Frequency and climatology of major avalanches at Rogers Pass, 1909 to 1977

Fitzharris, B. B.; National Research Council of Canada. Division of Building Research

Publisher's version / Version de l'éditeur:

Paper (National Research Council of Canada. Division of Building Research), 1981-01

National Research Council Canada
Conseil national de recherches Canada

ISSN 0381-4319

FREQUENCY AND CLIMATOLOGY OF MAJOR AVALANCHES AT ROGERS PASS, 1909 TO 1977

by B.B. Fitzharris

DBR Paper No. 956
Division of Building Research

Price $4.50 OTTAWA NRCC 19020

NATIONAL RESEARCH COUNCIL OF CANADA

DIVISION OF BUILDING RESEARCH

FREQUENCY AND CLIMATOLOGY OF MAJOR AVALANCHES AT ROGERS PASS, 1909 TO 1977

by

B.B. Fitzharris
Department of Geography, University of Otago
Dunedin, New Zealand

DBR Paper No. 956

of the

Division of Building Research

Ottawa, January 1981

FREQUENCY AND CLIMATOLOGY OF MAJOR AVALANCHES

AT ROGERS PASS, 1909 TO 1977

by B.B. Fitzharris

ABSTRACT

A seventy-year record has been compiled of the number and mass of avalanches and the length of railway covered by avalanches at the Canadian Pacific Railway at Rogers Pass, British Columbia. The data showed only weak periodicities of avalanche activity. Several frequency distributions were analyzed for fit of the data, and the Gumbel method found appropriate for short return periods, but the sample period was too short to make conclusions with respect to probable maximum events. The weather before and during intense periods of avalanche activity was investigated and two different circulation patterns responsible for frequent avalanches were defined.

FRÉQUENCE ET ASPECTS CLIMATOLOGIQUES DES AVALANCHES IMPORTANTES

SURVENUES À ROGERS PASS DE 1909 À 1977

par B.B. Fitzharris

RÉSUMÉ

Nous avons procédé à la compilation d'un dossier couvrant une période de soixante-dix ans sur le nombre et l'importance des avalanches survenues à Rogers Pass (Colombie-Britannique) et sur la longueur de voie ferrée appartenant à la compagnie de chemins de fer Canadien Pacifique recouverte par ces avalanches. L'information recueillie n'indique qu'une faible périodicité de ce type d'activité sismique. Nous avons procédé à l'analyse de plusieurs modèles de distribution de fréquence afin de déterminer celui qui correspondait le mieux aux données recueillies. La méthode Gumbel s'est révélée appropriée pour les retours périodiques de courte durée; cependant, la période considérée était trop courte pour tirer des conclusions valables quant à la probabilité d'avalanches importantes. On a également étudié les conditions atmosphériques avant et après des périodes intenses d'activité et l'on a déterminé deux modèles différents de circulation responsables d'avalanches fréquentes.

FREQUENCY AND CLIMATOLOGY OF MAJOR AVALANCHES AT ROGERS PASS, 1909 TO 1977

by

B.B. Fitzharris

PREFACE

Roads, railways, and buildings in the mountains are often located in areas exposed to snow avalanches, and when preventive measures are considered the question arises how frequently large, dangerous avalanches can be expected to occur. This problem was investigated by Blair B. Fitzharris when he was on sabbatical leave from the University of Otago, New Zealand, working as a visiting scientist with the Division of Building Research of the National Research Council of Canada.

A major difficulty in studying the frequency and size of major avalanches in Canada is the lack of long-time, complete observations of avalanche occurrences. Traffic routes and settlements began to penetrate the high mountain ranges less than 100 years ago, and the first railway line to cross the Rocky Mountains and Columbia Range was the Canadian Pacific Railway. Soon after its completion in 1885 avalanches became a major problem to the railway maintenance staff at Rogers Pass in the Mountain Division. The staff of the railway company not only removed avalanche snow from the line and built snowsheds and deflectors as protection but also recorded the location and type of the avalanches that had occurred. These records and later ones maintained by the Snow Research and Avalanche Warning Section of Parks Canada form the basis of this study.

DBR/NRC wishes to thank field staff for carrying out the observations and the Superintendent of CP Railway at Revelstoke for making the records available. Long-time data of avalanches are valuable not only for studies such as the present one but also when decisions about avalanche control methods must be made. For these reasons DBR wishes to encourage the collection of data in avalanche areas and hopes that this report will serve as a guide in their analysis.

Ottawa
January 1981

C.B. Crawford
Director, DBR/NRC

CONTENTS

FREQUENCY AND CLIMATOLOGY OF MAJOR AVALANCHES AT ROGERS PASS, 1909 TO 1977

by

B.B. Fitzharris

1. INTRODUCTION

A first step in establishing zones of avalanche hazard is to examine the historical record of past events. Unfortunately, for much of Western Canada the record of avalanches is either short (usually less than 10 years), incomplete, or unreliable. In fact, few continuous avalanche periods of more than 30 years have been assembled anywhere in the world: Frutiger (1977) listed avalanche catastrophes that significantly affected large areas of the Swiss Alps between 1808 and 1975; Loup and Lovie (1967) presented a graph of annual frequency of avalanches from 1901 to 1965 for the Tarentaise, France; Toushinsky (1966) gave the annual number of avalanches in the Khibiny, U.S.S.R., from 1940 to 1973; Armstrong (1978) compiled the number of avalanche deaths per year in Ouray County, Colorado, for the period 1877 to 1975. The best record for Western Canada is that for Rogers Pass, British Columbia, compiled by Schaerer (1962), giving the number of avalanches affecting the Canadian Pacific Railway line between Stoney Creek and Illecillewaet from 1910 to 1960. This record forms part of the present report; it has been checked, standardized for a homogeneous set of avalanche paths, and brought up to date.

In the study of other hazards such as floods, long records are examined statistically for trends and the probability, or return period, of the occurrence of events of a certain size. There is need to apply this type of analysis to avalanches. The Rogers Pass record provides an opportunity to pursue this approach and to determine the most appropriate probability distribution for avalanche data.

Experience has shown that very large avalanche events are often weather controlled: preceding weather may provide conditions that lead to an unstable snowpack, and any instability is usually released by a critical weather sequence involving wind, heavy precipitation or warming. In discussions of extreme avalanche events or winters, therefore, it is important that the climatology of the area is examined. It is also reasonable to expect that seasonal fluctuations in frequency and magnitude of avalanches will be related to variations in atmospheric circulation patterns. Important questions that arise are: how representative of avalanche activity has been the period since, say, the opening of the Trans-Canada Highway through Rogers Pass in 1962? How extreme were the recent heavy avalanche winters of 1971-72, 1973-74? Was the weather then different from that of other heavy avalanche seasons of the past?

The objectives of this report are therefore:

1. to construct a homogeneous, long-period avalanche record of selected paths at Rogers Pass.

2. to examine the climatology of extreme avalanche winters and intense periods of avalanche activity.

3. to examine the nature of avalanche data series, and to assess the most appropriate probability distribution for frequency analysis.

2. COMPILING THE AVALANCHE RECORD

2.1 Study Area

The avalanche area under study is a section of the main line of the Canadian Pacific Railway (CPR) between Golden and Revelstoke, British Columbia, where the line crosses the Selkirk Mountains at Rogers Pass. The Selkirk range has deep, narrow valleys and rugged mountains, which together with high snowfall produce numerous avalanches (Schaerer, 1962 and 1977). The average annual precipitation (1941-1970) at Rogers Pass, elevation 1320 m, is 1493 mm; 65 per cent of it falls in the form of snow.

The railway line over Rogers Pass was built in 1885, and in the years following completion numerous snowsheds were added as protection against avalanches. In 1916 the actual pass area containing the worst avalanches was by-passed by the 8 km long Connaught Tunnel under the summit.

In 1953 when consideration was given to Rogers Pass as a route for the Trans-Canada Highway an avalanche study was initiated by the Department of Public Works of Canada (DPW), the agency responsible for the construction of the highway. The highway was completed in 1962, and as it is in a national park has since been maintained by Parks Canada. The Park's Administration contains a Snow Research and Avalanche Warning Section (SRAWS) with responsibility for controlling avalanches by artillery and closing the highway during hazardous periods, as well as for artillery control of avalanches at the railway line (Parks Canada 1977).

The National Research Council of Canada (NRCC) assisted the Department of Public Works in the design of the avalanche control, and later continued a research program that included measuring the location and mass of avalanches at selected paths. The most active avalanche paths along the railway line are between Stoney Creek, 5 km east of the Connaught Tunnel, and Illecillewaet, 20 km west of the west tunnel portal (Figure 1). This is the area covered by the present study. The Downie area west of Illecillewaet was an avalanche trouble spot until 1939 when the railway line was moved to the opposite side of the valley. As the relocation of the line interrupted the collection of avalanche data in this area, it was excluded from the present study.

After examining the data from all sources 26 avalanche paths for which continuous, homogeneous records could be established, were retained for analysis. Their location is shown in Figure 1 and their characteristics listed in Table I.

2.2 Avalanche Data

Sources of data used to compile the record of avalanches are listed in Appendix A. Continuous records used in the analysis cover the period from the winter of 1909-1910 to the winter of 1976-1977 (Appendix B). Earlier reports of avalanche activity were available from old journals, newspapers, and books, but a continuous record could not be constructed.

The continuous, long period of records comes from a variety of sources, each of which recorded the occurrence and size of avalanches differently. Because the CPR data cover the longest period (1909 to 1952) and indicate avalanches that have run at least a clearly defined distance, they are regarded as the standard. Equivalent data were generated from the other sources to continue the record to 1977. Thus an avalanche must cross the railway line to be included in the record.

Four different measures were selected to represent the record for each winter:

1. Number of avalanches (ΣF) that affected the railway line for each winter in the period 1909 to 1977.

2. Mass of these avalanches (ΣM) for each winter in the period 1918 to 1977.

3. Length of railway line (ΣL) covered by debris of these avalanches for each winter in the period 1918 to 1977.

4. Avalanche activity index (ΣI) (Salway 1976), estimated or measured for each winter in the period 1896 to 1977.

2.2.1 Number of avalanches (F)

The early CPR records contain the date, dimensions, and locations of avalanche deposits that affected the railway line. More modern records of the National Research Council of Canada (NRCC), and sometimes of the Snow Research and Avalanche Warning Section (SRAWS), also note when avalanches reached the railway line. An avalanche must be larger than usual in order to affect the railway line; therefore it is assumed that all such avalanches were noted in the various reports and documents used to compile the record.

2.2.2 Mass of avalanches (M)

The NRC measures or estimates the location of the avalanche terminus, the length, width, and depth of the snow deposit, and the density of the snow. With this information the mass of the avalanche can be estimated. It has been found that the estimates of an experienced observer agree with measured amounts to within 10-15 per cent (Schaerer, 1975).

The SRAWS data give a measure of the avalanche terminus in terms of its position on the fan or in relation to the Trans-Canada Highway. The size of avalanche is indicated in qualitative terms only, as small, medium or large. Where avalanches reached the railway line they often also crossed the highway. In these cases SRAWS recorded the depth of deposit on the road and the length of road affected. The CPR data give the length of railway line covered by avalanche debris (L) and its depth (Z). Both the SRAWS and CPR records, therefore, provide a sample cross-section of the avalanche at either the highway or the rail line, allowing a cross-sectional area to be calculated:

$$A = L \cdot Z$$

The length of an avalanche deposit was set to the probable runout distance (D), which took into account the sample cross-section of the avalanche debris, terrain of runout zone, and description of avalanche. For very large events it was assumed that avalanches ran close to the maximum runout distance (D_{max}) of the last 100 years or so, as represented by the trimlines of vegetation. D_{max} was estimated using air photographs of scale approximately 1:12 000. The start of the runout zone for large avalanches was set with the help of people experienced in the area and usually occurred where the slop decreased to about 16 deg.

The volume (V) of the avalanche deposit was estimated by one of the following methods:

1. For unconfined avalanche paths with uniform, open slopes in the runout zone, $V = A \cdot D$.

2. For confined avalanche paths emerging from a gulley onto a fan (the deposit is often triangular in plan) $V = 0.5A \cdot D$.

3. For avalanches that crossed the river and moved up the opposite side of the valley (e.g. Twins, Lanark) the debris profile is not known; much snow may be dumped and channelled by the river and only the toe of the deposit push uphill to the CPR line. In these cases it was assumed that $V = 0.8\ A \cdot D$.

4. For some avalanche paths such as Fidelity, it was obvious that only the very tip of a large avalanche had cut the CPR line and that the sample cross-section area was not a good one. In these cases A was calculated by replacing L with the dimensions of the width of the runout zone.

   After finding the volume, the mass of each avalanche was estimated as $M = G \cdot V$, where G = density of the avalanche deposit, estimated from NRC tables (unpublished).

In 14 per cent of avalanche occurrences between 1918 and 1977 the only information on size was a qualitative description such as "similar size to last winter," or "two hours to clear debris." A rough estimate was made by comparison with other avalanches of known size on the same path. In 9 per cent of occurrences, no information was available as to size. Here it was assumed that the avalanches were small, with $M = 0.01\ Mo$, where Mo is the magnitude of the limit avalanche (Schaerer, 1975). The various types and quality of record used for estimating M on the 26 selected avalanche paths are contained in Appendix B.

2.2.3 Length of railway line covered by avalanche deposits (L)

The length of track covered by avalanches during one winter, summed for the 26 selected avalanche paths, was used as an index of avalanche activity. Values were obtained directly from CPR data or from other sources, as discussed.

2.2.4 Avalanche activity index (I)

The activity index is a numerical weighting scheme for representing avalanche activity in terms of the debris terminus, size, and moisture content for each event. Salway (1976) computed the index for each day for about 100 avalanche paths at Rogers Pass for the winters 1965-66 to 1972-73. He found a good correlation ($r = 0.92$) between the total winter avalanche activity index (ΣI) and total winter snowfall. The regression equation is:

$$\Sigma I = 2673 + 27.38S$$

where S = total winter snowfall at Rogers Pass in cm. This equation was used to estimate ΣI back to the winter 1896-97. The climatological station near Rogers Pass has had several site changes since 1896, and snowfall values were standardized by several methods (Appendix C).

2.3 Changes in Conditions at Rogers Pass over the Last Century

At the time of construction of the railway line in the 1880's, several large fires destroyed some of the forest near Rogers Pass. This was documented by Green (1890) and by Keefer (1888), who noted the consequences:

"During the summer of 1886, fires denuded the mountain sides, leaving no support for the snow on steep side hills, increasing the number of slides and the demand for shed extensions."

The frequency and magnitude of avalanches apparently increased, but with time they were reduced by natural forest regeneration: the site of a disastrous avalanche in 1910 is now overgrown; the Downie avalanches appear to run less frequently now than prior to 1940; the starting zone of Helen is covered with young trees and it has not affected the railway line for more than 40 years.

It is possible that some paths have become more active with time because large avalanches have cut a swath in virgin timber. Several comments in the CPR data give descriptions of large timber in the avalanche debris. It is clear that there is a close relation for vegetation, fire, and avalanches.

As part of the defence system for the Trans-Canada Highway through Rogers Pass, use of artillery to control avalanches has increased. This is thought to have altered the frequency and magnitude of small and medium avalanches since 1965, but the effect on very large ones is not clear. The frequent artificial release of avalanches may have prevented natural reforestation in some starting zones. Thus the use of artillery further complicates the relation of vegetation, fire, and avalanches.

The number, position and standard of snow-sheds protecting the railway has also varied over the years, but this is not an important consideration for the 26 selected avalanche paths, except at Laurie and CPR Sheds.

It follows from the above discussion that the avalanche records of number, mass, length of railway line covered, and activity index (F, M, L and I) may contain trends and discontinuities resulting from factors other than climatic variations.

2.4 Errors in Data

Errors occur in the time series for F, M, L, and I from two main sources. First, errors may exist in the original data. Second, there may be errors in interpreting these data to compile the time series records; such observational sources of error include:

1. Some avalanches may not have been noticed immediately because of storm or darkness, and therefore may have been assigned a later date than that of actual occurrence.

2. During hectic clearing operations following a multi-avalanche event on the railway line or highway, some avalanches may have been omitted from the record.

3. Two avalanches may have occurred on the same path, but been recorded as one.

4. Avalanches of light snow may have crossed the railway line and been passed through by a train, unnoticed and unrecorded. Conversely, if a train was hit by even a small avalanche or powder snow, the classification might have been for a significant avalanche and so recorded in the data.

5. Many observers tend to estimate the depth of deposit on the upslope side of the railway line, leading to a systematic error since such depths may be twice those on the downslope side.

6. CPR personnel may have overestimated the length of line covered by an avalanche because large avalanches tend to be impressive. Furthermore, removal of exceptional amounts of snow would impress the Company and there might have been some incentive to exaggerate amounts of avalanche debris.

Errors in interpretation might arise as follows:

a) In a few cases the description of an avalanche location suggests that it could have run on one of several paths.

b) Where qualitative or no description other than occurrence is given, estimates of M are no more than educated guesses and errors tend to be large.

c) Errors arise owing to the influence of terrain on the sample cross-section of the avalanche debris reported on the railway line or highway. Avalanche snow may have been trapped in a cut or have spilled along the length of the railway line, exaggerating the size of the deposit. These errors may occur in the estimates of M and L. The uncertainty of estimating M when avalanches cross the river and move up the opposite slope has been discussed.

d) At the Laurie and CPR Sheds paths, where there are tunnel and snow-shed complexes to protect the railway line, the record may be inconsistent. The CPR data indicate those avalanches that overwhelmed or caved in the defences. For this reason, only avalanches with $M > 5000$ tonnes were used from the modern data in compiling the record.

e) As most large avalanches occurred in January, the density of the snow used in calculating M was usually low (320 - 380 kg/m^3). Some catastrophic events (e.g. winter 1934-35) were, however, associated with rain and rapid warming, so that the avalanche deposit may have been wetter and more dense than was assumed. In these cases M would be underestimated.

f) There were problems in equating the information from the different data sources that might lead to error. The modern data of SRAWS refers to the highway rather than to the railway line. Once the avalanche crosses the highway the terminus position is occasionally difficult to determine.

It is considered that the most reliable time series are those for F and L. The series for L has little physical meaning except as an index of large-magnitude avalanche activity. M and I involve numerous assumptions, but because such long time series have not been available before they are worth reporting. In particular, estimates of M allow magnitude-frequency relations to be determined.

The records for avalanche mass, M, have been rated as to quality (Appendix B). The grade depends on type of data, on terrain in the run-out zone, on location of the railway line and its ability to "capture" a representative sample of avalanche debris, and on size of avalanche. Classification of estimates of M for the 192 avalanches between 1918-19 and 1967-77 were as follows:

excellent	14%
good	29%
moderate	28%
poor	29%

These quality estimates of M could also be aggregated for each winter. Classification of the estimates of ΣM for the winters 1918-19 to 1976-77 were as follows:

excellent	3%
good	27%
moderate	41%
poor	14%
no avalanches	15%

2.5 Avalanche Sites and Statistical Nature of Avalanche Data

Of the 26 avalanche paths used for this study, 15 were large (starting zone areas greater than 250 000 m^2) and 11 were medium (starting zone areas of 50 000 to 250 000 m^2) (Schaerer, 1975). Of the large avalanche paths, six could be called very large, with starting zones greater than 1 000 000 m^2.

The mass, M_o, of a limit avalanche was also determined for each path using Schaerer's (1975) method (Table I)

$$M_o = (s - r)\ a$$

where s = 30-year maximum water equivalent of the snow in the catchment area

r = a measure of the retention of snow due to terrain features such as ground roughness

a = total area of land surface from which snow could slide into the avalanche track; also includes zones outside the watershed that may contribute because of wind drifting.

It may be seen that the 26 paths tend to produce avalanches of widely varying size, with some accent on the upper end of the scale. Large and very large starting zones are broken into several gullies, and the occurrence of an avalanche from one may be independent of and have no influence on the others. Each gully is treated as a separate path, but on occasion avalanches can run simultaneously in two or more gullies and combine to form a large one. Other characteristics of the terrain have been summarized in earlier papers (Schaerer, 1972, 1975, 1977).

Avalanches from the large starting zones do not necessarily reach the railway line most frequently and those from smaller zones even less frequently. Frequency (F) and size of avalanche (M) depend also on the location of the railway line with respect to the run-out distance of the avalanche. The ratio of the run-out distance to the railway line (D') and the maximum run-out distance (D_{max}), as observed from vegetation patterns, is given in Table I.

The time series for F, M, and L fall into the class of non-annual exceedance series. As an avalanche must be large enough to cross the railway line to be recorded, such an event need not occur every year (i.e., $\Sigma F = \Sigma L = 0$). The minimum size of avalanche required to cross the railway line is the base value for that path. These series do not give annual maximum, as does the series for I, but provide non-annual maximum series for each path. The base value, however, is not the same for each available path selected, and may even differ on each path for wet and dry avalanches (Figure 2).

The avalanche paths selected for study may be divided into five main types, shown schematically in Figure 3. Type A paths are often steep . They figure in the CPR data because the railway line is forced to sidle round a mountain slope and cut across avalanche paths high up the run-out zone. The data series for this type of path contains all avalanches greater than medium size, and may approach an annual maximum series. Types B and C paths represent stages in a progression where the railway line is located further down the run-out zone towards the maximum run-out distance.

Avalanches on type C paths seldom reach the railway line, except for major events that cross the river about once in 10 to 30 years. Data from these paths clearly form non-annual maximum series that have large base values. Type D paths are similar but feature multiple starting zones. Some are capable of generating frequent, large avalanches, for example Ross Peak. Others, such as Jack MacDonald, must be very large to cross the river and affect the railway line more than 30 m up the opposite valley side. Such events may occur only once in 10 years. For avalanches such as Fortitude and Fidelity the railway line is located at the very end of the run-out zone. Only extremely large avalanches occurring perhaps once in 50 or 100 years are capable of crossing the railway line, so that for these paths the base value is very large.

Finally, for type E such as Laurie and CPR Sheds where there is some protection against avalanches, the data used in this report form a non-annual maximum series. The base value may have increased with time because of improvements in the tunnels and snow sheds.

In summary, the time series of F, M and L provide a non-annual exceedance series for each path. The data for each represent a sample of the population of all avalanches on that path. For paths of type D, the non-annual exceedance series represents the extreme tail of the population frequency distribution. For paths of type A, much more of the frequency distribution is available (Figure 2).

Values of F, M, L and I are summed, for each winter, for the 26 selected avalanche paths to give ΣF, ΣM, ΣL and ΣI, which may be regarded as annual series. If no avalanches reach the railway line, than all but ΣI have zero values for that winter.

3. AVALANCHE RECORDS

3.1 Prior to Winter 1909-1910

Early accounts of avalanche activity at Rogers Pass are fragmented and no continuous record can be established. They are often written without the benefit of previous exposure to avalanches or knowledge of earlier winters. Moreover, they frequently express amazement at the size and force of the avalanches.

The first reports of avalanching come from Walter Moberly, who mentions in his journal (26 September 1865) a trip up the Illecillewaet River and using a snow bridge on which his party crossed the stream flowing 250 feet below, unseen (Wheeler, 1905, p 165). The exact location is unknown, but the survival of avalanche snow through the summer suggests a very large event in the winter of 1864-65.

No other reports are available until the end of May 1881 when Major A.B. Rogers, accompanied by his nephew, made his first expedition up the Illecillewaet Valley. Beyond Albert Canyon, the nephew, A.L. Rogers, notes (see Wheeler, 1905, p 419):

> "There must have been heavy snows in the mountains the preceding winter, for snow on the level was several feet in depth in shade spots, and the next five days our course was across avalanches, some of which had started from the

very peaks and left a clear path behind them, crushing the timber into matchwood for several hundred feet on the opposite sides of the mountains. We crossed several snow-bridges under which the river passed, which were one hundred and fifty feet above the river's bed."

This description suggests that the winter of 1880-81 may also have been a heavy avalanche winter. Rogers reports that avalanches were still running at the end of May.

In 1883 a survey party also reported avalanches 14 miles west of the Rogers Pass summit. It came upon two large masses of frozen snow on either side of the river (Wheeler, 1905, p 165). Both reports are thought to be from the vicinity of the old Laurie mining camp and probably refer to the Laurie or Lanark avalanches.

There are numerous accounts of avalanche activity for the winter of 1884-85 and the two following. A detailed discussion has been given by Cunningham (1887a) in his journal of observations at a camp three miles east of the summit in the winter 1885-86. On 8 February 1885 there were three very large avalanches. Part of Mill's store was destroyed at the summit by what may have been either Cheops 1 or one of the MacDonald West Shoulder avalanches. Three men were killed 2 miles west of the summit at Avalanche Crest and one more perished 4 miles further west. It was generally believed that many others died in other disastrous February slides, but their deaths were concealed to prevent bad publicity for the new railway (Frontiers Unlimited, 1968). The winter of 1884-85 was extremely cold, with Arctic air apparently dominating the area during December and the first half of January. Cunningham (1887b) reports the thermometer dropped to -41°C. Snowfall was greater than 914 cm at the summit (which is about average), with heavy snowfalls during storms.

The winter of 1885-86 was much milder and the snowfall about half that of the previous winter. It was windier, however, so that snow drifted into the starting zones and numerous avalanches occurred. Cunningham perceptively notes (1887b)

"The slides of the winter 1885-86 were certainly less in bulk than those of 1884-85, but there was no such difference as would be inferred from a direct comparison of the respective snowfalls; and in some places slides occurred in the former year where there were none the year before."

He also noted that the vegetation indicated exceptional winters where "the slides descend in stupendous volume." He recorded the location of avalanches that buried the railway line during the 1885-86 winter (Table II), although most of his descriptions refer to avalanche paths immediately east of the summit where the railway line used to climb over the pass before completion of the Connaught Tunnel in 1916. Except for Connaught, Unnamed No. 6, and Stone Arch, these are not part of the 26 paths used to compile the long-term record of this report. The frequency of avalanches on Tupper 1, Tupper 2, Tupper 3 and Pioneer paths were slightly above average compared with experience of the last two decades. Cunningham's reported frequency on Lens is much higher than it is today, but may reflect proximity to the observation camp.

After the gale force winds, 12-20 February 1886, large avalanches were observed at MacDonald West No. 4 and Connaught paths. From the dimensions of the avalanche debris given by Cunningham, the estimated mass at MacDonald West was 42 000 t and ran right across the valley floor. This would be considered a very large avalanche at that site today and probably resulted from a large build-up of wind-blown snow in the starting zone. Subsequently, the CPR placed a long snow shed at this location, but it was apparently not needed thereafter because the railway line was outside the shed by the time of the disastrous 1910 avalanche near this site. There is evidence that no large avalanches ran at this location between 1886 and 1910. The avalanche at Connaught was large, with an estimated mass 117 000 t. Only three avalanches on this path have been larger in the last 60 years. On the other hand, avalanches at Tupper 1 and Tupper 2 were both smaller than the average maximum on these paths. It is concluded that 1885-86 was a winter with below-average snowfall but above-average avalanche activity.

The winter 1886-87 was again cold. Snowfall was about 950 cm, close to the average. The larger avalanche paths were inactive until mid-January when there was a brief burst of activity (Table III). A major event killed six men at the end of February, and there was nearly continuous avalanche debris from the Tupper Timber site to the Summit. Such activity in the Tupper area typically occurs about once in 10 years, as in this case, as a result of an inactive early winter followed by rapid warming during a storm. Avalanches were again active at Connaught, Unnamed No. 6, and Stone Arch. These frequencies were higher than average but not unusual, because the pre-1916 position of the railway line was further up the slope at these paths.

In the discussion following Cunningham's paper of 1887 it is interesting that at this early stage avalanches were predicted by readings of the barometer and thermometer. The guide rules were:

> "Snow falls during mild weather, and slides more frequently happen at such times; from all experience, it appears that slides are attended by a high thermometer, a low barometer and occur during or after a heavy fall of snow; wind is also more prevalent during mild weather."

Green (1890), who surveyed the Selkirks in the vicinity of Rogers Pass in the summer of 1888, found the forest close to Glacier House "utterly demolished by a recent avalanche, which had evidently fallen from the direction of Mount Sir Donald" (p. 68). The destruction shown by his illustrations was extensive. Elsewhere he noted cedars greater than 4 ft in diameter snapped across and split by the avalanche, the debris of which still covered the stream (p.135). Both references suggest that recent avalanche activity had been much greater than normal, possibly in the winter of 1887-88.

No other reports of avalanche activity appear until a dry snow avalanche swept away the station and roundhouse near the summit of Rogers Pass, killing eight people, on 30 January 1899 (Revelstoke Herald, 4 Feb. 1899). The avalanche is thought to have come from the Grizzly path, which only rarely runs large enough to reach the position of the early railway line. The same day a second slide broke through a snow shed near the summit, killing a workman inside (Frontiers Unlimited, 1968). Snowfall in the winter of 1898-99 was greater than 1300 cm, the highest recorded at Rogers Pass to that date (Vaux, 1900).

Glacier House was a popular mountaineers' retreat about the turn of the century, and many experiences were recorded in the "Glacier House Scrapbook" between 1897 and 1910. Unfortunately, all except one account are for the summer period, and in no account is there evidence of major avalanching.

The major disaster of 5 March 1910, when 62 railway men were killed, received a great deal of attention in the press (Calgary Herald, Province), but little information was given regarding winter snow conditions or weather. In fact, there is some uncertainty as to which path produced the avalanche, except that it appears to have come from one of the areas opposite Cheops. Compared with later avalanche activity, the winter of 1909-10 was not an exceptional winter.

Surveys of early newspapers, (Cariboo Sentinal, Victorian Colonist, Nelson Daily Miner, and Vancouver Province) uncovered 26 references to avalanches in British Columbia between 1870 and 1910. These early reports tended to stress local avalanche activity, and then only if injury, damage or a narrow escape resulted. The large city newspapers, especially in modern times, ignore local events, featuring large-scale disasters on main communication routes, or deaths. The human interest side of the story is stressed rather than the weather or nature of the avalanche. By themselves, newspapers do not give a good record of avalanche activity over a space of time, but they are useful as corroborative evidence. Results of the survey have been summarized in Table IV.

In summary, the record of avalanche activity at Rogers Pass is incomplete prior to the winter of 1909-10. Surveys of early journals, books and newspapers suggest that avalanche activity was heavier than normal in the 1880's, and may have been extreme during one winter. Between 1888 and 1910 avalanche activity appeared to be normal or less than normal. There is no evidence during this period of catastrophic, extreme avalanche events similar to those of 1920, 1933, 1935 and 1972. These events might therefore be considered the greatest since 1888 or even longer.

