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16. Abstract

The Central Avalanche Hazard Forecasting project had had two principal aims:

The design and establishment of an avalanche data network and central avalanche and mountain weather forecasting facility to serve the highway passes and other hazard areas of the Cascade Mountains in Washington.

Improvements in the practices of conventional avalanche forecasting and the introduction of new techniques in statistical analysis and pattern recognition.

Achievement of the first aim has been described in previous Reports 23.2 and 23.3. This present Report 23.4 gives the results of fundamental research into avalanche forecasting theory and discusses the application of these results to central avalanche forecasting for the Cascade Mountains of Western Washington.

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CENTRAL AVALANCHE HAZARD FORECASTING

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SUMMARY OF SCIENTIFIC INVESTIGATIONS

Research Project Y-1700 Phase 3

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1. INTRODUCTION

1.1 Scope of the Report

The Central Avalanche Hazard Forecasting project has had two principal aims:

The design and establishment of an avalanche data network and central avalanche and mountain weather forecasting facility to serve the highway passes and other hazard areas of the Cascade Mountains.

Improvements in the practices of conventional avalanche forecasting and the introduction of new techniques in statistical analysis and pattern recognition.

The project as originally constituted was to run for two years, and it was during this period that the first principal aim was largely accomplished. Details of the resulting forecasting facility have been summarized in previous reports. Report 23.3 was labelled Final Report in keeping with the terms of the original research contract. The contract was subsequently extended for a third year, with greater emphasis on research aimed at improvements in techniques. While the second report (23.3) touched on some aspects of forecasting techniques, like the preceding report it dealt predominantly with practical details of the operational forecasting system. The third and present report sets forth in much greater detail the evolved understanding of avalanche forecasting and applications to the forecasting system.

This report is divided into two parts. Part I, comprising sections 2 through 6, presents the fundamental results of research into avalanche forecasting theory and methods. Part II, comprising sections 7 through 9, discusses the application and implementation of these fundamentals to avalanche forecasting for the Cascade Mountains of Western Washington. Since this is an implementation report and the final report of this project, several ancillary topics for reference and information are presented in the Appendix.

1.2 The Parallel Development of Theory and Application

The initial design of the avalanche forecasting system was based on well-tried conventional methods. As experience was developed, innovations were introduced in both the avalanche and mountain weather forecasting which grew largely out of empirical knowledge. Some of these innovations related to the specific methods for the Washington Cascades, while others applied in a more general fashion to the overall forecasting process. At the same time these practical developments were under way, a more basic examination of the forecasting theory was taken in hand. The two approaches evolved side-by-side and eventually converged in such a manner that the theory was able to give an accurate description of the basic methods underlying practice and to point the way for improving the latter. The convergence has taken place toward the end of the project, and realization of some of the benefits will extend into future evolution of the forecasting operation.

The structure of the present report is designed to present first the findings of the research phase and then to illustrate their applications in practice. Section 2, 7 and 8 in particular illustrate the basis of the convergence phenomenon mentioned above.

1.3 Depth of the Subject Treatment

This report summarizes the main findings from the work under this project in an overview fashion. Enough details are presented to inform a reader previously unfamiliar with the topics and methods and to provide a training outline for newcomers to the forecasting program. A much more detailed treatment of the underlying principles will be developed at greater length elsewhere. In the interest of conciseness, many of the concepts presented, especially in sections, 2, 3 and 5, are set forth as simple assertions without the analytical support that has gone into their formation. A more detailed presentation awaits both the opportunity of a wider format and further refinements still in progress.

1.4 The Problem of Units

Avalanche science in the United States has long suffered from an uncomfortable mix of English and metric units, anticipating by a number of years the dichotomy now developing in many other areas as the metric system is slowly adopted. The present forecasting project is squarely in the middle of this problem. Some, but not all, of the field measurements in snow are in metric units, as are many of the internal data used by the National Weather Service. The avalanche data network largely receives field reports on weather, snowfall and avalanche sizes in English units and information released for public use also remains in English units. Available topographic maps are also in English units. Wherever quantitative data appear in this report, they are presented in the form customarily used without parenthetical conversions to the other system. This policy is adopted for conciseness and for the convenience of the customary users of the forecasting network. Individual aspects of the project results detailed elsewhere in scientific papers will appear exclusively in metric units.

1.5 Report Emphasis

Two previous reports issued under this Contract, No. 23.2 dated June 1976 and No. 23.3 dated June 1977, have described in detail the organization, instrumentation and communication practices of the central forecasting network. These reports provide the technical information needed for implementation of the network. The present report, No. 23.4, provides the conceptual background and methods of executing the actual avalanche forecasts at the Forecasting Center in Seattle.

2. A THEORETICAL BACKGROUND FOR AVALANCHE FORECASTING

2.1 Introduction

A primary characteristic of conventional avalanche forecasting successfully carried out in many areas of the world today is that its practitioners have a great deal of difficulty explaining just how they do it. The various snow, weather and avalanche parameters that have to be considered seem to be clearly, if not always accurately, understood and are communicated in various avalanche handbooks and manuals. But the intellectual process by which data from the winter environment are combined to produce a decision about snow stability has tended to remain obscure and, therefore, difficult to teach. It obviously improves with experience, but the capacity to learn from experience varies widely with different individuals, while the learning process itself is noticeably accelerated when the forecaster has a direct, personal responsibility for the consequences of his or her forecast decisions. The principal aim of forecasting research in this project has been to elicit the fundamental nature of conventional forecasting skills so that these may be communicated explicitly, identified by objective tests, and if possible, improved.

2.2 The Research Data Base

2.2.1 The Central Avalanche Forecasting Project

As the avalanche forecasting organization developed under the terms of this research contract, the operational forecasters maintained an on-going discussion and analysis of their techniques. As general forecasting principles were adapted to Cascade mountain conditions, a body of experience, both innate and recorded, began to accumulate. At the end of the second forecasting season, this experience was summarized in an algorithm, or decision tree, which outlined the reasoning process used to evaluate present and future snow stability and the influence on this of current and forecasted weather. This algorithm, together with an explanatory discourse, appeared in Report 23.3 documenting the second year of project research. (The algorithm is reproduced here as Figure 8.1.) During the third and final year of research the reasoning process represented by the algorithm, as well as those elicited through discussion and analysis, were identified and compared with conclusions drawn from the other date sources listed below.

2.2.2 Interviews with Skilled Forecasters

Experienced persons in the U. S. Forest Service, ski industry and highway departments throughout the western U. S. were interviewed at length about their forecasting techniques. In addition to project personnel, some twenty-five experts in avalanche forecasting were invited to discuss their methods in personal interviews. The amount of useful information communicated in these interviews varied widely, although the levels of experience and proven skills were uniformly high. In no case was a clear analytical method volunteered in detail, but rather the underlying principles had to be brought out by persistent questioning. The results did point to a common pattern in thought processes.

2.2.3 Compilation of Case Histories

The single most valuable source of data about forecasting methods came from a collection of ten case histories for specific forecasting episodes which had either been recorded in the past by a forecaster or were written in response to a specific request as part of this research. These contributions were all too few in number, for the abilities of introspection, self-analysis and exposition appear only rarely combined in one individual. But the case histories did provide the key insights into the nature of avalanche forecasting. It is not practical to present all the case histories here, but one of them dealing with Pacific northwest snow conditions is a good example of both the kind of information used by the forecaster and the way it was dealt with.

Forecaster's experience: 27 years in wide variety of climates.

Place and time: Paradise Valley, Mt. Rainier, April 1976.

Two days of clear weather had followed a spring snow storm with substantial amounts of new snow at higher elevations on Mt. Rainier. On the morning of the second day, a ski touring trip was made to Paradise Valley. Although the circumstances were ideal for wet snow avalanches (strong solar radiation on south exposures following new snow deposition), by the time Paradise was reached, a clear impression had been formed that little or no avalanching would occur that day. The following observations contributed to this impression:

1) Freezing level in the atmosphere was reported around 1800 m, but there was little melt above 1500 m. At the altitude of Paradise, about 1700 m, there was only limited snow melt even on slopes facing directly south.

2) The only observed avalanche activity on the second clear day after snowfall was some wet snow activity on steep, forested slopes below 1200 m. Only very small sluffing was observed up to 1500 m and no activity at all on south exposures above this altitude, an unusual circumstance given the season and snow conditions.

3) Tahoma and Kautz Creeks, glacier-fed streams, were running clear, indicating that no prolonged melt had been taking place at higher altitudes.

4) A considerable amount of new snow persisted on the rocks on higher parts of Mt. Rainier in spite of the previous sunny day, again indicating little or no melt at higher altitudes.

5) The snow was very bright in the sunlight, indicating a high albedo, characteristic of a snow surface with no free water present.

During the course of the ski tour to an altitude of about 2500 m, further observations confirmed the original impression:

6) North exposures and shaded slopes exhibited cold snow at the surface and poor consolidation of underlying layers.

7) By noon, many slopes showed the gleam of specular reflection associated with firnspiegel formation (a very thin ice layer produced by negative surface heat balance during sunshine).

8) Local, patchy firnspiegel was found everywhere underfoot above the 1700 m level.

9) There was poor spring skiing (the original purpose of the tour as conceived in Seattle) with no corn snow development at all even on the second day of hot spring sun. The snow was soft and unconsolidated under a shallow thaw layer at the surface.

