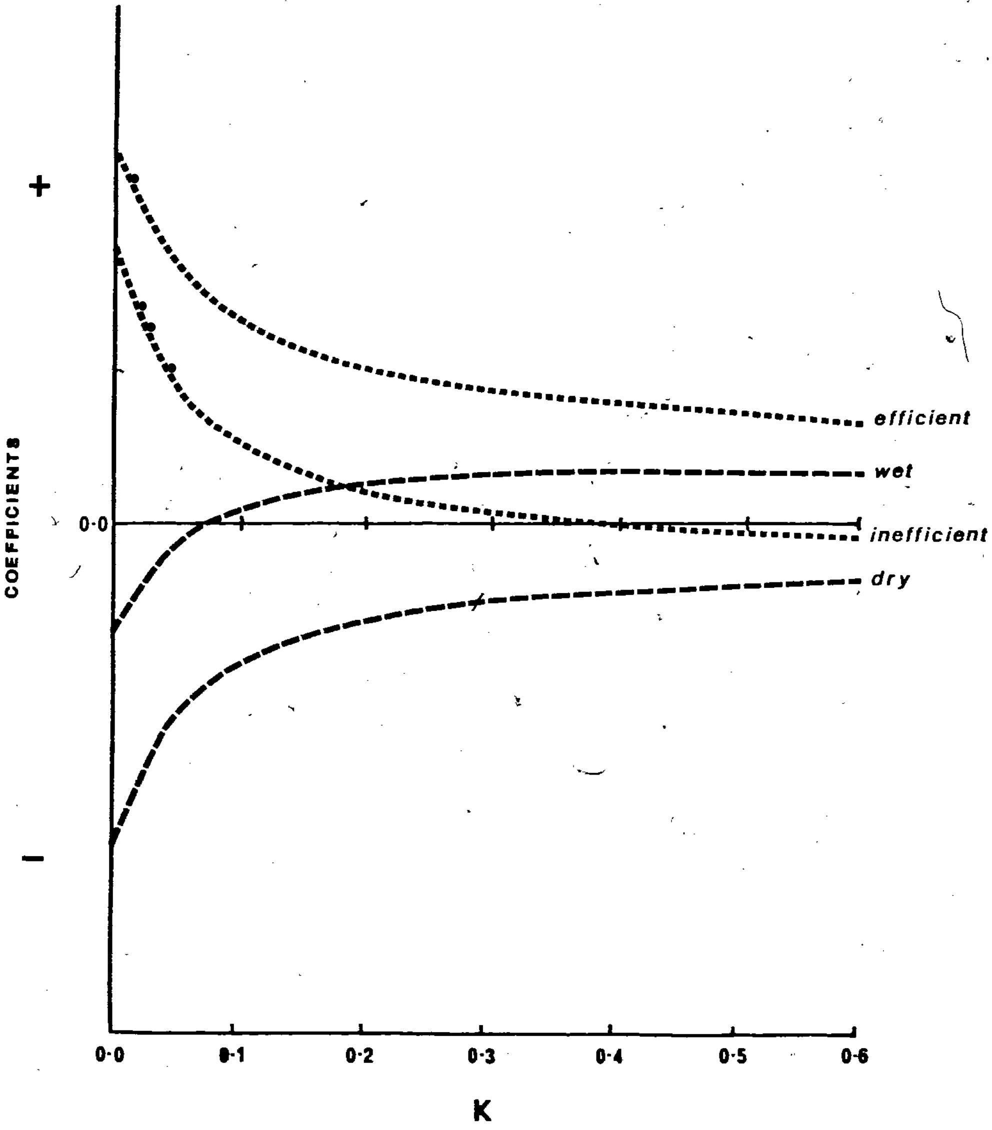


Figure 5.4. Ridge trace of Sentinel Glacier winter balance with Smallgrids wet, dry, efficient and inefficient synoptic types.

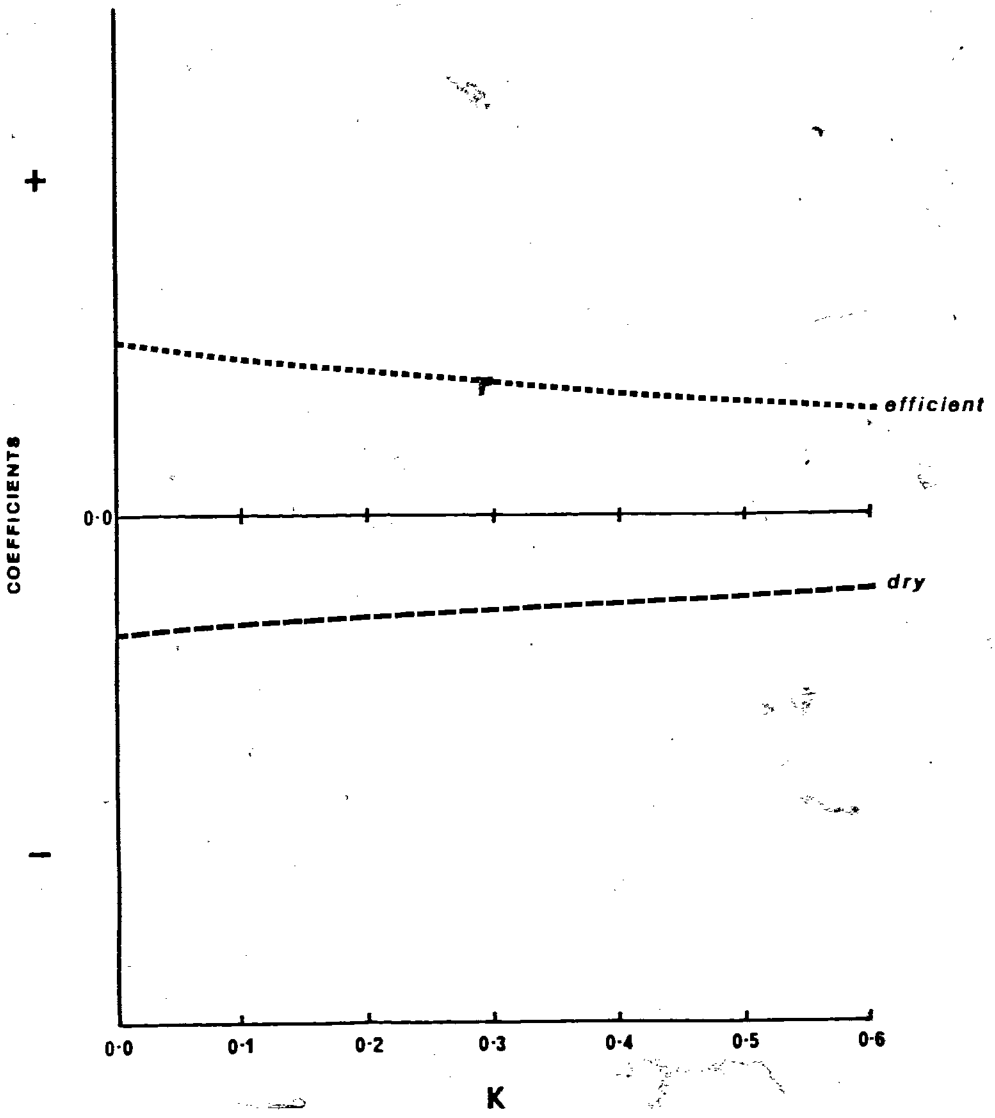


Figure 5.5. Ridge trace of Sentinel Glacier winter balance with Smallgrids efficient and dry synoptic types.

Table 5.10. Stepwise linear regression of Sentinel Glacier winter balance with Smallgrids efficient and dry synoptic type characteristics. Data for the year 1967-68 are removed.

CRITERION VARIABLE: Sentinel Glacier winter balance

PREDICTOR VARIABLE	CUMULATIVE R^2	R^2 CHANGE	REGRESSION COEFFICIENT
efficient	59.3	59.3	0.050
dry	80.0	20.7	-0.026
		(y-intercept)	1.408

F observed

F critical (at 2 and 3 degrees of freedom and with $\alpha = 0.10$) = 5.46

not form a wet/dry, efficient/inefficient or cool/warm couplet.

Nearly 60% of the variance in Sentinel winter balance is explained by efficient bearers of precipitation. Each of the important efficient types (1, 3, 4, 8 and 10) has a southwesterly cyclonic component to its airflow allowing it to pick up moisture over the Pacific before reaching Sentinel. In some cases, Types 1, 4 and 8 advect moist subtropical air into the area that, when combined with upward vertical motions and vorticity maxima, produce very heavy precipitation.

Approximately 20% of the variance in winter balance is explained by Sentinel dry type characteristics. Expecially important to years with low accumulation totals are those types with northerly flows (Types 5, 9, 14, 15 and 17) and those with 500mb ridges over Sentinel (Types 7 and 15).

5.2.3 Peyto Biggrids

Simple regressions of Peyto winter balance produce strong positive correlations with Biggrids wet, efficient and cool synoptic type characteristics and strong negative correlations with dry, inefficient and warm types (Table 5.11). Stepwise linear regression shows that just three variables explain nearly 97% of the variance in the data, but results in a regression coefficient of the wrong sign

Table 5.11. Simple two-variable regressions of Peyto Glacier winter balance with Biggrids synoptic type characteristics.

CRITERION VARIABLE: Peyto Glacier winter balance

PREDICTOR VARIABLE	r	r^2	F OBSERVED	F CRITICAL*	SIGNIFICANCE LEVEL
wet	0.6813	46.4	5.20	3.78	0.10
dry	-0.8744	76.5	19.49	13.75	0.01
efficient	0.5997	36.0	3.37	2.07	0.20
inefficient	-0.5365	28.8	2.42	2.07	0.20
cool	0.7261	52.7	6.69	5.99	0.05
warm	-0.7065	49.9	5.98	3.78	0.10

* At 1 and 6 degrees of freedom.

for the wet synoptic type characteristic (Table 5.12). Again, cause for this problem is seen in the correlation matrix of predictors which displays extremely high positive and negative correlations among the variables (Table 5.13).

A full model ridge regression shows considerable instability in all predictor variables (Figure 5.6). Efficient and dry predictors have very high coefficient values at K = 0.0, but both lose power quickly. Cool types also decrease in predictive power. Inefficient and warm types do not enter the regression equation until K = 0.02 and K = 0.04, respectively. Wet synoptic type characteristics reverse signs and develop the highest positive coefficient value. This is unexpected because the Pearson product-moment correlation of cool types with accumulation is greater than the r value for wet types with accumulation (Table 5.11). Inefficient type predictors have the wrong sign at K = 0.6, but become negative as K nears 1.0 (not shown in Figure 5.6).

Ridge regression of Peyto winter balance with wet, dry, cool and warm synoptic types shows continued instability (Figure 5.7). Wet and cool types are obviously collinear, as are dry and warm types. Wet and warm types still have the wrong sign at K = 0.0, although both quickly stabilize near K = 0.1. Wet and dry types appear to be the best predictors and produce a stable ridge trace when cool and warm synoptic

Table 5.12. Stepwise linear regression of Peyto Glacier winter balance with Biggrids synoptic type characteristics. All data are considered as a single group for significance testing. The F-levels of the efficient, cool and warm synoptic types are too low for inclusion.

CRITERION VARIABLE: Peyto Glacier winter balance

PREDICTOR VARIABLE	CUMULATIVE R^2	R^2 CHANGE	REGRESSION COEFFICIENT
dry	76.5	76.5	-0.047
efficient	90.2	13.7	0.018
wet	96.8	6.6	-0.008
		(y-intercept)	5.283

F observed = 40.5

F critical (at 3 and 4 degrees of freedom and $\alpha = 0.01$) = 16.7

Table 5.13. Correlation matrix of Peyto Glacier Accumulation season Biggrids synoptic type characteristics.

	WET	DRY	EFFICIENT	INEFFICIENT	COOL	WARM
WET	1.0000					
DRY	-0.9225	1.0000				
EFFICIENT	0.9821	-0.8829	1.0000			
INEFFICIENT	-0.8167	0.8419	-0.8670	1.0000		
COOL	0.8752	-0.8724	0.8724	-0.7891	1.0000	
WARM	-0.5196	0.6716	-0.4992	0.5467	-0.8279	1.0000

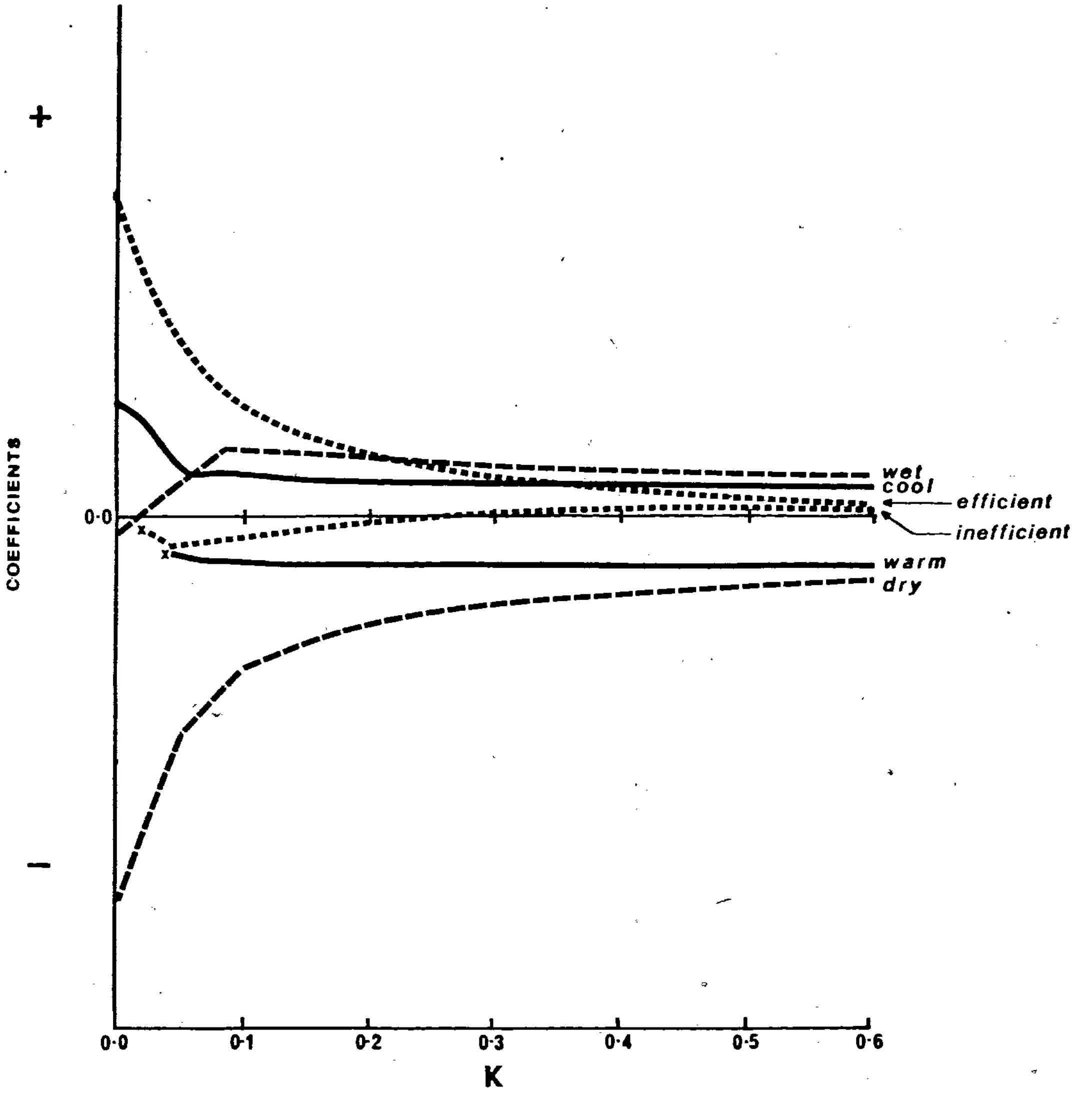


Figure 5.6. Ridge trace of Peyto Glacier winter balance with Biggrids synoptic type characteristics.