3.2 Period 1909 to 1977

The reconstructed records for ΣF, ΣM, ΣL are given in Figure 4 and for ΣI in Figure 5. Also shown are 5- and 15-year moving averages for ΣF and ΣI. The record for the number of avalanches, ΣF, shows long periods of low to moderate avalanche frequency separated by peaks of very much higher frequency in the winters 1919-20, 1932-33, 1934-35, 1967-68 and 1971-72. Other notable winters were 1917-18, 1951-52, 1953-54, 1955-56, 1959-60, 1973-74 and 1975-76. This pattern, whereby the extreme winters have many more avalanches than average (Figure 6), also appears in the frequency records of Loup and Lovie (1967) from the Tarentaise, and in those of Chishima (1976) from Japan.

The frequencies and return periods of avalanches affecting the railway line at each path are contained in Table V. A plot of return period against run-out distance to the railway line relative to the maximum run-out distance on that path produces a general exponential relation (Figure 7). Scatter about the line is produced by differences from path to path in the terrain of both the starting and run-out zones.

The record for ΣM displays characteristics similar to that for ΣF, but with more peaks (Figure 4). There is also a different ranking of heavy avalanche years, mainly owing to the wide range of avalanche starting zones of the 26 paths selected. A single avalanche on a large path, such as Ross Peak or Lanark, can contain more mass than 10 or so avalanches on smaller paths such as Couger Corner 3 and Couger Corner 6. Thus the winter 1936-37 ranks eighth on the list of ΣM, although only one avalanche reached the railway line (it happened to be on the large Jack MacDonald path, and had an exceptionally large mass). Conversely, ΣM for the winter 1971-72 was much lower than for other winters with high ΣF. In 1919-20 large avalanches ran on large paths, to give the maximum ΣM over the 59 years of record. Several winters during the 1940's and 1950's also come into greater prominence than is indicated by ΣF.

Values of ΣM (Figure 6) and the masses of the individual avalanches follow a log-normal distribution (Figure 8). Size of avalanche relative to the limit avalanche for each path (M/M_o) also shows a log-normal distribution (Figure 8). About one third of the avalanches were 1 to 2% of the size of their relative limit avalanche. Three, however, were greater than 0.2 times their limit avalanche: Connaught on 18 January 1920 (M/M_o = 0.27), Smart West on 9 January 1933 (0.42), and Couger Creek East on 7 February 1952 (0.23).

The maximum avalanche to occur on each path varies widely over the winters (Table V), but five paths had their largest avalanche in 1932-33, three in 1934-35, and two in 1919-20 and 1971-72. Thus winters with a high frequency of avalanches to the railway line also produced relatively large avalanches on many, <u>but not all</u>, paths.

Values of M/M_o for the largest avalanche on each path over the period 1918 to 1977 show a wide scatter when plotted against the return periods of Table V. Despite the wide range of snow and weather conditions experienced over 59 winters, some paths failed to produce large avalanches relative to their limit avalanche, suggesting that factors other than snow or weather determine magnitude-frequency relations.

The record for ΣL is intermediate between that of ΣF and ΣM, with outstanding winters again recorded as 1919-20, 1932-33, 1934-35, and 1971-72 (Figure 4).

The record for ΣI is distinctly different from that of the other three (Figure 5). It has no zero values and less extreme fluctuations. The highest winters were 1953-54, 1966-67, 1917-18 and 1971-72. Although the histograms for ΣF and ΣM are skewed, that for ΣI is more normally distributed (Figure 6).

The peaks in the ΣI record (and hence snowfall record) do not always correspond with those of ΣF, ΣM and ΣL. The correlation coefficient between ΣF and ΣI is low (0.41) and not significant (Figure 9). Correlation between ΣM and ΣI is even lower. These weather relations illustrate that winters of heavy snow are not always winters with large avalanches. When heavy winter snowfall does occur, avalanches may run so frequently as not to allow a large build-up in the starting zone. This, or artillary, may account for the relatively low ΣM for 1971-72. Some winters, such as 1910-11, 1963-64, do not produce avalanches large enough to reach the railway line, despite above-average ΣI and snowfall.

On the other hand, winters with light or moderate snowfall and little total winter avalanche activity can produce many large avalanches, as in 1934-35. Clearly, snowpack and meteorological factors other than total winter snowfall determine the frequency and size of avalanches that reach the railway line. This type of finding is consistent with those of Loup and Lovie (1967) and the experience of the local avalanche-warning staff at Rogers Pass; it is discussed in greater detail in Section 5 of this report.

On the scattergram of ΣF versus ΣI (Figure 9), most winters fall into an envelope given by the line:

$$\Sigma F = -5.9 + 0.59 \times 10^{-3}\ \Sigma I$$

The exceptions are those of 1934-35 and 1971-72, both of which seem to have been unusual. Using this line, $\Sigma F = 0$ when $\Sigma I = 10 \times 10^3$, suggesting that avalanches do not reach the railway line if ΣI is less than this quantity. This corresponds to a snowfall at Rogers Pass of less than 500 cm. Such low snowfalls have occurred only four times in the last 80 years; and it is concluded that in most years at Rogers Pass there is always sufficient snowfall for avalanches to reach the railway line. All that is required is suitable snowpack and weather conditions.

By taking into account avalanche frequency and magnitude an assessment was made of which winters were "worst": 1971-72, 1934-35, 1919-20, 1932-33, 1953-54, 1917-18, 1967-68, 1946-47, 1951-52, 1945-46, 1973-74.

3.3 Seasonal Distribution of Avalanches

Of the avalanches to affect the railway line from 1909 to 1977, 66 per cent occurred in January and February (Figure 10). The largest avalanches also showed a strong tendency for these months. Spring avalanches did not make a major contribution to ΣF, ΣM or ΣL, except at Laurie, and on avalanche paths with low elevation starting zones, and short runout distances to the railway line, (such as at the CPR Sheds).

3.4 Short Periods of Intense Avalanche Activity

The avalanche records were examined to identify periods of a few days when three or more avalanches affected the railway line (Table VI). In all, 19 periods were recognized, containing nearly half of all avalanches between 1909 and 1977. The most intense periods were in 1935 (F = 11) when the railway line had to be abandoned for a week, 1933 (F = 10), 1920 (F = 9), 1972 (F = 6), 1952 (F = 5), and 1968 (F = 5). Heavy avalanche winters tend to have at least one period of intense activity. During the winters 1919-20, 1932-33, and 1934-35, avalanches running within a few days of each other made up all, or the bulk, of the annual total. This suggests a pattern of critical storm conditions superimposed on a snowpack made weak by prior winter weather. On the other hand, the winter of 1971-72 was characterized by avalanches throughout the year, with several periods of intense activity.

Since the construction of the Trans-Canada Highway, there has been no avalanching equal to the severe, intense activity of 1920, 1933, and 1935. This may be due to the effectiveness of the artillery control but, as discussed later, weather conditions have not been conducive since 1935; it would be interesting to consider the effectiveness of avalanche control if similar conditions were to occur again.

3.5 Long-Term Trends and Periodicities

The 5- and 15-year running means give an indication of possible long-term trends in the avalanche records of ΣF and ΣI (Figures 4 and 5). The 15-year means for ΣF indicate no marked change in long-term avalanche frequency, except for a slight upward tendency in recent decades. This may reflect artillary control, more reliable observations, or changes in climate, but it is not large enough to be significant. The 5-year means for ΣF suggest a periodic pattern of several winters of higher avalanche frequency separated by periods of less activity.

The 15-year means for ΣI (or snowfall) also show no linear trend, but there is a suggestion of a broad peak about 1910-20, followed by a broad trough about 1935-45, then a rise to another broad peak in recent years. The 5-year running means illustrate smaller scale fluctuations embroidered on the long-term variations.

There is a strong suggestion that ΣM has decreased since the 1950's despite the high frequency of avalanches during the last decade. This may reflect the effectiveness of artillery control or of more reliable measurements, but it could also result from an absence of weather conditions conducive to multiple release of very large avalanches over the last three or four decades.

To investigate the frequency response of the avalanche records, spectral analysis was applied to the time series of ΣF, ΣM, ΣL, and ΣI, using the Tukey-Manning method and the approach described by Jenkins and Watts (1968). Correlograms and spectral density estimates were calculated for each series. These are short series for spectral analysis ($m = 59$ to 81), but must suffice as longer records are unavailable. Caution is required in interpreting the results because the addition of more winters of data could markedly alter them. Jenkins and Watts (1968) note that a short series with less than 100 observations can provide acceptable estimates of a smooth spectrum, but that it is often too short to provide an estimate of a spectrum that contains a narrow peak. To check the results, spectral analysis, using the maximum entropy method (Ulrych and Bishop, 1975) which is more powerful for short-time series, was also used.

All correlograms are similar to those for white noise (Figure 11), indicating that the avalanche data are produced by near-random events. A formal test for white noise (Jenkins and Watts, 1968) and the plot of the normalized final prediction error against order of the autoregressive model (Ulrych and Bishop, 1975) confirmed this result. All except the correlogram for snowfall decay rapidly to near zero after one lag. Thus the frequency and size of avalanches reaching the railway line are independent from one winter to the next. The correlogram for snowfall decays less slowly, with a correlation coefficient of 0.22 between one winter's avalanche activity and the next; this is just significant at the 95 per cent confidence level. It probably reflects a small amount of persistence in atmospheric circulation and weather pattern from one winter to the next.

Correlations at lag two of more than 0.25 for $\ln \Sigma M$ and $\ln \Sigma L$ suggest that a larger than normal avalanche year tends to be followed by another two years later. Beyond lag two, the correlations for all series are small and not significant and inferences based on them are suspect. It is worth noting, however, that between lag 4 and lag 11 correlations tend to be negative, indicating that large avalanche years are followed by small avalanche years for about a decade.

The power spectra for ΣF (Figure 12) and ΣM (Figure 13), obtained by using the maximum entropy method, display highest power at 0.055 cycle/year, with lesser peaks at 0.15, 0.23, 0.31, 0.40 and 0.47 cycle/year. Thus a periodicity of 18 years is suggested, with periodicities of just over 2 years and 3 to 7 years perhaps also present, but certainly not pronounced. The spectra are not concentrated at a single frequency but spread over a wide range, so that the series are not truly periodic. It should also be stressed that the suggestion of an 18-year periodicity in the record for the period 1909 to 1977 may itself be chance and might not appear again if a much longer period of record became available.

The power spectra for ΣL show similar results. Those for snowfall and ΣI show a number of peaks over the entire frequency range, but with no major peak at 0.055 cycle/year. Thus no periodicity that is useful for prediction appears in the avalanche time series at Rogers Pass, or in the snowfall record.

3.6 Comparison With Other Long Periods of Avalanche Records

In their study in the Tarentaise, Loup and Lovie (1967) recognized two distinct, but similar, periods of avalanche activity: from 1901-02 to 1931-32, where frequency tended to decline after an early maximum in 1903-04; from 1932-33 to 1964-65, when avalanche frequency again rose quickly to a maximum in the late 1930's and then declined to the 1960's. These results suggested a periodicity of about 30 years. Unfortunately, the data offered by Loup and Lovie appears to be incomplete, so that spectral analysis cannot be applied.

Frutiger (1977) noted that small or large avalanche catastrophes occur somewhere within the Swiss Alps on the average of every seventh year. In a given specific area, the average recurrence interval for major avalanche disasters appears to be every 25 years.

There has always been speculation on the relation between weather phenomena and solar activity. Kahn (1966) investigated the links between avalanches and solar cycles for the French mountains. His record of avalanche frequency was too short to be conclusive (1900 to 1915), but he believed that the meteorological factors important in avalanche evolution have an "invisible rhythm," that obeys a geometric progression of $\sqrt{2}$. Thus periodicities could be expected in avalanche records of 1.4, 2, 2.8, 4, 5.7, 8, 11, (corresponding to the solar cycle), 16, 22.6 and 32 years, and so on. The Rogers Pass avalanche series support some of these, but many of the $\sqrt{2}$ progressions are not represented so that Kahn's hypothesis is not proved.

Toushinsky (1966) plotted the number of avalanches per winter from 1937 to 1965 in the Khibiny region, U.S.S.R., and the solar activity as characterized by the Wolf sunspot numbers. A good correlation was reported about an 11-year cycle, but his test period was too short to be conclusive. The data from Rogers Pass do not support any relation between sunspot cycle and major avalanche winters (Figure 14). Major avalanche winters have occurred during peaks, troughs, rises and falls of the sunspot cycle in an apparently random manner. In a broader sweep, Toushinsky (1966) discusses evidence of a rhythm of 1800 to 1850 years in snow cover, avalanches and glaciation of the Northern Hemisphere back to early historical times (4000 B.C.).

The only other long-period avalanche record found in the literature was compiled by Armstrong (1978) for Ouray County, Colorado. Data on number of deaths per winter per 1000 population were estimated and spectral analysis applied. The correlogram, like those for the Rogers Pass time series, suggests that avalanches are independent of each other from one winter to the next and that their frequency is random. Peaks in the spectrum were broad, indicating no sharply defined frequency response, but with greatest power at 0.367, 0.167 to 0.20, and 0.033 cycle/year. These correspond to periods of 2.7, 5 to 6, and 30 years, and are somewhat similar to those for Rogers Pass.

To summarize, the literature in its search for rhythms has yet to show conclusively that there exists a consistent periodicity in avalanche activity, although broad classes of short-term, intermediate, and long-term periodicities may be recognized (Table VII). The Rogers Pass time series and data from Armstrong (1978), Loup and Lovie (1967), Frutiger (1977) and Kahn (1966) all suggest major avalanching every 18 to 30 years, but this rhythm cannot be defined more precisely. Only Toushinsky (1966) and Kahn (1966) report a correlation between the 11-year sunspot cycle and avalanche activity.

There appears to be little correlation between North America, Europe and Japan in the winters of major avalanche activity. A few catastrophic winters in the Swiss Alps have also been heavy avalanche winters at Rogers Pass, but the pattern of activity is not consistent. This is interesting because some authors (e.g., Toushinsky, 1966) believe that changes in the atmospheric circulation are responsible for avalanche rhythms, arguing that a pattern of fast zonal flow will produce avalanche activity different from that produced by large Arctic air intrusions and anticyclonic blocking. Similarity in behaviour of heavy avalanche winters might therefore be expected around the Northern Hemisphere.

Experience shows, however, that large avalanches are generated equally well by a number of different weather sequences. Their frequency also depends on the nature of the terrain in a given area. It is therefore unreasonable to expect that the same clearly defined periodicity will appear in avalanche records from different parts of the hemisphere, even if there existed a strong periodicity of atmospheric circulation patterns, in itself a doubtful proposition.

These arguments suggest that:

(a) Projections of avalanche activity into future winters by means of rhythms are unlikely to be successful. Rather, estimates of future avalanche activity must be made by statistical means by assigning probabilities of occurrence to certain sizes of avalanche.

(b) There is need to investigate further the relation between large-scale atmospheric circulation and avalanching in order to define any link between them.

4. AVALANCHE FREQUENCY

4.1 Frequency Prediction from Past History of Avalanching

Avalanche frequency can be expressed in terms of return period (T) in years or as its reciprocal annual probability (P). The return period is the average interval of time within which the magnitude of the event will be equalled or exceeded. The concept of return period is a statistical one and is not related to the timing of avalanche events. The avalanche conditions of each year may be considered to be independent of conditions in all previous years so that, say, the "30-year avalanche" may occur in successive years.

Within a given avalanche pattern T will vary considerably with location (Figures 2, 7); it also varies with the magnitude of event. Thus T can be calculated for (1) avalanches of specified magnitude, (2) for occurrences with runout distances greater than a specified distance, or (3) for avalanches of specified magnitude that have reached beyond a certain distance into the runout zone. The avalanche records of this study are suitable for calculation of return periods of types (2) and (3). The NRC data may be used to calculate return periods of type (1).

The past record is assumed to be representative of future probability, but on the time scale of centuries the frequency of an avalanche of a certain size on a particular path will fluctuate in response to climatic change. Over the last 100 years P and T do not seem to have changed with time for avalanche occurrence, but may have changed for mass. In general, the level of confidence increases greatly with the length of record. Ideally, the period of observation should be at least as long as the return period of interest. In engineering design return periods for 10 and 30 years will probably be useful. For zoning studies return periods of 100 years must be considered. The avalanche records of this study are sufficiently long to provide good estimates for the first two of the return periods.

Remaining questions include: Which frequency distribution is most appropriate for calculation of return periods? What is the relation between return periods calculated from annual series and those from partial duration series? Two subcases may be considered: partial duration series where the base is set as equal to the lowest annual avalanche, so that at least one avalanche in each year is included; and partial duration or non-annual exceedence series where the base is so large that avalanches do not exceed its value in all winters (as with avalanches that affect the railway line).

4.2 Frequency Distributions Appropriate for Avalanche Data

When there is an acceptable avalanche record available, a reliable estimate of the design extreme event can normally be obtained by frequency analysis, which derives the magnitude of the design event by fitting a frequency distribution to a series of recorded extreme events, such as a series of annual maximum avalanches. Several theoretical distributions have been proposed for this purpose, but in analogy to hydrology, no one distribution is likely to be suitable for all avalanche paths.

Of the many distribution functions available, those that tend to be most applicable to avalanches are derived from three basic, or parent, functions: the Gamma distribution, the Normal or Gaussian distribution, and the General Extreme Value (GEV) distribution of which there are three types (type 1 (EV1), also known as Gumbel, type 2 (EV2), also known as Fréchet or log-Gumbel, and type 3 (EV3), also known as Weibull. The three are also known as Fisher-Tippett distributions.

Mathematical descriptions of these basic distributions are given in Appendix D. Each distribution is characterized by as many as three parameters - location, scale and shape.

Special cases of the three basic distributions were applied to the avalanche data at Rogers Pass, using a number of different fitting techniques. In all, seven methods were tested:

4.2.1 Log-Pearson type 3 distribution

It is a three-parameter gamma distribution applied to the logarithms of the annual series and fitted by the method of moments. The method was recommended by the United States Water Resources Council (1967) to be uniformly adopted as the standard method for flood frequency analysis. It estimates a design event from the following equation after the annual series has been transformed to logarithms.

$$\log Q_T = \bar{Q} + k \cdot s$$

where Q_T = design event with a return period T

$\bar{Q}$ = mean of transformed series

S = standard deviation of transformed series

k = frequency factor, taken from a table (USWRC, 1967) and depending on T and the coefficient of skew of the transformed series.

4.2.2 Log-Pearson type 3 distribution, with adjusted coefficient of skew

This is the same as method 1 except that an adjustment is made to the coefficient of skew in order to correct for the bias due to length of record. The adjustment is made using a formula proposed by Bobee and Robitaille (1975), but is only applicable for record lengths of 20 years or greater.

4.2.3 Log-normal distribution

This is a two-parameter (location and scale) normal distribution applied to the logarithms of the annual series and fitted by the method of moments. The log-normal method has long been advocated for use in hydrological frequency analysis (Hazen, 1914; Chow, 1954). The program uses the more common two-parameter log-normal distribution rather than the three-parameter one (Kite, 1976). The application of the method involves the same operations as method 1, except that the coefficient of skew of the logarithms of the series is set to zero.

4.2.4 General extreme value distribtuion (GEV)

This uses the maximum likelihood method to fit the GEV distribution to an annual series. It is generally recognized as the most efficient for estimating the distribution parameters, and its use is recommended when the design event must be extracted from a small or irregular series (World Meteorological Association, 1969). It involves, however, equations that have no explicit solution. The solution is complex and requires the use of an iterative numerical scheme that is only worth attempting with a computer.

4.2.5 Extreme value 1 distribution (maximum likelihood method)

The EV1 is a two-parameter (location and scale) extreme value distribution. The application of method 4 will rarely result in the EV1 distribution being fitted to the series. To ensure that a fit is obtained with the EV1 distribution, this distribution is fitted (by the maximum likelihood method) separately to the series by setting the shape parameter k in the GEV distribution to zero.

4.2.6 Gumbel method

This is an EV1 distribution fitted by least squares (Gumbel 1954, 1966). It is probably the one most commonly used in engineering design of extreme events.

4.2.7 Jenkinson method

This is an EV1 distribution, fitted by following the procedure devised by Jenkinson (1955, 1969) and described by Samuelsson (1972). The method emphasizes the extreme part of a series of annual maxima or minima and, as shown by Samuelsson, can be applied as the standard one to extreme values that belong to several kinds of frequency distribution. Essentially, the method involves the generation of a larger series of 5-year extremes from the annual series by considering all possible combinations of items of five in the series. The EV1 distribution is then fitted to the series of 5-year extremes by the maximum likelihood method.

If an annual series is used in a frequency analysis instead of a series of 5-year extremes, it is quite possible that the series may be non-homogeneous. For an annual maxima series, for example, the smaller items may belong to one distribution (e.g., EV2) and the larger ones to another (e.g., EV3). Further, it can be shown mathematically (World Meteorological Organization, 1969) that the lower part (37 per cent) of an annual maxima series may not even belong to the extreme value distribution as it is defined. The advantage of the Jenkinson method is that it generally overcomes this problem of non-homogeneity of data. The use of 5-year extremes increases by fivefold the number of independent days so that from the way in which the extreme value theory is formulated (see Jenkinson, 1969; Samuelsson, 1972) the extremes should form a homogeneous set of data that conforms to the extreme value distribution.

Each of the seven methods was used to fit the theoretical frequency distributions to an annual series of avalanche data collected by NRC for 22 paths at Rogers Pass (Table VIII). All paths had records extending over more than 10 years, with an accumulated total of 320 years. The seven methods were also applied to the annual series of ΣF, ΣM, ΣL and ΣI. Often a frequency analysis is performed by fitting a curve to the plotted series by eye, then extrapolating it to obtain the design event. In this study the distributions were fitted analytically to the series, with the calculations done by computer using a program described by Maguiness (1977).

4.3 Plotting Positions

In order to assess fit of a distribution to the annual series it is necessary to define the return period or plotting position of each annual extreme. For the methods involving extreme value distributions the Gringorten (1963) formula was used to estimate plotting positions.

$$T = \frac{N + 0.12}{i - 0.44}$$

where T = return period of an annual extreme

i = rank of annual extreme in the series (1 for the largest, N for the smallest in an annual maxima series)

and N = number of annual extremes

The equation gives a very good approximation of unbiased plotting positions for the EV1 distribution (Natural Environmental Research Council, 1975, p. 65).

For the log-normal and log-Pearson type 3 distributions it was necessary to use another formula to obtain good approximations of the unbiased plotting positions. The Flood Studies Report (Natural Environmental Research Council, 1975) favoured the formula derived by Blom (1958) for the log-normal distribution and a so-called compromise formula for the log-Pearson type 3 distribution. As the two formulae give similar results, it was decided to use only the latter. The compromise formula is

$$T = \frac{N + 0.2}{i - 0.4}$$

4.4 Performance Criteria and Assessment

Most studies that have attempted to discriminate between frequency analysis methods have relied at least to some extent on objective goodness-of-fit indices. Recent examples of such studies in hydrology are those carried out by Benson (1968), Beard (1974), Kite (1976), Natural Environmental Research Council (1975), Kopittke and others (1976), and Bobee and Robitaille (1977). It has been found, however, that owing to the small samples available in hydrology, the classical goodness-of-fit indices such as Chi-square and Kolmogorov-Smirnov tests are not sufficiently sensitive or powerful enough to distinguish between the worth of different frequency analysis methods. The Flood Studies Report (Natural Environmental Research Council, 1975) indicated that other goodness-of-fit indices had major weaknesses and concluded that because of the deficiencies of goodness-of-fit indices a visual inspection must be made of the probability plots, of the plots of the observed data and the fitted frequency curves. The judgement on the performance of a method is, then a subjective one, ". . . but the objective tests that are available are so ineffective that their objectivity alone is insufficient to recommend them. . . ." (Natural Environmental Research Council, 1975).

As sample size also tends to be low for avalanche data, the same conclusions were assumed to apply. In this study, therefore, more emphasis was placed on the nature of the probability plots of the data than on Chi-square values indicating goodness-of-fit. Both were provided by computer. The probability plots were examined for each avalanche path or series and the performance of each frequency analysis method was classified as good, reasonable, or poor according to the following criteria:

(a) The frequency curve should fit the whole of the series well, but particularly the upper half.

(b) The frequency curve need not necessarily pass through the very largest items in the series, since there is a far larger sampling variation with these items.

(c) The frequency curve should appear to produce a good estimate of the 30-year avalanche

(d) The Chi-square value should not be abnormally high.

The performances of the methods were then quantified by arbitrarily allotting a value of 2 for each good fit, 1 for each reasonable fit, and 0 for each poor fit.

4.5 Results of Frequency Analyses

The results of the frequency analysis for the annual series of ΣF, ΣM, ΣL, and ΣI are given in Table IX. The series for ΣF was best-fitted with the log-Pearson method; the Jenkinson method appeared to be most appropriate for the other three annual series, although the type 3 GEV distribution (which has an upper bound) could also be used for ΣI and hence for snowfall.

Of more concern are the estimates of 10-, 30-, 50- and 100-year return period events. A winter with 14 avalanches from the 26 paths on the railway line has a probability of occurring once in 30 years; one with 19 avalanches on the railway line will occur with a probability of once in 100 years. For ΣF the winter of 1971-72 was greater than the estimated 100-year event for avalanche frequency; but it had return periods many times less for ΣL, ΣM, and ΣI. The winter of 1934-35 was close to the estimated 100-year event for length of railway line covered by avalanche debris (2510 m). On the other hand, the estimated mass of avalanches (ΣM) with a return period of 100 years was 869×10^6 kg, which is greater than that recorded for the winter of 1919-20.

Table X summarizes the performances of the different methods of frequency analysis, as applied to the annual maximum avalanches on paths listed in Table VIII. The score gives a quantified index of performance, with high scores being best. The adjusted log-Pearson method is not included in the table since in only one case was the record length long enough (20 years or greater) for an adjustment to be made to the coefficient of skew.

The Jenkinson method performed best, scoring 38 of a possible 44. It produced good fits on data for 16, or about three quarters of the avalanche paths, and gave no poor fits. The more familiar Gumbel method performed about as well, and it is probably easier and just as efficient to use this method in avalanche zoning studies for estimating smaller return periods. As will be discussed, Gumbel methods tend to fit data well for return periods of 30 years or less, but underestimate the size of avalanches at higher return periods.

The mass of the 30-year avalanche M_{30} was estimated as a proportion of the limit avalanche M_o for each path (Table VIII). As a general rule avalanche paths with medium size starting zones (50 000 to 250 000 m^2) produced 30-year avalanches that were 10 to 15 per cent of their limit avalanches; 30-year avalanches for paths with large starting zones (> 250 000 m^2) tend to range between 5 and 10 per cent M_o. Avalanche paths where the terrain in the starting zones is rough or those with multiple starting zones tend to have lower ratios M_{30}/M_o. These rules of thumb are slightly higher but generally similar to those found by Schaerer (1975) and could be useful for zoning studies where historical records are unavailable. Values of M_{30}/M_o were higher than those found by Schaerer because of inclusion of a larger than normal avalanche winter (1971-72) and because the Gringorten rather than the Weibull plotting positions were used. As noted in Table V, the 59 winters for which the mass of avalanches to affect the railway line is available produced maximum avalanches that were generally less than 25 per cent of the limit avalanche.

4.6 Hypothetical Shape of a Magnitude-Return Period Curve for Avalanches

As shown in Table X, the GEV distribution fitted by the maximum likelihood method produced a good score. Type 2 distribution was usually the preferred form; this is somewhat surprising since it has no upper bound and is rarely found in nature. The inclusion in the data sample of maximum annual avalanches from the winter of 1971-72, which was larger than normal, could have produced this upswing in the magnitude-return period curve.

Alternatively, the upswing could be a real effect in that abnormally large slabs do occasionally fracture in the starting zone, leading to rapidly increasing avalanche mass over a short range of return periods. It is also reasonable to expect that avalanches will have an upper bound, and will eventually display a flattened curve at high return periods as suggested by Figure 15 if a longer sample time is available. The result would be an S-shaped frequency response curve, as in a sigmoid growth curve.

For the majority of winters conditions are such that many small slabs produce small-to-moderate avalanches. The annual maximum single avalanche for one winter is but marginally larger than that for most other winters. Avalanches from these years dominate the lower return period of the magnitude-frequency relation. Occasionally, weather develops deep instabilities in the snowpack, and snow may release catastrophically during a large storm, or with rapid warming; in such cases snow slabs tend to be larger. As well, two or more starting zones may run simultaneously.

Each, fracture width of a snow slab, depth of slab through snow accumulation on a weak layer, and amount of snow in the avalanche path has an upper bound. The ultimate size of the largest slab will be constrained by the maximum likely precipitation in a "probable maximum storm," by feasible sequences of weather events, by the tendency for excess snow load to release because snow strength is not unlimited, and by the size and nature of terrain in the starting zone. Avalanches with very high return periods may therefore not differ significantly in magnitude.

The long record of avalanches that have reached the railway line at Rogers Pass forms a partial duration series that can be plotted on Gumbel graph paper using the Gringorten plotting positions to verify the hypothetical magnitude return period relationship (Figure 15). Plots were made for eight paths* that had more than six reliable estimates of avalanche magnitude over the period 1918 to 1977. All tended to show a relatively flat distribution at low return periods, with a steep increase in magnitude at intermediate return periods (see examples for Ross Peak and Connaught in Figure 16). There was a tendency for a flattening of the distribution at higher return periods, indicating a possible upper bound, at Observatory,

---

* Connaught, Observatory, Abbott 3, Ross Peak, Twins, Laurie, Jack MacDonald, Baird

Ross Peak, and Baird. The others showed a steady increase in magnitude with return period, presumably because terrain and weather conditions have not allowed an upper bound to be approached over the past 60 years.

Large differences in the nature of the S-shaped curves are probable among avalanche paths, depending on climate and on size and roughness of the starting zones. Instabilities in the snowpack may be more prevalent in climatic regions such as the Rocky Mountains or large precipitation events more common in others, for example in the Coast Range. In this way starting zones that are otherwise similar may produce different magnitude-return period curves. Much larger snowfalls are necessary to "over-ride" terrain and produce large slab fractures in paths with rough starting zones than in those with smooth starting zones. For these the steep part of the S-shaped curve may not be attained, except for return periods of hundreds of years or more. There is need to develop measurable terrain parameters that can characterize such differences in starting zone behaviour.

4.7 Relation of Partial and Annual Duration Series for Avalanches

It is possible to construct a partial duration series for an avalanche path by listing all avalanches greater than or equal to the smallest annual maximum event. In this way at least one avalanche in each year would be included, together with the sizeable, say, second or third ranked avalanches of major winters that would not normally be included in an annual series. Langbein (1949), working in hydrology, found that the recurrence intervals in partial duration series were smaller than those in annual series, but that the difference became inconsequential for floods with greater than about five-year recurrence intervals. It is assumed a similar relation holds for avalanches.

The mass of the avalanches that reach the railway line also constitutes a partial duration series for each path, although it is one whose base value is so large that events need not occur every year. These series were plotted on Gumbel paper using the Gringorten plotting position and compared with the annual maximum series for 12 paths. It was assumed as a first approximation that the avalanches affecting the railway line were the largest events of the 59 winters from 1918 to 1977 and they were ranked accordingly. Typical examples of the comparison between the partial and annual duration series is shown for Laurie (Figure 17) and for Twins (Figure 18).