Diverse observations about the state and behavior of the snow cover all had combined to form a meteorological picture of cool, dry air which promoted enough surface evaporation and radiation cooling to keep the snow surface temperature mostly below freezing in spite of intense spring sunlight on the predominantly south-facing slopes. The dominant factor in preventing the normal wet snow avalanches forming from the new snow-sunshine combination, thus, was low atmospheric humidity in the air mass over the southern Cascade Mountains of Western Washington, a factor not readily measurable (the nearest Weather Service radiosonde station is at Quillayute, 250 km to the NW), but which could be inferred from several lines of evidence about snow behavior.

2.3 The Fundamental Forecasting Process

2.3.1 General Observations

Some general observations are first made about the recurring patterns of forecasting exhibited by project personnel, experienced persons and the case histories; patterns that offer clues to the fundamental process involved. This process will then be explicitly identified in section 2.3.2.

1) There are few surprises for the experienced forecaster. Enough inferences can be generated, even about unknown areas and snow conditions, to prepare a reasonable estimate of snow stability before any venture is actually made into avalanche terrain. This is not to say that every avalanche on every individual slope can be accurately foreseen, but rather that the general pattern of snow stability for an area can usually be inferred even from highly indirect evidence. The process requires considerable experience and considerable understanding of the way weather interacts with the snow cover. Preliminary estimates of snow stability are then checked in the field against direct observations of snow behavior and avalanche occurrence.

2) There are no instant avalanche forecasts. There is no fixed formula that will produce a rating of snow stability when fed with arbitrary parameters for snow and weather conditions. The forecasting process, instead, is integrated through time, with evidence accumulating until it points to the prevailing state of the snow cover at a given time and place. This integration process is crucial. It appears in all of the case histories in various forms, and constantly re-appears in the interviews and observations of project performance. The time scale for integration can range all the way from a winter-long tracking of snow cover evolution to an hour or two spent on snow and weather phenomena as illustrated above in Section 2.2.3.

Integration times of weeks or months are common, leading to an often-expressed dislike on the part of avalanche forecasters for interruptions in the continuity of daily observations and forecasts.

3) The sources of information on snow conditions are highly diverse. Visual and kinesthetic observations of the snow cover provide many clues. Weather information plays a frequent role, both concerning current situations and past history for the winter. More direct evidence can be found by testing the mechanical state of the snow cover, with the ultimate expression of this being artificial avalanche release. Past avalanching history for the winter is another essential clue. Knowledge of local climate patterns can fill in many gaps in the observations. These data may be obtained by several routes--direct perception, written records, instruments, telemetry, media reports, even anecdotal and indirect sources. Not everyone will be able to emulate one forecaster's shrewd insight which enabled him to make an accurate forecast on the basis of second-hand accounts picked up in a bar, but such incidents do plainly illustrate the fact that information on snow stability is where you find it. The unifying methodology among workers of widely differing temperament and experience is that they all pursue with great determination every possible avenue for acquiring data about the state of the snow cover. Every available item, no matter how trivial, uncertain or apparently irrelevant, goes into the integration process. Moreover, data are never rejected because they duplicate some already in hand. On the contrary, overlapping, duplicate or redundant data are prized for their value in reinforcing or confirming what may already be known.

4) The diversity of useful data is not random. These data can readily be grouped into three different categories which bear with them distinctly different characteristics and modes of analysis. First, there is the meteorological category, embracing climate considerations and both past and present weather. This provides a wide body of readily available but indirect evidence about the snow cover. Then, there is snow cover itself, whose internal structure and external morphology bear witness in a less indirect fashion to current and potential states of stability. Finally, there is the category related to the actual mechanical state of stresses and strains within the snow, externally expressed through such direct evidence as failure planes, fracture propagation and actual avalanche release. While the first two categories play important roles in preparing general stability evaluations, it is noteworthy that practical decisions regarding public safety, such as the opening or closing of ski runs, the publication of a general avalanche warning or the initiation of avalanche control measures for a mountain highway, most often are based on information from the third category. As will be developed below, there is, in addition to the practical dictates of common sense, a sound theoretical reason for this bias.

5) The phenomenon of data diversity also applies to choices among data made in different locations and circumstances. One kind of forecast may rely heavily on weather data, another on mechanical stability

tests, and still another on visual observations in the field. Or perceptions of climate, weather and snow structure may be combined in different ways from one example to another. The detailed analysis of this question in one case history, where different observers used different data bases to make avalanche forecasts for a common location and winter with equal success, emphasizes this pattern of diversity. There must be considerable overlapping or redundancy of information if the same results can be achieved when different, although intersecting, subsets of data are used as the basis for forecasting. Closer examination of the subsets reveals further redundancy. Field observations are used to confirm meteorologically-based insights, weather history backs up the evidence from internal snow cover structure, or all of these may point to an instability for which actual reports of avalanche occurrence are redundant but reassuring confirmation. In fact the whole integration process described above consists of the cumulative accretion of often redundant pieces of information until a sufficiently reliable picture of snow stability emerges. Moreover, redundancy plays a wide enough role that more than one path of data accretion may be followed. Avalanche forecasting, it seems, is not a simple problem with a single, simple solution. There is more than one way to forecast an avalanche; a phenomenon rooted in the redundnacy of the data base.

2.3.2. Formal Statement of Forecasting Method

The demonstrated picture of avalanche forecasting is, thus, the cumulative integration through time of a widely diverse body of information that leads eventually to reliable knowledge about snow cover stability. This process is intuitively understood and practiced by every successful avalanche forecaster, but there is surprisingly little formal description of it in the literature. Of recent authors, Wilson (1977) has given the clearest expression of the principles involved: "No Single clue will tell you all you need to know; you'll have to be observant, and you'll have to make a continuing evaluation" (emphasis added).

If different people can use different subsets of data with equal success to perform the same task, is there, in fact, a single process that can be called "avalanche forecasting"? The answer is yes. First, let it be emphasized once more: the process as actually practiced is intuitive and only reluctantly described by its practioners; the examples of explicitly described methods elicited during this study are rare and hard to come by. There is common use of such terms as "seat of the pants," "feel for the snow" or "gut reaction." But on careful analysis an identifiable pattern does begin to take shape. The steps in avalanche forecasting are these:

1) Available data are collected about the place and time in question. Some of these data may be vague, anecdotal or general in nature (second-hand reports, climatology, past weather trends), while others may be quite precise (snowfall records, avalanche records, weather maps).

2) A hypothesis about snow stability is formed on the basis of the initially available data. (A first estimate may see an unstable snow pattern or the amount of snow required to overload a slope may be anticipated.)

3) The hypothesis is tested through observation and experiment. (Field checks are made for avalanche occurrence, mechanical tests are made for failure planes in new snow, or artificial release is attempted.)

4) On the basis of the tests, the hypothesis is confirmed or revised. This test-revision process may be repeated a number of times over time spans ranging anywhere from hours to months, if a sufficiently reliable picture about snow stability has not yet emerged.

5) Finally, the hypothesis is revised or confirmed to the point that it is seen to represent current reality of the snow cover. An evaluation or prediction is made. (Safe slopes are selected for skiing, a degree of hazard is estimated, or an avalanche warning is issued.)

6) Actual avalanche occurrences (or non-occurrences) are monitored to check prediction accuracy.

Even though the whole process if often compressed at the expense of one or more steps, it is still clearly recognizable as inductive logic of the scientific method. Induction may proceed by a number of paths and heretofore it has been done largely at the intuitive level with little guidance from rational analysis. Avalanche forecasting as actually practiced, thus, does not work from the premises of deductive logic, arguing that each specific instance of snow stability can be deduced from general rules about snow mechanics and avalanche formation. Instead it combines varying sets of minute particulars by inductive logic to reformulate again and again specific states of snow stability. The scientific method itself, rather than one or more specific mathematical constructs, emerges as the theoretical model for avalanche forecasting.

2.4 The Role of Iteration in Avalanche Forecasting

The inductive logic pattern identified above, and its cumulative integration through time to produce an avalanche forecast, is basically an iterative process where repeated feedback from observations refines an initial snow stability estimate until presumably it converges with reality. In the case of the field estimate of snow stability made for ski touring or other local and transient purposes, the iteration may be blurred when the full exercise of inductive logic becomes telescoped by time limits and a meager data base. In the case of a central forecasting office like the one developed under this project, daily forecasts are prepared for the same geographical region throughout each winter and iteration is fully developed as an on-going process that revises each day's forecast on the basis of expected weather for the next day.