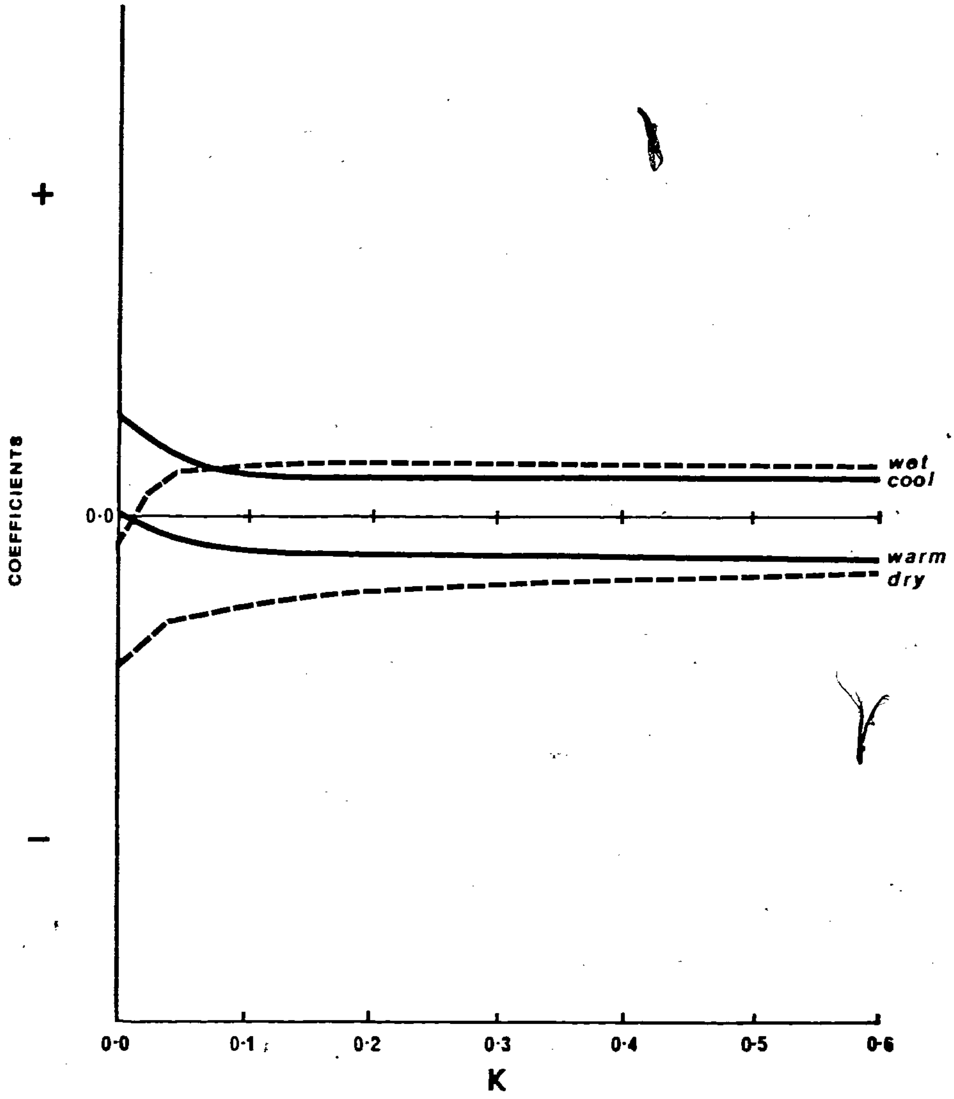


Figure 5.7. Ridge trace of Peyto Glacier winter balance with Biggrids wet, dry, cool and warm synoptic types.

types are removed (Figure 5.8). Stepwise linear regression of Peyto winter balance with Biggrids wet and dry synoptic type characteristics explains nearly 87% of the variance in winter balance at the 0.01 significance level (Table 5.14).

The Peyto Biggrids results demonstrate one important aspect of ridge regression in the analysis of highly correlated predictor variables. The dry synoptic type is clearly the most important (negatively correlated) variable. Simple r values suggest that the most important positively correlated variable is the cool synoptic type. Stepwise linear regression of all synoptic type characteristics suggest that another negatively correlated predictor, the inefficient type variable, should be included in the predictive equation. Only by ridge regression is it possible to discover that the best possible uncorrelated set of predictor variables includes dry with wet, and not cool or inefficient synoptic types.

76% of the variance in winter balance at Peyto is explained by the dry Biggrids synoptic types. Dry Types 2, 3 and 4 are important in terms of frequency and are also inefficient bearers of precipitation, meaning relatively little precipitation is delivered by these flow patterns. Type 2 is associated with subsiding northwesterly flow, while Type 4 days place a ridge of high pressure over Peyto Glacier. Type 3 finds Peyto just at that point in the long

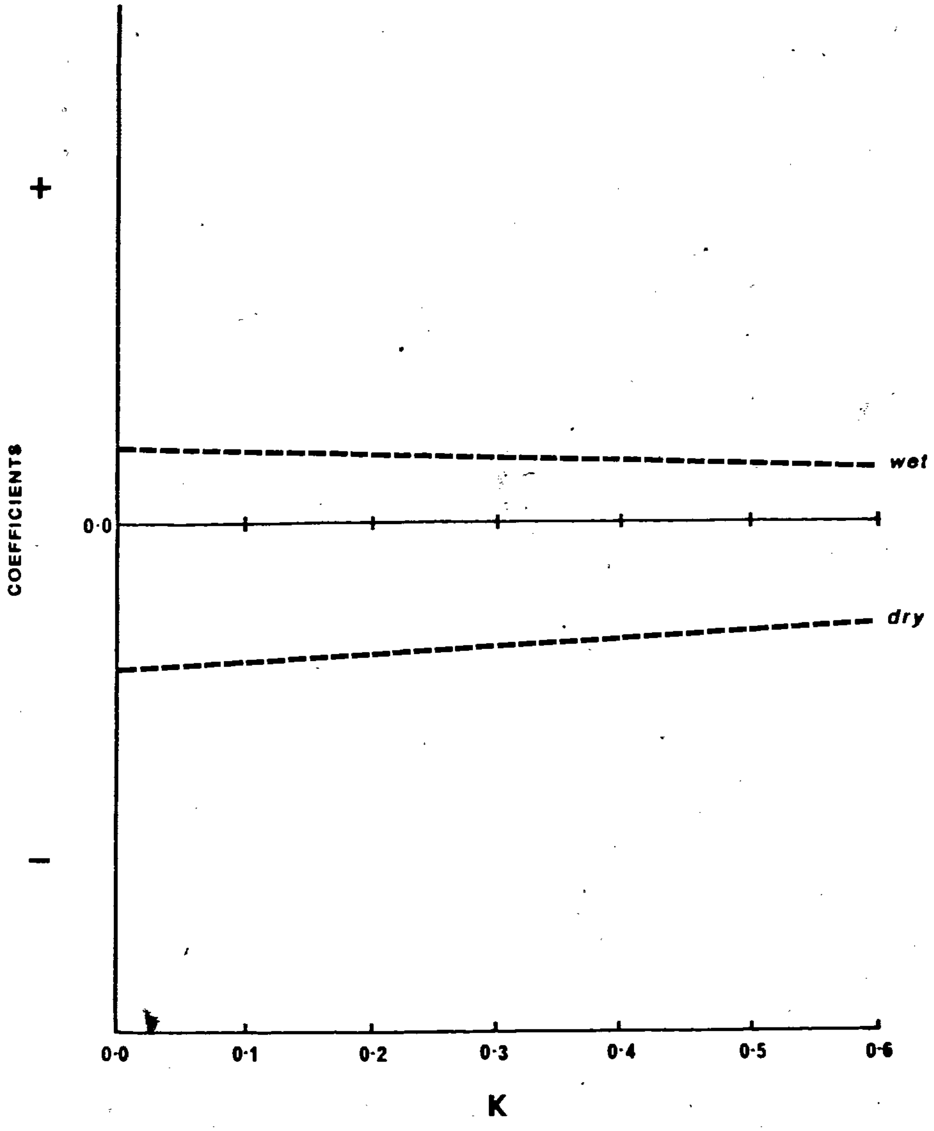


Figure 5.8. Ridge trace of Peyto Glacier winter balance with Biggrids wet and dry synoptic types.

Table 5.14. Stepwise linear regression of Peyto Glacier winter balance with Biggrids wet and dry synoptic types.

CRITERION VARIABLE	CUMULATIVE R^2	R^2 CHANGE	REGRESSION COEFFICIENT
dry	76.5	76.5	-0.039
wet	87.0	10.5	0.010
		(y-intercept)	6.147

F observed = 16.72

F critical (at 2 and 5 degrees of freedom and with $\alpha = 0.01$) = 13.27

wave pattern where anticyclonic vorticity decreases are accompanied by upper level convergence and consequent downward vertical motions. This contrasts with the position of Type 3 over Sentinel where negative vorticity is still increasing and accompanied by upper level divergence and attendant upward vertical motions. Thus, Peyto experiences inefficient precipitation under Type 3 regimes, whereas Sentinel receives heavy precipitation from this type.

Type 1 is not only wet, but also efficient and cool. 11% of the variance in winter balance is explained by this type; the only Biggrids type in the wet category.

5.2.4 Sentinel Biggrids

Regression analysis of Sentinel Glacier winter balance with the Biggrids synoptic type characteristics produces poor results. Simple regressions of accumulation with each of the predictor variables result in low r values (Table 5.15) All have the expected sign, but only the dry type reaches significance at the 0.20 level. Stepwise linear regression analysis (not shown) finds that no value entered into the second step produces a significant addition to the explanation provided by the dry synoptic type. Therefore, only 31% of the variance in the winter balance at Sentinel Glacier is explained by variations in the frequencies of the Biggrids synoptic type characteristics.

Table 5.15. Simple two-variable regressions of Sentinel Glacier winter balance with Biggrids synoptic type characteristics.

CRITERION VARIABLE: Sentinel Glacier winter balance

PREDICTOR VARIABLE	r	r^2	F OBSERVED	F CRITICAL*	SIGNIFICANCE LEVEL
wet	0.4203	17.7	1.07	----	not significant
dry	-0.5590	31.2	2.27	2.18	0.20
efficient	0.2970	8.8	0.48	----	not significant
inefficient	-0.3689	13.6	0.79	----	not significant
cool	0.3086	9.5	0.53	----	not significant
warm	-0.2181	4.8	0.25	----	not significant

* At 1 and 5 degrees of freedom.

The description of synoptic flow over Peyto for Biggrids dry types given in Section 5.2.3 holds for Sentinel, with one notable exception. Type 3 has divergent, rather than convergent flow over Sentinel, bringing efficient precipitation events and a marked increase in Winter season precipitation.

5.2.5 Summary

In three of the four cases studied, a large proportion of the total variance in winter balance is explained by simple climatological characteristics of the synoptic types. At Peyto Glacier, 75% of the variance is explained by cool and warm Smallgrids synoptic types and 87% is explained by wet and dry Biggrids synoptic types. At Sentinel Glacier, 80% of the variance in winter balance can be attributed to fluctuations in efficient and dry Smallgrids synoptic type frequencies. In the fourth case, Sentinel Biggrids, only the dry synoptic type characteristics are significantly correlated with winter balance, explaining 31% of the variance. It must be emphasized that because of collinearity in the predictor variable sets, conclusions such as "Peyto Glacier winter balance is associated with Smallgrids cool and warm type characteristics and not with wet, dry, efficient and inefficient types" are false. In this example, cool synoptic types are highly correlated with wet and efficient types and necessarily subsume some, but not all of the information in the latter two categories.

In most cases, much of the explained variance in winter balance appears to be controlled by airflow direction, moisture content, isobaric curvature, vorticity changes and vertical motions associated with the 500mb patterns. Slight differences in the spatial and temporal relationships of Peyto and Sentinel to the mid-tropospheric wave patterns accounts for some of the difference in winter balance at each glacier.

5.3 Summer temperature

Regressions of Summer mean daily maximum temperature with the Summer synoptic type characteristics frequencies are analyzed in this section. Again, results for Peyto Smallgrids, Sentinel Smallgrids, Peyto Biggrids and Sentinel Biggrids are presented separately.

5.3.1 Peyto Smallgrids

Simple regressions of Banff Summer mean daily maximum temperature with Smallgrids synoptic type characteristics produce disappointing results.(Table 5.16). Wet, inefficient and cool synoptic types are virtually uncorrelated with temperature, while the remaining type characteristics show

Table 5.16. Simple two-variable regressions of Banff Summer mean daily maximum temperature with Smallgrids synoptic type characteristics.

CRITERION VARIABLE: Banff Summer mean daily maximum temperature

PREDICTOR VARIABLE	r	r^2	F OBSERVED	F CRITICAL*	SIGNIFICANCE LEVEL
wet	0.0418	0.2	0.01	----	not significant
dry	-0.3929	15.4	1.28	----	not significant
efficient	-0.5265	27.7	2.68	2.00	0.20
inefficient	-0.0060	0.0	0.00	----	not significant
cool	0.0922	0.8	0.06	----	not significant
warm	-0.3647	13.3	1.07	----	not significant

* At 1 and 7 degrees of freedom.

weak r values. Unexpectedly, warm synoptic types are negatively correlated with Summer mean daily maximum temperature. This suggests that the seasonal mean temperature is independent of daily temperature variations. The only synoptic type characteristic to be weakly significant and to possess the expected sign is the efficient type, accounting for about 28% of the variance in the temperature data. Subsequent stepwise linear regression (not shown) added no other synoptic type characteristics to the efficient type.

Efficient precipitation bearing Smallgrids Summer types at Lake Louise suppress ablation at Peyto Glacier. These types fall into three categories. First are those types associated with 500mb divergence and upward vertical motion ahead of a trough (Types 3, 8, 12 and 16). Next are cold lows (11,13 and 18). Last are types in which precipitation efficiency is difficult to explain in terms of atmospheric flow (Types 2, 4 and 5). In each of the last three types, relatively low pressure is shown due north of Peyto, in the upper right quadrant of the Smallgrids map, which may trigger instability in the Lake Louise area.

5.3.2 Sentinel Smallgrids

Simple correlations of Alta Lake Summer mean daily maximum temperature with the Smallgrids synoptic type characteristics (Table 5.17) are much stronger than those of the Peyto Smallgrids situation. Because efficient types do not have the expected negative sign and inefficient types are highly correlated with dry types (r = 0.9289), a stepwise linear regresion using wet, dry, cool and warm synoptic type characteristics is presented (Table 5.18). Resulting regression coefficients display the expected signs, suggesting that ridge regression is not needed. However, an analysis of variance (not shown) demonstrates that the addition of cool and warm types to the equation does not significantly improve upon the 95% explanation provided by wet and dry type characteristics alone.

Dry Smallgrids types, which explain 74% of the variance in Summer temperature at Alta Lake, enhance ablation at Sentinel Glacier. In most cases, dry types are inefficient bearers of precipitation with above average temperatures. In a few infrequent cases (cold low Types 11, 13 and 18), dry types are really cool, efficient bearers of precipitation. Especially important dry types are Types 2 and 6, each occuring frequently with warm temperatures and clear skies. These two types are both associated with subsidence and northerly airflow over Sentinel.