The results show that some of the avalanches to affect the railway line are, in fact, smaller than some of the annual maximum avalanches that do not run that far. This is because powder avalanches often have high velocity and travel further than wet-snow, slow-moving avalanches of greater mass. It becomes clear that the annual and partial duration series can be plotted by markedly different straight lines. If both series are combined, they support a relation similar to that proposed in Figure 15. The annual series of the last 15 years belongs to the lower return period parts of the hypothetical magnitude frequency relation. The partial duration series for the past

59 years includes events from this lower part as well as some very much larger events from the intermediate return period part of the relation. Estimates of avalanches with greater than a 30-year return period from annual maximum series developed previously by NRC for Rogers Pass will obviously be too small and probably seriously in error.

4.8 Maximum Run-out Distance

A further problem is the run-out distance for very large avalanches. The maximum run-out distance, (D_{max}), determined from air photographs is bounded by 200+ year old trees and may therefore be considered the run-out distance for an avalanche with the same return period. D_{max} was plotted against the mass of the limit avalanche for the 26 paths under study. There is considerable scatter of data, but there exists an upper envelope that may be useful for zoning purposes (Figure 19). The values are generally below this line because:

(a) the starting zone is rough, and not all the snow would be released at once (e.g., Railroad Gunners),

(b) the run-out zone is confined by the opposite steep mountain wall (e.g., Twins),

(c) the avalanche has not run very large in the past 200 years, so that no expression is visible in the forest of what the actual 200-year event would be.

The equation of the upper boundary is

$$D_{max} = -1872 + 180 \ln M_o$$

where M_o is expressed in 1000 kg and D in metres.

$$\text{If } D_{max} = 0, \text{ then } M_o = 32.9 \times 10^6 \text{ kg.}$$

This value for M_o corresponds to a starting zone area of about 20 000 m^2, which can be interpreted as the minimum area to produce an avalanche large enough to run into the valley floor. The avalanche paths at Rogers Pass have this minimum starting zone area for a few that could be described as cliff types.

5. CLIMATOLOGY OF AVALANCHES

5.1 Avalanches and Weather

The principal causes of avalanches are: weak layers in the snowpack; excessive precipitation; wind drifting of snow; high temperatures. Large avalanches are usually a combination of more than one factor. They are often produced by a major storm, but they relate also to the antecedent winter weather, which has established weak layers within the snowpack.

Rogers Pass and the Selkirk Mountains are located intermediate between the climatic regime of the Coast Range, where heavy, frequent falls of snow occur at mild temperatures, and the climatic regime of the Rocky Mountains, where snowfall is light and winters are cold. Depending on weather type and pattern of atmospheric circulation, Rogers Pass may come under the influence of maritime Pacific or continental Arctic air masses. The location and intensities of three major pressure systems determine the character of the weather and propensity for avalanching: the Aleutian Low, the Pacific High and its extension along the North American West Coast, and the Arctic High. These determine the direction, character, and strength of airflow over British Columbia and the positions of the Arctic and Polar frontal systems.

Five methods are used to define the climatology of avalanches. All seek to identify the specific synoptic conditions that have triggered major avalanches as well as establish the nature of the atmospheric pattern that precedes them.

1. Examination of daily precipitation and maximum and minimum temperatures at Rogers Pass for major avalanche winters.

2. Case studies of the four biggest avalanche winters and of other periods of intense avalanche activity. Daily surface synoptic maps and upper air 500 mb charts were analysed.

3. Classification of daily synoptic maps for the period November, December, January, and February for nine major and nine minor avalanche winters: these were compared with each other and with a standard period to detect differences. First, 25 winter weather map types were established by computer correlations of daily January surface pressure patterns over British Columbia and the East Pacific Ocean for the years 1962 to 1972. Correlations of 0.80 or better were required for grouping. Then daily maps from 18 other winters were compared visually with these weather types and classified. The frequency of weather types for the winters 1963-64 to 1971-72 were regarded as a standard that represented average conditions. The total number of daily charts examined was 3252, of which 12.6 per cent could not be classified as types 1 to 25.

Similarly, upper air charts at the 500 mb level were classified for winters 1963-64 to 1971-72. Again, 25 types (types A-Y) were objectively determined, but this time a correlation coefficient of 0.90 or better was required for grouping. As upper air charts were not available until after the Second World War, some early major avalanche years could not be examined. Instead, frequencies of map types A to Y for major avalanche winters 1967-68 and 1971-72 were compared with average frequencies for the standard period 1962 to 1972, and with the minor avalanche winter 1963-64. All classifications were done by computer.

4. Hovmöller (1949) diagrams, which show the longitude and intensity of troughs and ridges at the 500 mb level in middle latitudes as a function of time of winter, were constructed for 1975-76 and 1976-77. These

attempt to illustrate differences in hemispheric atmospheric circulation between medium and small avalanche winters. Similar analyses for other winters were not attempted because data are not readily available in suitable form.

5. The regular discussions of monthly weather and circulation that appear in "Monthly Weather Review" were examined for major avalanche winters.

5.2 Case Studies of Weather and Circulation Patterns of Major Avalanche Winters

5.2.1 Winter 1919-20

The most significant feature of the early winter was a pronounced outbreak of Arctic air to the west of the Rockies rather than to the east as is normal. The result was a prolonged dry spell from mid-November to mid-December, with temperatures dropping to -30°C (Figure 20). This was followed by rapid warming as moist Pacific air intruded into Rogers Pass, but the associated snowfall was insufficient to trigger large avalanches. A second dry, cool spell of Arctic air was less intense, and was again followed by rapid warming, but this time it was associated with sustained storminess. Major avalanching on 17-18 January was triggered by a 24-h snowfall of 61 mm (water equivalent).

The surface synoptic charts for 15 January (Appendix E) show a strong northwest flow over Rogers Pass. A fast-moving occluded frontal system imbedded in this flow gave 5 mm of precipitation that became heavier on 17 January as a low in the Gulf of Alaska moved south across British Columbia. A slow moving trough developed across the Rogers Pass area from Prince Rupert to the Arctic front near Cranbrook, associated with two frontal systems and warm air advection from the southwest. Maximum temperatures rose to 8°C at Rogers Pass, the highest on record for January. CPR records report rain at the time of the large avalanches. By 19 January precipitation had ceased and the snowpack became more stable as drier, colder air invaded the area behind a Pacific cold front.

The atmospheric circulation pattern for the winter of 1919-20 produced persistent ridges of high pressure over the eastern Pacific. The resultant northerly flow over British Columbia favoured sustained outbreaks of Arctic air. Cyclonic depressions in the Gulf of Alaska were deflected towards the northeast by this ridge, giving lower than normal snowfall until January (Frankenfield 1920, Henry 1920). The major avalanche event occurred when this blocking pattern of meridional flow collapsed and moist, warm Pacific air overran the Arctic air, as storms traveled inland along more normal paths.

5.2.2 Winter 1932-33

The early winter was mild and snowy, but a prolonged outbreak of Arctic air produced dry, cold clear weather in early December (Figure 21). A return to the dominance of Pacific airstreams raised temperatures to just below freezing and gave a near continuous series of moderate to heavy snowfalls for the rest of December and the first half of January. Major avalanching between 5 and 10 January resulted from an intense snowfall with 160 mm precipitation in six days, and temperatures rising to just above freezing. Avalanches may have run on instabilities created by the December dry, cold period, and would have become large by picking up the ample snow provided by the sustained January precipitation.

Just prior to major avalanching pressures were high to the south and over the Pacific west of San Francisco (Appendix E). The Aleutian low was well developed, so that a persistent southwest air stream covered the province. Four vigorous frontal disturbances, each with well-defined warm sectors were steered by this flow to bring sustained heavy precipitation.

Large-scale atmospheric circulation patterns were highly variable along the Pacific Coast in December, producing the alternate influences of the Arctic High and Aleutian Low (Hurd 1932). By January the Aleutian Low had shifted further east than normal, with the Pacific anticyclone sloping between Hawaii and California. The main January storm track lay between the two pressure systems (Hurd 1933).

5.2.3 Winter 1934-35

This winter produced some of the most intense weather on record. A mild, relatively dry, November was followed by alternating periods of cold and mild weather (Figure 22). Four avalanches cut the railway line in early January after precipitation of 122 mm in six days. A subsequent, sustained outbreak of Arctic air sent temperatures down to -34°C, and kept snowfall low. Then, within a period of four days temperatures warmed to 3°C, heavy snow fell (66.0 mm precipitation in one day), and finally it rained. Storms produced strong winds. Between 22 and 26 January, in the most devastating period of avalanche activity seen at Rogers Pass, eleven avalanches crossed the railway line from the 26 sample paths. Many were very large (see Table V and Appendix B). The CPR records note "communications out in all directions - slides running in virgin timber - Mountain Subdivision abandoned!" The destruction closed the railway line for five days. Record precipitation, widespread flooding, avalanches and mud-flows were reported for the same time from Washington State (Fisher 1935).

Synoptic charts show that on the 20 January, prior to the major avalanche event, a high pressure centre of Arctic air lay just to the east of Rogers Pass. A vigorous Pacific depression in the Gulf of Alaska together with an associated warm front were approaching the coast (Appendix E). As the front crossed British Columbia, an east-west trough developed and the frontal system became nearly stationary near Rogers Pass. The associated convergence produced heavy precipitation. The warm temperatures resulted from a strong southwesterly flow between a ridge of high pressure in the south and a deep disturbance in mid Pacific. The situation was further aggravated by the passage of an extensive, occluded frontal system caught up in this flow.

Examination of larger circulation features revealed that the Aleutian Low was more intense and larger than normal in November. Pressures were much lower along the Pacific Coast, although at the same time the Pacific High was about normal. This distribution of pressure features favoured a mild, but relatively dry, southwest flow in early winter, with the Pacific High occasionally ridging to the north (Hurd 1934). By January a strong meridional flow pattern had developed. The Aleutian Low dominated much of the north Pacific Ocean, with pronounced southerly flow off the West Coast. Concurrent with this blocking pattern, the Arctic High was intense and sustained (Hurd 1935). Anticyclones, representing surges of cold air, slipped southward into British Columbia from the Yukon rather than to the east of the Rockies as is usual. This trough and ridge pattern quickly shifted eastwards in mid-January, so that British Columbia came under the influence of the southerly flow while still chilled by Arctic air.

5.2.4 Winter 1971-72

Although previous major avalanche winters were characterized by one intense period of avalanche activity, the winter of 1971-72 had several periods of less extreme activity (Figure 23). The first avalanche to reach the railway line was at Ross Peak on 23 December after 72.1 mm precipitation in five days. Later heavy precipitation yielding 64 and 58 mm on successive days and strong winds produced six avalanches between 20 and 24 January.

By the end of January Arctic air had invaded the region, with temperatures falling to -32°C. The subsequent warming was slow so that avalanche activity was not intense, but it spread out into mid-February and early March as the persistent snowfall continued. Another period of avalanching occurred in the spring, when maximum temperatures were sustained above 0°C for 15 days. On 16 March 22.6 mm of rain fell.

The synoptic situation for the first major avalanching, 20 to 26 January, produced a very strong pressure gradient between an intense Arctic High over the Yukon and a small deepening low off Vancouver Island. Subsequently, a trough that extended up to 500 mb level developed along the Arctic front, which lay over southern British Columbia. Further lows developed off the west coast to reinforce the continued convergence of moist air and strong zonal flow aloft.

The atmospheric circulation during the winter 1971-72 was considerably more zonal than for the other major avalanche winters. In November a weak ridge extended north from Oregon, with a more intense than normal, blocking high in the Arctic (Taubensee 1972a). A striking amplification of the east Pacific ridge was a major development in December (Dickson 1972). This spread to a complex of troughs over and near the west coast so that a predominant west to northwest flow was established. Cool to cold moist air was advected over British Columbia, since the province lay within the main strorm track.

The atmospheric circulation pattern in January was extremely vigorous. Over the Pacific the subtropical high pressure belt was stronger than normal and displaced north of its usual position. The mean 700 mb flow was near zonal over Rogers Pass, but much faster than normal. By this time the trough that lay over the west coast in December had progressed to the Mid-West (Wagner 1972). Rapid cyclogenesis occurred as Arctic air was advected from the north over the relatively warm waters of the Gulf of Alaska. Late in January this area of storminess sank southward, phased with cyclones spawned from a central Pacific trough. With many fast moving synoptic systems passing over Rogers Pass, temperatures showed unusual variability and rapid changes (Figure 23). The persistent, large anomalies typical of other big avalanche winters were absent.

During February, a ridge and trough blocking pattern was established at high latitudes over the Pacific (Taubensee 1972b). The trough lay in the Gulf of Alaska, so that warmer but still moist air crossed the province from the southwest. This pattern was established slowly, over almost a two-week period, and warming from the intense cold at the end of January was gradual; otherwise catastrophic avalanche conditions similar to those of 1920 or 1935 might have resulted.

5.2.5 Other Periods of Intense Avalanche Activity

The winter of 1951-52 produced moderate snowfall and mild temperatures for November and December, except for one intense but short Arctic air outbreak when the temperature plunged to -32°C. The major avalanche event, 7 to 9 February, was produced by an average daily precipitation of 21 mm and mild weather sustained over a two-week period. A near stationary frontal system lay southwest-northeast across Rogers Pass. Meanwhile, a very active Pacific storm over the Aleutian Islands spawned a rapid, eastward-moving surge of moisture with well developed warm and cold frontal systems. On 9 February the temperature rose to 3°C. Although the mean 700 mb flow was from the northwest in December, it became strongly zonal in January. Subsequently, a major trough developed over the west coast so that by February the weather became wetter and milder.

The major avalanche activity of the winter 1967-68 occurred between 18 and 23 January, associated with above-freezing temperatures, sustained snowfalls, and eventually rain. On one day alone 41 mm of rain fell, the highest recorded for any January at Rogers Pass. The first avalanches ran from precipitation associated with a series of occluded fronts crossing the province in strong, moist, mild southwesterly air streams.

In November 1967 the circulation consisted of one broad trough over most of the Pacific and a ridge along the coast. By December two troughs had formed, with the eastern one northwest of Hawaii and a near-zonal flow over British Columbia. This eastern trough intensified in January as a strong blocking ridge developed in the Aleutian-Bering Sea area. The blocking extended from the Bering Sea to Greenland at high latitudes, so displacing the westerlies to lower latitudes. Cold outbreaks of Arctic air were steered southwards over the province in the first part of January, so that the temperature at Rogers Pass dropped to -26°C. Later in the month a very strong zonal flow was established, with rapid cyclogenesis over the Gulf of Alaska, further developing into a large, deep trough that dominated the eastern Pacific. The resultant southwest flow steered frontal systems developing near Hawaii towards Rogers Pass, and precipitated the major avalanche event.

5.3 Comparison of Major and Minor Avalanche Winters using Surface Weather Types

The frequency of the surface synoptic weather types is shown for 18 major and minor avalanche winters in Table XI. Eight winters when no avalanches reached the railway line and the winter 1976-77 are classed as minor avalanche winters. The nine biggest avalanche winters from the time series of ΣF were subdivided into those with a generally zonal atmospheric circulation and those where meridional flow dominated. They may be thought of as "Coast Range" and "Rocky Mountain" winters, respectively.

The most distinctive weather types are those with pronounced differences in frequency when compared with the standard period between 1963 and 1972 (Tables XII, XIII, XIV). Major avalanche winters with zonal flow have a relatively higher frequency of days with types 5 and 10, when a well developed low in the Gulf of Alaska advects moist, unstable air over Rogers Pass (Figure 24). These winters also have a relatively low frequency of days of Type 8 (Figure 25), typical of Arctic air outbreaks over southern British Columbia (Table XIV)

Conversely, a type 8 situation is more frequent during major avalanche winters with meridional flow. Sequentially, it is often replaced by type 23 (Figure 25), when an active Pacific low pushes over the coast to displace the Arctic air and trigger an avalanche event. The normally-frequent types 2 and 3 seldom occur in major avalanche winters with meridional circulation (Figure 26). Many major avalanche winters have a relatively high frequency, of a trough extending from the Gulf of Alaska to Montana across the Rogers Pass area. If stationary, this pressure pattern produces sustained snowfalls conducive to avalanching.

Minor avalanche winters have frequencies of weather types similar to the standard period but with more type 9 days, when a strong ridge extends from the Pacific anticyclone over British Columbia (Figure 27). This synoptic type tends to give settled weather at Rogers Pass, allowing the snowpack to stabilize.

Both major and minor avalanche winters share higher than usual frequencies of some weather types, which represent a wide range of synoptic conditions. Thus differences among avalanche winters can be subtle and may depend as much on sequence of weather types as on frequency. There is need to develop climatological techniques to analyse such synoptic sequences.

5.4 Comparison of Major and Minor Avalanche Winters using 500 mb Weather Types

Experience has shown that the 500 mb flow between 5460 and 5700 m is a good indication of the steering flow, or storm track, for winter storms.

This upper air flow discriminates well among the three avalanche winters chosen for analysis (Table XIII). The winter of 1971-72 (a major avalanche winter with zonal circulation) had a higher frequency of weather type B when compared with the "standard period" (Figure 28). Weather type I in which storms are steered over the province from the west or southwest, were also common.

On the other hand, the winter of 1967-68 (a major avalanche winter with meridional circulation) featured types U and V, in which flow is slack at 500 mb over Rogers Pass. On type V days a closed low at 500 mb is associated with the main storm track located in the eastern Pacific, so that disturbances move from the northwest, but well offshore. Type U days show a blocking high aloft, with storms deflected to the north. Frequently these patterns were replaced by storms tracking directly over the province from the northwest (type C).

5.5 Hemispheric Scale Circulation Patterns and Avalanche Activity

Hovmöller diagrams illustrate the pattern of 500 mb troughs and ridges and their movement over time. During the minor avalanche winter of 1976-77 a strong but narrow blocking ridge along the west coast of North America showed remarkable persistence from November to mid-February. Storm tracks were pushed well to the west and north, so that mid-winter precipitation was much below normal. At the same time troughs over the Pacific and over eastern North America were near stationary, with a weaker circulation over Europe to give a two-wave pattern around the hemisphere. The pattern broke down after mid-February to a more normal zonal migratory one, with ridges and troughs moving steadily eastward.

During the moderately active avalanche winter of 1975-76, similar blocking patterns of a ridge along the west coast and a trough in the Pacific appeared on occasion, but it seldom persisted for more than two weeks. Instead, the ridges and troughs migrated eastward in a hemispheric three-wave pattern. As a consequence, the flow over British Columbia was strongly zonal, with regular passage of storms and normal, or above normal, precipitation over British Columbia. While instructive, it is difficult to extend Hovmöller analyses to other winters because vast amounts of data and computer time are required.

5.6 Summary of the Climatology of Major Avalanche Winters

Major avalanche winters at Rogers Pass appear to fall into two main categories:

5.6.1 Winters with strong zonal flow

Characteristic features include frequent storms, rapidly fluctuating but not extreme temperatures, and sustained snowfall. Major avalanches occur with warming above freezing or exceptional snowfall, but tend to be distributed throughout the winter. The winters of 1953-54, 1971-72 and 1975-76 belong to this category. The hemisphere atmospheric circulation patterns at 700 mb show only weak development of ridges or troughs over the eastern Pacific, with a tendency for northwest flow in early winter.

5.6.2 Winters with strong meridional flow

Characteristic features are a sustained thermal regime that rapidly breaks down or shifts to another that is markedly different. Temperatures are extreme. Prolonged intense outbreaks of Arctic air to the west of the Rocky Mountains are followed by a major storm with rapid warming to above 0°C, heavy snowfall, and sometimes rain. These winters give rise to catastrophic events in which many paths produce large avalanches within a few days. The winters of 1919-20 and 1934-35, and to some extent 1967-68, were of this category. The atmospheric circulation shows strong blocking patterns, with large anomalies in pressure, precipitation and temperature. Typically, a strong ridge over the eastern Pacific Ocean produces a cold, dry, northerly flow over Rogers Pass that is conducive to sustained flow of Arctic air. Following this, the upper air wave pattern abruptly changes so that the ridge moves east to cover the Prairies and is replaced by an active trough, with rapid intrusions of warm, moist Pacific air from the south to southwest over-riding the Arctic air and triggering large avalanche events.

Other winters, such as those of 1932-33 and 1951-52 appear to be intermediate between categories 1 and 2.

Extreme avalanche winters produce weather sequences that maximize the principal causes of avalanches. Early winter outbreaks of Arctic air are abnormally cold and sustained, encouraging weaknesses to develop within shallow snow cover and at the surface. The trigger storms are associated with record, or near record, snowfalls usually when frontal systems are near stationary or when lows intensify over Rogers Pass. Winds are often strong, so that there is much drifting snow. Finally, temperatures rise rapidly to above freezing, an unusual event in January at Rogers Pass, and it often rains. The combination of these extreme weather sequences is apparently required for catastrophic avalanches similar to those of the winters of 1919-20 and 1934-35, so that such winters occur rarely.

6. CONCLUSIONS

1) The winter of 1971-72 had more avalanches that reached the railway line than any in the last 70 years, possibly the last 90 years.

2) Other winters have experienced more intense avalanche activity, involving catastrophic release of much larger quantities of snow, the most spectacular being the winters of 1919-20 and 1934-35. This type of winter has not occurred within the past four decades and is thus beyond the personal experience of those at Rogers Pass.

3) Major avalanche winters are characterized by much larger and more frequent avalanches than those of average winters. Their impact tends to come as a surprise.

4) Rhythms in avalanche activity are weak and cannot at present provide a reliable method of prediction. The strongest periodicity is for about 18 years.

5) The Gumbel method of extreme value analysis is appropriate for estimating design avalanches with short return periods. The 30-year avalanche is 10 to 20 per cent of the limit avalanche for medium size paths and 5 to 10 per cent for large size paths.

6) Data from Rogers Pass for the period since the construction of the Trans-Canada Highway lead to serious underestimation of design avalanches for return periods greater than 30 years. For this reason the records of avalanche mass taken by NRC and SRAWS should be continued. They should also be extended to include Ross Peak and Connaught since there now exists a valuable historical record for these active paths.

7) A sigmoid growth curve appears to describe the magnitude of avalanches on Gumbel paper as return period increases. The data of avalanches reaching the railway line show that their magnitude increases rapidly for return periods higher than 30 years. Very large avalanches with high return periods may ultimately have an upper bound.

8) Major winters, when many catastrophic avalanches are released within a few days, feature a combination of weather conditions, each extreme. These conditions are intense, sustained cold with temperatures below -25°C, heavy precipitation in amount or intensity, strong winds, and rapid warming to above 0°C.

9) There are clear links between avalanche activity and atmospheric circulation over the eastern Pacific and western North America. Over the last 70 years major avalanche winters have fallen into two categories:

(a) winters with strong zonal flow, heavy snowfall and rapidly fluctuating temperatures when activity of major avalanches is spread. As a rule, major avalanches are produced by an unusually active front or a stationary low that give sustained snowfall and strong winds. Alternatively, avalanches may be released by warming from a sustained southerly flow, or by passage of a frontal system with a well developed warm sector. These winters may be categorized as "Coast Range" winters.

(b) winters with periods of sustained meridional flow and blocking when snowfalls are often average or below average. Several weeks of northerly or easterly flow emplaces Arctic air to the west of the Rocky Mountains. Subsequent rapid warming and heavy precipitation occur as the meridional pattern abruptly switches to a strong southerly flow, with a near stationary low frequently developing over southern British Columbia. These winters may be thought of as "Rocky Mountain" winters.

10) Minor avalanche winters have a larger frequency than usual on days with high pressure at the surface and a Pacific ridge aloft.

6.1 Suggestions for Future Research

The main areas where future research may be profitable are:

1) Further examination of historical records and documents of avalanche activity in the period 1880 to 1909 (study of early newspapers from Revelstoke would have highest priority).

2) Better understanding of the relation between roughness of the starting zone and avalanche frequency and magnitude. "Roughness" needs to be better defined so that it may be measured in the field or from aerial photographs and maps.

3) Investigation of the mesocale variations of the lower atmosphere at Rogers Pass. Good meteorological data are already available from Fidelity Mountain and other high-elevation stations. Now, models of the lower atmosphere need to be developed to help explain what happens when frontal disturbances cross Rogers Pass and Arctic air is replaced by Pacific air. Similarly, meteorological differences and their associated atmospheric processes on the east and west sides of the Pass need to be better defined.

4) Major avalanches on individual paths. The present study has concentrated on analysing the climatology of major avalanche winters as represented by combined activity on 26 sample paths. Analyses for two types of paths would possibly be rewarding: those where data are available (e.g., Ross Peak, Connaught, Laurie, Baird), and those whose behaviour appears to be irregular (e.g., Helen, Cougar Creek West).

5) Further analysis of the daily temperature and precipitation record at Rogers Pass. The models of Salway (1976) could be extended. The record could also be used to construct new models.

6) Developing new techniques to discriminate between sequences of synoptic maps for major and minor avalanche winters.

7) Further development of indices of atmospheric circulation over the eastern Pacific Ocean and western North America. These require analysis of vast amounts of daily data and would constitute a major computor study.

8) A study of how artillery control of avalanches alters their frequency and magnitude.

9) Examination of the climatology of avalanches in other regions of western Canada, where suitable data permit. Differences can be expected for the Coast Range and for the Rocky Mountains.

ACKNOWLEDGEMENTS

The author wishes to thank the National Research Council of Canada for financial and logistic support during this research; P. Schaerer, A. Salway, H. Norem, R. Perla, M. Church, V. Schleiss and W. Schleiss for their assistance and critical comments; the staff of the Atmospheric Environment Service, Vancouver; G. Freer, B.C. Department of Highways; and CP Railway for willing co-operation and use of their weather typing system; T. Ulrych, Department of Geophysics, University of British Columbia, who performed the maximum entropy method spectral analysis.

This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is published with the approval of the Director of the Division.

REFERENCES

ARMSTRONG, B.R. 1978: A history of avalanche hazard in San Juan and Ouray Counties, Colorado. In Avalanche Control, Forecasting, and Safety. Proceedings of a workshop held in Banff, Alberta. National Research Council Assoc. Com. on Geotechnical Research, Technical Memorandum No. 120, pp 199-218.

BEARD, L.R. 1974: Flood flow frequency techniques. Center for Research in Water Resources, University of Texas, Austin, Technical Report CRWR-119, October.

BENSON, M.A. 1968: Uniform flood-frequency estimating methods for federal agencies. Water Resources Research, Vol. 4, No. 5, pp 891-908.

BERTON, P. 1972: The great railway illustrated. McClelland and Stewart Ltd., Toronto.

BLOM, G. 1958: Statistical estimates and transformed Beta variables. John Wiley, New York.

BOBEE, B.B., ROBITAILLE, R. 1975: Correction of bias in the estimation of the coefficient of skewness. Water Resources Research, Vol. 11, No. 6, December, pp 851-854.

BOBEE, B.B., ROBITAILLE, R. 1977: The use of the Pearson Type 3 and Log Pearson Type 3 distributions revisited. Water Resources Research, Vol. 13, No. 2, April, pp 427-443.

CHISHIMA, S. 1976: Statistics of avalanches in Soyo District, Hokkaido. Seppyo, Vol. 38, No. 2, pp 1-5.

CHOW, V.T. 1954: The log-probability law and its engineering applications. Proc. ASCE Vol. 80, November, Separate No. 536, pp 1-25.

CUNNINGHAM, G.C. 1887a: Journal of observations in camp 3 miles east of Selkirk Summit, Winter 1885-1886 (kept by J.S. Vindir after April 18). Observations at Cascade Camp, Winter 1886-1887 kept by J.E. Griffith.

CUNNINGHAM, G.C. 1887b: Snowslides in the Selkirk Mountains. Canadian Society of Civil Engineers Transactions, Vol. 1, pp 18-24.

DICKSON, R.R. 1972: Weather and circulation of December 1971. Monthly Weather Review, Vol. 100, No. 3, pp 239-244.

FISHER, L.C. 1935: Floods, earth and snow slides, and an ice storm from unprecedented precipitation in the state of Washington, January 1935. Monthly Weather Review, February, p 58.

FRANKENFIELD, H.C. 1920: Weather of the Month. Monthly Weather Review, January, p 45.

FRONTIERS UNLIMITED, 1968: The Incredible Rogers Pass. Frontier Publishing Ltd., Calgary.

FRUTIGER, H. 1977: Avalanche damage and avalanche protection in Switzerland. In Glaciological Data; Avalanches. World Data Center A for Glaciology, Report GD-1, University of Colorado, pp 17-32.

GREEN, W.S. 1890: Among the Selkirk Glaciers. MacMillan and Co., London.

GRINGORTEN, I.I. 1963: A plotting rule for extreme probability paper. Journal of Geophysical Research, Vol. 68, No. 3, pp 813-814.

GUMBEL, E.J. 1954: Statistical theory of extreme values and some practical applications. U.S. Bureau of Standards, Applied Maths Series, 33, February, pp 15-16.

GUMBEL, E.J. 1966: Extreme value analysis of hydrologic data. In Statistical Methods in Hydrology, Proceedings of Hydrology Symposium No. 5, McGill University, Canada, 24-25 February, pp 147-169.

HAZEN, A. 1914: Discussion on Flood Flows by W.E. Fuller, Trans. ASCE Vol. 77, p 628.

HENRY, A.J. 1920: Weather of the month. Monthly Weather Review, February, p 106.

HOVMÖLLER, E. 1949: The trough-and-ridge diagram. Tellus, Vol. 1, No. 2, pp 62-66.

HURD, W.E. 1932: Weather of the month. Monthly Weather Review, December, p 264.

HURD, W.E. 1933: Weather of the month. Monthly Weather Review, January, pp 25-26.

HURD, W.E. 1934: Weather of the month. Monthly Weather Review, December, pp 469-470.

HURD, W.E. 1935: Weather of the month. Monthly Weather Review, January, pp 35-36.

JENKINS, G.M., WATTS, D.G., 1968: Spectral analysis and its applications. Holden-Day, San Francisco.

JENKINSON, A.F. 1955: The frequency distribution of the annual maximum (or minimum) values of meteorological elements. Quarterly Journal of Royal Meteorological Society, Vol. 87, pp 158-171.

JENKINSON, A.F. 1969: Statistics of extremes. In Estimation of Maximum Floods, Chapter 5, WMO Technical Note No. 98, pp 193-227

KAHN, M. 1966. Considérations préliminaries sur la répartition chronologique des avalanches de neige. International Symposium on Scientific Aspects of Snow and Ice Avalanches, Davos. IASH-AIHS Publication No. 69, pp 332-340.

KEEFER, T.C. 1888: The Canadian Pacific Railway. Transactions American Society of Civil Engineers, Vol. 19, No. 394, pp 55-58.