An initial stability estimate taken as the starting point for a forecast must thus be made de novo for random or transient situations. For a forecasting scheme working throughout a winter, it is continually reconstructed from the previous day's forecast and the report of subsequent snow cover evolution including avalanche falls. In either case the initial estimate crystallizes the state of the forecaster's prior knowledge concerning snow conditions. Information flow from the field--weather observations, snow data, avalanche occurrence records--then furnishes the basis for improving this state of knowledge in the case of a stability evaluation (in the sense defined by Perla and Martinelli, 1975) or projecting it into the future in the case of a true forecast. If the state of prior knowledge is poor, then most data elements reaching the forecaster will improve it and the information flow is high. On the other hand, if prior knowledge is excellent, that is, the current conditions of snow stability are known with hign accuracy, then little information is communicated no matter how dense the flow of data elements from the natural environment. The above syllogism states an elementary concept of information theory (Shannon, 1948), that the uncertainty, or entropy, associated with any act of communication diminishes with prior knowledge on the part of the receptor. If prior knowledge is complete, no information is communicated because the message is already known. Applied to avalanche forecasting, this means continually tracking weather, snow and avalanche conditions as they evolve so each new data event changes the picture as little as possible. Put another way, the overall strategy is to minimize the uncertainty introduced by each daily increment of change in snow and weather conditions. The working forecaster pursues this strategy through an iterative process that begins with the first snowfall each year and continues throughout the winter. Continuity is essential, for each day's stability estimate builds incrementally from that for the previous day. When continuity is broken, the level of prior knowledge for any given day drops abruptly and the forecaster must exert extra effort to rebuild it following the break in the chain of iteration. Perfect prior knowledge, with the information content of incoming data reduced to zero, is the ideal goal, never achieved but always pursued. Practical means for applying this iterative strategy to forecasting avalanches in the Cascade Mountains are introduced in Section 8.

Recognition of the above principles at work in conventional avalanche forecasting now leads to a primary axiom: Each avalanche forecast, each stability evaluation, for any path, at any time, begins with the first snowfall of winter.

2.5 The Role of Redundancy in Avalanche Forecasting

Review of findings given in 2.3.1, paragraph (5), has placed emphasis on many examples of redundancy among the data used for avalanche forecasting. While at first glance this might be taken to signify some data elements are unnecessary, the fact that overlapping or complimentary elements appear so frequently and are universally sought by diverse forecasters suggests that this phenomenon must perform a real function in heretofore obscure forecasting procedures.

The forecaster receives from nature, either by direct observation or indirect report, elements of information about snow stability. Seldom does each individual element bear the entire message about the current state of nature. Each brings with it an imperfect message. A temperature trend, for instance, may speak of changing viscosity and tensile strength of a slab layer but does not by itself announce the imminent fall of an avalanche. Accumulation of new snow tells of increasing stress on the snowpack, but does not by itself speak of the load-bearing capacity of the pack to sustain the stress. It is only when these elements and others combine that the forecaster can see an emerging picture of current or projected avalanche conditions. A single information element leaves a high degree of uncertainty about snow stability, but as more elements accumulate this uncertainty diminishes until reasonable confidence exists about the present state of nature. The message, in other words, finally gets through. This process is one of the two ways in which reliable communication can be assured, and it is called redundancy. Each individual message element is defective in that it does not bear the whole story, but the defects of the total message, in this case information about a state of nature, diminishes as redundancy increases. Entropy (uncertainty) is minimized.

The other way in which information can be reliably transmitted in such a situation is to eliminate all the possible messages except one, the correct one. This situation is approximated in avalanche forecasting when an avalanche fall is reported, for then the knowledge about snow stability for a particular path becomes unequivocal. The elimination, of course, is complete only for that particular path; the approximation enters when the firm knowledge about snow stability thus obtained is extended in time, as well as space, to other, adjacent paths. When avalanches do not fall, redundancy is the route to eliminating uncertaintly.

Because the role of redundancy arises at the intuitive level wherever avalanche forecasting is practiced, it might be expected that this reflects a basic attribute of human intelligence when dealing with complex natural phenomena. An extensive body of research in psychology by Garner (1974, 1975) supports this expectation. In his later work, Garner showed, from the basis of extensive tests for perception and pattern recognition in human subjects, that there were two basic limitations on perceiving and assimilating information. He termed these "state limitations" and "process limitations." A state limitation interferes with a given stimulus getting through to the subject and is shown to diminish with simple redundancy, or repetition, of the stimulus. Collection of numerous snowfall measurements to overcome natural variations or observation errors is an obvious example from avalanche forecasting; the "state limitation" for snowfall data is clear and no one depends on a single measurement.

A process limitation refers to the subject's difficulties in recognizing or analyzing a stimulus clearly received. Redundancy again turns out to be the countermeasure, this time in several different ways. Two redundant dimensions of stimuli may combine to form a new dimension easier to apprehend than either alone. Redundancy among stimuli can make it easier for the receptor to deal in memory with a large set of alternatives. Redundant dimensions are also shown to facilitate integration of numeric information, especially if two different dimensions appear in sequence. An obvious application again can be found in avalanche forecasting when several different lines of evidence about snow stability are considered, such as statistical records, contributory factor analysis and field reports on fracture propagation in snow. A reinforcing mechanism takes place to surmount the process limitations for interpreting each evidence individually.

Garner based his conclusions on extensive laboratory tests of pattern recognition, predominantly for geometrical figures. A bold extension is made here to the more complex and varied stimuli flowing from the natural environment to the analyst. The analogy obviously is far from exact, but the underlying psychological principle shown to inhere in the way subjects deal with stimuli (data or information) by responding positively to several forms of redundancy, fits the intuitive nature of conventional avalanche forecasting like a glove.

2.6 The Entropy Principle for Data Classification

The constantly recurring theme in all avalanche evaluations and forecasts is reference to weather, snow conditions, and avalanche occurrence. These are the three main data pillars that support the edifice of forecasting. Each has its own characteristics, usefullness and mode of analysis. The summary of conclusions given in 2.3.1, paragraphs 4 and 5, has reinforced this theme and expanded the concept of the third type of data to include other evidence about the mechanical state of the snow besides actual avalanche falls. The first step toward developing a formal distinction between the three basic kinds of data will be made here by introducing in Figure 2.1 a diagram showing the functional relationship between the data categories and the paths of information flow to the forecaster. Details given in this diagram will be clarified as the present discussion evolves.

Following conventions of set theory, the groupings of elements in Figure 2.1 are designated data spaces. (A space is an n-dimensional manifold in which elements of a representation can be ordered.) A data space is made up of series of event classes, each class consisting of a number of elementary events. The three principal data categories are designated as meteorology space, snow structure space and snow mechanics space respectively. An example of an event class in meteorology space is air temperature, which includes many possible elementary

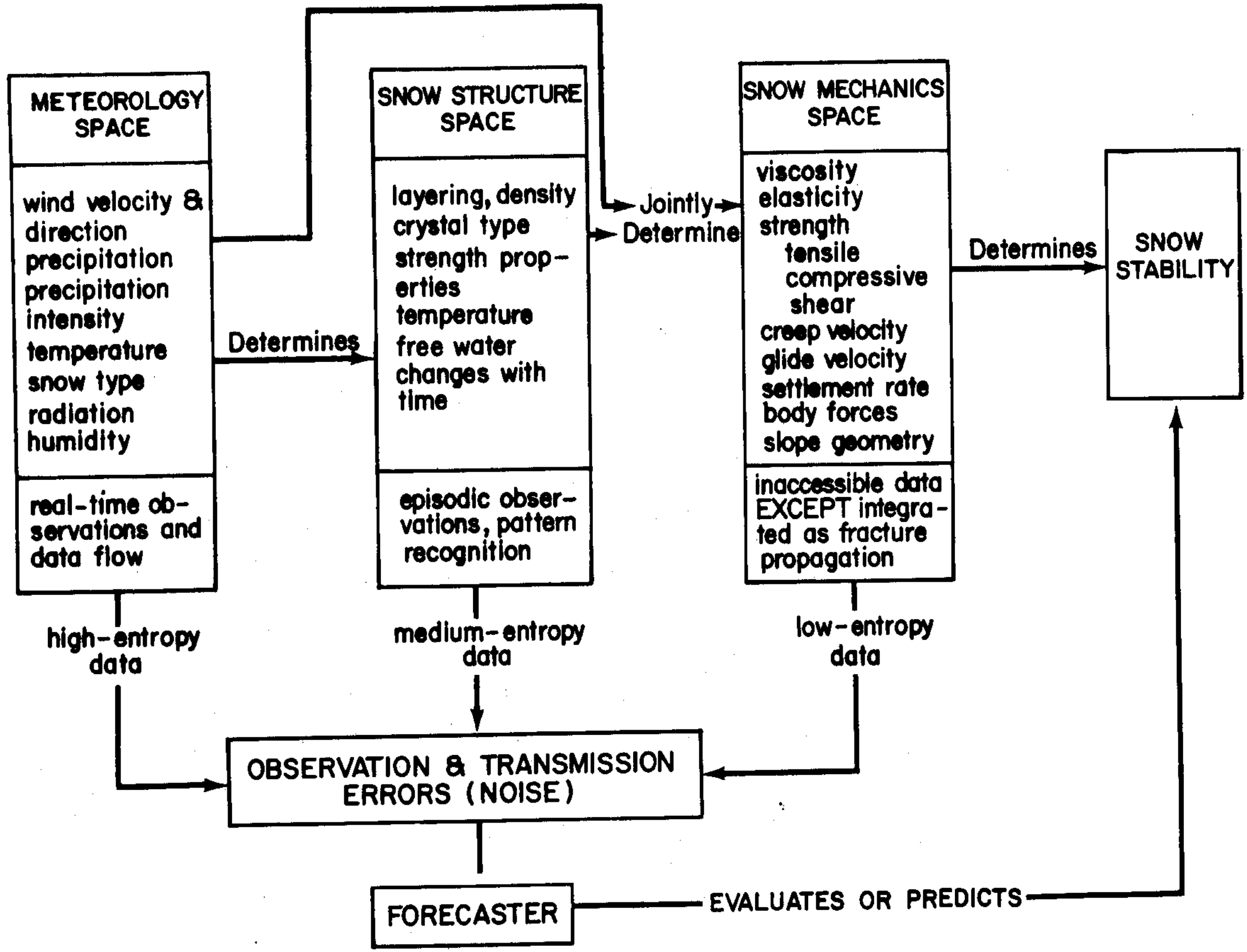


FIGURE 2.1 Data categories available from the natural environment, their causal relationship to snow stability and the paths of transmission to the avalanche forecaster.

events according to the climatological temperature range and the precision with which it is measured. Avalanche occurrence is an event class in snow mechanics space, but consists of only two elementary events for a given path, the fall or non-fall of an avalanche. Meteorology space embraces the data about the external atmosphere and includes normal synoptic weather observations, as well as specialized records of snowfall characteristics or other local conditions collected explicitly for avalanche forecasting. The body of data in meteorology space is large, often exists in the form of historical records and is the principal source of observations for statistical analysis of avalanche formation (see Section 3). Snow structure space embraces the data obtained by observing snow cover layering, temperature, crystal type, density, and the like. Details of these observations and their interpretation are discussed at length in section 5. The collected body of data in snow structure space is extremely limited and practically no systematic historical records exist except at a very few snow study sites throughout the world. Most such data the forecaster encounters are locally and sporadically collected for the express purpose of interpreting snow stability.