Wet Smallgrids types explain 22% of the variance in Alta Lake Summer temperature and can be important in suppressing ablation at Sentinel. These four types (1, 3, 4

Table 5.17. Simple two-variable regressions of Alta Lake Summer mean daily maximum temperature with Smallgrids synoptic type characteristics.

CRITERION VARIABLE: Alta Lake Summer mean daily maximum temperature

PREDICTOR VARIABLE	r	r^2	F OBSERVED	F CRITICAL*	SIGNIFICANCE LEVEL
wet	-0.2993	9.0	0.49	----	not significant
dry	0.8580	73.6	13.94	6.61	0.05
efficient	0.3370	11.4	0.64	----	not significant
inefficient	0.6882	47.4	4.50	4.06	0.10
cool	-0.0171	0.0	0.00	----	not significant
warm	0.1869	3.5	0.18	----	not significant

* At 1 and 5 degrees of freedom.

Table 5.18. Stepwise linear regression of Alta Lake Summer mean maximum daily temperature with Smallgrids wet, dry, cool and warm synoptic types. a) All four variables are considered as a single group for significance testing. b) Only wet and dry variables are considered as a single group for significance testing.

CRITERION VARIABLE: Alta Lake Summer mean daily maximum temperature

PREDICTOR VARIABLE	CUMULATIVE R^2	R^2 CHANGE	REGRESSION COEFFICIENT
dry	73.6	73.6	0.105
wet	95.8	22.2	-0.055
warm	97.9	2.1	0.016
cool	97.9	0.0	-0.004
		(y-intercept)	14.290

a) F observed = 23.38

F critical (at 4 and 2 degrees of freedom and with $\alpha = 0.05$) = 19.25

b) F observed = 45.83

F critical (at 2 and 4 degrees of freedom and with $\alpha = 0.01$) = 18.00

and 8) are all associated with southwesterly flow and upward vertical motions ahead of a trough of marine air. Although Types 1 and 4 have above average temperatures, ablation is partially suppressed by cloudy skies. Types 3 and 8 are associated with wet, cool conditions.

5.3.3 Peyto Biggrids

Correlations of Banff Summer mean daily maximum temperatures with the Biggrids synoptic type characteristics are poor (Table 5.19). Wet, efficient and cool types are associated with the expected negative signs, but only dry types are positively correlated with Summer temperature. Cool and efficient type characteristics are weakly significant (29% and 24% explained variance, respectively). Stepwise linear regression (not shown) only enters the cool variable into the regression equation, with the F-values of all other variables being too low for inclusion.

Of the Biggrids Summer pressure patterns advecting cool air into the Peyto Glacier area, only Type 2 is important. This relatively frequent type has a northwesterly airflow that lowers temperatures nearly 5 °C below the seasonal mean maximum daily temperature.

Table 5.19. Simple two-variable regressions of Banff Summer mean maximum daily temperature with Biggrids synoptic type characteristics.

CRITERION VARIABLE: Banff Summer mean daily maximum temperature

PREDICTOR VARIABLE	r	r^2	F OBSERVED	F CRITICAL*	SIGNIFICANCE LEVEL
wet	-0.4689	22.0	1.97	----	not significant
dry	0.1418	2.0	0.14	----	not significant
efficient	-0.4861	23.6	2.17	2.00	0.20
inefficient	-0.0203	0.0	0.00	----	not significant
cool	-0.5458	29.3	2.97	2.00	0.20
warm	-0.0591	0.4	0.02	----	not significant

* At 1 and 7 degrees of freedom.

5.3.4 Sentinel Biggrids

The results of simple regressions of Alta Lake Summer mean daily maximum temperature with Biggrids synoptic type characteristics are presented in Table 5.20. Wet, dry, cool and warm types are associated with the expected sign and are entered into a stepwise linear regression (Table 5.21). Cool, wet and dry types explain 96% of the variance in Summer temperature; warm type F-levels are too low for inclusion. However, the wet predictor's regression coefficient has the wrong sign, a result of the high correlation between wet and cool type characteristics (Table 5.22). A ridge trace (Figure 5.9) demonstrates that collinearity prevents the wet and dry variables from attaining correct signs until K nears 1.0 (not shown in Figure 5.9). The cool predictor coefficient value is too high at K = 0.0, while the warm value does not enter the equation until K = 0.02. Removal of the weak wet and dry predictor variables results in a stable trace (Figure 5.10) and 83% explanation in the total variance of Alta Lake Summer mean daily maximum temperature (Table 5.23).

Biggrids cool Types 2, 5 and 8 account for 74% of the variance in Alta Lake Summer temperatures. Each is very cool, with northwesterly airflow trajectories suppressing ablation at Sentinel Glacier. Type 8 is coolest, with temperatures nearly 7 °C below the mean, followed by Type 2

Table 5.20. Simple two-variable regressions of Alta Lake Summer mean maximum daily temperature with Biggrids synoptic type characteristics.

CRITERION VARIABLE: Alta Lake Summer mean daily maximum temperature

PREDICTOR VARIABLE	r	r^2	F OBSERVED	F CRITICAL*	SIGNIFICANCE LEVEL
wet	-0.2557	6.5	0.35	----	not significant
dry	0.2152	4.6	0.24	----	not significant
efficient	0.2948	8.7	0.48	----	not significant
inefficient	-0.3147	9.9	0.55	----	not significant
cool	-0.8618	74.3	14.43	6.61	0.05
warm	0.6701	44.9	4.08	4.06	0.10

* At 1 and 5 degrees of freedom.

Table 5.21. Stepwise linear regression of Summer mean daily maximum temperature at Alta Lake with Biggrids wet, dry, cool and warm synoptic types. All data are considered as a single group for significance testing. The F-level of the warm synoptic types is too low for inclusion.

CRITERION VARIABLE: Summer mean daily maximum temperature

PREDICTOR VARIABLE	CUMULATIVE R^2	R^2 CHANGE	REGRESSION COEFFICIENT
cool	74.3	74.3	-0.087
wet	92.6	18.3	0.044
dry	96.5	3.9	0.013
		(y-intercept)	16.525

F observed = 27.77

F critical (at 3 and 3 degrees of freedom and with $\alpha = 0.05$) = 9.28

Table 5.22 Correlation matrix of Sentinel Glacier Summer Biggrids synoptic type characteristics.

	WET	DRY	COOL	WARM
WET	1.0000			
DRY	-0.4851	1.0000		
COOL	0.6668	-0.2580	1.0000	
WARM	-0.1482	0.7710	-0.4705	1.0000

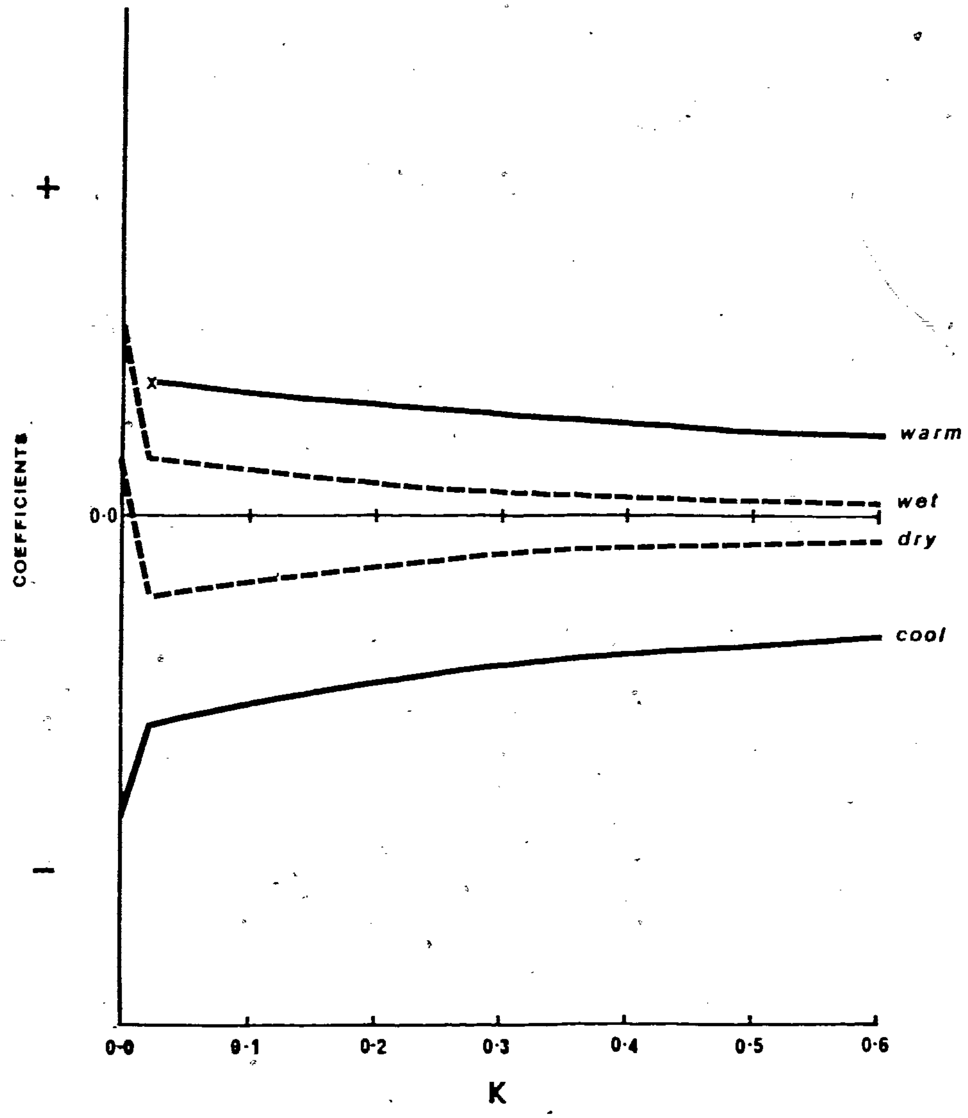


Figure 5.9. Ridge trace of Alta Lake Summer mean maximum daily temperature with Biggrids wet, dry, cool and warm synoptic types.

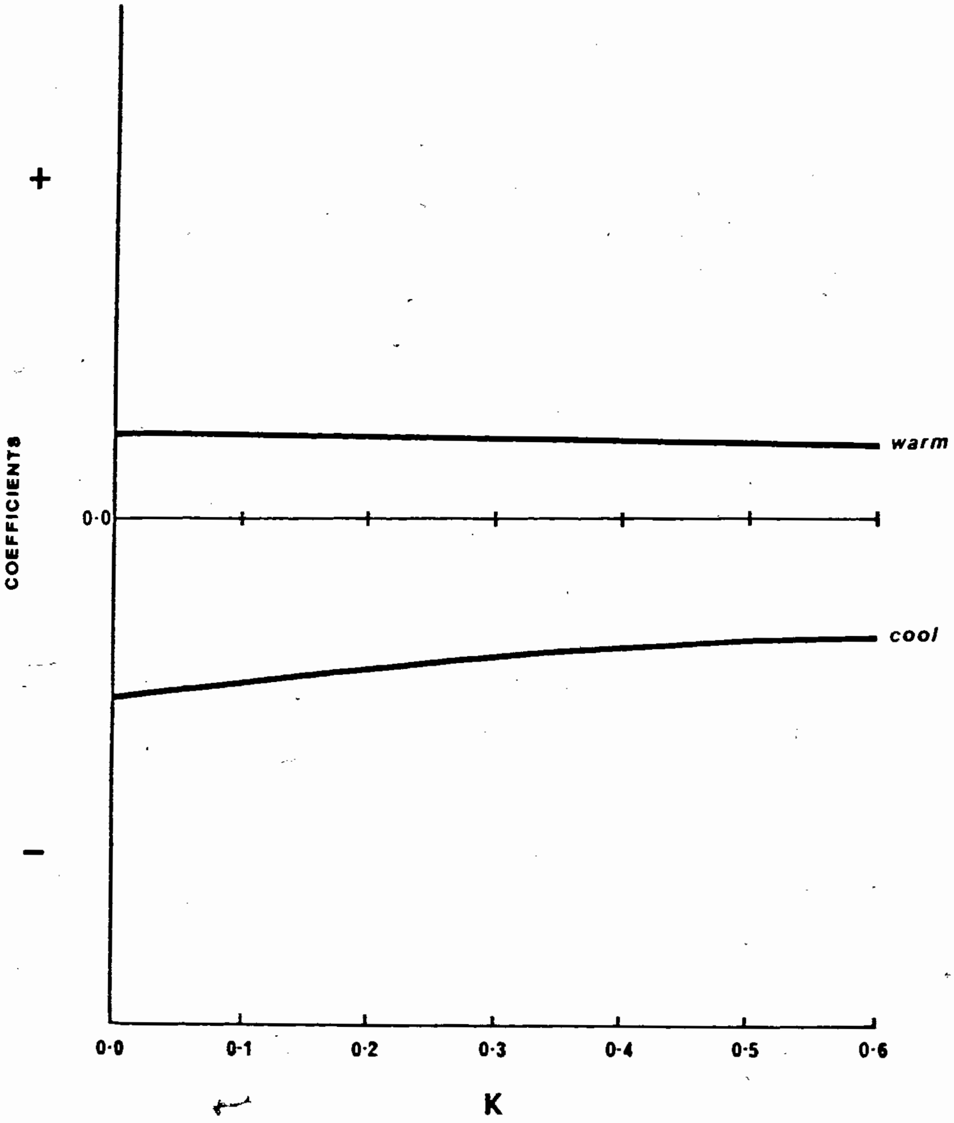


Figure 5.10. Ridge trace of Alta Lake Summer mean maximum daily temperature with Biggrids cool and warm synoptic types.

Table 5.23. Stepwise linear regression of Alta Lake Summer mean daily maximum temperature with Biggrids cool and warm synoptic types.

CRITERION VARIABLE: Alta Lake Summer mean daily maximum temperature

PREDICTOR VARIABLE	CUMULATIVE R^2	R^2 CHANGE	REGRESSION COEFFICIENT
cool	74.3	74.3	-0.048
warm	83.2	9.0	0.018
		(y-intercept)	18.839

F observed = 9.95

F critical (at 2 and 4 degrees of freedom and with $\alpha = 0.05$) = 6.94

(more than 4°C below average) and Type 5 (nearly 3°C below the mean).

Warm Biggrids Types 1, 3, 4 and 6 explain an additional 9% of the variance in Summer temperature. In each case, warm westerly to southwesterly marine air is advected into the region by the mid-tropospheric flow.

5.3.5 Summary

It appears that Summer temperatures in the Peyto Glacier vicinity are poorly related to synoptic-scale fluctuations, while Sentinel area Summer temperatures are associated with changes in synoptic type characteristic frequencies. For Peyto, only 28% explanation in temperature variance is afforded by Smallgrids efficient typ~~es,~~ and just 29% is provided by Biggrids cool synoptic type characteristics. On the other hand, Sentinel Smallgrids and Biggrids synoptic type characteristics both account for large proportions of the variance in Alta Lake Summer mean daily maximum temperature. Nearly 96% of the temperature variance is explained by Smallgrids wet and dry types, while more than 83% is explained by a combination of Biggrids cool and warm types.

A difference appears to exist between Smallgrids and Biggrids relationships to Summer temperature. Smallgrids types suppressing temperature (and presumably ablation) tend to be associated with cloudy, wet conditions. Those types favoring warmer temperatures and ablation tend to be dry, inefficient and cloud-free. Biggrids is related to temperature strictly by airflow characteristics: cool synoptic types have northerly airflow trajectories; warm days have westerly to southwesterly flows.