KITE, G.W. 1976: Frequency and risk analyses in hydrology. Inland Waters Directorate, Water Resources Branch, Dept. of Environment, Canada.

KOPITTKE, R.A., STEWART, B.J., TICKLE, K.S. 1976: Frequency analysis of flood data in Queensland. In Hydrology Symposium, Institution of Engineers, Australia, National Conference Publication, No. 76/2. pp 20-24.

LANGBEIN, W.B. 1949: Annual floods and the partial-duration flood series. Transactions American Geophysical Union, Vol. 30, pp 879-881.

LOUP, J., LOVIE, C. 1967: Frequency of avalanches in Upper Tarentaise (in French). Revue de Géographie Alpine, Vol. 55, No. 4, pp 587-604.

MAGUINESS, J.A. 1977: A computer program for flow frequency analysis. Technical Services Section, Water and Soil Division, Ministry of Works and Development, New Zealand.

NATURAL ENVIRONMENTAL RESEARCH COUNCIL (NERC) 1975: Flood Studies Report. In five volumes: Volume 1, Hydrological Studies, London.

PARKS CANADA, 1977: Snow war, a guide to the history of Rogers Pass. Ministry of Supply and Services, Ottawa.

SALWAY, A.A. 1976: Statistical estimation and prediction of avalanche activity from meteorological data for the Rogers Pass area of British Columbia. Unpublished Ph.D. Thesis, University of British Columbia.

SAMUELSSON, B. 1972: Statistical interpretation of hydrometeorological extreme values. Nordic Hydrology, Vol. 3, No. 4, pp 199-213.

SCHAERER, P.A. 1962: Avalanche defences for the Trans-Canada Highway at Rogers Pass. National Research Council, Canada, Division of Building Research, Technical Paper No. 141. (NRC 7020).

SCHAERER, P.A. 1972: Terrain and vegetation of snow avalanche sites at Rogers Pass. In Mountain Geomorphology, British Columbia Geographical Series No. 14, pp 215-222.

SCHAERER, P.A. 1975: Relation between the mass of avalanches and characteristics of terrain at Rogers Pass. International Association of Hydrological Sciences: Proceedings of the Moscow Snow and Ice Symposium IASH-AIHS Publication No. 104, pp 378-380.

SCHAERER, P.A. 1977: Analysis of snow avalanche terrain. Canadian Geotechnical Journal, Vol. XIV, No. 3, pp 281-287.

TAUBENSEE, R.E. 1972a: Weather and circulation of November, 1971. Monthly Weather Review, Vol. 100, No. 2, pp 171-176.

TAUBENSEE, R.E. 1972b: Weather and circulation of February, 1972. Monthly Weather Review, Vol. 100, No. 5, pp 411-416.

TOUSHINSKY, G.K. 1966: Avalanche classification, and rhythms in snow cover and glaciation of the Northern Hemisphere in historical times. International Symposium on Scientific Aspects of Snow and Ice Avalanches, Davos. IASH-AIHS Publication No. 69, pp 382-393.

ULRYCH, T.J., BISHOP, T.N. 1975: Maximum entropy spectral analysis and autoregressive decomposition. Reviews of geophysics and space physics. Vol. 13, No. 1, pp 183-200.

U.S. WATER RESOURCES COUNCIL (USWRC) 1967: A uniform technique for determining flood flow frequencies. Hydrology Committee, Bulletin No. 15, December, 15 pp.

VAUX, W.S. 1900: The Canadian Pacific Railway from Laggan to Revelstoke, B.C. Engineers Club of Philadelphia, Proceedings, Vol. 17, No. 2, pp 64-86.

WAGNER, A.J. 1972: Weather and circulation of January, 1972. Monthly Weather Review, Vol. 100, No. 4, pp 322-328.

WHEELER, A.O. 1905: The Selkirk Range. Government Printing Bureau, Ottawa.

WORLD METEOROLOGICAL ORGANISATION (WMO) 1969: Estimation of Maximum Floods, Technical Note No. 98.

TABLE I. CHARACTERISTICS OF AVALANCHE PATHS SELECTED FOR STUDY

Path	Type	Artillery Control	Limit Avalanche (10^6 kg)	Mean Slope of Track (deg)	Mean Slope Run-out Zone (deg)	Maximum Run-out Distance (m) D_{max}	Relative Run-out Distance to Railway D'/D_{max}
Connaught	(A)B	yes	1 136	32	15	560	0.16
Unnamed No. 6	(A)C		250	32.5	6	305	0.89
Stone Arch	(A)C	yes	164	36.8	8	215	0.77
Observatory	(B)D	yes	308	34	11	320	0.63
Abbott 3	(A)B	yes	166	34	12	165	0.52
Abbott 4	(A)B	yes	116	32	14	90	0.67
Cheops South 1	C		371	35.1	12	290	0.79
Cougar Creek E	D		447	38.2	8	380	0.47
Cougar Creek W	D		1 299	38.2	8	495	0.91
Cougar Corner 6	B	yes	56	42.6	5	90	0.72
Cougar Corner 3	B		83	41.8	11	150	0.97
Cougar Corner 2	B	yes	281	41.7	15	270	0.80
Ross Peak	D	yes	3 161	32	7	530	0.80
Railroad Gunners	D	yes	1 387	28	4	200	0.70
Smart East	D	yes	288	39.7	7	360	0.89
Smart West	D	yes	272	39.7	5	190	0.40
Fidelity	D	yes	1 407	28	11	535	0.92
CPR Sheds	E		58	34.5	28	75	0.33
Park One	D	yes	1 122	38	-8	205	0.44
Fortitude	D		11 640	22	15	1 050	0.94
Laurie	E		865	33	-8	305	0.07
Lanark	D		5 242	30	9	610	0.90
Twins	D	yes	699	36.3	-16	105	0.71
Jack MacDonald	D		2 898	28	8	535	0.68
Baird	B	yes	319	34	15	170	0.44
Helen	D		1 658	30	3	250	0.92

Notes:
1. Path type: letters in brackets give path type before construction of Connaught Tunnel in 1916. Path types are illustrated in Figure 3.
2. Artillery control is intermittent on some paths.
3. Mean slope of track: a decimal indicates that slope measured from maps scale 1:5,000; otherwise from maps scale 1:50,000.
4. Mean slope of run-out zone; measured from maps scale 1:50,000. Downslope and upslope portions included.
5. Maximum run-out distance (D_{max}) and run-out distance to railway line (D') obtained from air photos, scale = 1:12,000.

TABLE II. SUMMARY OF CUNNINGHAM'S DIARY, WINTER 1885-86

Main Periods of Activity	Number of Avalanches	Weather
4 Jan - 6 Feb	4	T = 7-28°F. Steady snow, with 8.0 in. and 5.5 in. recorded on preceding days.
28 Jan - 1 Feb	24	T = 28°F. Heavy snow 14 in./day after 3 days with 10 in. Wind T = 35°F and rain.
5 Feb - 8 Feb	22	T = 32°F, rain. T rose to 35°F with heavy rain and wind.
12 Feb - 20 Feb	17	T = 34°F. Gale force winds drifted much snow and broke trees. T = 21°F, then 18°F.
Spring	10	Sunslides

Avalanche Path	Number of Avalanches on Railway Line
Lens	14
Tupper 2	13
Tupper 3	8
Tupper 1	8
Pioneer	7
Tupper Minor	6
Double Bench	4
Stone Arch	4
Unnamed No. 6	2
Connaught	2
Other Paths	23
Total	91

TABLE III. SUMMARY OF GRIFFITH DIARY, WINTER 1886-87

Main Periods of Activity	Number of Avalanches	Weather
13 Jan - 14 Jan	13	Heavy snowfall 12 in./day. T = 26°F rising to 30°F. More heavy snow.
27 Feb - 1 Mar	27+	Windy with light snow. T = 22°F, then rapid warming to 34°F and rain. Further snow.

Avalanche Path	Number of Avalanches on Railway Line
Lens	18
Tupper 2	7
Double Bench	7
Opposite Grizzly	4
Tupper Timber	2
Avalanche Crest	2
Stone Arch	1
Unnamed No. 6	3
Connaught	1
Other Paths	17
Total	62

TABLE IV. PERIODS OF INTENSE AVALANCHE ACTIVITY AS REPORTED IN NEWSPAPERS

Date	Location
- Feb 1871	Cariboo
2-3 Apr 1898	Yukon
- Jan 1899	Rogers Pass, Kootenays
- Dec 1899	Rogers Pass, Kootenays, Skagway, Alaska
Winter 1902-03	Kootenays
- Jan 1904	Rogers Pass, Squamish
1-9 Mar 1910	Rogers Pass, Kootenays, Washington
Spring 1929	Stewart
28-30 Dec 1937	Kootenays, Coquihalla Pass, Fraser Canyon
17-23 Feb 1949	Fraser Canyon
- Jan 1950	Fraser Canyon
1-2 Feb 1960	Rogers Pass
29 Jan 1962	Prince Rupert, Terrace
2-11 Jan 1963	Rogers Pass, Rockies

Sources: Cariboo Sentinal, Victoria Colonist, Nelson Daily Miner, Vancouver Province

TABLE V. FREQUENCY AND LARGEST RECORDED AVALANCHE AFFECTING THE RAILWAY LINE 1909 to 1976

Avalanche Path	Number of Occurrences	Return Period	Largest Recorded Avalanche Year	M (10^6 kg)	M/M_o
Connaught	22	3.1	1920	312	0.27
Unnamed No. 6	2	34.0	1934	3.4	0.01
Stone Arch	5	13.6	1935	26	0.16
Observatory	9	7.5	1965	24	0.08
Abbott 3	10	6.8	1949	23	0.14
Abbott 4	5	13.6	1920	19	0.16
Cheops South 1	4	17.0	1933	68	0.18
Cougar Creek E	6	11.3	1952	101	0.23
Cougar Creek W	3	22.7	1935	41	0.03
Cougar Corner 6	6	11.3	1972	7.3	0.13
Cougar Corner 3	1	68.0	1952	0.8	0.01
Cougar Corner 2	5	11.6	1971	12	0.04
Ross Peak	23	3.0	1946	404	0.13
Railroad Gunners	6	11.3	1923	15	0.01
Smart East	4	17.0	1933	39	0.13
Smart West	6	11.3	1933	112	0.42
Fidelity	2	34.0	1966	62	0.04
CPR Sheds	7	9.7	1972	4.9	0.08
Park One	6	11.3	1933	229	0.20
Fortitude	1	68.0	1935	82	0.01
Laurie	23	3.0	1954	153	0.18
Lanark	6	11.3	1951	207	0.04
Twins	10	6.8	1935	60	0.09
Jack MacDonald	9	7.5	1937	306	0.11
Baird	21	3.2	1922	20	0.06
Helen	3	22.7	1933	30	0.02

TABLE VI. SHORT PERIODS OF INTENSE AVALANCHE ACTIVITY 1909 TO 1977

Period	F	M (10^6 kg)	L (m)	Avalanche Path
3-8 Feb 1918				Stone Arch, Baird, Railroad Gunners
15-18 Jan 1920	9	813	1 843	Abbott 3, Baird, Smart East, Observatory, Connaught, Abbott 4, Railroad Gunners, Ross Peak
5-10 Jan 1933	10	552	2 270	Twins, Cheops South 1, Smart East, Park One, Helen, Abbott 3, Ross Peak, Smart West, Twins
2-6 Jan 1935	4	240	678	Connaught, Stone Arch, Lanark, Twins
22-26 Jan 1935	11	435	1 838	Jack MacDonald, Connaught, Smart East, Twins, Laurie, Cheops South 1, Abbott 3, Abbott 4, Ross Peak, Cougar Creek West, Fortitude
24 Mar 1939	3	50	198	CPR Sheds (E), CPR Sheds (W), Laurie
17 Feb 1949	3	146	351	Baird, Jack MacDonald, Abbott 3
7-9 Feb 1952	5	107	503	Cougar Creek East, Cougar Corner 6, Cougar Corner 3, Cougar Corner 2, CPR Sheds
16-24 Feb 1954	3	522	915	Connaught, Jack MacDonald, Ross Peak
11 Jan 1956	3	243	788	Connaught, Ross Peak, Laurie
5-18 Feb 1965	4	48	463	Park One, Abbott 4, Observatory, Abbott 3
18-23 Jan 1968	5	112	372	Ross Peak, Stone Arch, Railroad Gunners, Laurie, CPR Sheds
6-10 Apr 1970	3	116	488	Smart West, Ross Peak, Observatory
23-31 Dec 1971	4	20	338	Ross Peak, Cougar Corner 2, Baird, Laurie
20-24 Jan 1972	6	46	535	Cougar Corner 6, Cougar Corner 2, Observatory, Railroad Gunners, Cheops South 1, Twins
5-17 Mar 1972	4	26	430	Connaught, Abbott 3, CPR Sheds, Park One
13-17 Jan 1974	4	52	333	Smart West, Connaught, Cougar Corner 6, Ross Peak
11-16 Jan 1976	3	18	184	Jack MacDonald, Baird, Cougar Corner 2
11 Feb 1976	3	8	91	Cougar Corner 6, Park One, Baird

TABLE VII. AVALANCHE PERIODICITIES POSTULATED IN THE LITERATURE

LOCATION	SOURCE	PERIODICITY (YEARS) SHORT-TERM	INTERMEDIATE	LONG-TERM	VERY LONG-TERM
Tarentaise	Loup and Lovie (1967)			30	
Swiss Alps	Frutiger (1977)		7	25	
France	Kahn (1966)	2	4, 5.7, 8, 11, 16	23, 32	
U.S.S.R.	Toushinsky (1966)		11		1800-1850
Colorado	Armstrong (1978)	2-3	5-6	30	
Rogers Pass	This study	2	3-7	18	

TABLE VIII. AVALANCHE PATHS USED IN TESTING FREQUENCY DISTRIBUTIONS OF ANNUAL MAXIMUMS

Avalanche Path	Period of Record (years)	Limit Avalanche (10^6 kg)	M_{30}/M_o
Unnamed No. 6	11	250	0.15
Stone Arch	11	164	0.22
Tupper 3*	18	176	0.10
Atlas*	17	59	0.16
Tupper 2*	20	668	0.09
Tupper 1*	18	340	0.10
Pioneer*	18	46	0.12
Tupper Cliffs*	17	19	0.17
Tupper Timber*	18	70	0.16
Tupper Minor*	18	68	0.07
Double Bench*	18	270	0.19
Tractor Shed W*	19	122	0.19
Cheops South 1	11	371	0.05
Cougar Creek E	11	447	0.08
Cougar Creek W	11	1 299	0.02
Cougar Corner 6	11	56	0.13
Cougar Corner 2	11	281	0.05
Smart East	11	288	0.03
Smart West	12	272	0.05
CRP Sheds	11	58	0.10
Laurie	11	865	0.05
Twins	17	699	0.05

M_{30} = Estimate of mass of 30-year avalanche using best-fit frequency distribution

M_o = Limit avalanche

* = Paths not included in long-term records of avalanches reaching railway line

TABLE IX. RESULTS OF FREQUENCY ANALYSIS PER ANNUAL SERIES OF ΣF, ΣM, ΣL, and ΣI

Return Period (years)	ΣF (number)	ΣM (10^6 kg)	ΣL (m)	ΣI (10^3)
10	8	395	1122	33.4
30	14	540	1792	37.7
50	16	728	2097	39.4
100	19	869	2510	41.4
Best-fit frequency distribution method	log Pearson	Jenkinson	Jenkinson	GEV (type 3) or Jenkinson
Maximum recorded 1909-77 Winter	21 (1971-72)	817 (1919-20)	2516 (1934-35)	45.1 (1953-54)
Estimated return period for winter 1971-72	200 years	6 years	52 years	28 years

TABLE X. SUMMARY OF PERFORMANCE OF DIFFERENT METHODS OF FREQUENCY ANALYSIS USING ANNUAL MAXIMUM AVALANCHES ON 22 PATHS

Performance Category	Method					
	1 log-Pearson type 3	3 log-normal	4 GEV	5 EV1	6 Gumbel	7 Jenkinson
Good	13	8	13	2	14	16
Reasonable	7	5	6	0	8	6
Poor	2	9	3	19	0	0
Score	33	21	32	4	36	38

Weights used in scoring:	good	2
	reasonable	1
	poor	0

Maximum possible score: 44

TABLE XI. FREQUENCY OF SURFACE SYNOPTIC WEATHER TYPES FOR MAJOR AND MINOR AVALANCHE WINTERS (PER CENT)

Winter	WEATHER TYPE 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
	Major Avalanche Winters																								
1919-20	25	5	4	4	4	1	5	8	3	1	2	3	4	0	1	8	1	0	2	3	5	1	4	1	5
1932-33	13	3	14	7	13	8	5	0	0	6	7	1	6	3	1	1	2	0	1	2	3	0	0	0	4
1934-35	18	12	5	10	9	5	5	0	2	1	5	0	2	7	1	4	0	0	0	0	4	8	2	0	0
1951-52	12	8	5	6	21	4	4	1	3	2	8	0	1	4	1	4	1	0	0	3	2	3	1	3	3
1953-54	18	9	16	6	9	6	3	2	2	3	4	0	1	4	0	1	2	0	0	0	5	4	0	4	1
1959-60	21	19	8	4	4	3	6	0	3	1	3	1	0	0	3	8	1	0	0	0	1	11	2	1	0
1967-68	32	8	17	4	1	4	3	6	0	2	1	2	1	2	1	0	0	1	0	1	7	4	2	1	0
1971-72	23	30	6	5	3	2	4	4	9	1	0	3	1	1	1	3	0	2	1	0	0	0	1	0	0
1975-76	25	14	13	4	11	1	4	1	9	4	3	0	0	1	2	4	0	0	0	1	1	1	0	0	1
	Minor Avalanche Winters																								
1911-12	30	11	15	3	8	4	4	0	2	0	3	0	0	2	5	4	0	1	1	0	2	4	0	1	0
1914-15	17	10	7	10	12	4	3	0	5	0	6	1	1	0	2	3	3	1	0	2	1	10	1	1	0
1927-28	20	16	8	4	3	5	2	3	10	1	4	3	0	1	3	5	0	0	1	0	3	7	0	0	1
1930-31	34	8	19	2	8	1	2	0	8	1	0	1	0	1	1	1	0	0	0	0	1	12	0	0	0
1931-32	7	3	21	7	9	5	3	0	8	3	9	0	0	1	5	8	2	0	0	2	3	1	1	0	2
1935-36	17	18	7	6	7	2	4	1	3	3	9	0	2	3	2	4	0	1	1	0	2	8	1	0	0
1956-57	21	9	6	5	9	3	3	0	7	2	9	0	3	1	2	9	0	0	1	0	4	1	2	2	1
1963-64	43	16	1	10	0	4	2	2	1	4	2	0	2	0	2	0	1	4	4	1	0	0	0	1	0
1976-77	30	17	11	1	2	1	8	1	9	1	1	0	2	0	1	2	0	0	0	0	0	6	0	7	0

Note: Days that could not be classified as types 1 to 25 were excluded from percentages.

TABLE XII. AVERAGE FREQUENCY OF SURFACE SYNOPTIC WEATHER (PER CENT)

Nature of Winter	Number of Winters	WEATHER TYPE 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
"Standard" 1963-1972	9	32	13	12	10	5	4	3	2	3	1	1	1	1	1	1	<1	1	1	1	1	<1	1	1	1	<1
Minor, Zonal	9	24	12	11	5	6	3	3	1	6	2	5	<1	1	1	2	4	<1	<1	<1	<1	1	4	<1	1	<1
Major, Zonal	6	19	14	11	5	10	4	4	<1	4	3	4	1	1	3	1	3	1	<1	<1	1	2	3	1	1	1
Major, Meridional	3	25	8	9	6	5	3	4	5	2	1	3	2	2	3	1	4	<1	<1	<1	1	3	4	3	<1	2

TABLE XIII. FREQUENCY OF 500 mb WEATHER TYPES FOR SELECTED AVALANCHE WINTERS (PER CENT)

Nature of Winter	Number of Winters	WEATHER TYPE A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
"Standard" 1963-1972	9	32	18	6	5	3	5	4	4	2	2	2	2	1	1	<1	2	1	1	2	1	2	<1	<1	<1	<1
1963-1964, Minor	1	43	16	1	10	0	4	2	2	1	4	2	0	2	0	3	0	1	4	4	1	0	0	0	1	0
1967-1968, Major	1	32	8	17	4	1	4	3	5	0	2	1	2	1	2	1	0	0	1	0	1	7	4	2	1	0
1971-1972, Major	1	23	30	5	5	3	2	4	4	9	1	0	3	1	1	1	3	0	2	1	0	0	0	1	0	0

TABLE XIV. DISCRIMINATING SYNOPTIC MAP TYPES FOR MAJOR AND MINOR AVALANCHE WINTERS

Nature of Winter	Synoptic Types with Higher than "Standard" Frequency	Synoptic Types with Lower than "Standard" Frequency
Minor	9, A, D, J	C
Major, Zonal	5, 10, 14, B, I	8, A
Major, Meridional	8, 14, 21, 23, C, U, V	2, 3, A
Differences from "standard", common to major and minor winters	11, 16, 33	1, 4

Note: "Standard" frequency is for the period 1963-1972.

Numbers refer to surface map patterns, letters to 500 mb map patterns.

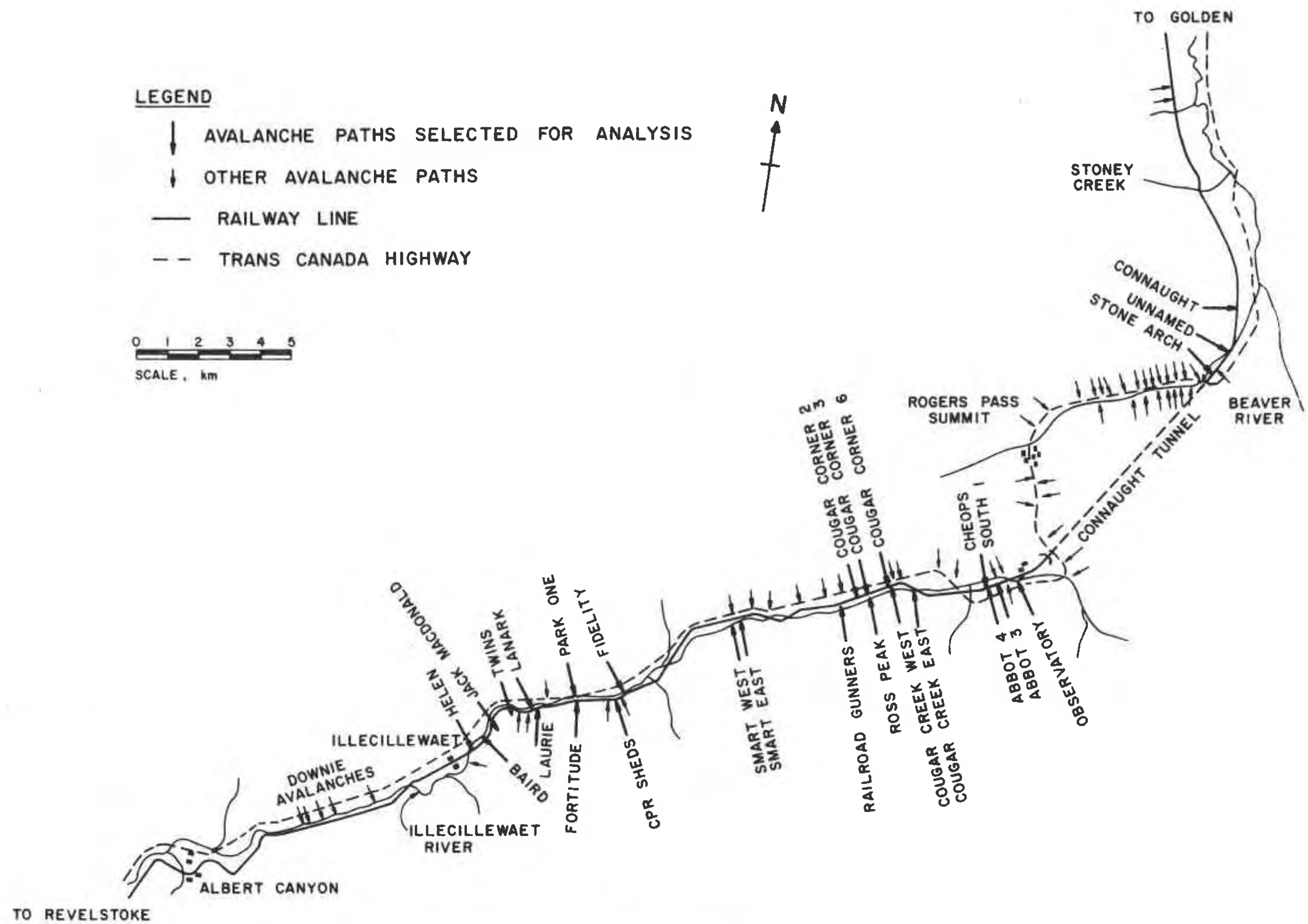


FIGURE 1
LOCATION OF AVALANCHE PATHS

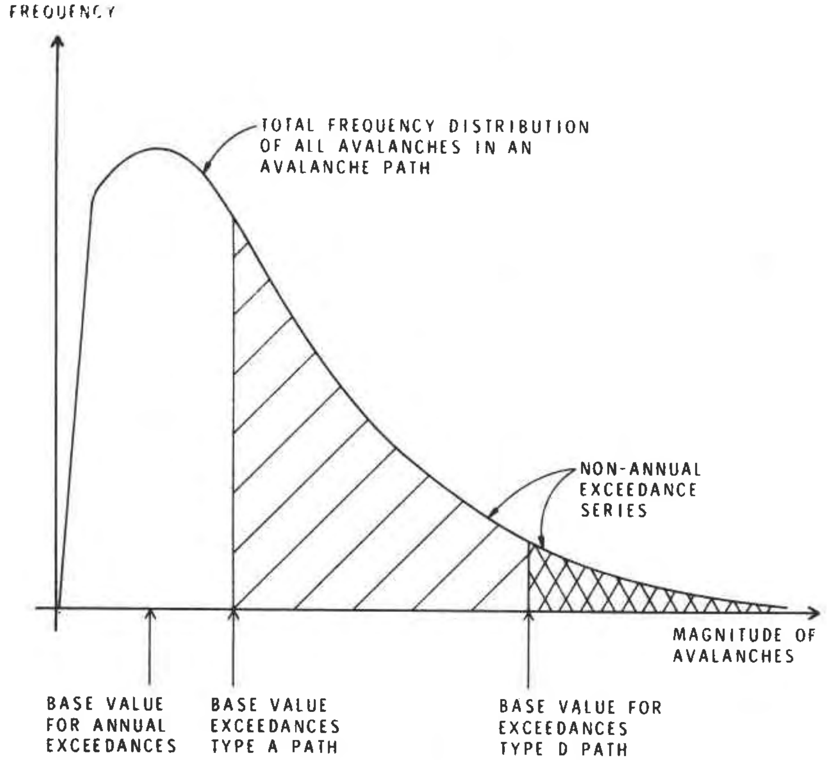


FIGURE 2

RELATION OF NON-ANNUAL EXCEEDANCE SERIES TO TOTAL FREQUENCY DISTRIBUTION

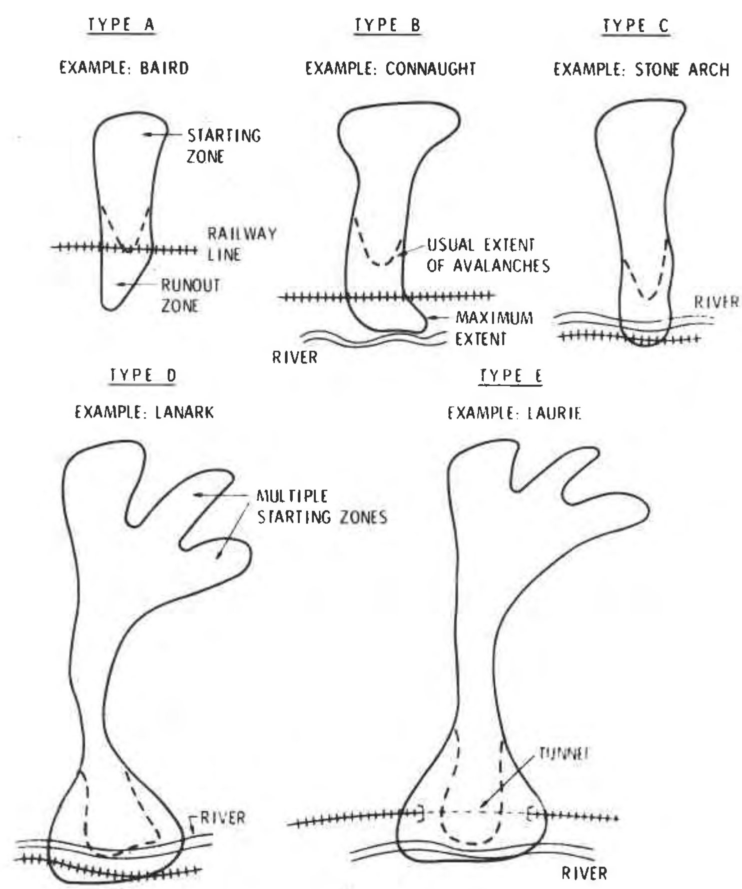


FIGURE 3

TYPES OF AVALANCHE PATH CONTAINED IN THE DATA SERIES

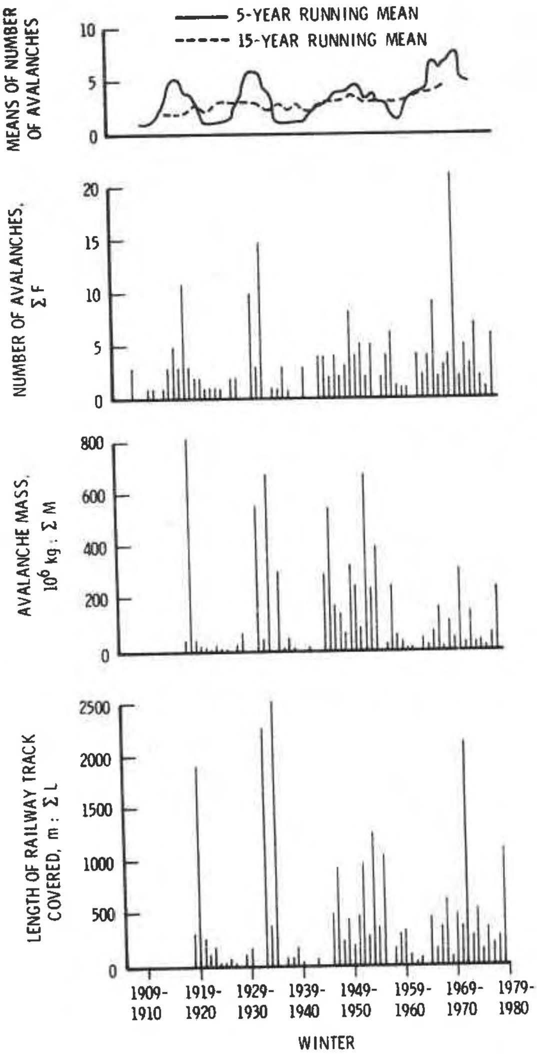


FIGURE 4

NUMBER OF AVALANCHES; TOTAL MASS OF AVALANCHES; AND LENGTH OF TRACK COVERED PER WINTER

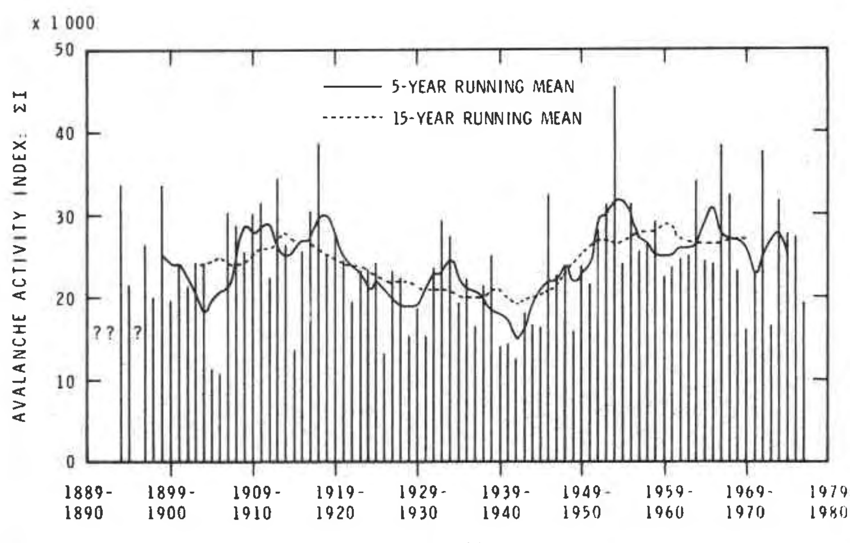
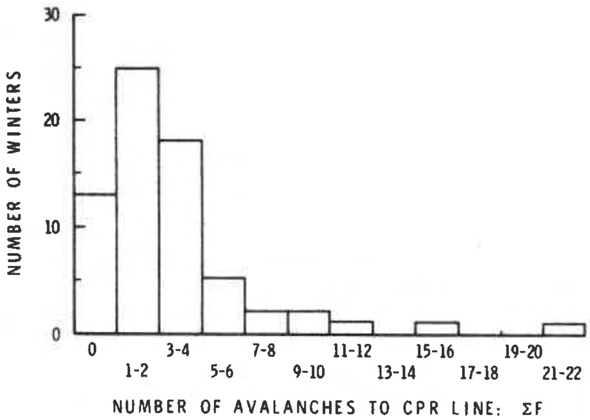
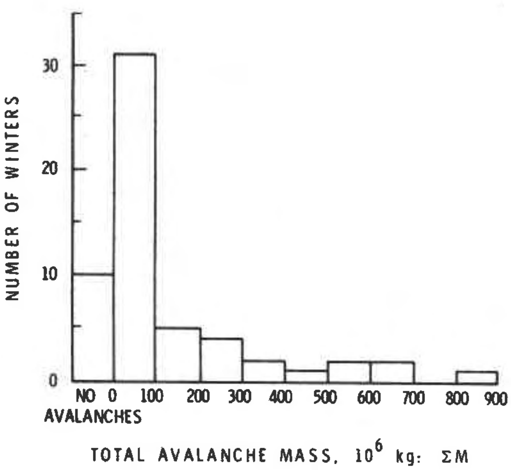