Snow mechanics space in the present context has a double significance. Snow mechanics in the strict sense includes the body of data about stresses, strains, and mechanical properties like shear strength or viscosity. If these were known in detail, presumably the state of snow stability could in principle be deduced. But such data are precisely those most difficult to obtain, expecially on a real-time basis, as avalanche conditions develop during a storm. The effects, however, of interacting stress and strength are expressed as readily-observable behavior of snow: the development of failure planes in test samples, abrupt settlement and fracture propagation in the snow cover and avalanche release itself. It is these latter consequences, or integrated results, of mechanical states that here are subsumed under the heading of snow mechanics space.

The repeated, instinctive sorting of data by empirical avalanche forecasters into the three spaces shown in Figure 2.1 suggests that fundamental differences exist among these categories. In the terminology given above, these differences can be stated as follows: Moving from left to right in the Figure 2.1 diagram, the data spaces embrace successively fewer event classes and especially fewer elementary events in each class. Meteorology space, on one hand, has many richly-populated event classes, such as air temperature or wind velocity with many possible values, while at the other end of the diagram, snow mechanics space in its integrated form has a few event classes consisting of two or at most three elementary events, such as the occurrence or non-occurrence of an avalanche. Snow structure space falls between these extremes. It is obvious that an event class in meteorological space has many more degrees of freedom for data representation than does an event class in snow mechanics space. The information transmitted to the forecaster from one data space is thus seen to have a quite different quality than that from another space.

The differences in information from the separate data spaces can be quantified by reference again to the fundamentals of information theory. In this context it is important at the start to emphasize the special meaning of the term "information" used in this context. It does not in the usual semantic sense mean a quantity of knowledge that may be conveyed by an act of communication, but rather it measures the degree of uncertainty on the part of the message receptor about what is going to be conveyed. To take an example, a large and complex body of data about snow depth distribution to a mountainous area conveys zero information to an avalanche forecaster who already knows what this distribution may be. The same data, on the other hand, has a very high information content for another forecaster who is in a state of complete uncertainty about the same snow depth distribution. A quantitative measure of information is thus related directly to the amount of prevailing uncertainty on the part of the receptor. Garner (1974) has given a lucid summary of this concept from a slightly different point of view: "The amount of information obtained from any event or act of communication is not a function of what does happen; rather it is a function of what could have happened, but didn't." The actual quantity of information is defined mathematically as the average logarithm of the improbability of a message (Shannon, 1948):

$$H = -\sum_{0 \to i} p_i \log_2 p_i$$

where H is the measure of information in bits (binary digits) and p is the probability of each individual message element. In the context of the concepts presented in Figure 2.1, if an event class in one of the data spaces consists of i elementary events, then each of these has a probability p_1, p_2, p_3.....p_i and the amount of uncertainty associated with a single communicated datum about the event class if given by H.

Various authors have given different names to H: uncertainty, originality, entropy of selection, selective information content. Shannon's original paper cited above used the simple term "entropy" because the expression for H had the same form as that for entropy in statistical mechanics and this term is adopted here.

A further distinction in terms now needs to be recognized, for some authors have also suggested separate, and varying, terms for the value of i, or the number of identifiable, independent modes in which information (data, messages) can vary. The term <u>potential information</u> will be used here for i. The amount of information, or entropy, is defined by H, while Garner's body of events "that could have happened, but didn't" is the potential information. The expression for H given above defines the functional relation between these two quantities.

A fundamental feature in Figure 2.1 can now be identified: the amount of entropy associated with each data space decreases from left to right. The significance of this fact for avalanche forecasting will be analyzed below. Examples of calculating actual H-values for various kinds of avalanche forecasting data are given in the Appendix.

2.7 Applications to Avalanche Forecasting

2.7.1 The Relation of Data Entropy to Forecasting Experience

The amount of experience and technical sophistication about weather and snow required for avalanche forecasting is directly proportional to the potential information of the data source. In the case of snow mechanics space where the degrees of freedom or potential information are low for such features as avalanche occurrence or fracture propagation in snow (event classes contain few elementary events), interpreting the data is simple. It takes no experience whatsoever to recognize an unstable snow condition when an avalanche is actually seen to fall and even the most casual-minded skier very quickly learns the survival value of paying attention to visible, audible or kinesthetic evidence of fracturing. Meteorology space, on the other hand, abounds with features exhibiting high potential information, for the degrees of freedom in the data are large (event classes are thickly populated) and there are many things that "could have happened, but didn't." Determining how a given sequence of weather patterns affects radiation balance of the snow cover, hence its temperature and hence the kind and amount of metamorphism, requires a good knowledge of snow and atmospheric physics, as well as general meteorology. So does the intepretation of precipitation patterns in time and space. The forecaster who deals with such data has to draw on a reservoir of knowledge and experience to cope with the problem. Probably the commonest mistake of well-intentioned but untrained people anxious to evaluate or forecast snow stability is to begin by trying to interpret meteorological and complex snow structure data. Such efforts are often lost in a sea of potential information. This is not to say that highly practical meteorological rules of thumb (e.g., "beware of rain on a layer of new snow") should be ignored, but rather that detailed interpretations and projections about snow stability can easily go astray when the knowledge-experience reservoir is small.

2.7.2 Low-Entropy Meteorological Data

Not all the event classes in meteorology space have a rich population of elementary events. There is one class that has very low potential information and that is a change in the weather. In general terms, it does not matter what the change is as long as some aspect of current meteorology undergoes a change. This reduces to the low-entropy case of $H = 1$ for there are only two possible events--either the weather changes or it doesn't. This situation is highly relevant for avalanche forecasting, for most avalanche situations develop when there is a change in the weather or, to be more precise, a change in the mechanical or thermal energy state of the snow cover. Many of the important rules of thumb--for instance the one advising "beware of rain on a layer of new snow" mentioned above--actually address one facet or another of weather changes and, hence, rank right alongside data from snow mechanics space in providing useful information about snow stability. The fact that the temperature this morning is -5°C is a rather equivocal high-entropy piece of information to an avalanche forecaster, but the fact that it fell 10° from a previous value of +5° some 12 hours earlier is highly instructive about snow stability.

2.7.3 Information Flow Patterns and Feedback

The amount of entropy a forecaster has to deal with obviously is going to depend on his posture in respect to the flow of available data. The office-based forecaster works with a flow of high-entropy data predominantly in meteorology space but supplements this with snow structure information whenever possible.

Low entropy data from snow mechanics space is not directly accessible but is highly valued when forwarded from the field by reliable observers. The field worker on the other hand, has direct and frequent access to snow mechanics space, especially when avalanche control by artificial release is routinely practiced. The latter deals with a much lower level of entropy, a preferred position when practical safety decisions such as opening or closing a ski run or a highway need to be made. The office-based forecaster usually depends on a much broader base of information to reach reliable decisions about snow stability, reflecting the application of redundancy as a principle for reducing entropy. Figure 2.2 summarizes these concepts graphically.