5.4 Summary and discussion

In this chapter, the relationship between simple climatological characteristics of the synoptic types and winter balance or Summer mean daily maximum temperature was analyzed. A summary and discussion of the results of this analysis in terms of the first two objectives of the thesis follows.

The first objective was to determine whether a relationship exists between synoptic-scale circulation patterns and glacier mass balance fluctuations at Peyto and Sentinel. The results suggest that changes in winter balance are closely associated with synoptic-scale atmospheric circulation. Both Smallgrids and Biggrids synoptic type characteristics predict most of the variance in Peyto's winter balance, while Smallgrids fluctuations relate well to changes in Sentinel's winter balance. Climatological properties of the 500mb pressure patterns, such as moisture source, airflow direction, isobaric curvature, vorticity and vertical motion, account for enhanced or suppressed accumulation at Peyto and Sentinel. In both Smallgrids and Biggrids situations, cyclonic flows favor accumulation, while anticyclonic flows bring much less moisture to both glaciers, thus suppressing accumulation.

Interpretation of annual ablation is not straightforward because of the difficulties involved in relating the complex energy exchange at a glacier surface to simple changes in the frequency of synoptic type characteristics. However, fluctuations in Summer mean daily maximum temperature, which together with season length roughly makes up the total melt energy (melting degree days) at a glacier, are associated with changes in the frequencies of Smallgrids and Biggrids synoptic type characteristics at Sentinel Glacier. A strong relationship between synoptic type characteristics and Summer temperature is not present at Peyto Glacier. Cloudy conditions under Smallgrids regimes suppress temperature and ablation, whereas sunny skies raise temperatures and enhance glacier melt. Biggrids northerly airflow types bring cool temperatures to southwestern Canada. Southwesterly to westerly Biggrids flow raises temperatures and favors ablation.

More light can be shed on the relationship between synoptic-scale atmospheric circulation and glacier mass balance at Peyto and Sentinel when the second thesis objective is examined. That objective seeks to determine whether changes in the synoptic-scale and level of information used in the weather maps influence the results.

For winter balance at Sentinel, 80% of the variance is explained by Smallgrids types, while Biggrids only explains 31%. This suggests that Sentinel accumulation may be controlled by small-scale, high-wavenumber synoptic activity. Long wave control on the mass balance of Sentinel may still be present, however. Evidence on the extent of the glacier ca.100 yr B.P. (Mathews, 1951) and ca.6000 yr B.P. (Mokievsky-Zubok, 1973a) suggests that Sentinel is in phase with the hemispheric glacier advances of the Holocene proposed by Denton and Karlen (1977). Therefore, it follows that if high-wavenumber types do control the winter balance of Sentinel, then the smaller scales of synoptic activity are still constrained by long-term trends in the larger scales of the atmospheric circulation. Hasselmann (1976), Frankignoul and Hasselmann (1977), and Lemke (1977) have demonstrated that random activity within broad atmospheric trends is possible. However, short wave variations within long wave patterns have not been analyzed using their methodology.

At Peyto, better explanation of the total variance in winter balance is given by Peyto Biggrids (87%) than Peyto

Smallgrids (75%) synoptic type characteristics. If this difference is real and not due to problems in the present model (Chapter 6), then this suggests that the climatological characteristics of Peyto Smallgrids are more dependent on the long wave control of Peyto Biggrids than is the Sentinel accumulation situation. Perhaps friction induced by the rough terrain of the Cordillera dampens some of the high frequency atmospheric oscillations within the deep, vigorous fronts crossing the mountains in Winter. Thus, upon reaching Peyto, the effect of small-scale synoptic variation is subsumed by the more general long wave atmospheric flow.

At Alta Lake, 96% of the variance in Summer temperature is explained by Smallgrids synoptic type characteristics, while 83% of the variance is explained by Biggrids types. Using similar reasoning to that applied to Sentinel winter balance, it can be argued that Summer temperature is controlled more by smaller-scale synoptic activity. Evidence presented in Section 6.2.2 suggests that this argument may be tenable. These results may be physical manifestations of the statistical relationship between Smallgrids and Biggrids pointed out in Section 4.4. Summer temperature characteristics appear to be related to generalized large-scale atmospheric flow, while Summer cloud cover is more specific in location and related to small-scale atmospheric perturbations within larger wave patterns. However, as suggested above, Biggrids airflow is better related to Summer temperature than it is to winter balance (83% explained variance for the former; 31% for the latter). This suggests that, somewhat like Peyto winter balance, high frequency atmospheric activity is dampened over Sentinel Glacier in summer. In this instance, general subsidence of the eastern limb of the Pacific high appears to inhibit Smallgrids activity from above. This contrasts with the topographic effect that seems to constrain the short waves from below in the Peyto case.

Neither the Smallgrids nor Biggrids synoptic type characteristics frequencies seem to be related to Summer mean daily maximum temperature at Banff (28% and 29% explained variance, respectively). This lack of statistical explanation in the seasonal mean is difficult to interpret. Although daily fluctuations in climatological parameters, such as katabatic winds (Stenning, et al., 1981), appear to be related to synoptic weather patterns at Peyto, some other factor or factors not accounted for in the present synoptic climatological model must control Summer mean temperature in the region.

Analysis of just Smallgrids or Biggrids synoptic types would have resulted in a loss of information. The use of Biggrids alone would have missed the association of Sentinel winter balance and Summer temperature with high-wavenumber synoptic type fluctuations, which appear to be important to the climate of the region. Conversely, if just Smallgrids had been used, relationships between large-scale synoptic circulation patterns and Peyto winter balance and Alta Lake Summer temperatures would have been overlooked. Based on these findings, it appears that synoptic climatologists must either perform a "double" study, as in this work, or select for analysis one of a relatively detailed regional approach (such as Smallgrids) or a more general synoptic climatology (such as Biggrids). When choosing the latter course, the investigator must be aware that he may be sacrificing information for economy of effort.

6. Variability of the Synoptic Climatological Model

The nature and the strength of the relationship between elements of glacier mass balance at Peyto and Sentinel Glaciers and simple characteristics of the Smallgrids and Biggrids synoptic types were determined in the previous chapter. In this chapter, the variability of that synoptic climatological model is examined. Specifically, the third thesis objective, identification of sources of error in the model is addressed. To achieve this objective, the explained and unexplained variance in winter balance is analyzed, followed by a similar analysis of Summer temperature. In both cases, the problem of within-type variation is studied. In one instance, the information lost when discarding collinear variables is demonstrated. Finally, other shortcomings of the synoptic climatological approach used in this thesis are discussed.

6.1 Interannual variability of winter balance

In Section 5.2, four situations were analyzed to determine the relationship between winter balance and the synoptic type characteristics. It was shown that large proportions of the variance in winter balance can be accounted for by just two synoptic type characteristics of

Peyto Smallgrids, Sentinel Smallgrids and Peyto Biggrids. The total variance of the fourth situation, Sentinel Biggrids, was not explained well by the type characteristics. In the present section, the interannual variability in observed and predicted winter balance of all but the Sentinel Biggrids situation is studied.

6.1.1 Peyto Smallgrids

Observed winter balance, predicted winter balance from the Smallgrids cool and warm synoptic types, and residuals for eight winter balance seasons at Peyto Glacier are presented in Table 6.1. The winter balance totals of 1968-69, 1969-70, 1970-71 and 1973-74 are predicted well by the regression equation. Relatively large residuals in the remaining years demonstrate that cool and warm type frequencies alone do not adequately describe the winter balance.

The residuals of some years can be accounted for by within-type variation. Tables 6.2 and 6.3 show the interannual variation in mean grid height, grid intensity, maximum daily temperature and daily precipitation of the cool and warm Smallgrids synoptic types. Mean grid height may be interpreted as a rough measure of surface-500mb atmospheric thickness. Mean grid intensity is the mean standard deviation of the 500mb values of the daily grids;

Table 6.1. Interannual variation in Peyto Glacier winter balance predicted by Smallgrids cool and warm synoptic types.

YEAR	OBSERVED WINTER BALANCE (m)	PREDICTED WINTER BALANCE (m)	RESIDUAL (m)	COOL TYPE FREQUENCY	WARM TYPE FREQUENCY
1966-67	2.06	1.89	0.17	123	119
1967-68	1.63	1.44	0.19	94	119
1968-69	1.43	1.47	-0.04	101	125
1969-70	1.07	1.14	-0.07	87	134
1970-71	1.31	1.39	-0.08	110	142
1971-72	1.67	1.89	-0.22	112	105
1972-73	1.72	1.59	0.13	113	130
1973-74	1.62	1.70	-0.08	124	135
$\bar{x}$	1.56	1.56	0.00	108	126
s	0.30	0.26	0.15	13	12

Table 6.2. Interannual variation in climatological parameters of the Peyto Smallgrids Accumulation season cool synoptic types.

YEAR	MEAN SMALLGRIDS HEIGHT (m)	MEAN SMALLGRIDS INTENSITY (m)	MEAN MAXIMUM DAILY TEMPERATURE (°C)	MEAN DAILY PRECIPITATION (mm)
1966-67	5458.9	101.7	1.5	2.5
1967-68	5452.3	96.2	0.5	1.6
1968-69	5416.0	90.6	-2.1	1.2
1969-70	5468.9	88.2	2.0	0.5
1970-71	5449.7	104.8	-0.7	1.0
1971-72	5438.2	101.5	-1.2	1.4
1972-73	5488.1	77.5	2.1	2.0
1973-74	5438.4	99.5	1.0	1.4
$\bar{x}$	5451.3	95.0	0.4	1.4
s	21.7	9.1	1.6	0.6

Table 6.3. Interannual variation in climatological parameters of the Peyto Smallgrids Accumulation season warm synoptic types.

YEAR	MEAN SMALLGRIDS HEIGHT (m)	MEAN SMALLGRIDS INTENSITY (m)	MEAN MAXIMUM DAILY TEMPERATURE (°C)	MEAN DAILY PRECIPITATION (mm)
1966-67	5423.6	103.3	4.7	2.9
1967-68	5441.1	106.3	6.2	1.5
1968-69	5417.3	102.6	4.9	1.5
1969-70	5628.7	95.5	4.0	1.1
1970-71	5440.3	98.3	6.7	1.6
1971-72	5421.7	107.1	5.8	2.5
1972-73	5446.0	96.7	6.2	1.0
1973-74	5429.1	98.5	7.3	1.9
$\bar{x}$	5456.0	101.0	5.7	1.8
s	70.6	4.4	1.1	0.7

that is, a measure of the dispersion of the isobars across the map surface (Moritz, 1979). Much of the underprediction of winter balance in 1966-67 can be attributed to mean daily precipitation totals that are well above the eight-year means in both cool and warm synoptic type situations. However, the same reasoning cannot be applied to the other poorly predicted years. In 1967-68, both precipitation figures are near the mean. In 1971-72, winter balance is overpredicted, but mean daily precipitation for warm types is one standard deviation above the mean; this should lead to underprediction. In 1972-73, a somewhat balanced situation exists, with mean daily precipitation for cool types being one standard deviation above the mean, and precipitation for warm types being more than one standard deviation below the mean. Possible reasons for the unexplained variation in this and other cases will be discussed in Section 6.3.

Within-type variation can also account for some of the smaller residuals in years that are predicted well by the cool and warm Smallgrids types. For example, 1969-70 has a very low frequency of cool types and an above average number of warm types (Table 6.1). These figures lead to a slight overprediction of winter balance. However, the warm tendency of the season is reinforced by increased mean Smallgrids heights (especially in the case of the warm types), below average grid intensities and low mean daily precipitation figures. All of the above suggest warmer, drier conditions than those predicted by the synoptic type frequencies witnessed in that year.

6.1.2 Sentinel Smallgrids

Predicted winter balance and residuals from the Sentinel Smallgrids efficient and dry synoptic types for seven winter balance seasons at Sentinel Glacier are shown in Table 6.4. The years 1968-69, 1970-71 and 1971-72 are well predicted by the efficient and dry types. The winter balances of 1969-70 and 1973-74 are over- and underpredicted, respectively, with these residuals being attributed to within-type variation (Tables 6.5 and 6.6). Increased mean grid heights, weak intensities, warmer and drier conditions mark 1969-70. Decreased grid heights, increased intensities, cooler than expected temperatures and sharp increases in mean daily precipitation are seen in the dry synoptic types of 1973-74. Residuals for the years 1967-68 and 1972-73 are not accounted for by within-type variations.

6.1.3 Peyto Biggrids

Wet and dry Peyto Biggrids synoptic type characteristics accurately predict the Peyto Glacier winter

Table 6.4. Interannual variation in Sentinel Glacier winter balance predicted by Smallgrids efficient and dry synoptic types.

YEAR	OBSERVED WINTER BALANCE (m)	PREDICTED WINTER BALANCE (m)	RESIDUAL (m)	EFFICIENT TYPE FREQUENCY	DRY TYPE FREQUENCY
1967-68	3.42	3.79	-0.37	91	77
1968-69	3.52	3.70	-0.18	97	91
1969-70	2.62	2.94	-0.32	74	80
1970-71	3.86	3.86	0.00	82	59
1971-72	2.94	3.01	-0.07	79	86
1972-73	3.38	2.79	0.59	77	91
1973-74	4.81	4.45	0.36	99	66
$\bar{x}$	3.51	3.51	0.00	86	79
s	0.70	0.61	0.35	10	12

Table 6.5. Interannual variation in climatological parameters of the Sentinel Smallgrids Accumulation season efficient synoptic types.

YEAR	MEAN SMALLGRIDS HEIGHT (m)	MEAN SMALLGRIDS INTENSITY (m)	MEAN MAXIMUM DAILY TEMPERATURE (°C)	MEAN DAILY PRECIPITATION (mm)
1967-68	5409.7	110.3	5.8	13.6
1968-69	5373.2	104.3	3.6	10.1
1969-70	5404.6	100.4	3.9	6.1
1970-71	5345.5	102.4	3.5	8.6
1971-72	5347.6	107.5	3.6	11.1
1972-73	5392.4	98.5	4.0	9.3
1973-74	5358.3	100.0	4.7	11.4
$\bar{x}$	5375.9	103.3	4.2	10.0
s	26.7	4.3	0.8	2.4

Table 6.6. Interannual variation in climatological parameters of the Sentinel Smallgrids Accumulation season dry synoptic types.

YEAR	HEIGHT (m)	INTENSITY (m)	TEMPERATURE (°C)	PRECIPITATION (mm)
1967-68	5452.0	95.9	4.2	1.9
1968-69	5386.3	88.6	0.7	2.0
1969-70	5484.7	90.4	6.4	0.9
1970-71	5378.9	96.5	1.0	1.7
1971-72	5403.0	103.1	0.8	2.1
1972-73	5484.8	94.5	5.7	1.4
1973-74	5401.6	105.2	2.1	3.8
$\bar{x}$	5427.3	96.3	3.0	2.0
s	45.6	6.1	2.4	0.9

balance totals of 1968-69 through 1972-73 (Table 6.7). The underprediction of 1966-67 is attributable to within-type variation: decreased mean heights, increased intensities and above average daily precipitation characterize both the wet and dry synoptic types (Tables 6.8 and 6.9). The overprediction of 1973-74 is associated at least in part with slightly greater atmospheric thicknesses, decreased grid intensities, warmer temperatures and drier conditions during wet synoptic type days. The residuals of 1967-68 cannot be accounted for by within-type variation.