FIGURE 5

AVALANCHE ACTIVITY INDEX (Σ I), WINTERS 1893-94 TO 1976-77





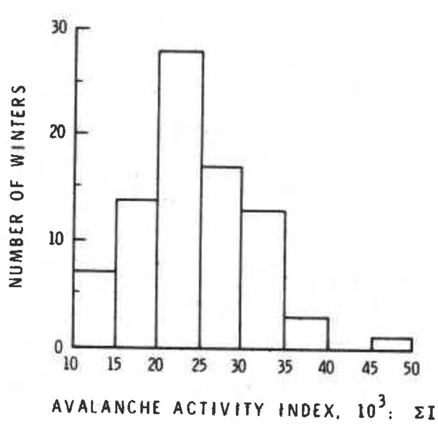


FIGURE 6

FREQUENCY DISTRIBUTIONS FOR ΣF, ΣM, ΣI

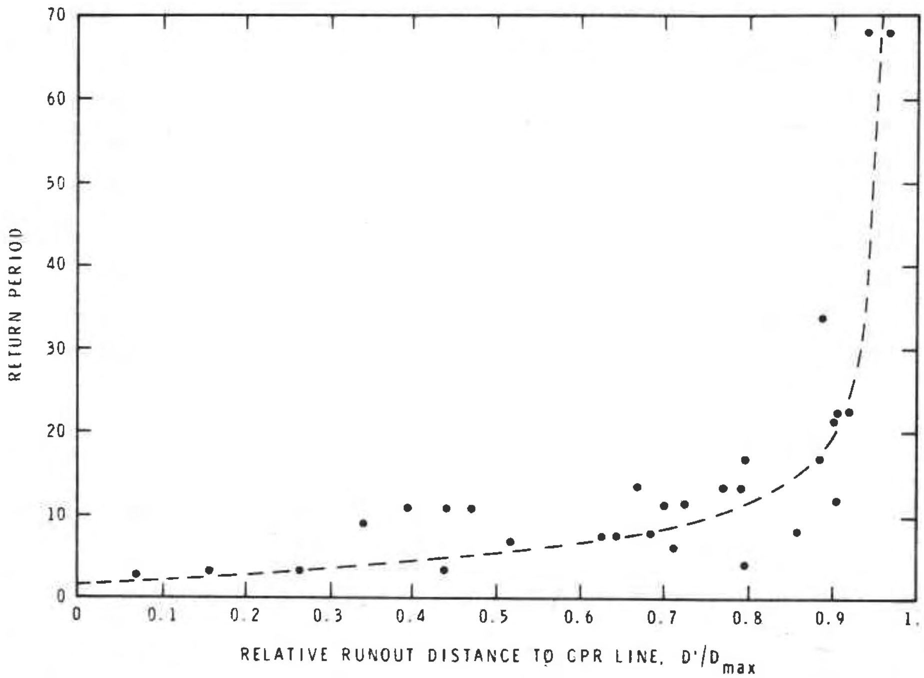
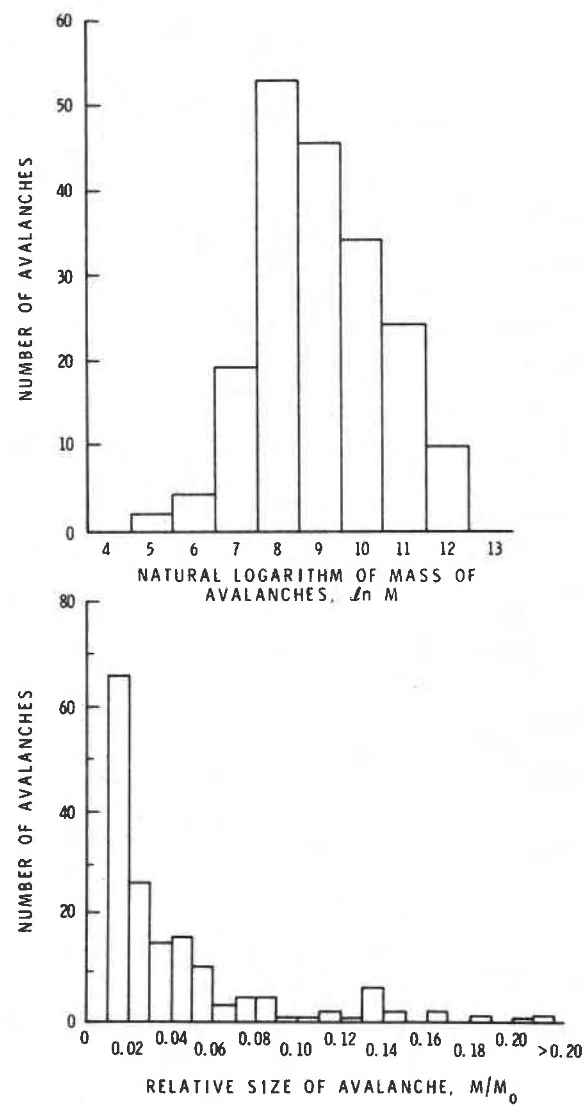


FIGURE 7

POSITION OF RAILWAY LINE AND EXPECTED AVALANCHE RETURN PERIOD



n = 192: TOTAL NUMBER OF AVALANCHES

M_0: MASS OF LIMIT AVALANCHE

FIGURE 8

FREQUENCY DISTRIBUTIONS FOR MASS OF AVALANCHES TO REACH THE LINE (M) AND RELATIVE SIZE OF AVALANCHE. WINTERS 1918 TO 1977

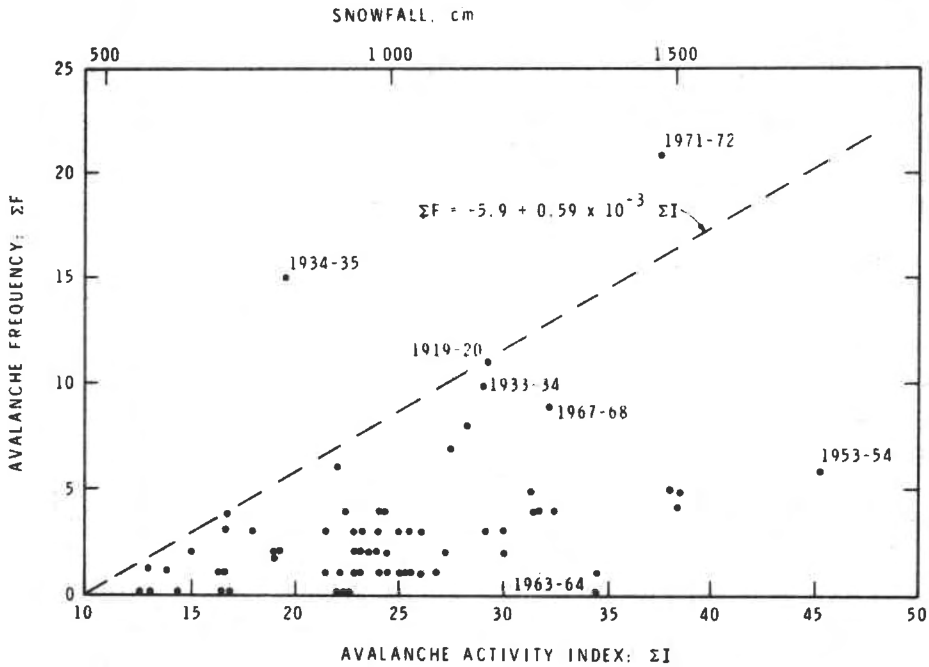


FIGURE 9

RELATION OF AVALANCHE FREQUENCY ON RAILWAY LINE AND AVALANCHE ACTIVITY INDEX FOR WINTERS 1909-10 TO 1976-77. SNOWFALL AT GLACIER (AES) ALSO SHOWN

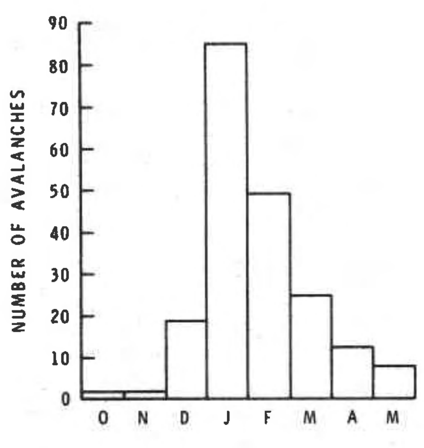


FIGURE 10

FREQUENCY DISTRIBUTION OF MONTH OF AVALANCHE 1909 TO 1977

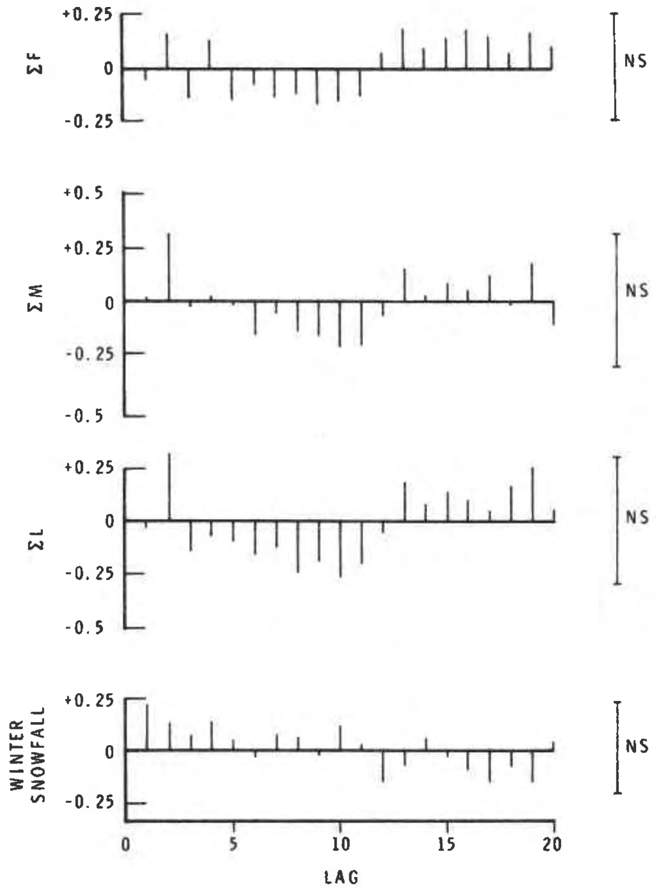


FIGURE 11

SPECTRAL ANALYSIS: CORRELOGRAM FOR NUMBER OF AVALANCHES (ΣF), TOTAL MASS (ΣM), LENGTH OF TRACK COVERED (ΣL), AND WINTER SNOWFALL.

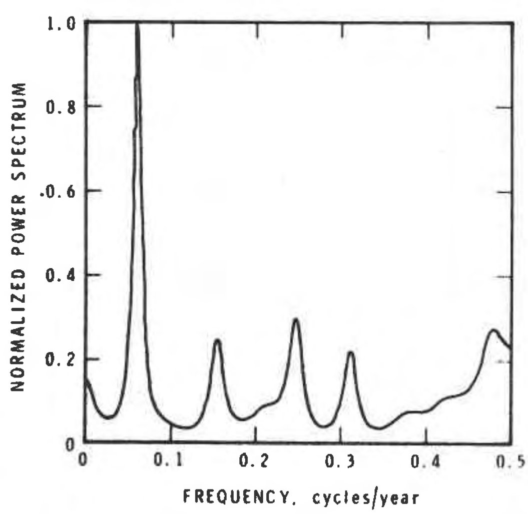


FIGURE 12

SPECTRAL ANALYSIS: BEST ESTIMATES OF MAXIMUM ENTROPY METHOD POWER SPECTRA FOR ΣF

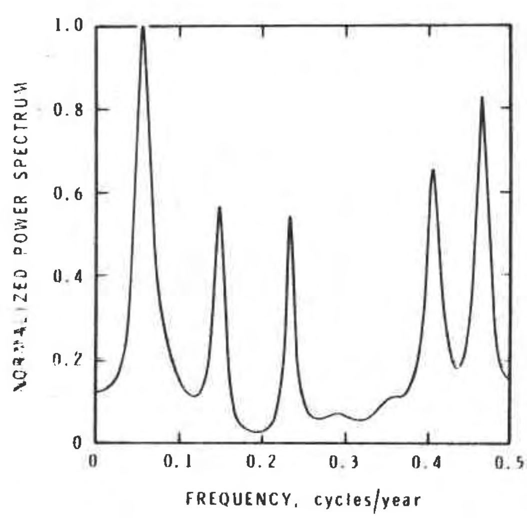


FIGURE 13

SPECTRAL ANALYSIS: BEST ESTIMATES OF MAXIMUM ENTROPY METHOD POWER SPECTRA FOR ΣM

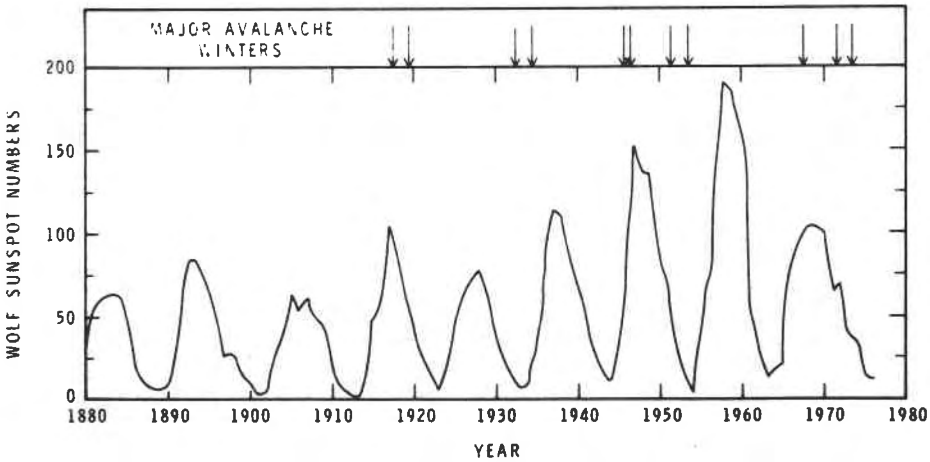


FIGURE 14

RELATION OF SUN SPOT NUMBERS AND MAJOR AVALANCHE WINTERS AT ROGERS PASS, 1909-1977

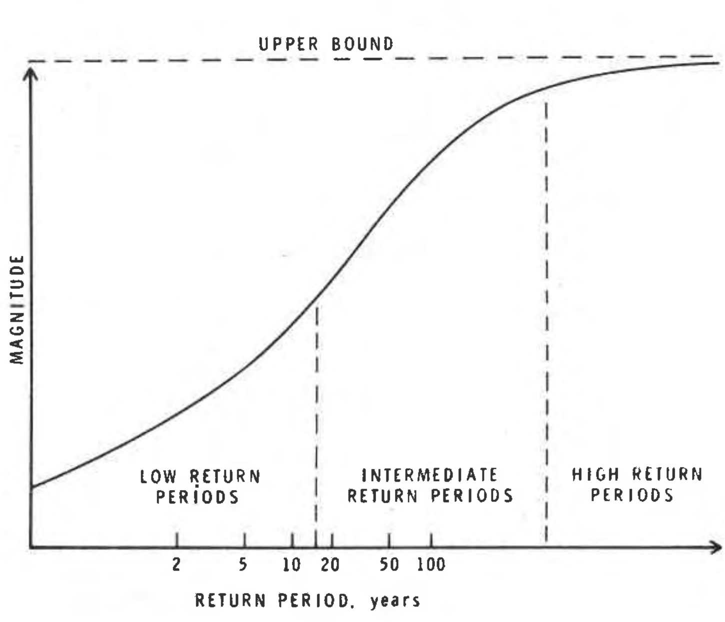


FIGURE 15

HYPOTHETICAL SHAPE OF A MAGNITUDE-RETURN PERIOD CURVE FOR AVALANCHES

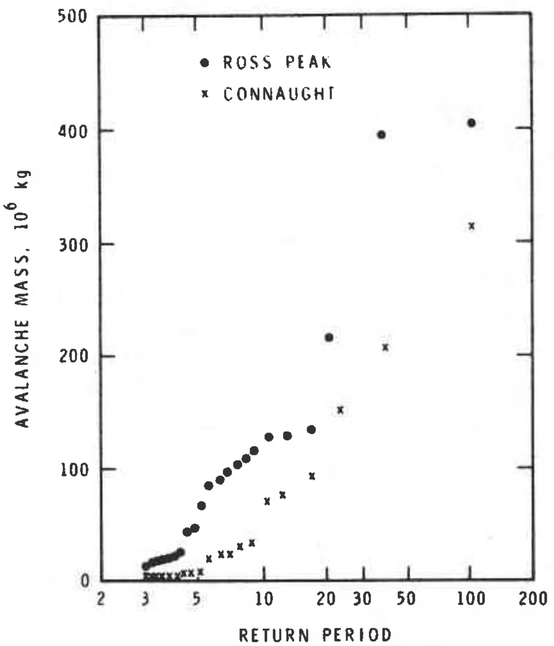


FIGURE 16

PARTIAL DURATION SERIES FOR AVALANCHES ON RAILWAY LINE AT ROSS PEAK AND CONNAUGHT PATHS

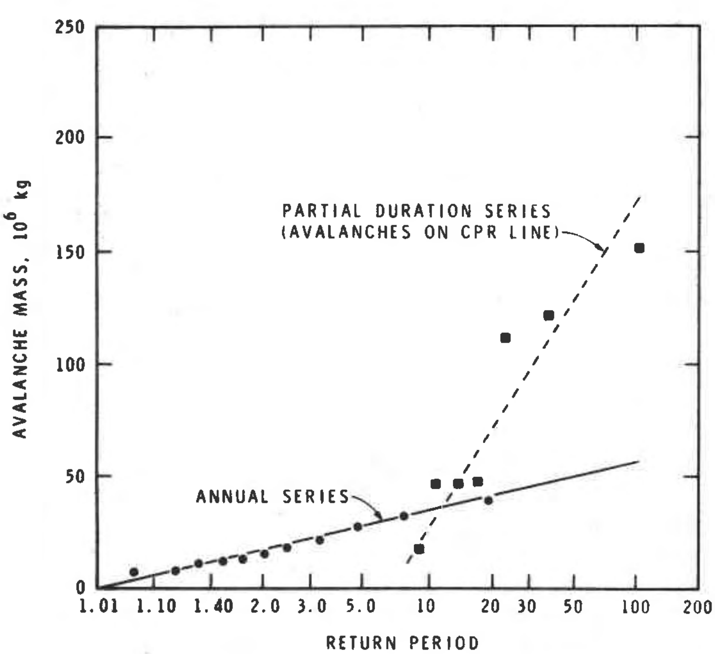


FIGURE 17

ANNUAL AND PARTIAL DURATION SERIES FOR LAURIE AVALANCHE PATH

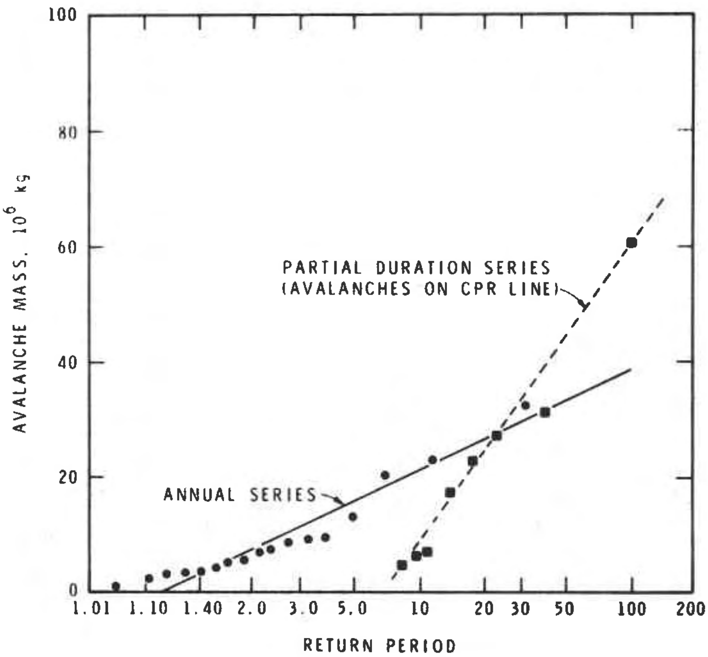


FIGURE 18

ANNUAL AND PARTIAL DURATION SERIES FOR TWINS AVALANCHE PATH

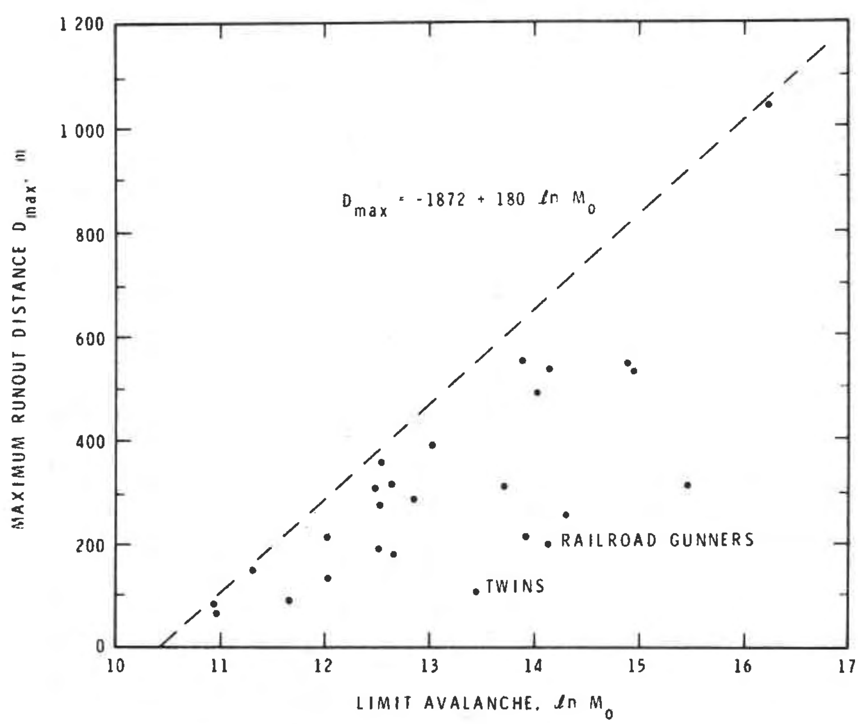


FIGURE 19

MAXIMUM RUNOUT DISTANCE AND SIZE OF LIMIT AVALANCHE

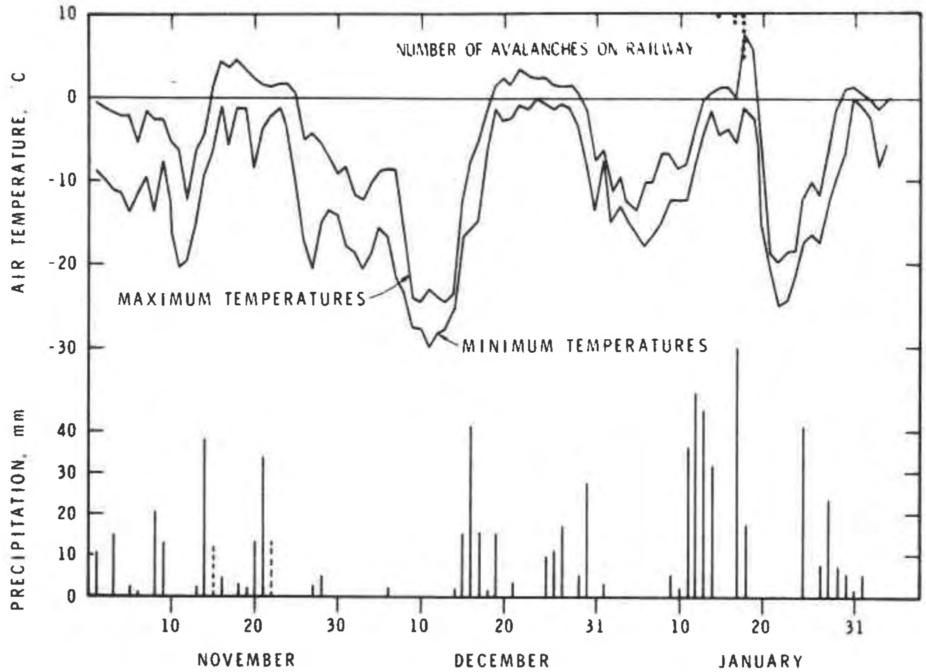


FIGURE 20

DAILY TEMPERATURES AND PRECIPITATION AT ROGERS PASS, WINTER 1919-20

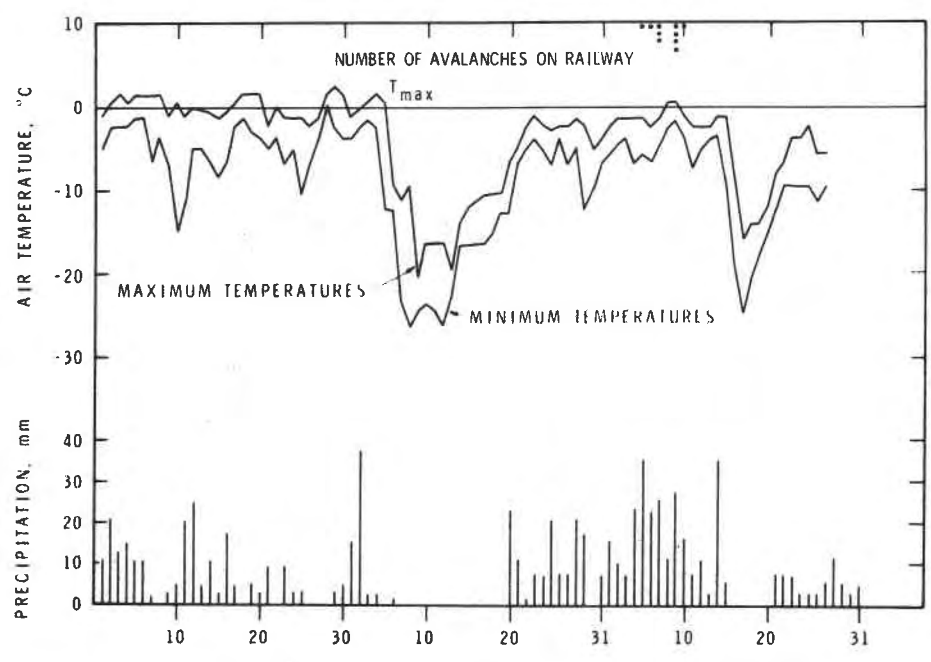


FIGURE 21

DAILY TEMPERATURES AND PRECIPITATION AT ROGERS PASS, WINTER 1932-33

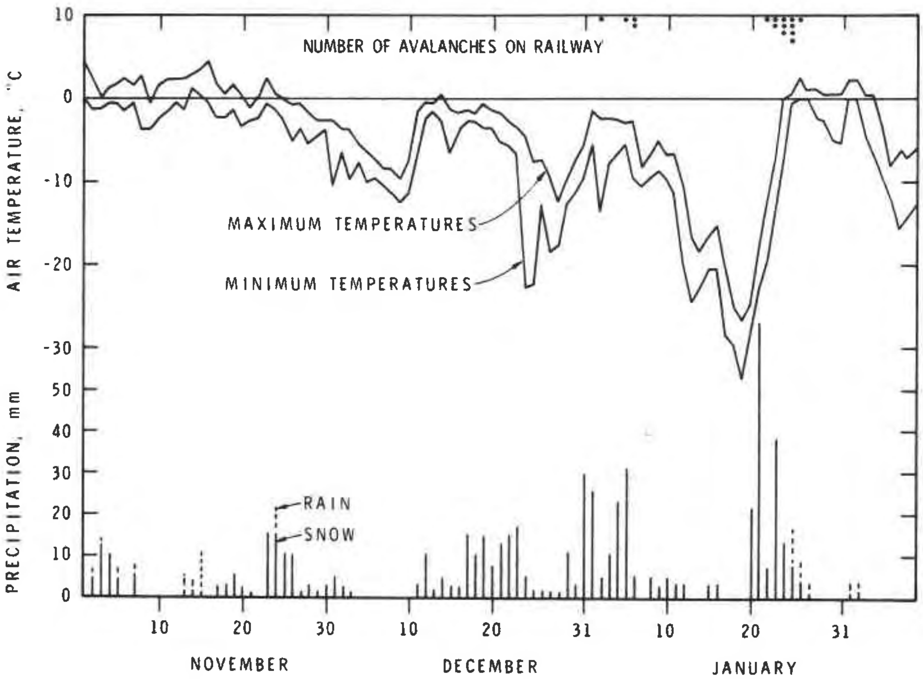


FIGURE 22

DAILY TEMPERATURES AND PRECIPITATION AT ROGERS PASS, WINTER 1934-35

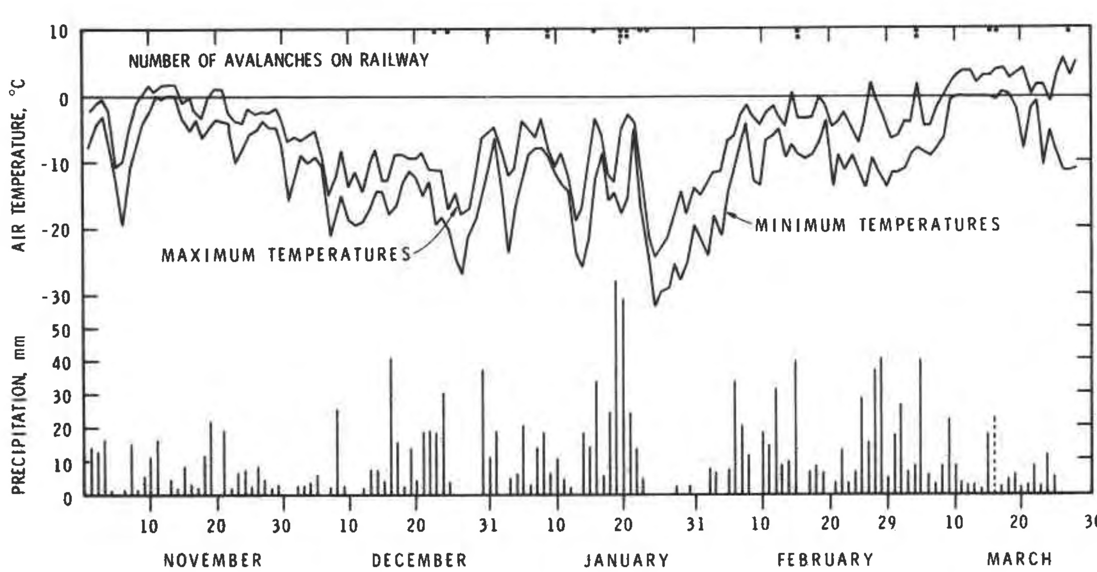
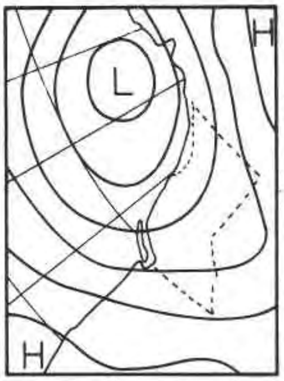