Prediction models can be made more functional by the introduction of feedback, a short-term variant of the basic iteration process. This means that a forecast does not remain static, but can be continually revised and improved by feedback of data from nature. In the case of avalanche forecasting, it is useful to distinguish the difference between active and passive feedback, for these involve quite different processes of predicting avalanche behavior. The office-based forecaster is involved in the passive feedback system. He prepares a forecast, then waits passively for data return from the field. This return may consist of late developments in weather or snow structure evolution or may be actual reports of avalanche occurrence. The forecast can then be modified accordingly, with the disadvantage that modifications based on avalanche occurrence reports may come too late to be useful unless they involve the tracking of storm-generated avalanches across a wide geographical area. The field evaluator, on the other hand, has the opportunity to obtain active feedback of information on snow stability by putting his estimate of snow conditions to a real-time test. In terms of operational research theory (Rivett, 1972), this means that the forecasting model involves control as well as prediction. The test usually means artificial

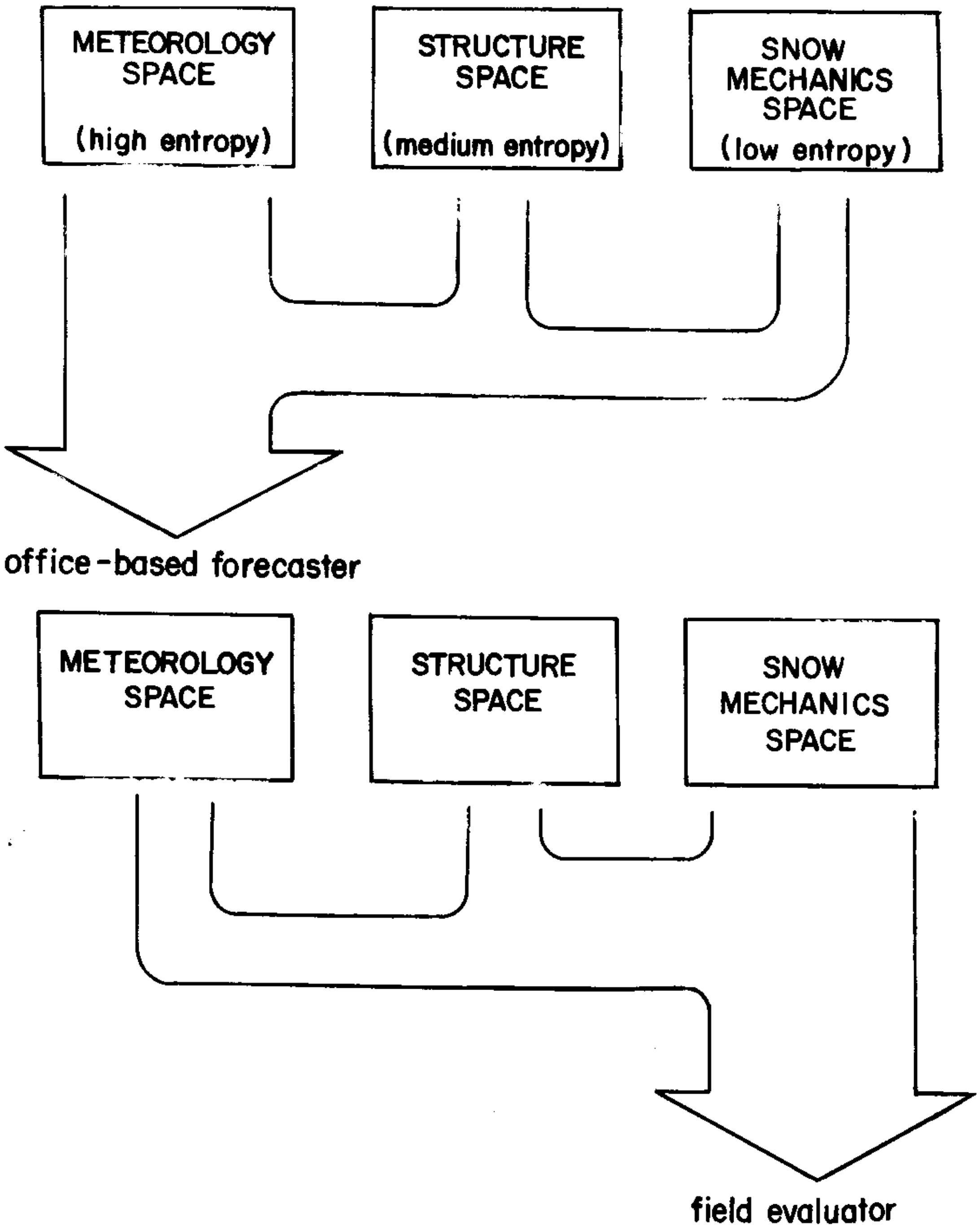


FIGURE 2.2 The relative amounts of high, medium and low entropy information available for two basically different types of avalanche forecasting.

release measures or test-skiing activities to observe the mechanical behavior of snow following lesser degrees of disturbance. In the latter cases the feed-back loop involves low-entropy information in snow mechanics space, hence it provides much stronger validation of the evaluation or forecast.

2.7.4 Instrument and Data Transmission Design

Present techniques in avalanche forecasting often expose the forecaster to an unnecessarily large body of potential information, thereby introducing undesirable excess entropy. Careful design of instruments or data-collection systems with a view to reducing unnecessary entropy can simplify both the data collection and the forecasting logic based on it. A good example is wind velocity, which is normally observed with standard anemometers producing a velocity continuum subdivided by convenient units such as miles per hour or knots. From the avalanche forecasting standpoint, there is little advantage in being able to distinguish between, say, winds of 17 and 18 mph. The major distinction of importance is between winds that transport a lot, moderate, little or no amounts of snow. This can easily be related to wind force on the Beaufort scale, hence an anemometer (or conversion unit) that provides a wind output based on this scale would drastically reduce the number of elementary events in the event class "wind", thus reducing the potential information and the associated entropy. The same concept applies to temperature. Small differences in air or snow temperature are critical in the vicinity of the freezing point, but become much less important at temperatures departing widely from this vicinity. The forecaster gains very little in learning that the air temperature is -12° instead of -13° except an excess of unwanted potential information and entropy.

An independent confirmation for the principle of selecting data to minimize potential information is found in section 5, where extensive application of cluster analysis techniques to evaluating the significant elements in snow cover profiles has shown that the most reliable predictors of failure plane locations in a snow cover are the hand hardness test and snow crystal types. While these parameters suffer the apparent disadvantage of being the most subjectively observed ones, they are also precisely those parameters (event classes) in snow structure space with the lowest potential information.

2.8 The Underlying Principle in Avalanche Forecasting

This present study has sought to understand the nature of conventional avalanche forecasting as widely practiced today. The practioners commonly develop a real skill on the basis of empirical experience, a knowledge of basic snow behavior and a healthy measure of intuition. The insights set forth in this chapter point to an underlying structure to the whole forecasting process. Application of inductive logic, reaching a decision about snow stability, the selection of data from the natural environment and the widespread appeal to redundancy all embrace a common feature that constantly appears by unconscious choice. This feature which forms the underlying principle in avalanche forecasting, is the act of minimizing entropy.

3. STATISTICAL APPLICATIONS FOR AVALANCHE FORECASTING

3.1 Introduction

The advent of high speed computers in the 1950's and the subsequent development of powerful statistical methods of processing and interpreting data using computers in the 1960's and 70's have opened up a more quantitative approach to avalanche forecasting. Numerous researchers have applied various statistical tools to meteorological and snowpack observations attempting to arrive at a reliable forecast model. Most of these researchers have approached the problem in three steps: One, several different statistical methods are tried; two, the optimal combination of meteorological and snowpack variables is selected (ordinarily a different set with each individual statistical method); and three, a representative avalanche "index" is developed, i.e., a dependent variable is created that is considered indicative of the level of avalanche activity.

The purpose here is to review and evaluate the available statistical forecasting models to determine which schemes hold the most promise for the avalanche situations which prevail in the Washington Cascades and Olympics.

3.2 Statistical Methods

Six types of statistical analysis have been predominantly used in producing avalanche forecasting models: regression analysis, factor analysis, discriminant analysis, cluster analysis, local dynamic models, and time series. These have been applied either individually or in combination with one or more of the other techniques.

3.2.1 Regression Analysis

Regression analysis is concerned with finding the relationship between one or several independent variables and some continuous dependent variable. As avalanche occurrence is essentially a "yes or no" phenomena (i.e., a nominal level variable in statistical venacular), it is normally modified in some fashion into a continuous variable. This has been done by counting the number of avalanches on a given day and by preparing an artificial avalanche hazard probability. Difficulties exist with this method in that the validity of the new avalanche hazard variables is often questionable, and its form is such that is is almost always a constant close to zero.

3.2.2 Factor Analysis

Factor analysis is always applied in combination with one of the other statistical techniques, ordinarily discriminant analysis. It is used primarily to find relationships among a group of variables and to construct new "independent" variables. This analysis is carried out using the method of principle components. This method determines which linear combination of the variables best explains the total variance of the group. Next the second best linear combination is found with the stipulation that it be orthogonal to the first. This process is carried out until all of the variance is explained or, more often, until only a small improvement in the explanation of the variance is obtained with each new component (i.e., orthogonal linear combination). This results in a set of variables that are entirely independent of each other or what is called a set or principle components. In this analysis, it is not necessary to separate independent from dependent variables unless they are differing level variables.

3.2.3 Discriminant Analysis

Discriminant analysis assumes that subclassifications exist within a population of dependent variables that can be differentiated by some unique linear combination of independent variables. This technique seems to lend itself well to avalanche forecasting as it is efficient in handling variables of one type routinely recorded in avalanche work. The idea behind discriminant analysis is that given some research subject population (e.g., objects, events, people, etc.) which resolves itself into distinct groups or sub-populations, it is possible to discriminate between these groups by using a set of suitably combined variables. Discriminant analysis then resolves itself into two parts: the selection of the best combination of discriminating variables, and then, the classification of new, unknown subjects into their appropriate groups based solely upon the derived set of discriminating variables. Most research in avalanche forecasting using discriminant analysis has involved choosing the best discriminating variables and developing the optimal avalanche index to associate with them.

3.2.4 Cluster Analysis

Cluster analysis in its simplest terms attempts to establish the number of distinct groups into which population may be separated. No previous assumptions need be made about the characteristics of the groups. The avalanche situation each day may be characterized by n meteorological and/or snowpack observations. In the analysis, those days characterized by similar measurements are grouped together in an n-dimensional sample space. Various criteria and iterative methods are applied to obtain a set of "p" clusters which are distinct in sample space.