The year 1967-68 is better predicted by an equation based on a stepwise linear regression of the cool and warm Biggrids synoptic type characteristics (Table 6.10). Although only 56% of the variance in winter balance is explained by these two types, prediction of this year is accurate. The explanation provided by the stable variables remaining in a ridge regression was called a "minimum reliable estimate" (Section 5.2.1). It was suggested that some of the unexplained variance could probably be accounted for by the variables removed from the analysis. The present case is a statistically significant illustration of that point. Some of the unexplained variation in each of the cases investigated in this chapter can probably be attributed to information lost by removal of correlated predictor variables.

Table 6.7. Interannual variation in Peyto Glacier winter balance predicted by Biggrids wet and dry synoptic types.

YEAR	OBSERVED WINTER BALANCE (m)	PREDICTED WINTER BALANCE (m)	RESIDUAL (m)	WET TYPE FREQUENCY	DRY TYPE FREQUENCY
1966-67	2.06	1.88	0.18	179	65
1967-68	1.63	1.75	-0.12	136	79
1968-69	1.43	1.42	0.01	142	86
1969-70	1.07	1.04	0.03	124	100
1970-71	1.31	1.35	-0.04	145	87
1971-72	1.67	1.66	0.01	165	74
1972-73	1.72	1.64	0.08	172	73
1973-74	1.62	1.78	-0.16	202	62
$\bar{x}$	1.56	1.56	0.00	158	78
s	0.30	0.28	0.11	26	13

Table 6.8. Interannual variation in climatological parameters of the Peyto Biggrids Accumulation season wet synoptic types.

YEAR	MEAN BIGGRIDS HEIGHT (m)	MEAN BIGGRIDS INTENSITY (m)	MEAN MAXIMUM DAILY TEMPERATURE (°C)	MEAN DAILY PRECIPITATION (mm)
1966-67	5515.4	227.4	3.4	3.1
1967-68	5517.3	211.9	3.5	2.0
1968-69	5534.5	194.8	2.9	1.6
1969-70	5524.5	206.5	3.6	0.9
1970-71	5520.7	209.3	1.5	1.5
1971-72	5494.5	232.5	-0.2	2.4
1972-73	5532.0	206.5	3.1	1.9
1973-74	5534.5	208.5	4.0	1.7
$\bar{x}$	5521.7	212.2	2.8	1.9
s	13.3	12.1	1.4	0.7

Table 6.9. Interannual variation in climatological parameters of the Peyto Biggrids Accumulation season dry synoptic types.

YEAR	MEAN BIGGRIDS HEIGHT (m)	MEAN BIGGRIDS INTENSITY (m)	MEAN MAXIMUM DAILY TEMPERATURE (°C)	MEAN DAILY PRECIPITATION (mm)
1966-67	5508.5	204.1	2.3	1.4
1967-68	5512.6	193.1	3.4	0.9
1968-69	5499.2	169.7	0.8	1.3
1969-70	5564.2	185.8	3.1	0.8
1970-71	5515.8	188.9	6.0	1.5
1971-72	5557.5	172.4	5.2	0.7
1972-73	5524.9	172.2	5.3	0.4
1973-74	5540.8	187.0	4.9	1.3
$\bar{x}$	5527.9	184.2	3.9	1.0
s	23.8	12.0	1.8	0.4

Table 6.10. Stepwise linear regression of Peyto Glacier winter balance with Biggrids cool and warm synoptic types.

CRITERION VARIABLE: Peyto Glacier winter balance

PREDICTOR VARIABLE	CUMULATIVE R^2	R^2 CHANGE		REGRESSION COEFFICIENT
cool	52.7	52.7		0.006
warm	56.2	3.5		-0.005
			(y-intercept)	1.110

F observed = 3.21

F critical (at 2 and 5 degrees of freedom and with $\alpha = 0.20$) = 2.26

6.2 Interannual variability of Summer temperature

In Section 5.3, four situations were analyzed to determine the relationship between Summer mean daily maximum temperature at Banff and Alta Lake and the synoptic type characteristics. Large proportions of the variance in Alta Lake temperatures are explained by just two synoptic type characteristics of both Sentinel Smallgrids and Sentinel Biggrids. Explanation of the variance in Banff temperatures by Peyto Smallgrids and Peyto Biggrids synoptic types is poor and not readily explained on other physical grounds. In this section, the interannual variability in the observed and predicted Alta Lake mean daily maximum temperature for Sentinel Smallgrids and Sentinel Biggrids is examined.

6.2.1 Sentinel Smallgrids

Alta Lake Summer temperatures are predicted accurately by Sentinel Smallgrids wet and dry synoptic types (Table 6.11). The residuals are not widely dispersed, with only 1967-68 and 1970-71 temperatures being one standard deviation or more away from the mean. 1970-71 is slightly overpredicted, possibly due to within-type variation. Cooler than average temperatures are seen in both wet and dry types for that year (Tables 6.12 and 6.13). On the other hand, although temperatures are underpredicted for 1967-68, within-type variation suggests that overprediction is in

Table 6.11. Interannual variation in Alta Lake Summer mean daily maximum temperature predicted by Smallgrids wet and dry synoptic types.

YEAR	OBSERVED TEMPERATURE (°C)	PREDICTED TEMPERATURE (°C)	RESIDUAL (°C)	WET TYPE FREQUENCY	DRY TYPE FREQUENCY
1966-67	20.8	20.7	0.1	84	89
1967-68	19.0	18.7	0.3	72	67
1968-69	20.0	20.1	-0.1	69	78
1969-70	19.4	19.3	0.1	86	78
1970-71	18.9	19.1	-0.2	81	74
1971-72	20.3	20.4	-0.1	66	79
1972-73	18.7	18.8	-0.1	86	73
$\bar{x}$	19.6	19.6	0.0	78	77
s	0.8	0.8	0.2	8	7

Table 6.12. Interannual variation in climatological parameters of the Sentinel Smallgrids Summer wet synoptic types.

YEAR	MEAN SMALLGRIDS HEIGHT (m)	MEAN SMALLGRIDS INTENSITY (m)	MEAN MAXIMUM DAILY TEMPERATURE (°C)	MEAN DAILY PRECIPITATION (mm)
1966-67	5610.3	93.3	20.7	4.2
1967-68	5598.2	80.6	18.5	4.1
1968-69	5604.9	86.3	19.8	4.3
1969-70	5618.1	91.2	20.7	1.9
1970-71	5605.2	87.6	18.5	2.9
1971-72	5612.0	84.2	20.3	3.2
1972-73	5599.5	88.0	19.2	2.1
$\bar{x}$	5606.9	87.3	19.7	3.2
s	7.1	4.2	1.0	1.0

Table 6.13. Interannual variation in climatological parameters of the Sentinel Smallgrids Summer dry synoptic types.

YEAR	MEAN SMALLGRIDS HEIGHT (m)	MEAN SMALLGRIDS INTENSITY (m)	MEAN MAXIMUM DAILY TEMPERATURE (°C)	MEAN DAILY PRECIPITATION (mm)
1966-67	5654.6	67.1	17.7	0.3
1967-68	5653.0	70.9	16.7	0.7
1968-69	5646.1	63.9	16.5	0.8
1969-70	5629.6	82.7	16.9	0.5
1970-71	5654.6	69.7	15.9	1.1
1971-72	5671.2	71.9	19.8	0.7
1972-73	5627.2	75.8	17.7	0.3
$\bar{x}$	5648.0	71.7	17.3	0.6
s	15.4	6.1	1.3	0.3

order, due to the cooler and damper than average conditions of the wet and dry synoptic types. Other synoptic type characteristics, like those of Section 6.1.3, do not offer significant improvement in prediction.

6.2.2 Sentinel Biggrids

The predicted Summer temperatures at Alta Lake from the Sentinel Biggrids cool and warm synoptic types (Table 6.14) are much more variable than those predicted by Sentinel Smallgrids wet and dry types. Relatively large residuals are present in 1966-67, 1969-70 and 1970-71.

The underprediction of 1966-67 Summer temperature may be related to the anomalously high temperatures of the cool, but not the warm synoptic types of that season (Tables 6.15 and 6.16; see Section 6.3). It is important to note that the extremely high mean maximum daily temperature of the Biggrids cool types in 1966-67 is associated with a significantly below average mean Biggrids height; a physically unreasonable situation. However, checking back to Table 6.12, the Sentinel wet Smallgrids types display the expected above average atmospheric thickness and above average temperature values for this year. This case shows that Biggrids does miss detail that Smallgrids types pick out at Sentinel Glacier. This strengthens the argument put forward in Section 5.4 that Sentinel Glacier mass balance is

Table 6.14. Interannual variation in Alta Lake Summer mean daily maximum temperature predicted by Biggrids cool and warm synoptic types.

YEAR	OBSERVED TEMPERATURE (°C)	PREDICTED TEMPERATURE (°C)	RESIDUAL (°C)	COOL TYPE FREQUENCY	WARM TYPE FREQUENCY
1966-67	20.8	20.5	0.3	22	151
1967-68	19.0	18.9	0.1	40	108
1968-69	20.0	20.1	-0.1	26	137
1969-70	19.4	18.9	0.5	43	119
1970-71	18.9	19.5	-0.6	36	129
1971-72	20.3	20.3	0.0	14	117
1972-73	18.7	18.8	-0.1	44	116
$\bar{x}$	19.6	19.6	0.0	32	125
s	0.8	0.7	0.3	12	15

Table 6.15. Interannual variation in climatological parameters of the Sentinel Biggrids Summer cool synoptic types.

YEAR	MEAN BIGGRIDS HEIGHT (m)	MEAN BIGGRIDS INTENSITY (m)	MEAN MAXIMUM DAILY TEMPERATURE (°C)	MEAN DAILY PRECIPITATION (mm)
1966-67	5703.9	137.7	18.3	2.9
1967-68	5713.1	139.8	14.9	3.0
1968-69	5724.8	142.8	15.8	2.6
1969-70	5700.0	145.8	15.2	1.3
1970-71	5716.6	146.0	14.7	3.8
1971-72	5724.2	134.3	18.1	2.0
1972-73	5715.0	136.7	15.1	1.3
$\bar{x}$	5713.9	140.4	16.0	2.4
s	9.4	4.6	1.5	0.9

Table 6.16. Interannual variation in climatological parameters of the Sentinel Biggrids Summer warm synoptic types.

YEAR	MEAN BIGGRIDS HEIGHT (m)	MEAN BIGGRIDS INTENSITY (m)	MEAN MAXIMUM DAILY TEMPERATURE (°C)	MEAN DAILY PRECIPITATION (mm)
1966-67	5697.0	155.2	20.0	2.0
1967-68	5715.2	155.4	20.6	2.8
1968-69	5701.7	158.2	20.9	2.4
1969-70	5716.0	159.7	20.8	1.3
1970-71	5703.9	150.3	20.2	1.7
1971-72	5715.8	149.7	20.8	1.8
1972-73	5717.0	140.3	20.2	1.3
$\bar{x}$	5709.5	152.7	20.5	1.9
s	16.1	6.6	0.4	0.6

associated with smaller climatic scales than Biggrids.

Tables 6.15 and 6.16 show that overprediction of 1970-71 temperature may be the result of cooler and damper cool synoptic types than average. On the other hand, the large positive residual for 1969-70 cannot be attributed to within-type variations. No other statistically significant synoptic type characteristics, similar to those shown in the Peyto Biggrids accumulation case (Section 6.1.3), can account for this variation in predicted Summer temperature.

6.3 Inadequacies of the synoptic climatological model

In the previous sections of this chapter, it was demonstrated that some of the unexplained variance in the synoptic climatological model developed in Chapters 4 and 5 can be attributed to either within-type variation or, at least in one case, to explanatory variables discarded because of collinearity. In the following, sources of error (unexplained variance) are attributed to the methodology used by the present author and to problems inherent to the Kirchoffer sums of squares classification technique. Elimination of these sources of error should result in stronger statistical relationships between synoptic-scale weather and glacier mass balance in southwestern Canada.

6.3.1 Error introduced by the present methodology

Some aspects of the methodology used in this thesis weakens the relationship between the synoptic types and mass balance at Peyto and Sentinel. The first methodological problem suggested below is probably the most important source of unexplained variance in this study. The others are relatively minor sources of error, but should be mentioned.

Use of the synoptic type characteristics of Bradley and England (1979) in Section 5.1.2 of the present thesis causes a considerable loss in explained variance due to collinearity among the predictor variables. Categories based on physical properties of the synoptic types, such as cyclonic/anticyclonic flow over the Peyto and Sentinel areas, would probably eliminate the problems of collinearity and would result in greater statistical explanation. However, these categories must be subjectively determined and for that reason are not applied here.

The mixing of stratigraphic and fixed date mass balance measurement systems outlined in Section 4.1 introduces some error into the model. This problem cannot be avoided because the fixed date system, by which the mass balance data were determined, imperfectly models natural accumulation and ablation seasons.

The sampling procedure presented in Section 3.1 also introduces a small amount of unexplained variation to the results. For example, 2.6% of the Smallgrids days are missing. Although most of these missing days are evenly distributed throughout the study period, one notable exception occurs in the Fall of 1972-73, where 27% of the days are missing (Appendix I). This may affect the results slightly. The solution to the above problem is to subjectively type the missing days after establishing the objective synoptic type keydays. This is not done in the present study because the scales of the synoptic charts available for subjective interpretation do not match the Smallgrids and Biggrids synoptic-scales and/or contour intervals and would introduce subjectivity into the objective classifications.

A temporal problem affecting the results of this study is caused by the relationship between the synoptic hour chosen to represent Smallgrids and Biggrids and the time when ground-based data are measured. In the present study, 1200 GMT 500mb pressure surfaces are used with daily precipitation and daily maximum temperature. Both of these parameters are measured locally at approximately 0000 GMT. Precipitation is in phase with the synoptic types: the pressure patterns are associated with the precipitation of the 12 hours preceeding and the 12 hours following the type. This makes the unexplained variance in accumulation somewhat dependent on the nature of the intertype transition frequencies and type persistence (Moritz, 1979). For temperature, the use of 1200 GMT synoptic types means that the types and temperatures are 180° out of phase. In essence, the types are "predicting" the maximum temperature of the following 24-hour period. The effects of serial correlation (Moritz, 1979) and the use of seasonal averages ameliorates this source of error in the temperature data. Because a choice had to be made between either temperature or precipitation being out of phase with the synoptic types, temperature was chosen as the lesser of two evils.

6.3.2 Error introduced by the objective classification

The strength of the relationship between the 500mb patterns and glacier mass balance is weakened by shortcomings built into the Kirchhofer sums of squares classification technique. The first three sources of error described below may be important to all synoptic climatologies. The last two probably do not account for much unexplained variance.

Even with average conditions from representative areas, subsynoptic spatial resolution of the model is not fine enough to account for all possible local- and meso-scale variations. For example, at the local-scale, topographic influences are important. The configuration of the landscape surrounding the glacier basin channels local winds, which determine accumulation patterns, and controls shadows, which affect the energy balance. At the meso-scale, precipitation patterns within mountainous regions are quite variable, especially in summer. As an illustration of this point, it was determined in Section 4.1 that precipitation data at Lake Louise and Alta Lake explain only 15% and 50% of the variance in Peyto and Sentinel daily precipitation, respectively. Thus, variability in local- and meso-scale data can only be avoided if perfect correlations between glaciometeorological data and nearby meteorological stations are found, or if year round weather observations are taken at the glaciers.