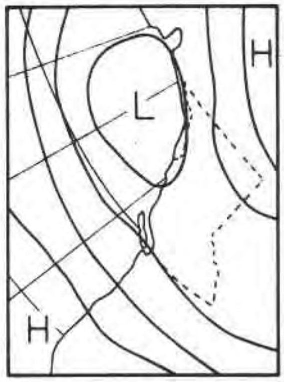
FIGURE 23

DAILY TEMPERATURES AND PRECIPITATION AT ROGERS PASS, WINTER 1971-72

TYPE 5



TYPE 10



TYPE 14

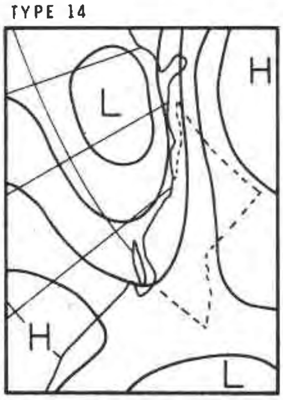
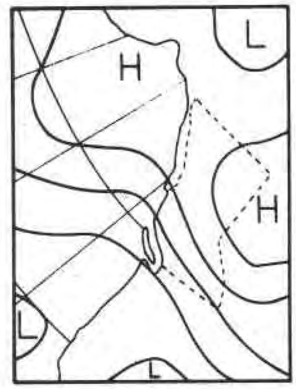


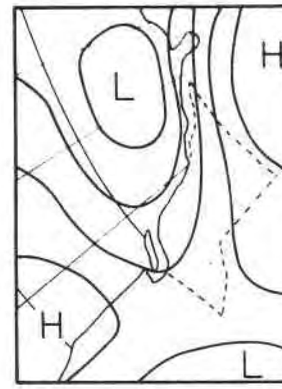
FIGURE 24

SURFACE SYNOPTIC WEATHER TYPES WITH HIGHER THAN USUAL FREQUENCIES DURING MAJOR AVALANCHE WINTERS WITH ZONAL CIRCULATION OVER BRITISH COLUMBIA

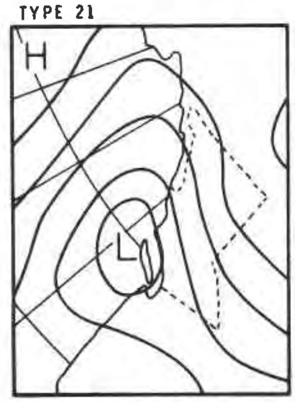
TYPE 8



TYPE 14



TYPE 21



TYPE 23

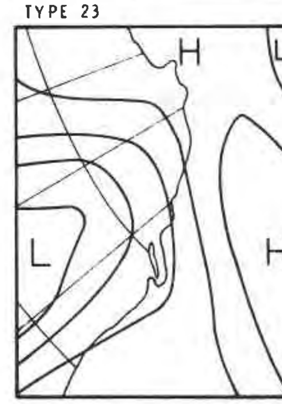
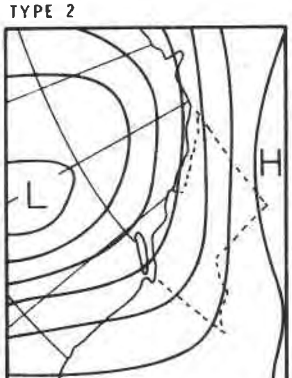


FIGURE 25

SURFACE SYNOPTIC WEATHER TYPES WITH HIGHER THAN USUAL FREQUENCIES DURING MAJOR AVALANCHE WINTERS WITH MERIDIONAL CIRCULATION OVER BRITISH COLUMBIA

TYPE 2



TYPE 3

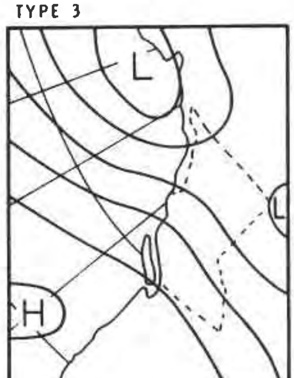


FIGURE 26

SURFACE SYNOPTIC WEATHER TYPES WITH LOWER THAN USUAL FREQUENCY IN MAJOR-MERIDIONAL AVALANCHE WINTERS

TYPE 9

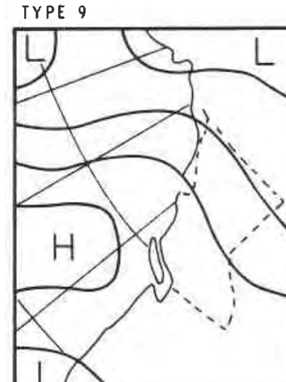


FIGURE 27

SURFACE SYNOPTIC WEATHER TYPE WITH HIGHER THAN USUAL FREQUENCY DURING MINOR AVALANCHE WINTERS

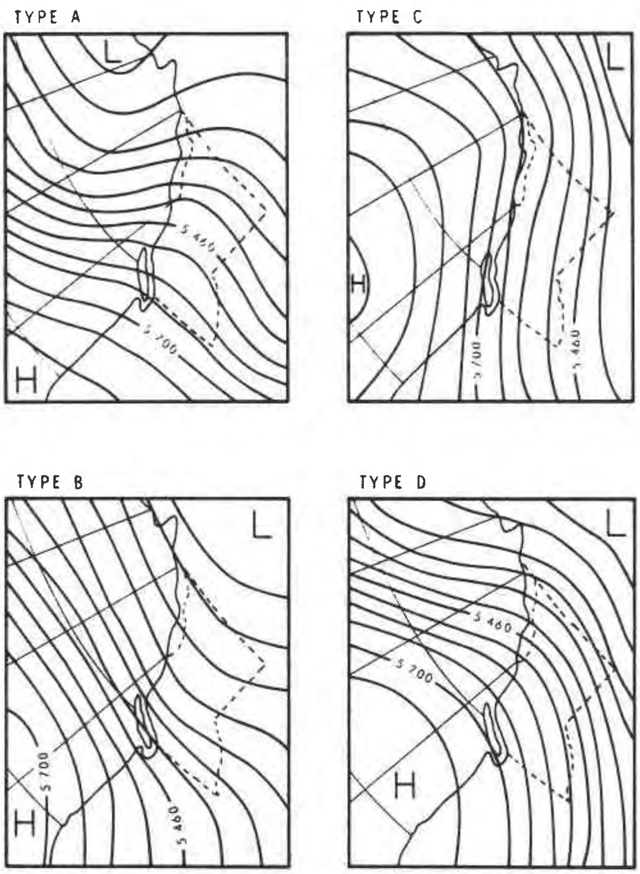


FIGURE 28

DISCRIMINATING MAP TYPES AT 500 mb FOR MAJOR AND MINOR AVALANCHE WINTERS. HEIGHT OF 500 mb SURFACE GIVEN IN METERS

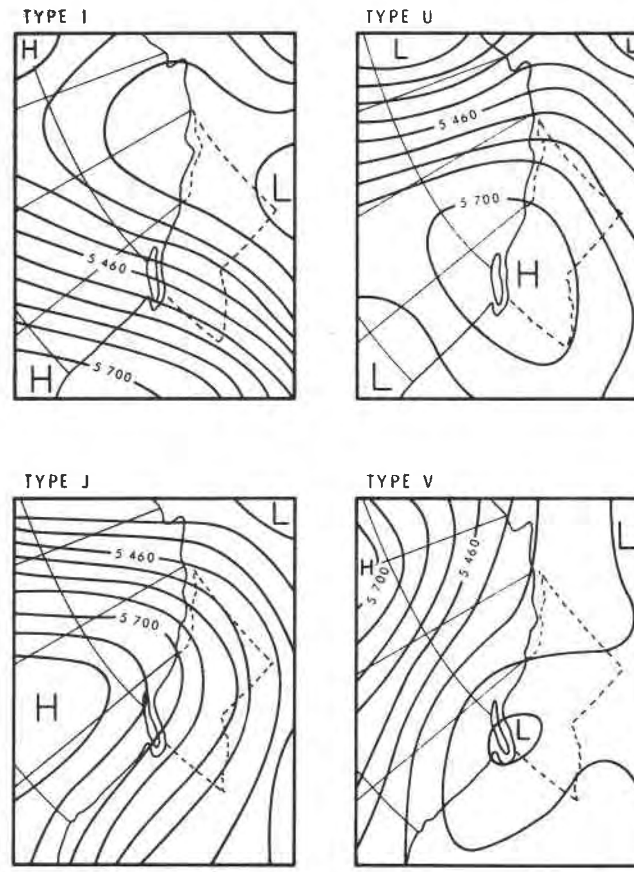


FIGURE 28 cont'd

APPENDIX A

SOURCE OF AVALANCHE DATA

Period	Source	Notes
1909-1952	Canadian Pacific Railway (CPR)	Records of large events cutting line, with date, length of track covered, depth on track, and location in railway miles from Field to Revelstoke.
1953-1957	Department of Public Works (DPW)	Location of large avalanches, dates, width, depth on proposed highway line. Some data of 1956-1957 lost. See also record in Schaerer (1962).
1957-1960	National Research Council (NRC)	Location, date, depth and width on proposed highway line. Terminus and type of snow noted.
1960-1965	Snow Research and Avalanche Warning Section (SRAWS)	Reports contained in NRC files; some are lost and record good for larger events only. Date, location, type of snow terminus, width and depth on highway.
1965-present	SRAWS	Date, location, terminus, type of snow, size classification; for larger events that crossed highway, width and depth on highway.
1966-present	NRC	Date, location, terminus, width, length, depth, for all events; type of snow (estimated specific gravity or estimate of moisture of avalanche); calculated value of mass of avalanche.

APPENDIX B

AVALANCHES USED FOR ANALYSIS

Table B1 contains the following information:

Avalanche path	- listed from east to west, in the direction of the railway mileage
Length	- length, in feet, of railway track covered by avalanche snow (unit feet retained because used in most of the records)
Mass	- mass of avalanche snow estimated as described in Section 2.2.2 of this report
Record type	- code numbers indicate the type of record available; type of record influenced the reliability of the estimates of avalanche mass

Code	Source	Record type	Portion of record
1	NRC	High quality observation of dimensions and density of debris and calculation of mass	14%
2	CPR SRAWS	The records give length and depth of rail line covered by debris. The density was estimated according to Schaerer (1972)	48%
3	SRAWS	Dimensions of avalanche debris at centre line of Trans-Canada Highway only	15%
4	various	Qualitative description of avalanche only	14%
5	various	No information on mass, only date of occurrence	9%

Winter	Date	Avalanche Path	Length (ft)	Mass M (10^6 kg)	Record Type	Record Quality
1909-10	24 Jan	Unnamed No. 6			5	poor
	18 Mar	Observatory			5	poor
	19 Mar	Abbott 3			5	poor
1910-11		none	0		5	poor
1911-12		none	0		5	poor
1912-13	12 Apr	CPR sheds			5	poor
1913-14	14 Mar	Connaught		24	4	poor
1914-15		none	0			
1915-16	16 Feb	Observatory			5	poor
1916-17	25 Mar	Connaught			4	poor
	27 May	Connaught		83	4	poor
	3 Feb	Cougar Corner 6			5	poor
1917-18	4 Feb	Stone Arch			5	poor
	18 Mar	Stone Arch			5	poor
	8 Feb	Railroad Gunners		5.6	2	good
	30 Mar	Laurie			5	poor
	5 Feb	Baird		21	2	good
1918-19	28 Jan	Twins	450	17	2	moderate
	7 Mar	Twins	280	22	2	moderate
	7 Mar	Twins	280	5.5	2	moderate
1919-20	18 Jan	Connaught	1 000	209	2	good
	18 Jan	Connaught	1 500	312	2	good
	18 Jan	Observatory	450	21	2	moderate
	9 May	Observatory	150	11	2	moderate
	15 Jan	Abbott 3	600	19	2	moderate
	18 Jan	Abbott 4	700	19	2	moderate
	18 Jan	Ross Peak	1 400	211	2	good
	18 Jan	Railroad Gunners	100	1.5	2	good
	17 Jan	Smart East	100	5.4	2	moderate
	11 May	Smart East	100	3	4	poor
	17 Jan	Baird	200	5.1	2	good

Winter	Date	Avalanche Path	Length (ft)	Mass M (10^6 kg)	Record Type	Record Quality
1920-21	15 Jan	Connaught	350	21	2	good
	10 Feb	Cheops South 1	150	7.7	2	moderate
	14 Jan	Laurie	250	18	2	moderate
1921-22	12 Dec	Baird	200	5	4	poor
	8 Feb	Baird	225	20	2	good
1922-23	17 Jan	Railroad Gunners	500	15	2	good
	19 Mar	Baird	75	2.9	2	good
1923-24	14 Mar	Smart West	100	3	4	poor
1924-25	20 Jan	Helen	125	22	2	moderate
1925-26	23 Mar	Laurie	300	10	2	moderate
1926-27	27 Apr	Abbott 3	150	4.9	2	moderate
1927-28		none				
1928-29	9 Mar	Cougar Creek East	100	3.5	2	good
	7 Mar	Baird	300	15	2	good
1929-30	2 Feb	Connaught	500	36	2	good
	17 Feb	Observatory	50	2	2	moderate
1930-31		none				
1931-32		none				
1932-33	9 Jan	Abbott 3	500	16	2	moderate
	6 Jan	Cheops South 1	1 200	68	2	good
	9 Jan	Ross Peak	350	21	2	good
	7 Jan	Smart East	600	39	2	moderate
	9 Jan	Smart West	2 000	112	2	moderate
	7 Jan	Park One	1 500	229	2	moderate
	7 Jan	Park One	600	22	2	moderate
	5 Jan	Twins	200	7.6	2	moderate
	10 Jan	Twins	150	6	2	moderate
	9 Jan	Helen	350	33	2	moderate
1933-34	23 Dec	Connaught	1 000	34	2	good
	23 Jan	Unnamed No. 6	150	3.4	2	good
	23 Dec	Helen	80	9	2	moderate

Winter	Date	Avalanche Path	Length (ft)	Mass M (10^6 kg)	Record Type	Record Quality
1934-35	2 Jan	Connaught	1 200	150	2	moderate
	23 Jan	Connaught	250	8.7	2	good
	5 Jan	Stone Arch	400	26	2	good
	23 Jan	Abbott 3	500	8.6	2	moderate
	25 Jan	Abbott 4	500	5.4	2	good
	25 Jan	Cheops South 1	500	17	2	good
	25 Jan	Cougar Creek West	700	41	2	good
	25 Jan	Ross Peak	1 140	127	2	good
	24 Jan	Smart East	500	32	2	moderate
	26 Jan	Fortitude	660	82	2	poor
	24 Jan	Laurie	560	48	2	moderate
	6 Jan	Lanark	25	3.6	2	moderate
	6 Jan	Twins	600	60	2	poor
	24 Jan	Twins	500	32	2	poor
	22 Jan	Jack MacDonald	200	33	2	moderate
1925-36		none				
1936-37	11 Feb	Jack MacDonald	300	306	4	moderate
1937-38	28 Dec	Connaught	300	8.4	2	good
1938-39	24 Mar	CPR Sheds	100	1.7	2	moderate
	24 Mar	CPR Sheds	50	1.7	2	moderate
	24 Mar	Laurie	500	46	2	moderate
1939-40	10 Feb	Stone Arch	150	2.3	2	good
1940-41		none				
1941-42		none				
1942-43	27 Mar	Cougar Creek East	100	4.4	2	good
	12 Apr	Laurie	50	6.2	2	moderate
	12 Apr	Baird	25	1.4	2	good
1943-44		none				
1944-45		none				
1945-46	18 Jan	Ross Peak	1 000	104	2	good
	2 Feb	Jack MacDonald	500	180	2	moderate
	25 Feb	Baird	75	5.7	2	good
	25 Feb	Baird	50	3.8	2	good

Winter	Date	Avalanche Path	Length (ft)	Mass M (10^6 kg)	Record Type	Record Quality
1946-47	10 Dec	Ross Peak	900	109	2	good
	10 Dec	Ross Peak	200	404	2	good
	25 Jan	Fidelity	20	25	2	good
	24 Jan	Baird	170	5.2	2	good
1947-48	17 Feb	Connaught	300	27	2	good
	14 Feb	Jack MacDonald	500	150	2	moderate
1948-49	17 Feb	Abbott 3	600	23	2	moderate
	4 Apr	Laurie	300	8.6	4	poor
	17 Feb	Jack MacDonald	500	121	2	moderate
	17 Feb	Baird	50	3.2	5	poor
1949-50	26 Dec	Ross Peak	300	20	2	good
	26 Dec	Ross Peak	300	44	2	good
1950-51	10 Feb	Laurie	500	121	2	moderate
	1 Apr	Laurie	250	5	4	poor
	10 Feb	Lanark	800	207	2	moderate
1951-52	7 Feb	Cougar Creek East	1 250	101	2	moderate
	7 Feb	Cougar Corner 6	100	0.5	4	poor
	7 Feb	Cougar Corner 3	100	0.8	4	poor
	7 Feb	Cougar Corner 2	100	3.8	4	poor
	21 Jan	Ross Peak	1 200	135	2	good
	9 Feb	CPR Sheds	100	0.6		poor
	27 Jan	Baird	250	7.6	2	good
	28 Mar	Baird	50	3.2	5	poor
1952-53	? Jan	Ross Peak	300	3.2		poor
	?	Laurie	300	8.6		poor
	? Feb	Lanark	300	53		poor
	?	Baird	50	3.2		poor
1953-54	16 Feb	Connaught	1 300	77	2	good
	2 Feb	Ross Peak	1 500	396	2	good
	4 May	Laurie	1 000	153	2	moderate
	16 Feb	Jack MacDonald	200	48	2	moderate
	6 Jan	Baird	110	1.6	3	good
1954-55	14 Feb	Ross Peak	800	127	2	good
	5 Apr	Laurie	400	111	2	moderate

Winter	Date	Avalanche Path	Length (ft)	Mass M (10^6 kg)	Record Type	Record Quality
1955-56	11 Jan	Connaught	1 000	70	4	poor
	11 Jan	Ross Peak	1 300	116	2	good
	12 Jan	Laurie	280	48	2	moderate
	1 Mar	Jack MacDonald	580	143	3	good
	14 Apr	Baird	300	14	3	good
1956-57		none				
1957-58	16 Jan	Ross Peak	250	20	4	poor
	24 Jan	Laurie	250	8.7	5	poor
1958-59	20 Nov	Laurie	250	8.7	5	poor
	31 Dec	Laurie	250	8.7	5	poor
	18 Dec	Laurie	300	53	4	poor
1959-60	12 May	Cougar Creek East	100	6.4	3	good
	17 Feb	Ross Peak	300	64	2	good
	24 Nov	Laurie	250	8.7	5	poor
	12 May	Laurie	250	8.7	5	poor
	29 Jan	Twins	200	5.1	3	moderate
	29 Jan	Baird	30	0.3	3	good
1960-61	22 Feb	Ross Peak	300	32	4	poor
1961-62	2 Feb	Abbott 3	100	1.5	3	good
1962-63	1 Jan	Observatory	260	6.1	3	good
1963-64		none				
1964-65	18 Feb	Observatory	320	24	3	good
	27 Feb	Abbott 3	330	6.6	3	good
	8 Feb	Abbott 4	140	2.2	3	good
	5 Feb	Park One	730	15	3	moderate
1965-66	30 Mar	Connaught	300	11	5	poor
	26 Feb	Smart West	210	3.4	3	moderate
1966-67	5 Jan	Abbott 3	600	7	3	good
	5 Jan	Abbott 4	190	1.5	3	good
	2 Feb	Cougar Creek West	90	1.7	1	excellent
	18 Dec	Fidelity	300	62	3	moderate

Winter	Date	Avalanche Path	Length (ft)	Mass M (10^6 kg)	Record Type	Record Quality
1967-68	29 Mar	Connaught	300	11	5	poor
	20 Jan	Stone Arch	600	23	1	excellent
	18 Jan	Ross Peak	250	20	4	poor
	4 Feb	Ross Peak	200	14	3	moderate
	20 Jan	Railroad Gunners	50	14	4	poor
	23 Jan	CPR Sheds	220	2.8	1	excellent
	4 Jan	Laurie	105	7.2	1	excellent
	20 Jan	Lanark	300	53	5	poor
1968-69	5 Jan	Railroad Gunners	50	5	4	poor
	6 Apr	CPR Sheds	220	2.9	1	excellent
1969-70	10 Apr	Observatory	250	22	3	good
	6 Apr	Ross Peak	1 000	86	3	moderate
	6 Apr	Smart West	350	11	1	excellent
1970-71	7 Dec	Connaught	300	11	4	poor
	16 Jan	Connaught	200	4	2	good
	29 Jan	Cougar Corner 6	300	2.8	1	excellent
	29 Feb	Cougar Corner 2	360	12	1	excellent
1971-72	5 Mar	Connaught	200	4	4	poor
	28 Mar	Connaught	200	4	4	poor
	21 Jan	Observatory	450	8.3	3	good
	5 Mar	Abbott 3	685	13	3	good
	16 Feb	Abbott 4	250	1.9	3	good
	23 Jan	Cheops South 1	280	7.1	1	excellent
	9 Jan	Cougar Creek East	300	37	1	excellent
	16 Feb	Cougar Creek East	700	10	1	excellent
	20 Jan	Cougar Corner 6	400	7.3	1	excellent
	25 Dec	Cougar Corner 2	410	7.4	1	excellent
	20 Jan	Cougar Corner 2	140	11.6	1	excellent
	23 Dec	Ross Peak	250	20	4	poor
	9 Jan	Ross Peak	1 155	90	3	good
	21 Jan	Railroad Gunners	50	5	4	poor
	16 Mar	CPR Shed	120	4.9	1	excellent
	16 Jan	Park One	265	7	3	moderate
	17 Mar	Park One	125	4	3	moderate
	31 Dec	Laurie	400	6.5	1	excellent
	13 May	Lanark	300	53	4	poor
	24 Jan	Twins	200	7	4	poor
	31 Dec	Baird	50	3.2	5	poor
1972-73	26 Dec	Cougar Creek West	700	27	1	excellent
	26 Dec	Smart West	200	0.4	3	good

Winter	Date	Avalanche Path	Length (ft)	Mass M (10^6 kg)	Record Type	Record Quality
1973-74	16 Jan	Connaught	200	4	4	poor
	16 Jan	Cougar Corner 6	90	4.4	1	excellent
	17 Jan	Ross Peak	600	43	3	moderate
	30 Jan	Ross Peak	625	98	3	good
	13 Jan	Smart West	200	0.8	1	excellent
1974-75	12 Feb	Connaught	200	4	4	poor
	13 Apr	Twins	250	24	1	excellent
	30 Dec	Baird	50	3.2	5	poor
1975-76	11 Feb	Cougar Corner 6	50	2.4	1	excellent
	16 Jan	Cougar Corner 2	300	3.8	1	excellent
	11 Feb	Park One	200	3	3	moderate
	31 Oct	Laurie	300	13	1	excellent
	11 Jan	Jack MacDonald	230	13	3	moderate
	11 Jan	Baird	75	2	3	good
	11 Feb	Baird	50	3.2	5	poor
1976-77	10 Feb	Laurie	200	5	1	excellent
	25 Apr	Laurie	500	15	1	excellent

APPENDIX C

RELATION OF SNOWFALLS AT VARIOUS CLIMATOLOGICAL STATIONS NEAR ROGERS PASS

The daily temperature and precipitation record of the Atmospheric Environment Service (AES) is incomplete and has suffered numerous site changes since measurement began in October 1892

Station Number	Station Name	Latitude	Longitude	Elevation (ft)	Period	Location
1173180	Glacier	51° 16'	117° 28'	4072	Oct 1892-Apr 1897	Glacier House
1173180	Glacier	51° 14'	117° 29'	4072	Jan 1902-Feb 1902	Glacier House
1173180	Glacier	51° 14'	117° 29'	4072	Mar 1902-Jun 1903	Glacier House
1173180	Glacier	51° 14'	117° 29'	4072	Dec 1903-Apr 1906	Glacier House
1173180	Glacier	51° 14'	117° 29'	4094	Jan 1908-Nov 1952	Wardens' cabin
1173180	Glacier	51° 14'	117° 29'	4094	Sep 1953-Apr 1954	Fanhouse
1173180	Glacier	51° 14'	117° 29'	4094	Jan 1955-Jul 1956	Fanhouse
1173180	Glacier	51° 14'	117° 29'	4094	Oct 1956-Mar 1957	Fanhouse
1173190	Avalanche RS	51° 16'	117° 30'	3860	Oct 1957-Jun 1965	Fanhouse
1173191	Rogers Pass	51° 17'	117° 31'	4340	Jun 1965-present	Summit

This record has to be adjusted to make the snowfall data homogeneous and synthesized to estimate missing data. All snowfalls were arbitrarily adjusted to those at the Warden's cabin, and are here called Glacier (AES) snowfall. Several methods were used:

a. Regression relations between winter snowfall at Glacier (Warden's cabin) and the long period of snowfall recorded by the CPR at Glacier Railway Station for the winters 1909-10 to 1951-52.

b. Double mass curves.

c. Comparisons of ratios of mean snowfalls at AES stations and the CPR record.

SUMMARY

Station	Winter	Relation	Adjustment
Glacier	1896-97 to 1951-52	AES = -14 + 0.98 CPR	none
Glacier	1952-53 to 1956-57	AES = 0.97 CPR	none
Avalanche RS	1957-58 to 1964-65	AES = 0.97 CPR	none
Avalanche RS	1965-66 to present	AES = 0.96 CPR	none

It was considered that snowfalls from 1896 to 1965 are homegeneous; since 1965 they should be multiplied by 1.02 to standardize.

APPENDIX D

BASIC FREQUENCY DISTRIBUTIONS

DEFINITIONS

The probability of occurrence f(x) of a continuous random variable x (in this case an extreme event) is called the probability density function, abbreviated as pdf. F(x) is the distribution function, abbreviated as df, and is defined as the probability that the random variable is less than or equal to x. The relation between the two functions is

$$F(x) = \int_{-\infty}^{x} f(x)\, dx$$

By definition

$$F(\infty) = \int_{-\infty}^{\infty} f(x)\, dx = 1$$

GAMMA DISTRIBUTION

This is the Pearson type 3 distribution with the pdf

$$f(x) = \begin{cases} \dfrac{(x-x_o)^{\gamma-1}}{\beta^{\gamma}\Gamma(\gamma)} \; e^{-1(x-x_o)/\beta} & , x > x_o \\ 0 & , x \leq x_o \end{cases}$$

where

x_o = a scale parameter

γ = a shape parameter

and β = a scale parameter

If $\gamma = 1$, f(x) describes an exponential distribution; if $x_o = 0$, f(x) describes a two-parameter Gamma distribution.

The log-Pearson type 3 distribution has the pdf

$$f(x) = \begin{cases} \dfrac{(\ln x - x_o)^{\gamma-1}}{x\beta^{\gamma}\Gamma(\gamma)} e^{-(\ln x - x_o)/\beta} & , x > e^{x_o} \\ 0 & , x \leq e^{x_o} \end{cases}$$

The df must be calculated numerically in both cases.