3.2.5 Non Parametric Local Dynamic Models

This method makes essentially the opposite assumption from that made in cluster analysis; namely, it assumes that there are no truly distinct groups in sample space, but rather only changing, but continuous, concentrations of points. In the analysis the position of a given day (object, etc.) is noted in sample space. All other days (objects, etc.) within a predetermined radius are then extracted. Usually some characteristic is being sought (e.g., the occurrence of avalanches), in which case the probability of the occurrence of that characteristic is expressed in terms of the number of neighbors in which this characteristic is found. The most difficult part of this analysis is determining the optimal size for the radius of extraction in sample space.

3.2.6 Time Series

The time series methods which have been applied to avalanche forecasting are closely related to those employed in controlling industrial processes through feedback. These methods develop a mathematical model which can be used to forecast the behavior of a system based on its past performance and its current inputs. The approach is somewhat different from the usual time series as it does not assume any type of cyclical behavior or trends--although these can be incorporated into the models--but instead it attempts to develop a stochastic model which will respond in a fashion statistically similar to the real system. This method results in a forecast equation which gives the expected value for a desired parameter in terms of a linearly weighted combination of current and previously occurring quantities. As there are several distinct forms of time series models available, analysis consists primarily of selecting the best model and, subsequently deriving the appropriate weights for the forecast equation from the available data. This type of analysis requires that the forecast variable be more than a binary variable, although mathematically it can be either discrete or continuous.

3.3 A Review of Recent Research

Some of the first quantitative work done in relating avalanche occurrence to a set of independent variables was accomplished by Perla (1970). Strictly speaking, this work did not require the computation of regression relations and was not truly a predictive model. Rather, it was more of a test of the strength of the relationship between the set of ten contributory factors proposed by Atwater (1954) and an avalanche index. In a sense this was a graphical cross between regression and factor analysis. Perla used 19 years of data (1950-1969) from Alta, which consisted of 107 storm periods.

3.3.1 Perla (1970)

Perla's general conclusion is "the probability of avalanche hazard varies considerably with precipitation and wind direction and only slightly with temperature change and seems to have no definite relation to wind speed or settlement rate." He also notes that a stronger relationship appears to exist between maximum precipitation intensity than to average precipitation intensity, from which he concludes that the snowpack is sensitive to the rate of loading.

Perla's analysis was a significant first step in relating avalanche hazard to measurable quantities; however, the graphical analyses were only a step above the empirical findings of Atwater. It did have the net effect of confirming that some of the proposed factors had some statistical relationship to the occurrence of avalanches while it cast doubts on others, at least for the paths under consideration.

One difficulty, which keeps occurring in all of the statistical techniques examined is the highly correlated nature of many of the independent variables. This consistently poses the problem that the effects of one variable on the occurrence of avalanches cannot be easily separated from that of another.

3.3.2 Judson and Erickson (1973)

The work of Judson and Erickson (1973) can best be broken into two parts: the first deals mainly with univariate regression and variable selection; the second deals with discriminant analysis.

Judson and Erickson carried Perla's analysis further to the computation of regression relations and the consideration of a larger group of contributory factors. They initially used seven winters of data (1963-1970) from the Central Rockies. They used data on 23 slide paths, 19 of which were controlled. Weather data were taken from Berthoud Pass. The total number of avalanches on the 23 paths was counted, regardless of size, and plotted as a simple function of weather factors or simple combinations of weather factors. On the basis of these plots some of the factors were rejected and the remainder kept for further analysis.

The variables that were judged to be significant were then subjected to a univariate regression analysis for 81 storm periods between 1963-1970. From this analysis, the authors found that the sum of the maximum precipitation intensities for each 6 hour period multiplied by a constant for excess wind speed (constant = 1 for less than 27 mph, constant = .3 for greater than or equal to 27 mph) gave the best results. They named this the storm index; it gave a correlation of 0.85 with a standard deviation of 2.5 for the data considered. Results for other variables were not given.

A subsequent test of the storm index for 20 storms during the winter of 1971-72 showed a fair amount of agreement between this index and the number of slides on the 23 paths . The main difficulty in evaluating the usefulness of the work of Judson and Erickson lies in the obscure definition of their storm index. It is unclear when during a storm the predictor (i.e., the storm index) should be evaluated, and, further, it is unclear to what period it applies. Unless the number that the regression equation is computing can be given a better intrepretation, their storm index cannot be considered of much value in operational work.

Regression analysis has only been applied in a rather limited fashion to avalanche forecasting, being confined to linear, univariate analysis. It has served principally as an aid in identifying variables which are indicative of avalanche activity. Since we are dealing with a very complex phenomena which has a complicated relationship to the variables that are being used to predict it, it would seem that a more rigorous application of regression analysis would be in order. It is unfortunate that no one has apparently attempted a multivariate regression analysis which would allow the simultaneous usage of all of the information available. This could also be carried one step further by applying non-linear multivariate regression analysis to the data. These types of analyses would yield more complete information on the strengths of relationships between avalanche occurrence and the contributory variables.

In order to use regression relations directly as forecast aids, we will require two improvements. First, it will be necessary to break the "count" period down in some fashion so that the number produced by the relation will have some useful meaning to a forecaster. Secondly, the number forecast by this type or regression relation will only be a predictive number if the relation is supplied with forecast meteorological variables, otherwise it will only serve as an evaluator of past events.

One of the earlier applications of discriminant analysis was by Judson and Erickson in their 1973 article. They used the results of a univariate analysis (previously described) to select 13 variables--meteorological variables and simple combinations of meteorological variables--to be submitted to discriminant analysis. The authors chose to study the avalanche activity individually on each of "10 well defined, controlled paths." They examined the period 11/15-4/15 during the winters from 1952-1971. The cutoff date of 4/15 was chosen to minimize radiation effects and to avoid the wet avalanche season. Judson and Erickson chose their groups to consist of: stable days, days on which control work produced no avalanches and there were no natural slides on a given slide path; and, unstable days, days on which there was either a natural slide or a slide triggered by control work on a given path. A day was labeled as either stable or unstable individually for each path. They then developed separate discriminant functions for each of the paths, submitting the same variables for discriminant analysis.

Judson and Erickson studied the paths for intervals between control efforts or natural releases on each of the slide paths. Discriminant functions which were statistically significant were derived for 8 of the 10 paths. Two of the paths proved to have incomplete data on the avalanche activity. From the stepwise selection the authors found three significant variables:

Sum of 6 hourly negative departures from 20°F.

Sum of maximum consecutive 3 hour precipitation intensity within each 6 hour period decayed over the interval. (The decay is accomplished by multipying the P.I.'s by 1 for the first two days, decreasing to 0.5 by fifth day, and to a constant 0.2 by the ninth day.)

Sum of windspeeds greater than 15 mph resolved to an optimal direction for each path.

They noted that the second variable dominated on five paths whereas the third dominated on three of the paths. Interestingly, they note that the three chosen variables do a better job of predicting avalanche days than the original 13. Further they note that the paths which run least often have the strongest temperature dependences in their discriminate analysis. Finally, the authors felt that the discriminant functions for these paths could be used as a predictor of avalanche activity over the surrounding 100 square miles.

The chief difficulty in Judson and Erickson's analysis is their development of discriminant functions for individual paths. Although this has the advantage of homogeneity in the physical conditions the "research subject" will experience, it drastically reduced the size of the data sample. The assumption of normal distribution of avalanche days, normally only loosely adhered to in larger samples, becomes highly suspect in small samples due to the increased influence of sampling errors. It would seem more fruitful to choose a group of paths with similar physical attributes and similar release behavior.

3.3.3 Bois and Obled (197x)

Bois and Obled (197x) began with a lengthy preparation of the variables to be submitted to discriminant analysis. They applied factor analysis to create a set of 10 variables from a set of 17 prescreened variables. These 10 variables described 92% of the total variance of the 17 variables, this giving a more compact description of the phenomena. They argued that their set of variables was particularly suited to discriminant analysis due to its orthogonal nature and the more symmetric distributions of the variables--these characteristics better satisfying the assumptions of discriminant analysis.

The authors analyzed 15 winters of data for 1954-1969 from Davos, considering only naturally occurring slides. They chose three classifications of groups; 1) days with dry avalanches, 2) days with wet avalanches, and, 3) days without avalanches. They chose from their group of days without avalanches a sample group which more closely approximated the number of days with avalanches. This presumably will yield a group whose variance-covariance matrices would more closely resemble that of the avalanche days since the likelihood of sampling errors is more nearly equal if groups are of similar sizes.

Using these groups the authors then developed discriminant functions in several different fashions. They developed two-group discriminant functions for dry avalanche days versus non-avalanche days. They then modified this work in two ways. They randomly chose three different sets of days from the total data set and computed three different discriminant functions to test for differences in the weighting factors due simply to the samples chosen. Also, they inputted a priori probabilities of group membership into the functions. This analysis produced discriminant functions that gave probabilities of inclusion into both groups. Unfortunately, they did not describe how they derived these probabilities.

The authors found the variations in the computed weights in the three different discriminant functions to vary by as much as 50% or more for the most important variables. They did not comment on this; however, it would seem that much of the observed variation could be attributed to sampling variability due to the small samples they worked with. The fact that they diminished their sample size by one-third to perform this experiment probably invalidates their results. (Note that the total number of avalanche days available was only 68 which left about 23 days apiece for each of the test samples.) No results were given for the results of inputting a priori probabilities into these groups.