The two synoptic scales used in this study are probably not the optimal scales for analyzing the relationship between mass balance and atmospheric circulation. The results are dependent on the resolution of the data. For instance, it is possible that more explanation in the variance of Sentinel's winter balance could be afforded by 500mb data with resolution finer than Smallgrids. Overland and Hiester (1980) have noted when using gridded data sets, like those of NCAR, it is possible to miss high-wavenumber features of circulation important to the climate of a region. Presently, there is no technique for optimizing the scales used in a synoptic climatology. The investigator must rely upon an understanding of the research problem, follow convention and/or use intuition to select the scale and data to be analyzed.

Within-type variability is a potential source of error in any synoptic climatology. Although there are many ways in which the problem may arise, the following suggests one possible cause for some of the within-type variation identified in Section 6.1 and 6.2. The precise location of the mean inflection point in a trough or ridge can change from year to year (Keen, 1980). Slight alterations in the location of this point can affect the horizontal and vertical motions over an area and, therefore, its climate. This problem is not great in large-scale weather maps with relatively fine resolution and many synoptic types (e.g. Smallgrids). In cases where small-scale maps with generalized data and few synoptic categories are used, this kind of variation can be a major source of error. For example, with average conditions for Biggrids Type 1, both the Peyto and Sentinel areas experience heavy precipitation because of increasing negative vorticity, divergence and upward vertical motions in the middle troposphere. A shift of the main trough and ridge system a few hundred kilometers to the west would give Sentinel the same conditions but reverse those over Peyto to decreased anticyclonic vorticity, convergence and subsidence. Such a case appears to have happened in 1973-74. At Peyto, wet type frequencies

(Table 6.7) "skyrocketed" because of a dramatic increase in the number of Type 1 days. However, winter balance was near average and is overpredicted by the model because of higher mean Biggrids heights, decreased intensities and warmer temperatures in the wet types (Table 6.8). At the same time, Sentinel experienced its largest winter balance of the IHD, some 35% above the nine year average. Increased cyclonic activity and shifts in the mean positions of long wave troughs and ridges are often related to the occurrence of anomalous sea surface temperatures. This has been studied extensively by Namias (1975) and others.

Another way in which the sampling procedure of Section 3.1 introduces unexplained variance into the results is related to days not classified by the sums of squares technique. For Smallgrids, 3.7% of the days were unclassified. Most of the Smallgrids unclassified days are randomly distributed throughout the 9 glaciological years of the study. However, the months of May and June have several unclassified days which are not evenly distributed (Appendix I). This two month period averages 3.0 unclassified days in each of the four sample years, but averages 6.8 unclassified days in each of the remaining 5 years of the study period. This may represent a missing, albeit minor synoptic type which may change the explained variance by a percentage point or two.

Another temporal problem may affect most synoptic climatologies. Because the mean duration of his 21 synoptic types was about 35 hours, Moritz (1979) has suggested that the 24-hour synoptic period might be too short to define synoptic types. Unfortunately, all data collection is based on the 24-hour day, so that this source of error might be difficult to correct.

6.4 Summary

In many cases, a large proportion of the interannual variability in the elements of the mass balance of Peyto and Sentinel Glaciers can be explained by simple climatological characteristics of the Smallgrids or Biggrids synoptic types. Unexplained variance can be attributed to within-type variation, information lost by the removal of collinear explanatory variables in the regression analyses, or other inadequacies inherent both in the Kirchhofer sums of squares technique or in its application in the present research.

7. Conclusions

It has long been assumed that glacier behavior and the circulation of the atmosphere are related. Attempts to link qualitatively annual mass balance to synoptic-scale atmospheric fluctuations have been promising. The present thesis makes a quantitative examination of the relationship between synoptic-scale climate and glacier mass balance in the Cordillera of southwestern Canada. In this chapter, the results of the study are summarized, followed by suggestions for further research.

7.1 Summary of the results

The results can be summarized in terms of the three original objectives. First, the mass balances of Peyto and Sentinel Glaciers are shown to be related to the synoptic-scale climate of southwestern Canada. Because a large proportion of the variance in winter balance is explained by the climatological characteristics of the synoptic types, it is apparent that the 500mb synoptic patterns passing over the area control accumulation totals. Synoptic types with cyclonic curvature over the Peyto and Sentinel areas favor accumulation, whereas types with anticyclonic curvature inhibit build-up of the regional snowpack. However, ablation seems to be only partially controlled by synoptic-scale weather as expressed by the 500mb patterns. The total energy available for ablation, as expressed by melting degree days derived from Summer mean maximum daily temperature and the length of the Summer season data, only explains 50% of the variance in summer balance at Peyto Glacier and 80% at Sentinel. In turn, the synoptic type characteristics explain less than 30% of the variance in melting degree days at Peyto. At Sentinel, most of the variance in total melt energy (98% and 83% for Smallgrids and Biggrids, respectively) is explained by the synoptic type characteristics. As expected, ablation appears to be suppressed by synoptic types associated with cloudy days (Smallgrids) and/or lower temperatures (Biggrids) at both glaciers. Ablation is enhanced by types associated with warm, sunny days.

Second, changes in the scale of, and level of information presented by the synoptic types used to analyze the climate-mass balance relationship do affect the results. Sentinel Glacier winter balance is predicted well by the Smallgrids synoptic type characteristics (80% explained variance) and not by Biggrids types (31% explained variance). Biggrids synoptic type characteristics are more closely related to Sentinel summer balance (83% explained variance in Summer temperature), but again not as closely as

Smallgrids types are related to summer balance (98% explained variance in Summer temperature). This suggests that Sentinel mass balance is controlled by high-wavenumber synoptic-scale patterns. On the other hand, Peyto Glacier winter balance is better predicted by Biggrids than Smallgrids synoptic type characteristics (87% and 75% explained variance, respectively). Apparently, much of the short wavelength variability within the long wave atmospheric flow is dampened by the rough topography of the Canadian Cordillera. Summer temperatures in the Peyto area are poorly predicted by both Smallgrids and Biggrids synoptic types (28% and 29% explained variance, respectively).

Third, unexplained variance in the synoptic climatological model may be the result of errors introduced by the methodology used by the present author and of problems inherent to the Kirchhofer sums of squares classification technique. Elimination of these errors from the model would probably increase the level of explained variance and strengthen the statistical relationship between glacier mass balance and synoptic-scale circulation. Sources of unexplained variance attributable to the methodology include information lost by removal of correlated predictor variables in the regression analysis, mixing of stratigraphic and fixed date mass balance measurement systems, failure to type subjectively missing days in the synoptic type catalogs, and nonsynchroneity of daily maximum temperature and synoptic type occurrence. The first problem, use of the climatological characteristics of the synoptic types as suggested by Bradley and England (1979), is probably not the ideal manner in which to aggregate the data and results in considerable lost explanation due to collinearity among the variables. Perhaps divisions based on physical properties of the synoptic types, such as cyclonic/anticyclonic flow, would be more appropriate and would avoid the problems of collinearity. The last three methodological problems do not appear to introduce much unexplained variance into the model.

Sources of unexplained variance inherent to the sums of squares classification technique include subsynoptic-scale resolution, identification of the precise synoptic-scale necessary to best analyze the data, within-type variation, infomation lost to unclassified days in the synoptic catalog, and the 24-hour time frame imposed on the data. The last two sources of error do not seem grave, but the first three may be important sources of error in any synoptic climatology. Use of Smallgrids and Biggrids in the present study partly circumvents problems caused by choice of synoptic-scales. Subsynoptic-scale resolution can only be avoided by using glaciometeorological data that is truly representative of its region. Although Peyto and Sentinel are presumed to be representative of the glaciers in their areas, glacier representativeness is a difficult problem yet to be resolved for any glacierized area. Within-type variation was investigated in terms of the synoptic type characteristics used in this thesis, but a more exhaustive treatment of this source of error should be undertaken.

7.2 Suggestions for further research

Many possibilities for further research are suggested directly or indirectly by this thesis. Several of these are discussed below under the headings of glacier-climate research, synoptic climatological research and regression techniques.

7.2.1 Glacier-climate research

Although relationships between the circulation of the atmosphere and glaciers have long been assumed, much basic research needs to be done. For example, Lamb (1968) suggests that the positions of centers of atmospheric activity, such as long wave troughs and ridges and cyclogenetic regions, particularly are important to glacier mass balance and therefore warrant study. The present study has confirmed that synoptic-scale features are related to mass balance in southwestern Canada. However, the specific mechanisms linking glaciers to large-scale climate can only be suggested by synoptic climatological techniques and must be investigated by detailed atmospheric studies such as that of Keen (1980) in the Canadian High Arctic. Quantitative assessment of glacier-climate relationships, as carried out in Chapter 5 of the present study, was beyond the scope of Keen's research. Application of this methodology to the present data might uncover relationships among centers of action, atmospheric patterns and glacier mass balance.

As an offshoot of the large-scale atmospheric research suggested above, a study of the effect that blocking episodes and cold lows have on glacier mass balance in southwestern Canada should be useful. The present study shows that persistent synoptic-scale ridging is related to dry winter months. Such synoptic types may well be a form of classical blocking activity (Rex, 1950; Treidl, et al, 1981). In the case of cold lows, Walker (1961) states that in some areas of British Columbia, over 50% of the summer precipitation is associated with such features. Thus, it is possible that the appearance of persistent atmospheric blocks or cold lows during the winter and summer seasons could determine the nature of those seasons. Furthermore, the appearance of these features during transitional periods could prolong or abruptly end glacier accumulation or ablation.

A glacier-climate problem that has not been handled for mountainous regions is the relationship between the energy balance at the glacier surface and synoptic-scale weather. It might be possible to modify the work of Vowinckel and Orvig (1972) and Alt (1975) to model synoptic energy budgets at Peyto or Sentinel Glaciers. The results of such modelling would help fill the gaps in our knowlege of atmospheric circulation-surface linkages made evident in the present study.

7.2.2 Synoptic climatological research

Synoptic climatology is a rapidly expanding field of study. Several possible areas of further research are suggested by this thesis.

An extension of the present study backwards and forwards in time is desirable. Unfortunately, data sparsity places restrictions on such an extension. The NCAR 500mb data set runs only from 1946 to the present, so that 1946-47 is the earliest glaciological year that could be typed. Banff and Lake Louise temperature and precipitation data extend back well beyond that year and continue to the present. Alta Lake data begin in 1950 and extend only to mid-1976. Perhaps most importantly, although mass balance data for Peyto and Sentinel exist to the present, measurement programs only started in 1965-66.

Extension of the methodology of this thesis to the pre-1946 period may be possible by the integration of many data sources and modelling based on the results of the present work. However, great care must be taken when using recent weather types to characterize previous weather regimes. Gribbin and Lamb (1978) point out that some atmospheric patterns of the Little Ice Age may not be seen today. Similarly, atmospheric configurations common today may have been relatively rare or absent in the past.

Little is known about the within-type fluctuations of objective classifications over time. For example, if within-type trends exist over time, they must be identified and methods for detrending the data must be established. This is not thought to be a problem in the short time frame of the present research, but could be critical to studies based on longer periods, such as that of Bradley and England (1979) which uses NCAR data back to 1946. This sort of within-type variation might be another severe limitation on the application of present-day synoptic types to the Little Ice Age.

Another issue brought forward by this thesis involves determination of the optimal synoptic-scales used in a synoptic climatology. Additionally, it has been suggested that the density of pressure surface data presented on a weather map can influence the results. Basic research on scale and data optimization techniques would be very useful.

The results of synoptic climatological research are hindered by the problems of subsynoptic-scale resolution detailed in Section 6.3. Also, relationships between objectively determined synoptic types and large-scale atmospheric phenomena, such as standing waves, are not clear. This suggests that basic research in the association between synoptic types and all other scales of atmospheric activity is needed.

7.2.3 Regression techniques

Regression analysis is often misused, with one of the most severe violations of the regression model being the handling of collinear data. Ridge regression is applied in the present study to eliminate correlated predictor variables. The technique can also be used to remove the effect of the correlations and still retain some of the predictor variables eliminated in this study (Hoerl and Kennard, 1970b). A slight increase in the explained variance would result. However, using ridge regression in this manner requires a great deal of subjectivity and would make results difficult to replicate. For that reason, this variation of the ridge regression technique was not used in the present thesis. Objectification of this part of the ridge regresssion model is needed. Alternatively, creation of an objective regression technique that would permit inclusion of additional correlated predictor variables and increase explained variance would be useful.

7.2.4 Recapitulation

Basic studies are needed on many aspects of glacier-climate research, synoptic climatological research and statistical techniques used with synoptic climato~~lo~~gies. No single study can resolve the questions posed by the present thesis. Only step-by-step solutions to each of the suggested research problems can clarify glacier-climate relationships in southwestern Canada.

APPENDIX I:

SMALLGRIDS SYNOPTIC TYPE
CATALOG FOR THE GLACIOLOGICAL
YEARS 1965-66 TO 1973-74

GLACIOLOGICAL YEAR 1965-66

DAY

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	1	1	4	4	4	1	1	1	3	7	1	1	6	1	12	6	1	1	1	1	1	1	1	1	1	1	4	1	1	M	1
NOV	1	1	4	1	10	10	U	4	4	10	9	9	9	9	2	1	4	4	3	12	6	8	11	16	5	U	6	1	4	1	
DEC	1	1	1	1	4	4	4	1	3	15	8	2	5	6	12	2	6	1	6	1	2	6	1	10	3	10	U	11	3	3	16
JAN	6	3	3	8	1	1	1	8	2	1	2	6	1	12	6	6	1	5	5	2	2	2	5	6	7	7	6	7	10	8	1
FEB	7	1	1	1	3	U	12	2	2	2	3	5	5	5	14	2	M	2	1	1	1	4	4	4	8	1	3	1			
MAR	16	16	6	4	4	4	1	1	1	1	2	4	4	4	4	18	15	4	8	3	2	6	1	6	6	1	1	1	1	1	6
APR	1	2	14	6	2	9	9	9	M	3	3	3	1	1	3	5	5	5	5	2	2	2	2	6	3	5	2	2	6	1	
MAY	1	4	1	6	1	4	4	4	8	12	15	8	16	12	1	3	2	6	12	M	3	2	6	6	1	8	8	3	3	11	13
JUN	13	13	U	U	9	7	1	4	4	4	U	6	M	6	15	4	4	4	4	4	8	3	3	2	1	4	4	8	10	10	
JUL	11	U	U	5	5	13	16	2	2	16	5	5	13	U	17	4	4	4	3	9	7	7	U	11	5	5	M	12	3	1	1
AUG	1	1	1	3	U	15	4	1	12	3	2	2	3	6	3	3	2	2	14	6	8	17	17	17	1	1	8	11	17	12	6
SEP	1	6	6	1	1	1	1	4	4	8	16	U	U	4	4	4	4	8	6	6	1	1	4	4	4	15	1	6	2	6	