NORMAL DISTRIBUTION

The two-parameter normal distribution is a symmetrical distribution with the pdf

$$f(x) = \frac{1}{\sqrt{2\pi}\,\sigma} e^{-\frac{1}{2}\{(x-\mu)/\sigma\}^2} \quad , -\infty < x < \infty$$

where μ = a location parameter (mean)

σ = a scale parameter (standard deviation).

It may be transformed to the asymmetrical log-normal distribution which has the pdf

$$f(x) = \begin{cases} \dfrac{1}{x\sqrt{2\pi}\,\sigma} e^{-\frac{1}{2}\{\ln x - \mu)/\sigma\}^2} & , 0 < x < \infty \\ 0 & , x \leq 0 \end{cases}$$

The df must be calculated numerically in both cases.

GENERAL EXTREME VALUE DISTRIBUTION

The pdf for this distribution is

$$f(x) = \frac{1}{\alpha}[1-k(x-u)/\alpha]^{1/k-1} e^{-\{1-k(x-u)/\alpha\}^{1/k}}$$

where u = a location parameter

α = a scale parameter

k = a shape parameter,

and the df is

$$F(x) = e^{-\{1-k(x-u)/\alpha\}^{1/k}}$$

The range of x in which the pdf is non-zero is defined by the value of k as follows:

(a) if $k < 0$, the pdf is non-zero for $u + \frac{\alpha}{k} \leq x < \infty$ and the distribution is EV2;

(b) if $k > 0$, the pdf is non-zero for $-\infty < x \leq u + \frac{\alpha}{k}$ and the distribution is EV3;

(c) if $k = 0$, the pdf is non-zero for $x > 0$ and the distribution is EV1. In this case the pdf simplifies to

$$f(x) = \frac{1}{\alpha} \exp\left[-(x-u)/\alpha - e^{-(x-u)/\alpha}\right] \quad , x > 0$$

and the df is

$$F(x) = \exp\left[-e^{-(x-u)/\alpha}\right] \quad , x > 0$$

The difference between the three types of extreme-value distribution is illustrated below.