The authors also developed discriminant functions for the case of three groups; that is, days with wet avalanches, days with dry avalanches, and days without avalanches. Again they introduced a priori probabilities to modify the disciminant function classifications. These probabilities varied from month to month; for example, the a priori probabilities for January of any day being a day with a dry slide, a wet slide, or no slides are 13.7%, 1.2%, and 85%, respectively, and similarly for March 7%, 7%, and 86%, respectively. The authors noted that for months where a given type of slide predominated, these probabilities had the effect of causing an underestimate of the occurrence of the other type of slide.

The success of the developed discriminant functions is not well discussed. The authors show several graphical examples; however, they gave no overall figures for the study. Additionally, the tests they did run were only for periods from which the discriminant functions were derived, hence this was not a good test of the application of their functions to forecasting. No discussion was given of the behavior of the discriminant function derivation using their highly modified input variables.

3.3.4 Bois, et al.(1975)

The paper of Bois, et al. (1975) represents a considerable refinement of work of Bois and Obled (197x). They begin with a set of elaborated variables, which is simply the raw meteorological variables in various simple combinations.

They considered two groups at a time; that is, they considered dry avalanche days versus non-avalanche days, and wet avalanche days versus non-avalanche days, confining themselves to only natural releases. Also, the analyses were performed on a month by month basis to alleviate any seasonal variations, thus they computed different discriminant functions each month for each of these groups.

Two different sets of discriminant functions were developed using two sets of variables. These sets were formed by applying two statistical tests of significance in the selection of the "best discriminating" variable, namely, the Wilkes U test and the Mahalanobis' D^2 test.

The authors found that both criteria showed that the bulk of the discrimination is contained in 8-10 variables. Further, the authors noted that the different selection methods chose different variables; however, the changes consisted of highly correlated variables replacing each other, so that the methods point towards the same physical processes preceding avalanche activity.

The authors next tested the ability of the two discriminant functions to forecast avalanche occurrences. They used data from two winters not included in the development of the functions. The authors generally found that the two functions behaved similarly though the one produced using Mahalanobis test gave a somewhat quicker response to changing conditions. They also noted that there tends to be a twenty-four hour shift between the forecast avalanche occurrence and the observed occurrence (i.e., avalanches begin to occur twenty-four hours before they are forecast), particularly near the beginning of a new avalanche cycle. They attribute this to the fact that the meteorological data in the model only goes through 8 a.m. of the day being forecast, whereas the avalanche observations go throughout the entire day. It is notable that the authors produced probabilities of occurrence of avalanches on a given day, rather than declaring a day as simply an avalanche or non-avalanche day. Unfortunately, the authors do not include an explanation of the computation of the probabilities, which makes it more difficult to judge their success. There is also no discussion of the relative weights computed for each of the discriminant functions, which does not allow any interpretation of the variability in weights between the highly correlated variables that replace each other in the two functions.

Bois, et al., have produced a model which seems (from their examples) to forecast some of the more major cycles; however, even in their examples, the models sometimes produce low probabilities of avalanche occurrence when avalanches have occurred, while at the same time giving high values for periods when no avalanches are observed to occur. The twenty-four hour time lag pointed out by the authors further cripples the models as forecast aids in an operational situation.

3.3.5 Bovis (1976)

Bovis (1976) summarizes work carried out since 1974 in the San Juan Mountains of Colorado towards the adaptation of discriminant analysis to avalanche forecasting. The avalanche data used was from approximately 150 slide paths adjacent to US Highway 550, passing over Red Mountain Pass. Slides were both controlled and uncontrolled. Meteorological data were measured at or near Red Mountain Pass during the winters from 1971-1975. Bovis submitted ten meteorological variables to discriminant analysis. He used standard discriminant analysis techniques with forward stepwise inclusion to select the variables. The criterion for selection was the maximization of the Mahalanobis distance between group centroid projections onto the discriminant axis. He also applied an F ratio test for significance in the stepwise selection and found that the variables selected and the weights derived were similar. He settled upon using the Mahalanobis criterion. He derived the discriminant functions for two groups at a time, namely, dry avalanche days versus non-avalanche days, and wet avalanche days versus non-avalanche days.

Bovis introduced several important modifications in the way he carried out his analysis. He used time integrated variables over two, three and five day intervals, and developed discriminant functions separately for each of these intervals. Most importantly, he modified his avalanche data by stratifying the avalanche activity on the basis of the number and size of avalanches on a given day. He developed separate discriminant functions for each of the stratifications.

Additionally, Bovis examined some of the problems associated with the non-normal distribution of the discriminant groups. He attributed an apparent positive skewness in the distributions to precipitation terms during the dry slide season and to temperature terms during the wet slide season. He applied a logarithmic transformation to the offending variables and found a marked decrease in the skewness of avalanche days although non-avalanche days were much less improved.

Bovis also computes probabilities that a given day is an avalanche or non-avalanche day. The probabilities were arrived at by using a standardized discriminant function, that is, a function that is derived from variables that have been normalized to their mean and variance. This type of discriminate function will give a standardized discriminant score which can be read as a probability from a table of cumulative normal deviates. He found that classification based on probability of inclusion when used with transformed variables gave a 10% increase in the accuracy of classification. He also noted that the percentage of misclassified days was almost equal for both the avalanche and non-avalanche days which he interprets as an indication that the two distributions are close to normal.

Using all of the above mentioned modifications, Bovis proceeded to search for the most reliable discriminant functions for classifying groups, and, having determined these he continued to develop a complete forecasting methodology. Initially, he found that the two-day time step for meteorological integrations was consistently the most accurate and computationally the easiest integration to perform, thus the three and five day integrations were discarded. Next, using the transformed variables, he developed separate discriminant functions for dry avalanches and wet avalanches for each of the stratifications of avalanche activity which had a sufficient number of cases to be statistically significant. Bovis found in all cases that a maximum of four variables, and ordinarily only three, carried the bulk of the discriminating information.

Bovis found that the variables selected differed between dry avalanche days and wet avalanche days mostly in the relative weights assigned in the discriminant function. For dry slides, the 24 hour and 48 hour precipitation terms dominated, while temperature variables carried significantly smaller weights, if included at all. The reverse was true for wet avalanche days. The variation in selected variables with each stratification was not particularly significant. In all but one instance, the primary discriminating variable was not changed. The changes that were noted between stratifications was that of one highly correlated variable replacing another. He did find a large variation in the percentage of misclassifications between stratifications, ranging from 31% to 12% for dry avalanche days and from 40% to 18% for wet avalanche days.

With the results of his study , Bovis developed a forecasting methodology, which he applied to the winter of 1975-76, which was not part of the data used to derive the discriminant functions. As part of his investigations, Bovis found a clear transition from the dry avalanche season to the wet avalanche season in the San Juan Mountains. Thus, his first step in forming a forecast is to test for the likelihood of dry avalanches. A negative result indicates either no avalanches or wet avalanches, in which case the wet avalanche discriminant function is applied to determine a positive or negative indication of wet slides. This procedure is performed for each of the stratifications beginning with Bovis' stratification #V, the most active and dangerous level. The probabilities that are produced from this analysis not only give the forecaster an indication of the occurrence of avalanches, but an idea of the magnitude of the activity. The functions developed by Bovis have the further capability of limited updating during the day which helps to keep the forecasts more current with on going weather conditions.

Interestingly, as part of his examples of the use of the discriminant functions for forecasting, he notes a situation where a forecaster may be required to drop or modify variables in order to get more representative values from the functions. This points out that output from discriminant analysis is only objective guidance for a forecaster and still requires subjective modification by a human being to produce a useful forecast.

The introduction of the stratification of avalanche days is probably the single most important advance in this paper, as it results in a greater amount of information being produced by the functions; however, this is at the cost of diminishing the data base for the discriminant functions, which in turn decreases their reliability. It is important that Bovis did not test for normal distributions on the data used for each individual stratification. It is arguable that the normality test he employed is a very weak test of normality, but it would have been interesting to see if the same level of significance is maintained for the discriminant functions using smaller samples of data. This type of analysis is particularly important since he is relying heavily upon a normal distribution assumption both in his development of the discriminant functions and in the derivation of his probabilities for classification into each of the groups.

3.3.6 Salway (1976)

Salway (1976) used observations of approximately 100 classified avalanche paths in the Rogers Pass area of the Trans-Canadian Highway. The avalanche observations included information on the time of occurrence, moisture content, size, and runout distance of each individual avalanche. Weather and snowpack data were taken twice daily at the Rogers Pass Snow Study Plot. The data in the study was for eight winters between 1965 and 1973.

Salway defined an avalanche index for each slide occurrence by applying different numerical scales or weights to the three recorded physical attributes (i.e., moisture content, size, and length of runout) and multiplying the three numbers together, giving a single number which characterized each slide. For example, a weighting scheme might consist of moisture contents of 1 to 3, size of 1 to 6 and runout distances of 1 to 12. If a given slide had values of 2, 3, and 7 respectively, the index characterizing the slide would be 2 x 3 x 7 = 42. These numbers were then summed for each day giving an "avalanche activity index" which characterized each day.