U = unclassified

M = missing NCAR data

GLACIOLOGICAL YEAR 1966-67

DAY

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	2	5	2	1	1	1	1	2	6	1	3	16	6	12	2	1	2	1	1	8	12	6	1	1	1	1	6	1	1	6	6
NOV	1	2	2	2	2	5	5	2	2	2	2	1	1	4	4	4	10	10	4	10	16	5	2	2	2	6	1	1	7	10	
DEC	18	4	4	U	8	8	3	2	1	1	4	1	1	1	1	1	1	1	1	1	15	1	4	8	5	14	6	2	2	2	6
JAN	2	6	1	3	5	2	6	2	1	1	1	6	2	2	1	2	5	6	1	1	1	10	10	10	10	10	1	1	1	1	6
FEB	1	6	2	3	2	2	2	1	6	2	1	1	3	2	16	2	6	5	2	M	14	6	1	4	1	4	4	1			
MAR	3	5	5	5	5	2	2	2	3	11	11	5	16	U	10	4	4	8	1	M	1	1	8	3	3	2	1	8	12	16	5
APR	5	5	2	5	5	5	2	6	8	3	2	1	8	11	12	11	13	5	5	5	5	4	1	8	8	18	13	13	M	13	
MAY	14	14	14	5	2	2	2	3	11	16	13	2	6	6	6	1	1	6	6	1	1	1	3	16	U	1	4	4	8	U	U
JUN	12	12	5	5	2	2	2	5	5	2	5	5	2	2	6	2	2	7	7	4	U	5	5	14	6	1	6	1	3	2	
JUL	6	6	1	3	2	3	M	3	2	1	4	4	4	1	1	1	8	1	8	16	5	2	9	9	9	2	6	1	1	3	9
AUG	2	2	1	10	16	U	2	6	15	1	1	10	10	7	10	7	4	1	1	1	1	1	1	2	6	1	1	4	4	4	4
SEP	8	6	1	1	4	1	1	1	1	1	3	6	15	15	M	4	4	15	6	6	1	2	1	M	M	6	1	1	4	8	

U = unclassified

M = missing NCAR data

GLACIOLOGICAL YEAR 1967-68

	DAY																														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	8	18	U	1	8	1	1	1	1	4	1	6	3	2	1	1	1	1	6	1	1	1	2	1	3	1	1	2	6	1	1
NOV	2	2	2	14	4	4	1	1	1	1	1	10	4	4	3	12	M	16	5	2	2	2	2	2	2	2	M	6	8	3	
DEC	1	4	1	1	8	4	8	6	6	1	2	5	14	6	1	2	2	5	5	16	2	1	1	2	2	2	2	5	5	5	2
JAN	5	5	14	2	5	2	3	2	10	3	6	1	4	4	4	4	1	1	1	1	6	1	1	3	16	5	5	5	5	16	3
FEB	6	1	1	1	2	1	1	15	15	4	4	U	14	U	U	7	7	7	1	1	4	1	1	M	4	6	U	4	4		
MAR	4	1	1	1	8	4	4	15	15	6	4	4	10	U	U	3	12	12	6	4	4	4	1	1	8	1	1	1	3	2	9
APR	16	14	15	4	12	2	2	2	1	1	3	5	2	1	16	5	2	1	16	5	2	7	8	6	2	2	6	1	1	1	
MAY	1	6	1	3	5	2	6	U	U	U	16	16	5	5	5	2	7	4	4	4	18	4	4	4	4	1	4	4	10	1	1
JUN	4	1	1	1	1	U	15	U	15	4	4	18	U	U	6	1	1	1	1	M	1	2	2	6	1	1	1	5	14	U	
JUL	4	7	4	4	1	1	7	1	4	4	4	8	1	10	3	1	1	10	U	U	3	2	6	7	7	6	1	1	2	14	2
AUG	2	2	2	2	16	11	9	9	10	8	1	1	3	U	U	17	8	8	11	13	12	1	4	8	8	8	1	6	6	6	1
SEP	2	2	2	2	6	2	6	1	1	1	4	1	1	4	12	6	3	3	16	12	12	6	6	1	1	1	2	6	1	6	

U = unclassified

M = missing NCAR data

GLACIOLOGICAL YEAR 1968-69

DAY

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	2	6	4	8	1	16	5	6	3	3	10	8	1	8	12	6	1	6	1	3	1	1	1	1	M	6	1	1	8	3	6
NOV	4	4	U	4	4	4	4	1	1	1	1	3	2	2	16	2	7	1	1	1	1	1	1	3	2	1	2	15	1	3	
DEC	12	2	1	6	1	6	1	1	4	4	16	6	4	M	4	U	15	16	5	5	5	U	10	10	U	5	5	5	5	14	1
JAN	2	6	1	1	1	1	M	2	3	8	8	8	8	8	3	16	2	16	16	5	5	5	5	5	9	11	5	5	5	5	2
FEB	2	6	1	1	1	3	1	4	8	4	4	8	3	10	4	4	4	4	8	15	15	4	U	U	11	13	U	U			
MAR	U	4	8	6	3	5	14	5	U	U	4	15	6	1	1	1	10	3	9	2	2	2	2	2	2	2	2	2	7	4	4
APR	4	4	M	4	8	8	15	4	4	4	1	4	4	3	6	4	1	15	1	6	1	4	4	18	15	15	1	8	U	15	
MAY	17	15	12	12	6	2	6	6	7	15	1	1	3	9	2	U	U	9	9	6	7	7	4	4	4	10	10	1	1	2	6
JUN	6	6	1	1	1	7	4	8	U	14	14	14	U	U	U	U	7	7	2	6	M	6	1	12	U	U	13	U	5	9	
JUL	9	3	16	16	5	5	2	6	1	8	1	3	3	9	9	9	2	6	1	3	2	2	6	8	16	12	3	3	2	1	1
AUG	1	M	M	11	U	5	U	1	1	M	3	2	1	1	8	3	1	8	1	1	1	1	1	4	4	4	11	16	2	2	6
SEP	1	8	5	2	U	1	1	1	4	15	1	1	3	5	6	1	4	8	8	12	6	4	8	6	1	1	3	1	1	3	

U = unclassified
M = missing NCAR data

GLACIOLOGICAL YEAR 1969-70

	DAY																														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	3	16	5	14	15	4	4	4	15	5	14	U	U	U	U	18	18	U	2	1	1	1	10	11	U	4	18	14	1	1	6
NOV	15	4	1	4	8	1	8	3	12	2	2	2	6	6	3	16	M	6	1	4	6	M	1	6	1	15	1	15	1	1	
DEC	1	4	4	2	7	15	15	4	4	4	4	4	4	1	U	7	M	4	4	4	4	4	1	15	1	16	2	6	2	6	2
JAN	2	2	5	16	1	15	1	1	3	2	2	2	1	1	2	9	2	1	4	4	4	1	10	10	1	1	16	2	7	6	1
FEB	2	6	3	2	1	1	1	1	1	7	7	7	7	7	1	4	3	2	15	1	7	4	4	15	9	9	5	5			
MAR	5	5	5	9	7	1	1	7	U	7	7	4	1	4	15	3	5	14	6	2	M	2	6	2	6	5	2	5	5	5	14
APR	M	2	M	1	1	1	6	1	1	1	2	5	5	14	U	14	6	1	12	16	12	M	12	3	3	16	5	2	2	2	
MAY	6	6	M	4	1	1	15	4	8	18	18	18	U	1	1	1	3	1	3	M	4	1	6	6	1	3	3	2	2	6	15
JUN	1	1	4	8	1	4	4	4	8	3	2	5	U	U	12	14	4	2	6	1	1	6	1	3	1	1	8	8	12	15	
JUL	4	4	4	1	M	1	1	1	1	1	3	2	2	1	1	1	M	4	1	1	16	2	1	3	3	3	11	11	16	5	5
AUG	U	15	15	4	4	4	8	2	2	1	1	1	3	6	1	3	2	2	6	2	6	2	2	U	3	2	3	3	6	1	1
SEP	1	M	8	16	2	2	2	2	2	M	5	5	5	5	2	1	1	1	3	12	12	M	2	2	6	M	1	1	1	6	

U = unclassified

M = missing NCAR data

GLACIOLOGICAL YEAR 1971-72

DAY

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	6	1	1	M	1	1	6	15	1	1	1	6	3	16	5	5	12	3	1	3	1	8	3	12	2	2	5	14	12	16	2
NOV	2	2	1	9	9	7	8	1	4	10	3	1	8	2	2	2	2	2	6	6	1	2	4	8	3	1	1	3	12	6	
DEC	4	8	3	2	2	5	2	2	16	5	2	16	2	16	5	6	1	5	2	2	10	8	10	9	5	5	5	2	12	12	M
JAN	2	5	2	2	2	2	1	2	2	2	2	2	2	2	1	1	3	2	3	1	1	3	9	9	5	13	13	5	14	2	5
FEB	5	9	9	2	2	1	6	3	15	M	3	1	3	6	6	3	1	1	4	4	4	4	U	5	2	3	1	1	3		
MAR	2	1	2	2	1	2	2	6	1	1	1	1	1	1	6	1	1	1	1	1	1	4	4	8	13	5	5	5	2	2	1
APR	3	2	2	1	4	4	4	4	4	3	3	16	2	6	3	3	5	2	1	1	3	6	4	8	12	6	4	8	U	6	
MAY	1	1	6	9	14	U	13	18	4	15	15	M	1	1	1	1	3	5	14	15	15	12	3	2	6	15	4	4	4	4	4
JUN	1	1	1	1	4	1	4	4	4	18	18	U	7	4	4	8	2	2	2	16	2	16	5	U	12	2	6	1	1	2	
JUL	2	14	9	7	7	4	4	18	11	M	4	1	1	2	2	2	2	5	5	5	5	2	3	3	8	1	1	1	1	6	1
AUG	2	6	6	1	6	6	6	1	1	10	10	11	11	11	11	M	18	M	11	4	4	4	15	15	1	1	1	1	1	2	M
SEP	2	5	M	6	2	2	6	3	16	5	5	5	2	2	2	2	2	3	8	6	8	3	16	5	2	M	5	2	6	6	

U = unclassified

M = missing NCAR data

GLACIOLOGICAL YEAR 1970-71

DAY

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	2	2	1	3	16	5	5	2	2	2	2	2	5	6	1	1	1	1	1	M	8	15	8	3	16	6	15	1	4	4	4
NOV	4	4	4	4	18	18	1	4	3	15	4	15	4	1	1	3	2	2	2	2	5	2	1	3	5	2	16	M	2	8	
DEC	3	8	3	2	1	M	1	1	6	1	12	1	M	1	1	M	16	5	5	5	5	14	5	14	2	1	1	1	3	1	1
JAN	2	5	14	14	M	2	2	2	2	3	11	11	16	3	1	1	1	1	1	2	2	2	2	2	2	1	6	1	6	2	6
FEB	1	12	2	2	5	14	7	15	1	1	6	1	6	1	1	1	7	4	5	15	1	3	6	1	12	12	16	5			
MAR	14	1	3	2	12	1	8	1	1	1	1	4	15	4	1	2	14	6	1	2	2	1	4	8	6	3	1	M	1	3	6
APR	1	1	6	1	1	4	1	4	4	8	16	7	1	1	3	7	12	12	1	8	4	4	8	U	U	14	12	6	4	1	
MAY	1	2	6	12	3	2	15	12	M	1	4	4	4	1	1	12	6	15	8	5	6	6	1	1	8	M	M	15	8	U	16
JUN	U	15	12	U	U	4	18	U	U	8	1	4	4	U	5	14	U	4	4	4	4	4	4	U	11	16	5	U	1	1	
JUL	3	2	6	8	3	5	U	10	U	11	11	U	U	U	8	1	7	1	1	1	6	6	2	2	2	2	M	14	2	7	4
AUG	4	8	1	4	8	8	3	9	9	7	7	10	10	8	3	3	1	1	4	4	8	8	1	1	1	1	1	1	4	4	18
SEP	8	16	15	1	8	3	1	1	1	4	1	1	2	2	2	14	14	2	2	5	2	6	8	16	16	5	2	16	16	5	

U = unclassified
M = missing NCAR data

GLACIOLOGICAL YEAR 1972-73

DAY

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	2	1	1	M	M	M	M	M	3	5	5	2	M	5	5	U	U	M	6	6	6	M	2	6	3	5	2	M	14	6	6
NOV	1	1	1	8	1	M	3	1	4	8	8	15	17	2	M	12	7	18	U	15	15	1	1	2	1	2	2	2	2	2	
DEC	2	5	5	5	5	5	5	5	5	M	9	5	2	2	1	4	1	1	1	1	1	2	1	3	1	1	3	2	15	1	6
JAN	1	5	5	5	5	14	5	U	U	U	4	1	1	1	1	1	1	4	12	1	2	M	M	1	3	6	4	4	10	1	6
FEB	1	3	U	5	U	U	18	4	1	9	3	2	1	1	1	1	1	6	3	6	1	1	M	1	1	1	4	1			
MAR	1	6	8	12	6	2	1	12	2	3	5	12	5	12	1	1	3	1	8	1	3	2	15	1	3	2	16	2	15	1	8
APR	12	6	15	6	2	5	14	6	15	15	1	3	2	6	12	1	3	12	12	2	6	2	2	2	6	1	3	2	2	14	
MAY	15	4	8	12	15	8	1	4	1	U	4	4	4	4	4	1	1	1	3	2	6	1	4	4	8	U	15	6	15	8	16
JUN	5	2	2	1	1	1	1	1	3	2	4	4	18	8	15	U	U	4	4	1	M	4	4	4	1	1	1	3	3	16	
JUL	2	1	1	4	3	3	10	10	10	10	2	2	6	12	2	2	2	6	1	8	3	11	11	10	1	6	7	1	1	1	1
AUG	1	1	1	12	2	5	14	1	1	2	2	1	1	1	1	3	16	9	9	11	11	11	8	16	M	2	2	2	6	3	5
SEP	6	1	6	1	1	4	12	6	1	1	1	9	9	M	14	7	4	4	4	8	1	1	1	12	2	6	1	1	1	3	

U = unclassified

M = missing NCAR data

GLACIOLOGICAL YEAR 1973-74

DAY

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	5	M	6	1	3	3	12	16	2	2	12	6	1	1	4	1	1	1	1	1	4	4	8	8	6	6	1	1	6	2	2
NOV	5	5	5	5	11	11	3	M	10	10	10	1	8	8	8	3	2	16	6	3	16	5	6	5	16	2	1	1	10	10	
DEC	8	6	3	6	1	1	1	6	1	1	4	4	M	1	1	1	1	6	4	4	1	1	6	1	2	2	7	U	2	14	U
JAN	5	5	5	5	5	5	5	5	5	5	2	2	3	1	1	1	1	4	1	3	2	2	2	6	16	2	2	2	2	2	10
FEB	2	2	6	M	2	2	2	6	2	1	1	3	1	1	4	3	M	1	2	15	4	8	6	4	4	10	1	10			
MAR	1	16	2	2	2	2	16	6	1	4	M	4	8	6	1	1	5	2	5	2	9	9	2	9	7	10	4	4	1	10	1
APR	4	3	M	1	1	1	1	1	1	1	1	2	15	4	8	1	1	1	6	2	1	8	16	U	17	U	12	2	7	1	
MAY	16	2	2	1	1	1	1	1	8	12	8	3	12	8	U	13	13	5	2	1	4	4	8	1	1	3	2	2	5	U	6
JUN	1	1	1	3	6	12	2	2	6	1	1	1	7	1	8	1	6	1	1	1	4	8	8	3	1	4	8	6	1	3	
JUL	2	2	1	3	9	16	U	8	8	4	8	4	4	4	8	8	10	8	8	10	1	1	1	1	2	1	1	1	1	2	7
AUG	4	15	15	1	3	2	5	5	2	2	5	5	5	5	5	9	9	M	5	2	2	1	3	2	2	2	9	9	9	9	14
SEP	14	U	1	1	1	3	6	4	1	5	5	14	6	1	1	1	1	2	2	7	7	2	2	6	6	2	2	2	2	6	

U = unclassified
M = missing NCAR data

APPENDIX II:

BIGGRIDS SYNOPTIC TYPE
CATALOG FOR THE GLACIOLOGICAL
YEARS 1965-66 TO 1973-74

GLACIOLOGICAL YEAR 1965-66

DAY

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	1	1	1	1	5	1	1	3	6	1	1	3	1	1	1	2	2	2	2	1	1	1	3	6	1	1	4	1	1	M	1
NOV	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	3	3	3	1	
DEC	1	1	1	1	1	6	1	1	1	1	1	1	1	4	4	1	1	1	1	1	1	1	2	5	1	2	1	1	2	2	2
JAN	2	2	1	1	1	1	1	1	1	1	1	1	1	1	3	U	3	6	6	1	1	1	1	1	1	1	1	3	3	3	3
FEB	1	1	1	6	1	1	1	2	2	4	1	1	1	1	1	1	M	1	1	3	3	3	5	5	3	1	2	1			
MAR	1	2	2	7	3	6	6	1	1	1	1	1	1	1	5	1	2	1	1	1	2	1	4	1	3	3	3	3	3	3	6
APR	3	3	3	3	3	3	3	3	M	1	2	2	2	1	6	6	1	2	2	2	1	1	1	1	1	1	2	1	1	1	
MAY	1	1	1	1	1	1	1	3	3	3	7	7	1	1	2	1	1	3	3	M	1	2	2	1	1	1	5	8	8	8	8
JUN	U	4	1	1	1	1	1	1	1	1	2	1	M	1	1	4	4	5	5	5	2	2	2	2	2	1	1	5	5	2	
JUL	2	2	5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	8	6	1	1	1	1	1	M	1	1	1	1
AUG	1	1	1	1	1	1	1	1	1	5	8	8	1	1	1	1	1	1	1	1	1	1	3	4	1	1	5	1	1	5	2
SEP	1	1	1	1	3	1	5	1	5	5	2	2	4	4	4	4	5	5	U	6	6	1	3	1	1	1	1	1	3	3	

U = unclassified
M = missing NCAR data

GLACIOLOGICAL YEAR 1966-67

DAY

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	3	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1
NOV	4	1	3	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1	1	1	1	1	6	6	1	
DEC	3	3	1	2	1	2	2	2	1	1	1	1	1	1	1	1	1	1	1	3	1	3	3	3	3	U	4	4	3	1	1
JAN	1	1	1	1	1	1	4	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	1	1	6	1	1	1
FEB	1	1	1	1	1	1	4	4	1	1	1	1	1	1	1	1	1	1	1	M	1	1	3	3	6	1	1	1			
MAR	1	1	1	1	4	1	1	1	1	1	1	1	1	1	1	1	3	1	1	M	1	1	1	2	2	2	1	1	2	2	2
APR	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	1	1	2	2	4	4	1	4	4	4	1	4	M	4	
MAY	4	4	1	1	1	1	1	3	6	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	2	1	4	5	U	U
JUN	U	2	2	1	1	1	1	2	1	4	2	2	2	2	1	4	1	1	1	1	1	1	4	4	4	1	1	1	1	1	
JUL	1	3	3	1	1	1	M	1	1	1	1	1	3	3	6	1	5	1	5	1	1	1	1	1	1	1	1	1	1	1	1
AUG	1	1	1	1	1	1	1	1	1	4	6	6	6	4	4	4	4	4	4	1	1	1	1	1	1	1	1	1	1	4	4
SEP	5	5	U	U	5	5	1	1	1	1	2	2	4	U	M	4	4	4	1	1	1	6	1	M	M	1	4	1	6	6	

U = unclassified

M = missing NCAR data

GLACIOLOGICAL YEAR 1967-68

DAY

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	2	2	1	1	1	1	1	1	3	3	5	1	1	1	1	1	1	1	6	1	1	2	2	1	1	3	3	1	1	1	1
NOV	1	4	4	3	3	4	1	1	1	1	1	1	1	3	1	1	M	1	1	1	4	1	1	1	1	1	M	1	1	1	
DEC	2	1	1	1	2	2	5	7	1	1	1	1	U	4	1	1	2	7	2	2	2	1	1	1	4	1	1	4	1	1	1
JAN	1	1	1	1	1	1	1	1	1	5	2	1	U	U	6	5	2	1	1	1	1	1	3	6	1	1	2	2	2	1	2
FEB	1	1	1	1	6	6	6	U	3	3	U	U	U	4	4	1	3	1	1	3	3	3	3	M	3	3	3	3	U		
MAR	U	3	6	1	4	1	1	1	1	1	1	4	1	1	1	1	1	2	2	4	4	4	6	1	1	1	1	1	1	1	1
APR	1	1	4	1	1	1	2	1	1	1	1	2	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1	1	1	1	
MAY	1	1	1	1	1	1	2	4	1	4	4	2	2	2	2	1	3	3	3	3	3	4	4	5	2	U	U	U	6	6	1
JUN	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	M	1	1	1	1	1	1	1	1	1	2	
JUL	1	1	1	4	4	1	1	1	1	1	1	5	2	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
AUG	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	2	2	1	2	2	2	1	8	8	8	2	1	1	1
SEP	1	1	1	1	1	1	1	1	1	1	6	5	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	

U = unclassified

M = missing NCAR data

GLACIOLOGICAL YEAR 1968-69

DAY

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	1	1	1	1	1	1	1	2	2	1	1	2	2	2	2	2	U	5	1	1	1	1	1	3	M	1	3	3	1	1	2
NOV	2	1	1	1	1	1	4	3	3	3	3	6	1	1	1	1	1	3	3	6	1	1	1	1	1	1	1	4	1	1	
DEC	2	1	1	1	3	3	3	6	1	1	1	1	4	M	6	1	1	7	7	U	2	2	1	1	1	1	2	U	U	7	3
JAN	3	1	3	3	1	1	M	1	1	8	8	8	1	U	2	2	1	1	1	1	1	2	2	1	1	1	2	2	2	2	1
FEB	1	1	1	1	1	1	1	1	1	1	3	3	3	1	2	1	3	U	4	2	2	2	2	1	1	U	1	1			
MAR	4	4	4	U	1	3	U	U	4	4	3	3	3	1	1	1	1	1	1	1	1	1	1	4	3	3	1	1	1	1	1
APR	1	1	M	1	1	1	4	4	4	4	4	1	5	2	2	1	1	5	5	1	1	8	6	U	1	4	4	4	4	1	
MAY	1	1	1	5	1	1	1	1	3	3	3	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1
JUN	4	4	3	1	1	1	1	4	4	4	1	1	1	4	4	4	4	1	1	1	M	1	1	1	2	2	4	1	1	1	
JUL	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	6	1	1
AUG	1	M	M	5	1	1	1	1	1	M	6	1	1	1	5	5	1	5	5	5	5	1	1	5	5	1	1	1	2	1	1
SEP	1	1	5	2	2	1	1	3	1	4	4	1	1	1	1	1	1	1	2	2	2	2	1	1	1	1	1	1	1	1	

U = unclassified

M = missing NCAR data

GLACIOLOGICAL YEAR 1969-70

DAY

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	1	2	2	2	2	1	1	1	1	4	U	U	4	4	4	4	4	4	1	1	1	1	1	1	1	4	4	4	4	1	1
NOV	U	U	5	6	6	2	2	2	2	1	1	3	3	3	3	1	M	1	1	3	1	M	1	1	1	4	1	1	1	3	
DEC	3	1	3	6	1	4	U	7	7	7	3	3	1	3	6	1	M	1	3	1	1	1	1	1	1	6	1	4	1	4	3
JAN	U	3	3	3	1	3	3	3	6	1	1	1	1	1	1	1	1	1	3	3	3	1	1	1	1	1	1	4	4	1	1
FEB	1	1	1	1	1	1	1	4	6	6	4	3	3	1	1	1	1	1	4	4	1	1	1	4	3	3	1	1			
MAR	1	2	2	2	1	1	1	1	3	U	7	7	3	3	3	1	1	U	4	4	M	1	6	3	1	4	3	1	1	4	4
APR	M	1	M	1	1	1	1	1	1	1	1	2	U	2	2	4	1	2	2	7	7	M	2	1	1	2	2	2	2	2	
MAY	4	1	M	1	1	1	1	1	2	2	2	2	1	1	1	1	1	1	1	M	1	1	1	1	1	1	1	2	2	2	1
JUN	4	4	U	U	U	6	1	2	2	2	U	U	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	2	2	
JUL	2	1	1	3	M	1	1	1	1	5	5	1	1	1	1	1	M	1	4	5	5	2	2	2	1	1	1	1	2	1	1
AUG	1	1	1	1	1	5	5	5	6	6	6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SEP	1	M	1	1	2	2	2	1	1	M	1	1	1	1	1	1	1	1	1	2	2	M	1	2	1	M	1	1	1	1	

U = unclassified

M = missing NCAR data

GLACIOLOGICAL YEAR 1970-71

DAY

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	1	1	3	1	1	2	2	1	U	U	1	1	1	1	4	1	1	5	5	M	2	2	2	2	2	U	U	U	U	U	7
NOV	U	U	U	U	U	4	4	1	1	1	1	4	4	U	6	1	1	1	1	1	1	1	3	6	1	1	1	M	1	1	
DEC	2	1	1	1	1	M	1	1	1	1	1	1	M	1	1	M	1	1	1	1	1	1	1	1	3	1	3	3	1	1	1
JAN	1	1	U	U	M	U	U	1	1	1	1	1	2	1	1	1	3	3	6	6	1	1	1	1	1	3	3	3	1	3	3
FEB	3	1	1	2	1	3	3	3	3	1	1	1	6	6	1	1	1	1	4	4	4	5	1	1	1	2	7	1			
MAR	1	4	5	6	1	3	3	3	1	1	1	1	1	2	1	3	1	1	3	3	1	3	3	1	1	1	1	M	1	1	1
APR	1	3	3	1	4	5	6	1	1	1	2	1	1	1	1	2	U	2	2	2	U	U	U	U	U	U	7	3	3	3	
MAY	3	3	6	6	1	1	4	1	M	4	4	4	5	5	1	1	4	4	4	4	4	1	1	1	3	M	M	1	1	U	4
JUN	4	4	4	5	2	4	4	1	1	2	2	2	2	U	U	1	1	1	1	1	1	1	1	1	5	1	2	2	2	1	
JUL	1	1	1	1	1	1	1	1	1	5	1	1	1	1	1	1	1	1	4	1	1	1	1	1	1	1	M	4	4	4	4
AUG	4	4	5	5	5	5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	5	1	1	1	6	6	1	1	4	5
SEP	2	2	2	2	2	2	1	1	1	1	5	6	1	1	1	4	4	4	1	4	4	1	1	1	1	2	2	2	2	2	

U = unclassified

M = missing NCAR data

GLACIOLOGICAL YEAR 1971-72

	DAY																														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	2	2	1	M	1	1	3	3	3	1	1	1	1	1	1	2	2	2	2	2	2	1	5	2	2	2	2	2	2	2	2
NOV	2	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	U	1	1	3	1	1	1	1	1	1	1	1	3	
DEC	1	1	5	2	2	1	2	1	1	2	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	4	1	1	4	M
JAN	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	1	1	1	1	1	1	1	1	1	1	1	1	1	4	1	1
FEB	1	1	1	3	1	1	3	3	3	M	1	1	1	1	1	1	1	1	6	6	1	1	1	1	1	1	1	1	1		
MAR	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	6	1	1	1	1	3	6	8	8	U	U	U	U	3	3
APR	3	6	1	1	1	8	8	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	3	5	5	6	1	5	5	5	
MAY	5	1	1	1	1	1	1	4	4	1	1	M	4	1	1	6	6	2	U	4	U	U	2	2	2	2	4	4	4	4	4
JUN	6	1	1	1	1	1	1	1	4	U	4	1	1	1	1	1	1	1	1	4	4	6	U	U	U	1	1	1	1	1	
JUL	1	1	4	4	1	1	1	1	1	M	1	1	1	1	1	1	1	1	1	2	2	2	1	1	1	1	1	1	1	1	1
AUG	1	1	1	1	1	1	1	3	1	1	1	1	1	1	2	M	1	M	5	1	4	4	4	4	4	1	1	1	1	1	M
SEP	1	1	M	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	2	2	1	1	2	2	2	M	1	1	1	1	

U = unclassified

M = missing NCAR data

GLACIOLOGICAL YEAR 1972-73

DAY

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	1	1	1	M	M	M	M	M	1	1	1	1	M	1	1	1	1	M	1	1	1	M	1	1	1	1	1	M	1	4	1
NOV	1	4	1	1	1	M	1	1	1	1	1	1	1	1	M	1	1	1	1	4	4	3	1	1	1	1	3	1	1	1	
DEC	1	1	1	1	1	1	1	1	1	M	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	4	2	4
JAN	1	1	2	1	1	1	4	4	4	4	1	1	1	1	1	1	1	1	1	1	2	M	M	1	1	2	1	1	1	1	1
FEB	1	1	1	1	1	1	4	4	4	1	1	2	1	4	4	3	4	1	1	1	1	1	M	1	1	1	1	1			
MAR	1	1	1	1	2	2	2	4	2	2	2	1	2	2	1	1	5	8	1	1	2	2	4	4	4	1	1	2	4	2	2
APR	U	U	U	U	1	1	4	3	U	3	3	3	1	1	2	2	1	2	2	2	2	1	1	1	1	1	1	1	1	1	
MAY	2	4	3	1	1	2	1	1	1	1	3	3	3	3	4	3	3	6	6	1	1	1	8	U	7	U	U	4	4	1	1
JUN	1	2	2	2	1	1	1	1	1	1	1	1	1	5	2	2	2	2	4	4	M	1	1	1	1	1	1	3	8	8	
JUL	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	5	2	2	2	1	1	1	4	1	4	4
AUG	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	5	2	2	1	1	1	1	1	5	M	2	2	2	1	2	2
SEP	2	2	2	1	1	1	5	1	1	1	1	1	1	M	4	4	4	1	1	1	1	1	2	2	2	1	1	1	5	5	

U = unclassified

M = missing NCAR data

GLACIOLOGICAL YEAR 1973-74

DAY

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
OCT	2	M	1	1	1	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	5	6	6	1
NOV	3	1	1	1	1	1	1	M	3	1	1	1	1	1	1	8	1	1	1	2	2	2	1	1	1	2	2	1	1	1	
DEC	1	2	1	1	4	1	1	1	1	1	1	1	M	1	1	3	6	3	4	1	6	1	1	1	1	1	1	1	1	1	4
JAN	4	4	4	1	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
FEB	1	1	1	M	1	1	4	3	3	1	1	1	1	1	1	1	M	1	1	1	1	5	3	3	6	1	1	1			
MAR	1	1	2	1	1	1	1	2	1	1	M	5	1	1	1	3	6	1	1	1	1	1	1	1	1	1	1	1	1	1	1
APR	2	1	M	1	1	1	1	1	1	1	2	2	4	4	4	4	1	1	1	2	2	1	1	6	4	4	4	4	1	1	
MAY	1	1	1	1	1	3	3	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	1	1	1	1	8	1	1	1	1
JUN	1	1	1	1	2	2	2	2	2	1	1	3	1	1	3	3	3	1	1	1	1	5	5	6	6	6	6	6	1	1	
JUL	1	1	1	1	1	2	2	2	5	5	2	2	1	1	5	5	5	5	5	6	6	1	1	1	1	1	1	1	3	3	3
AUG	4	4	4	4	5	5	5	2	2	2	2	1	1	1	1	1	1	M	1	1	2	1	1	1	1	1	1	1	1	1	1
SEP	4	4	4	1	1	1	1	1	1	1	1	4	4	1	1	4	1	1	1	1	4	4	1	1	1	1	1	1	1	1	

U = unclassified

M = missing NCAR data

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