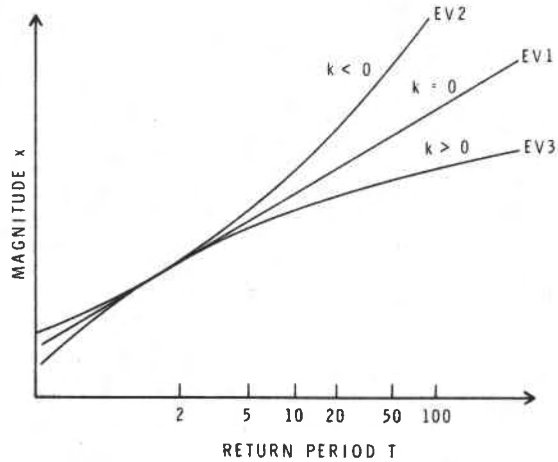


FIGURE D-1

ILLUSTRATION OF THE THREE TYPES OF EXTREME VALUE DISTRIBUTION WITH REFERENCE TO AN ANNUAL MAXIMA SERIES

APPENDIX E

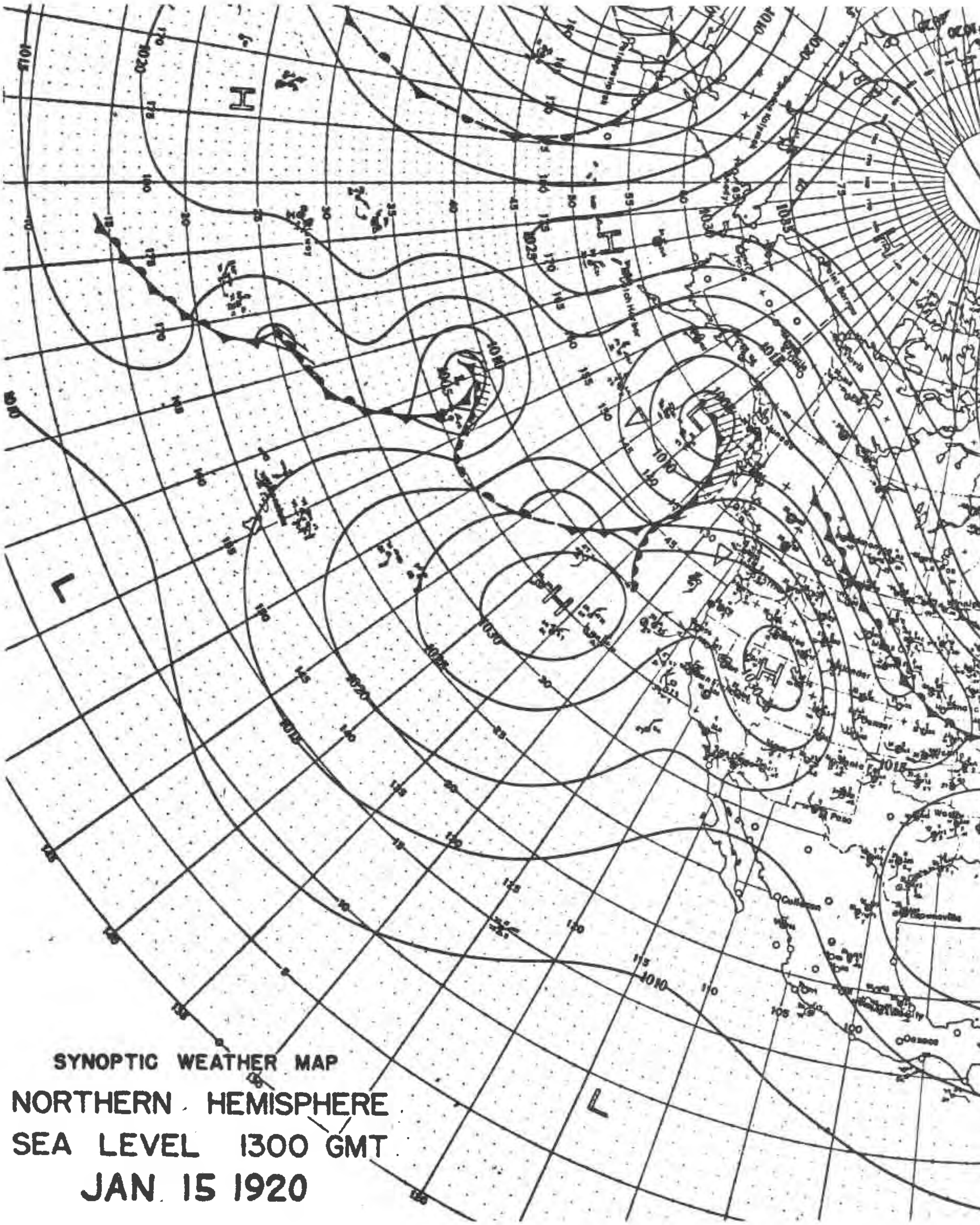
WEATHER MAPS FOR THE MOST INTENSE PERIODS OF AVALANCHE ACTIVITY

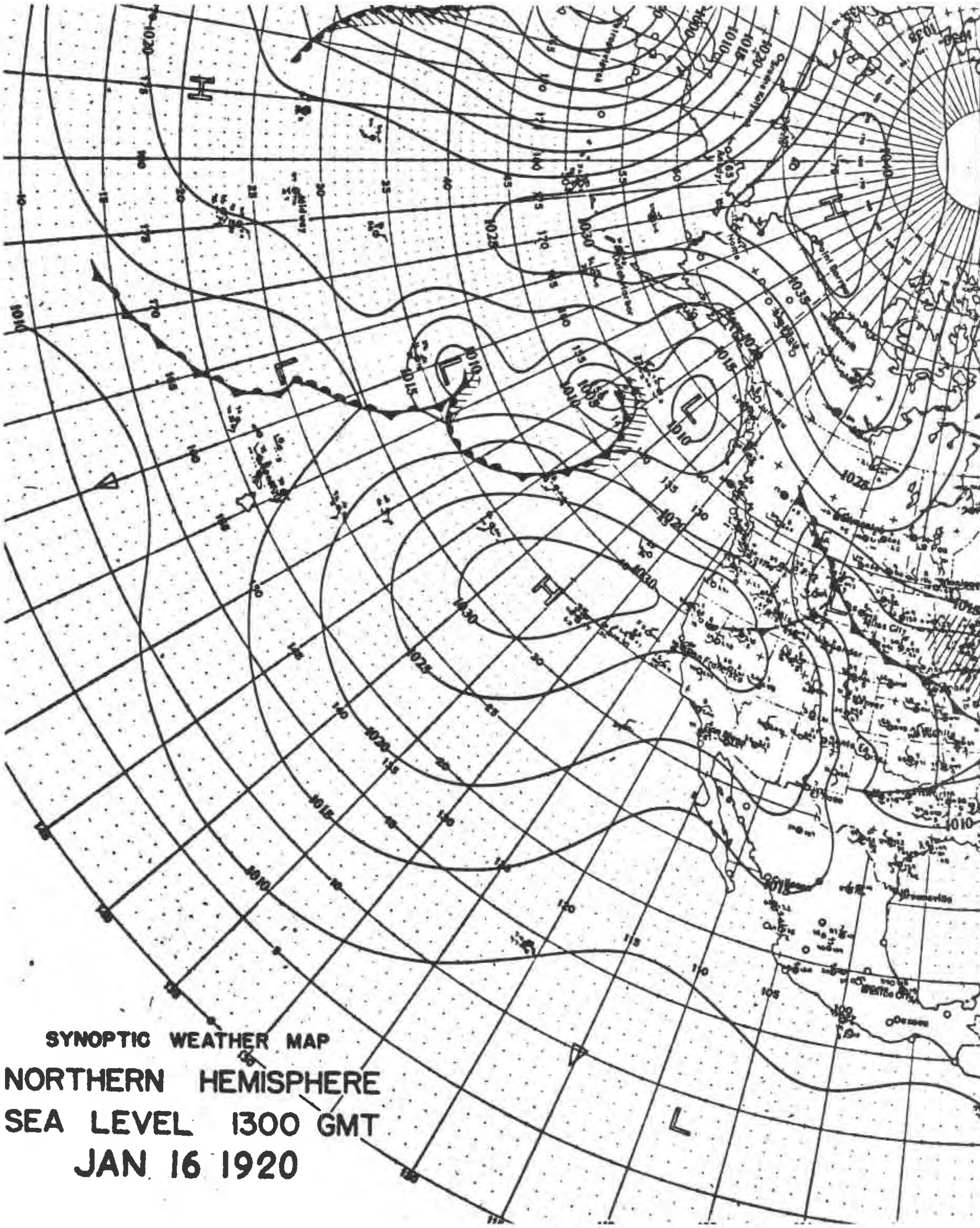
CONTENTS

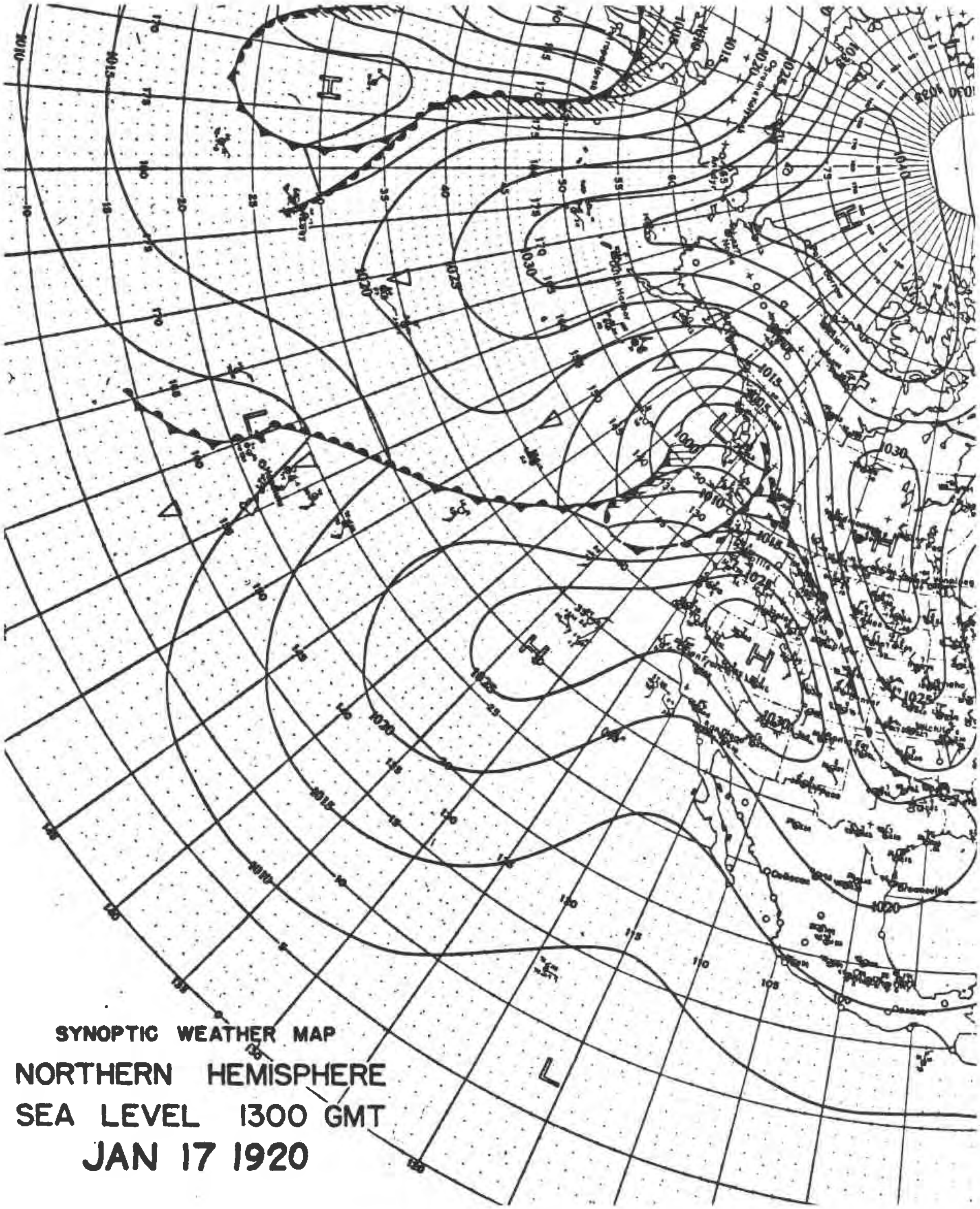
SYNOPTIC WEATHER MAPS

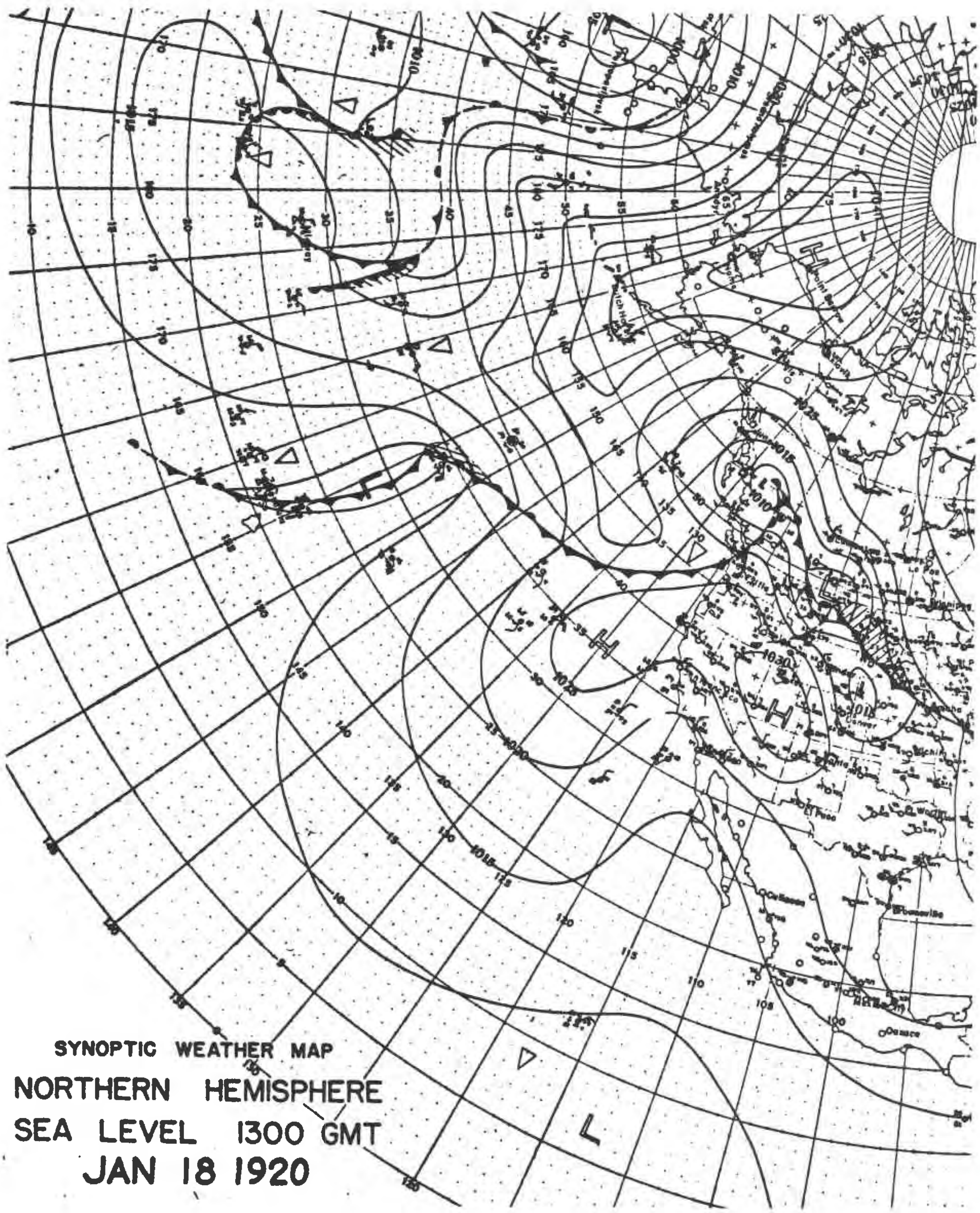
NORTHERN HEMISPHERE

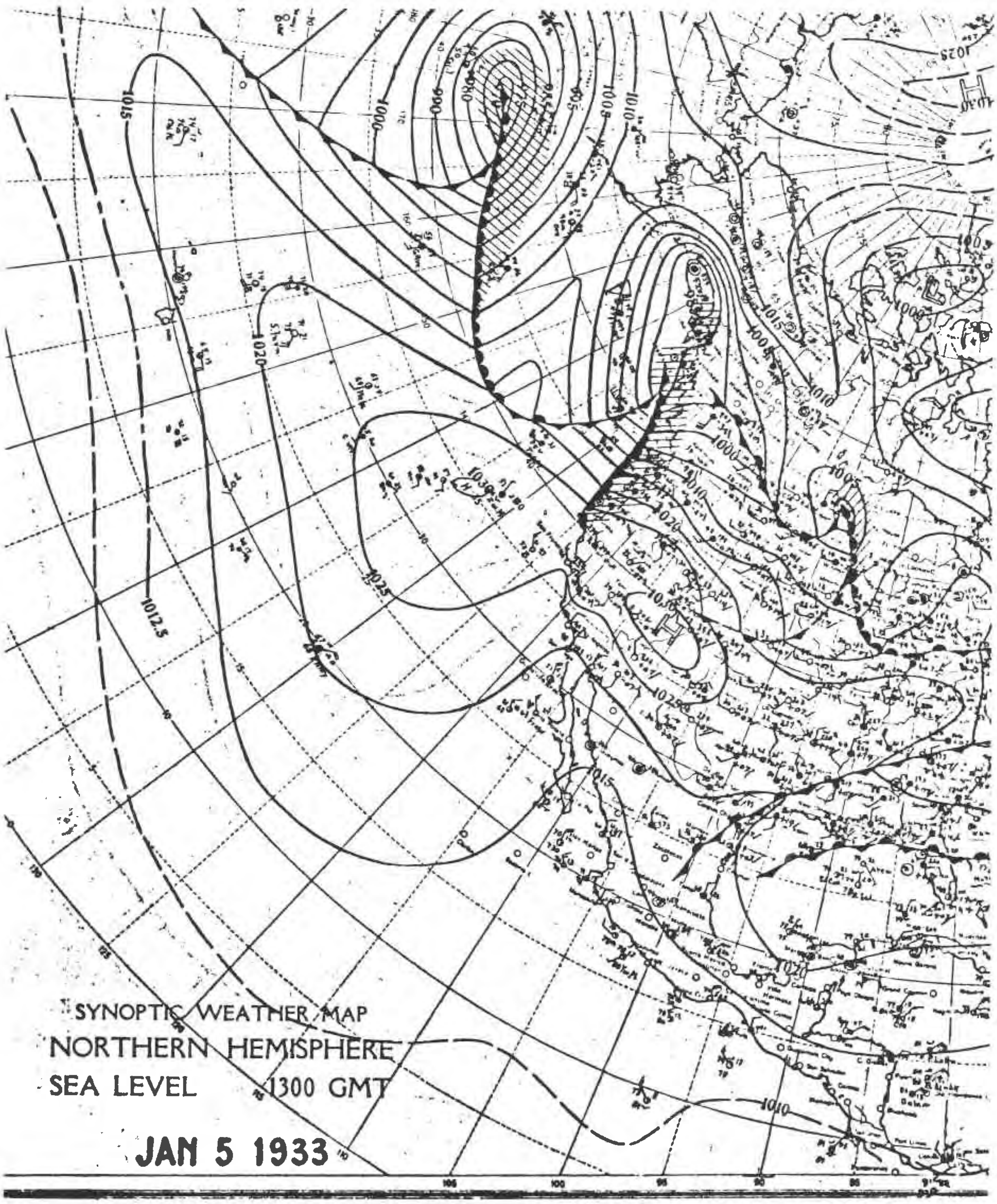
SEA LEVEL 1300 GMT

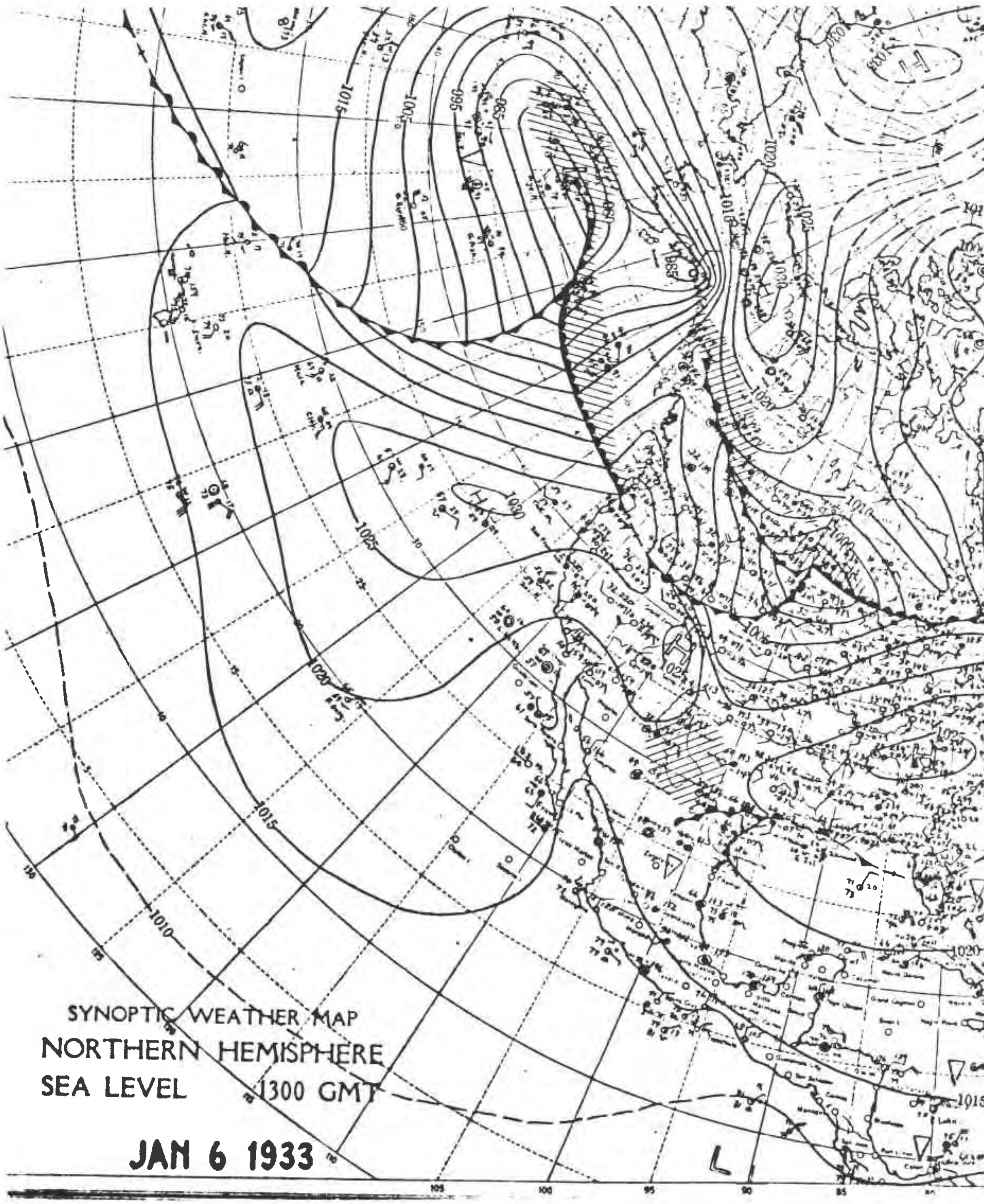

SYNOPTIC WEATHER MAP
NORTHERN HEMISPHERE
SEA LEVEL 1300 GMT
JAN. 15 1920

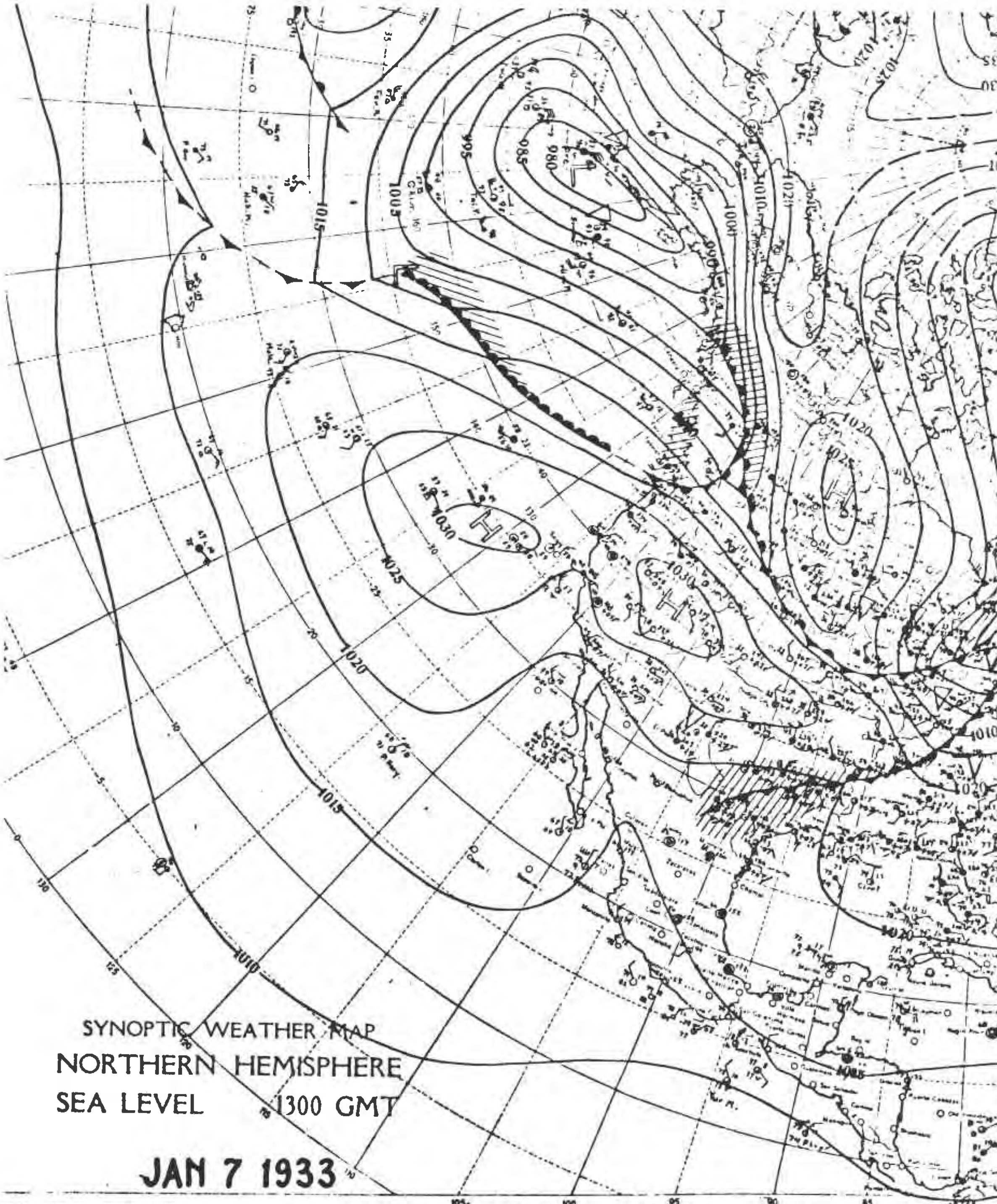

SYNOPTIC WEATHER MAP
NORTHERN HEMISPHERE
SEA LEVEL 1300 GMT
JAN 16 1920

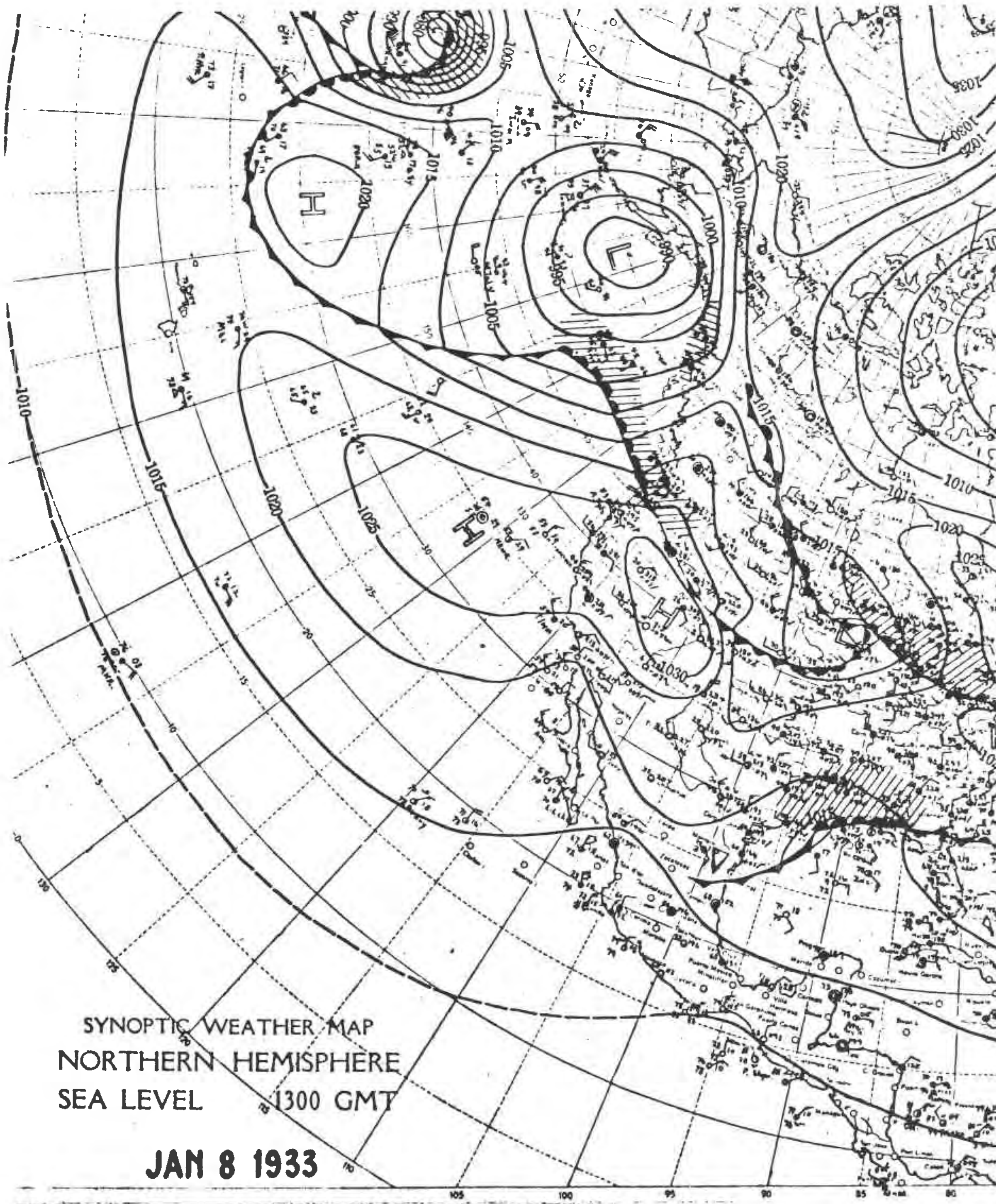

SYNOPTIC WEATHER MAP
NORTHERN HEMISPHERE
SEA LEVEL 1300 GMT
JAN 17 1920

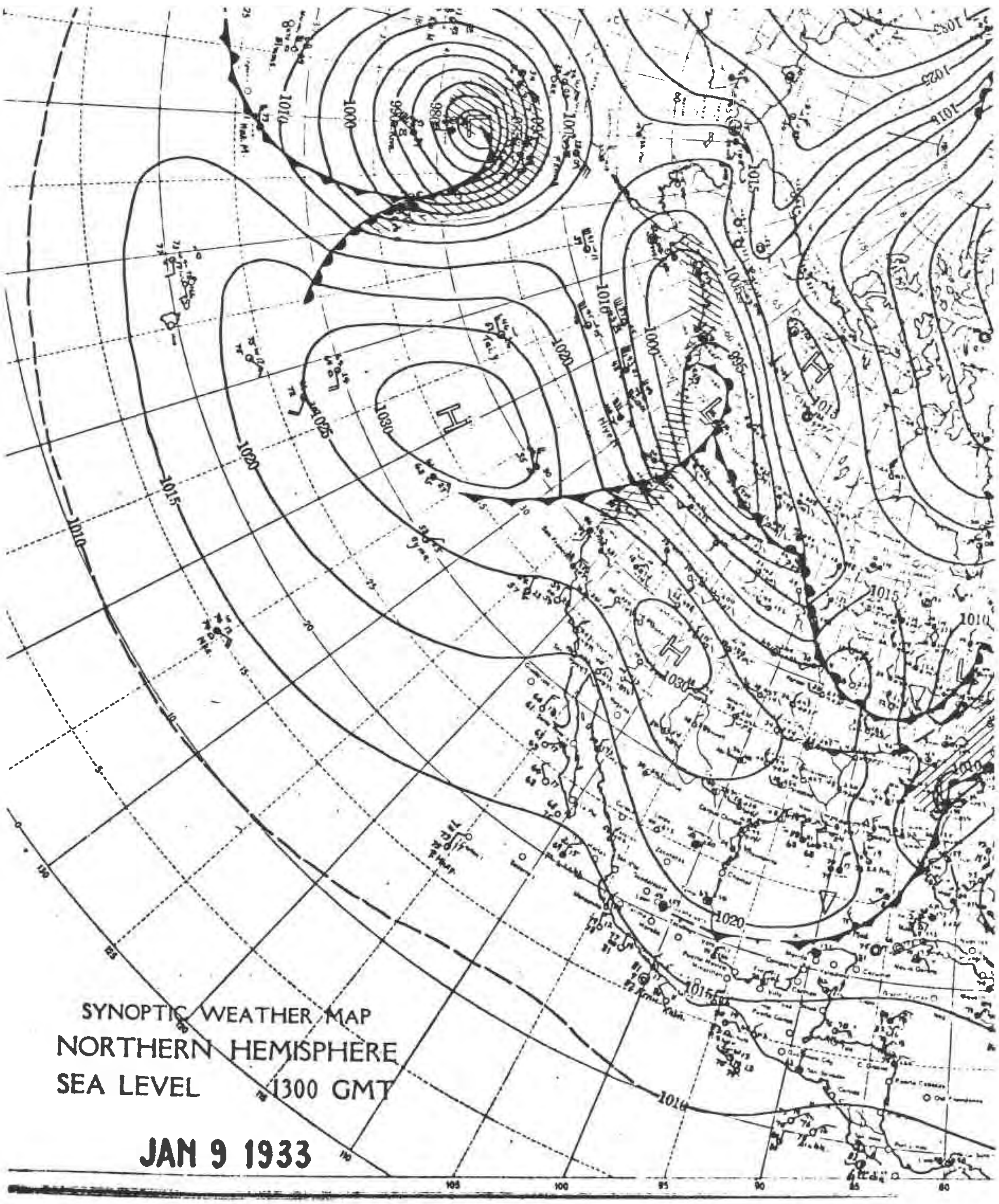

SYNOPTIC WEATHER MAP
NORTHERN HEMISPHERE
SEA LEVEL 1300 GMT
JAN 18 1920

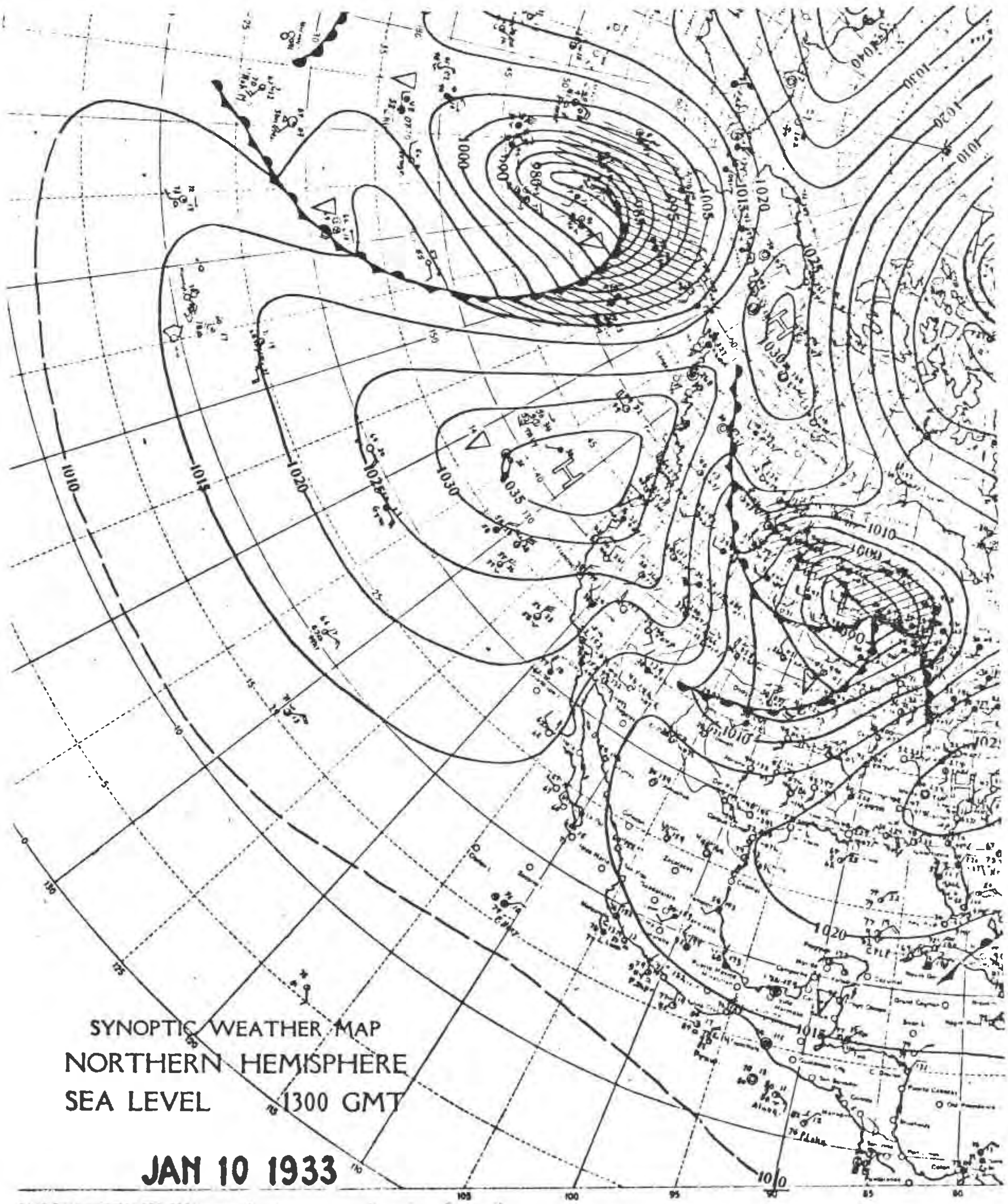

SYNOPTIC WEATHER MAP
NORTHERN HEMISPHERE
SEA LEVEL
1300 GMT
JAN 5 1933

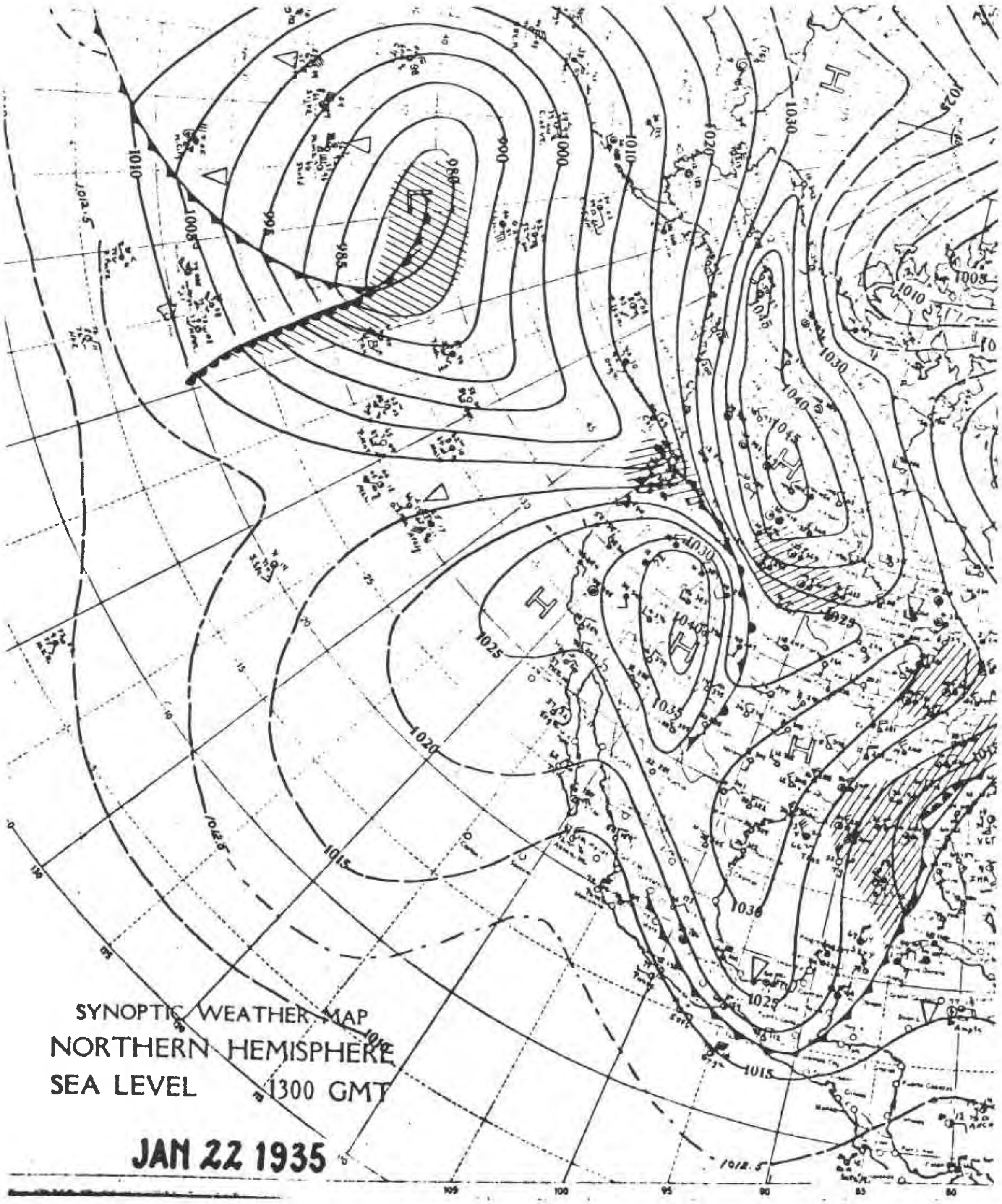

SYNOPTIC WEATHER MAP
NORTHERN HEMISPHERE
SEA LEVEL 1300 GMT
JAN 6 1933

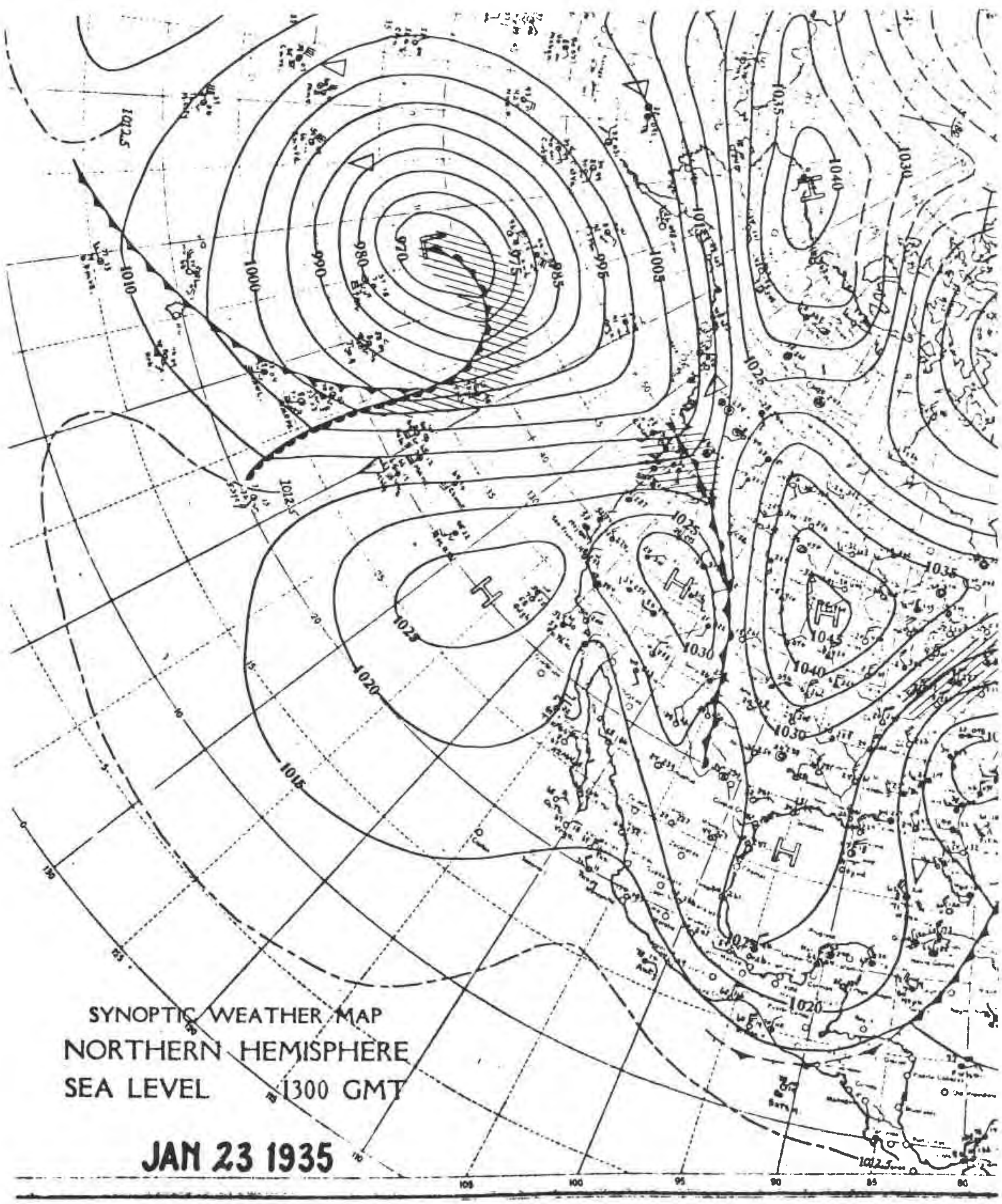

SYNOPTIC WEATHER MAP
NORTHERN HEMISPHERE
SEA LEVEL 1300 GMT
JAN 7 1933

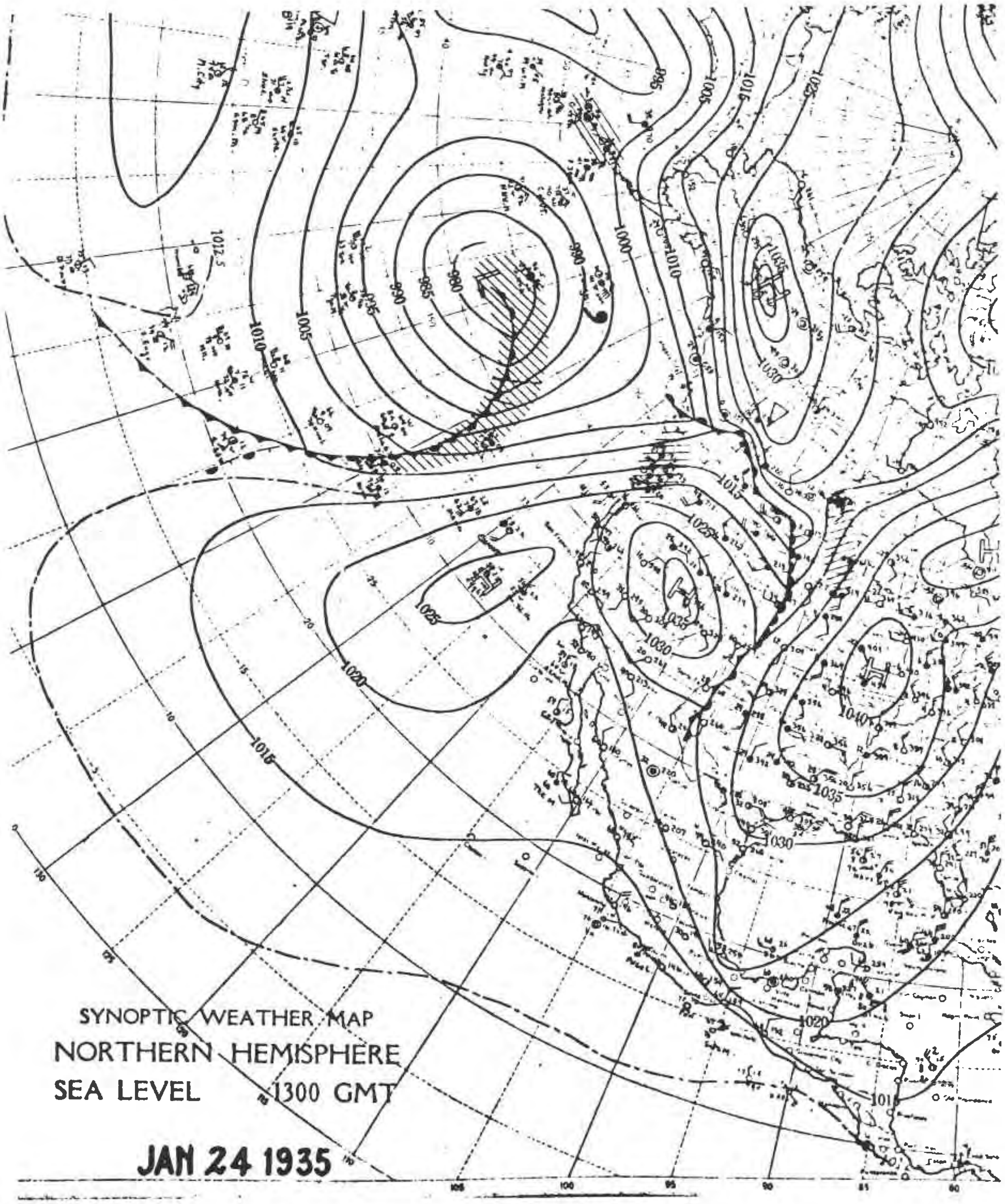

SYNOPTIC WEATHER MAP
NORTHERN HEMISPHERE
SEA LEVEL 1300 GMT
JAN 8 1933

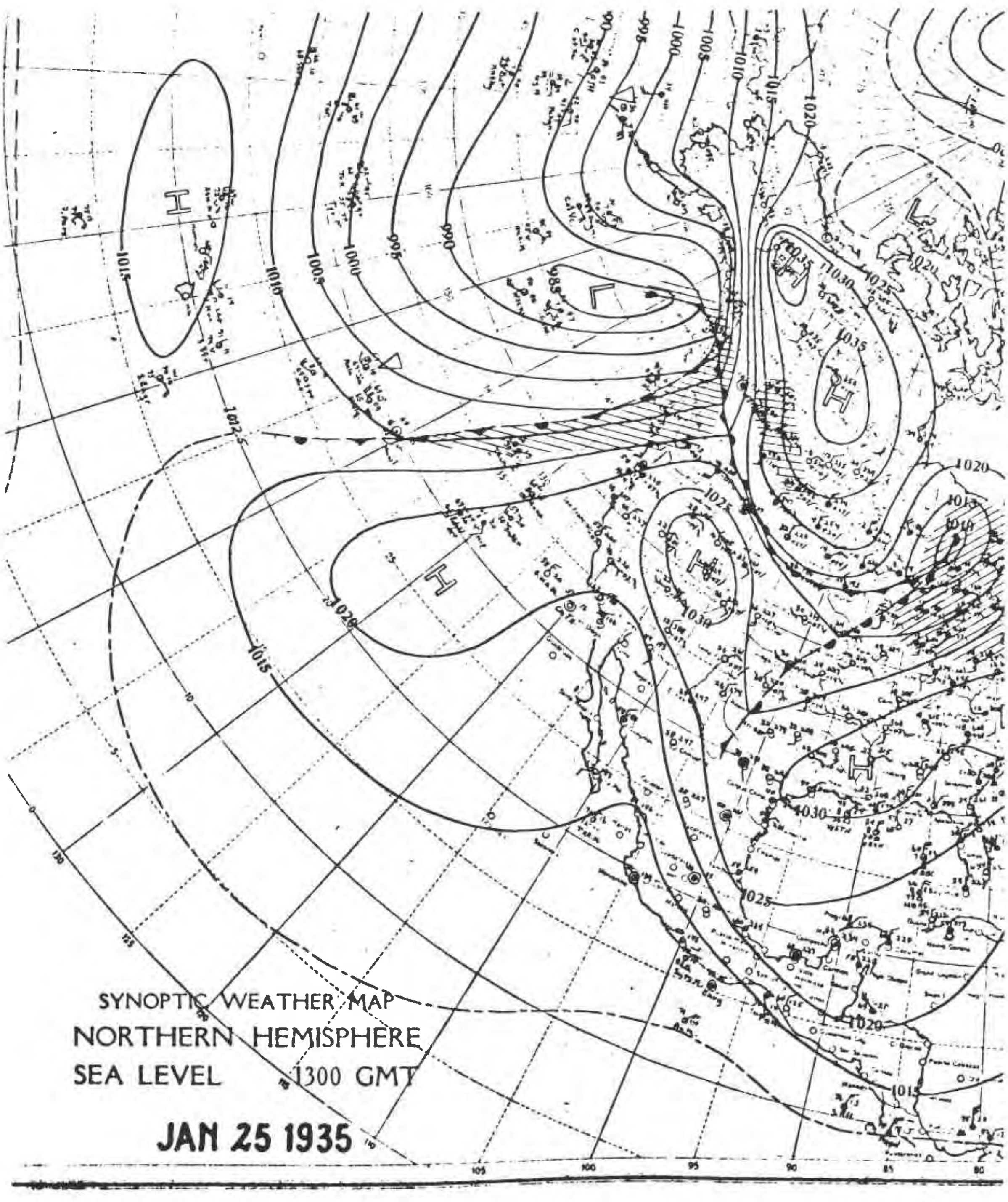

SYNOPTIC WEATHER MAP
NORTHERN HEMISPHERE
SEA LEVEL 1300 GMT
JAN 9 1933

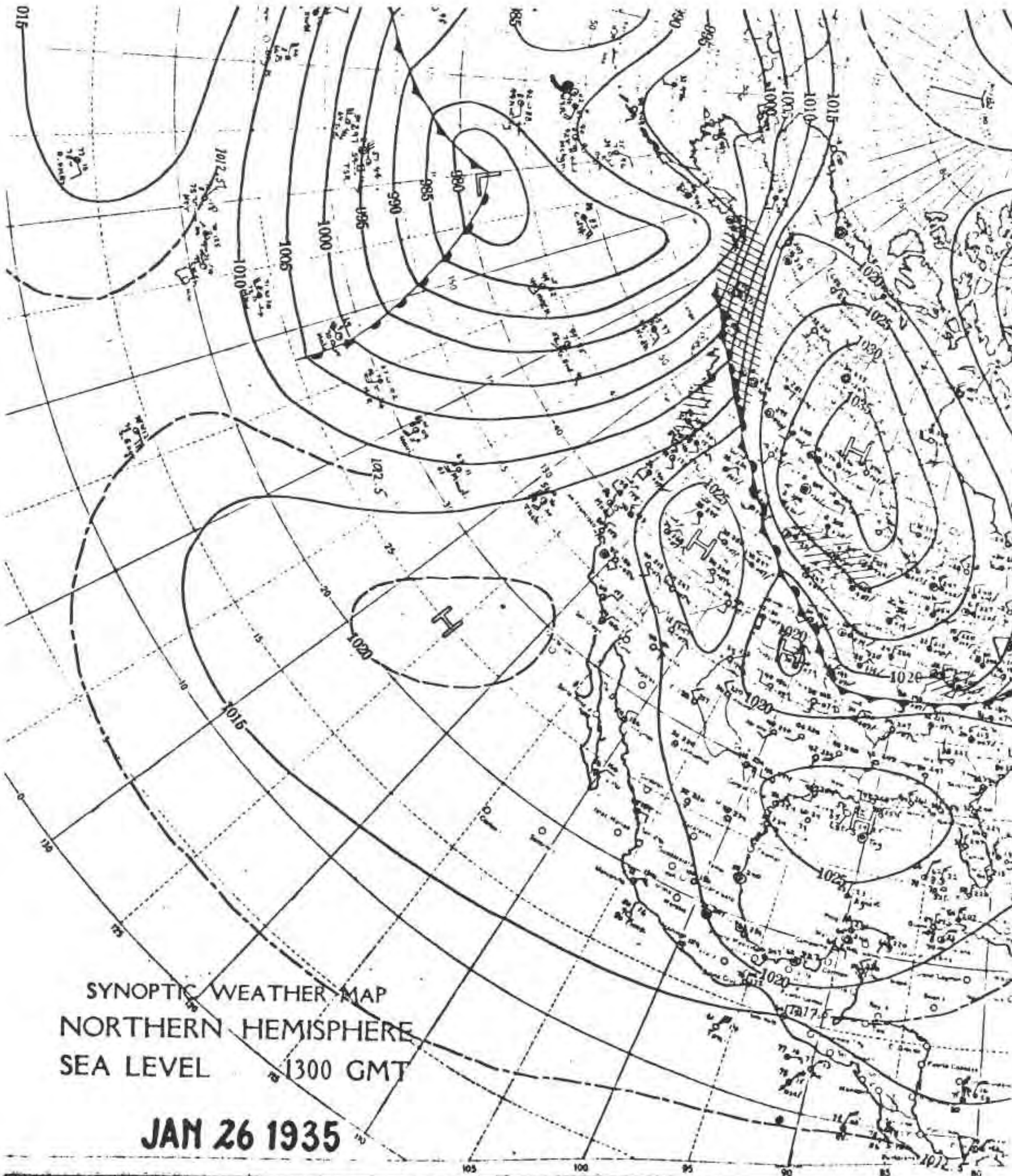

SYNOPTIC WEATHER MAP
NORTHERN HEMISPHERE
SEA LEVEL 1300 GMT
JAN 10 1933


SYNOPTIC WEATHER MAP
NORTHERN HEMISPHERE
SEA LEVEL 1300 GMT
JAN 22 1935
1010
1005
1012.5
990
985
980
990
1000
1010
1020
1030
1025
1035
1040
1045
1030
1025
1020
1015
1030
1025
1015
1012.5
1010
1005
105
100
95
90
85
80


SYNOPTIC WEATHER MAP
NORTHERN HEMISPHERE
SEA LEVEL 1300 GMT
JAN 23 1935


SYNOPTIC WEATHER MAP
NORTHERN HEMISPHERE
SEA LEVEL 1300 GMT
JAN 24 1935


SYNOPTIC WEATHER MAP
NORTHERN HEMISPHERE
SEA LEVEL 1300 GMT
JAN 25 1935


SYNOPTIC WEATHER MAP
NORTHERN HEMISPHERE
SEA LEVEL 1300 GMT
JAN 26 1935