Salway tried numerous weighting schemes seeking an optimal avalanche activity index. This was achieved by performing individual linear correlations between the different avalanche activity indices and the observed weather and snow quantities. The weighting schemes producing the best correlations were then retained for the remainder of the analysis.

To further improve the correlations, Salway tried partitioning the data. This was begun by breaking the winter into two separate halves; the first half consisted primarily of dry slides associated with new precipitation, and the second half consisted primarily of wet slides associated with warmer temperatures (this was similar to the separation introduced in several of the earlier studies). Additional partitioning of the data was performed in both time and space such as breaking the avalanche data into east and west side slides, etc. The best correlations were obtained using an avalanche activity index based on once daily data including all slides (both naturally and artificially triggered) over both sides of the pass for the first half of the winters (i.e., for dry slides) for the entire eight seasons. This index was most highly correlated to a meteorological-snowpack variable that consisted of the total snowpack depth times the water equivalent of new precipitation times the relative humidity.

Using time series methods outlined in Box and Jenkins (1970), Salway tested models for individual winters using three different avalanche indices and the four independent variables found to be most correlated to the indices. Models were derived for the first parts of the winters only. The quality of the models was judged on the value of the correlation coefficient squared (r^2) between the observed series and that produced by the models.

The yearly models, by and large, contain a single unlagged term plus some lagged noise terms and in a few cases a single lagged term. Unlagged terms refer to data taken on the current day. The 1st lagged term of a variable is the value of the variable on the preceding day, the second lagged term from two days prior, etc. In time series models of the form employed by Salway, the time series equations contain stochastic noise terms. Thus the forecast avalanche indices are highly dependent on the forecast metorological variables. Interestingly, some of the models depend on the second lagged variable but not on the first; that is, on observed values of the variable 48 hours earlier but not on the observed value 24 hours earlier. Salway also built models for the entire period 1968-1973 which showed the same trends as the yearly models but tended to include more lagged terms--up to three lags--and lagged values of the avalanche index. The period models uniformly had lower r^2 values than the yearly models. Each of these models is developed using only one of the independent variables and its various lags and lagged values of the avalanche activity index.

The best model developed using a single independent variable and its lagged terms (i.e., SWH) was next expanded to include a second independent and its lagged terms (i.e., WEXTMI). The time series method of Box and Jenkins (1970) chose out which terms were significant in the time series and the final coefficients were then determined by a multiple regression fit to the data. Giving the following time series:

AVAL = 0.0947AVAL1+ .0589AVAL2+6.850SWH-0.937SWHI1+0.131WE*TMI1- .0350WE*TMI2

where:

AVAL	≡	Forecast Avalanche Activity Index
AVAL1, AVAL 2	≡	Avalanche Activity Index lagged 1 and 2 day, respectively
SWH	≡	Forecast value of Total Snowdepth x Water Equivalent of new precipitation x relative humidity
SWH1	≡	lag 1 value of SWH
WE*TMI1, WE*TMI2	≡	Lag 1 and Lag 2 values, respectively, of Water Equivalent of new precipitation x minimum temperature.

This equation gave an r^2 (correlation coefficient squared) value of 0.651. The predicted avalanche index was found to be significant at the 95% level within the range of $\pm$ 120 (the avalanche indices generally running from 0 to 600+) assuming that the forecast meteorological variables are forecast perfectly.

One of Salway's most interesting developments was the introduction of the weighted avalanche activity index which appears, at first, to be a significant advance in expressing avalanche activity as a continuous ordinal level variable. Salway tried numerous weighting schemes searching for an optimal avalanche activity index--optimal in the sense of predictibility; however, he did not obtain a particularly large variation in the correlations between the different avalanche activity indices and the most highly correlated independent variable (i.e., SWH). The lowest correlation (r) was 0.71 and the highest 0.78. Most significantly, the simplest avalanche activity index which consisted of a simple count of the number of avalanches occurring each day (similar to Judson and Erickson (1973)) had a correlation coefficient of 0.74 and that which counted only medium and larged sized slides had a correlation coefficient of 0.77. It seems that these simple indices, which are subject to much less subjective error in measurement, provide almost as good a measure of avalanche activity as the more elaborate indices. Further, examining Salway's models which contain a single independent variable, there is little variation in his r^2 measure of accuracy for the various avalanche activity indices, particularly with the independent variables that show higher simple correlations such as SWH. The r^2's for the time series models based on SWH only ranged from 0.559 to 0.580.

The use of the avalanche indices raises the frequent question in avalanche forecasting, "what quantity is to be forecast?" There is some question of the legitimacy of choosing the quantity to be forecast solely on the basis of its predictability as Salway did. There should be consideration of the trade-off's between increasing predictability and decreasing utility, informationally, of any index which is to be used operationally. It is necessary to establish what an index means (e.g. avalanche index = 300) in operational terms before its utility can be ascertained. Unfortunately, in Salway's analysis there was no consideration given to usefulness in choosing the "best" forecasting model.

It is also notable that, based on the correlation analysis, Salway confined his analysis to the "first parts" of the winters (that which is dominated by dry slides). The deletion of the "second parts" was only fleetingly discussed and the applicability of this method to temperature related slides is not addressed. Further, as even the author noted, the use of a single transition date from precipitation related events to temperature related events is highly unrealistic, as the transition takes place over a period of time. The fact that temperature related avalanches and precipitation related avalanches can occur at any time during the winter will weaken any model that excludes either type of avalanche as do Salway's models.

Salway is somewhat misleading in his work, giving the impression that the time series method he used gives an entirely different approach to creating a forecasting equation; however, the time series method as he applied it is simply a method of variable selection (as is stepwise deletion in discriminant analysis). In fact, it only serves to choose which lags of a variable should be included in the forecasting equation after the variable has been chosen by a simple correlation analysis. The final forecast equation is gained by doing a least squares fit of the coefficients to the lagged variables chosen. After this fit is done, some of the variables may be dropped, if their fitted coefficient is considered negligible. Hence, this form of time series approach only gives an indication of which lags may be significant. The final determination is made with the least squares fit. There is very little difference between this kind of analysis and simply doing a multiple regression analysis on the independent variables including the previous (lagged) values. A comparison of the time series and multiple regression techniques applied to the same data set would be useful in determining which technique is better.

At first it is very surprising that no lagged avalanche variables appear in most of the simple models. However, since no lagged variables appear in almost all of the simple models, this would seem to imply very little correlation of events between successive days. This fact may be related to the real weakness of the models, that is, they depend almost entirely upon forecast meteorological variables rather than currently measured ones. This can be seen simply if one of the model forecast equations is examined

$$\text{AVAL} = 13.02\text{SWH} + 3.683\text{SWHI}$$

The unindexed AVAL refers to the values of AVAL forecast for the next 24 hours (i.e., the value which will be recorded the next morning). The unindexed SHW obviously refers to the value of SWH that will be measured the next day; hence, it must be a forecast value. Note that it carries four times the weight of the lagged (i.e., measured in this instance) variable; thus, the weight of the AVAL forecast is placed on the forecast meteorological variable. As this analysis is heavily biased towards new snow avalanches, it is not surprising that the coming weather conditions are the strongest determinant of the future avalanche activity.

The results presented by Salway, in general, show an "accuracy" of between 70-80%, which is comparable to other statistical techniques and to purely manmade forecasts. The models presented must be considered particularly poor when compared to other techniques as the results are based principally upon perfect weather forecasts. Most other statistical models have not included forecast quantities, and, yet, many are at least equal to the models presented by Salway. It is a major weakness of this work from both a theoretical and a practical standpoint that the effects of less than perfect weather forecasts were not considered either qualitatively or quantitatively.

In conclusion, this work is interesting in its presentation of a correlation analysis of differing weighting schemes for an avalanche index with a wide spectrum of snow and weather variables. Unfortunately, it was not demonstrated that the rather circuitous time series approach used in developing the forecast equations gives any useful improvement over straightforward regressions, particularly since the former method considers only a relatively small number of variables (both present and lagged) at one time. The conclusions presented by Salway seem to be erroneous or overly optimistic at the least. The general accuracy is not significantly different from earlier works, and when it is noted that these models used perfect weather forecasts, it is even more questionable whether they are as accurate as earlier models.

3.3.7 Obled and Good (1979)

Obled and Good (1979) developed a set of three different types of models which they have applied to operational forecasting. Their Type I models were essentially those detailed in Bois, et al. (1975) previously discussed. Although some improvements were made in the selection of variables in the discriminate functions (namely, the use of non-parametric selection methods that do not depend on normality assumptions), the Type I models were not significantly changed, so no further discussion will be undertaken. The Type II models that were presented consist of a combination of cluster analysis and discriminant analysis, and the Type III models were based principally on Local Dynamic Models. The data used in these models are the same as those described in Bois, et al. (1975).

Obled and Good began with the weather and snow data from only those days on which at least one avalanche occurred. They then applied cluster analysis to this data set to determine the number of significant groups (or clusters) that could be found in sample space. They did this after partitioning the data set into two groups: January-February and March-April. The analysis identified three distinct groups in January-February and four groups in March-April. These groups consisted of member days with similar weather and snow conditions. The occurrence of an extra group in the March-April analysis was attributed to the tendency of a new weather type to appear as spring approaches (i.e., warm, clear days).

The days making up each of the cluster groups were then used to produce a multigroup discriminant function. This function was then applied to the remainder of the data set (i.e., the non-avalanche days) identifying each of the remainder days as a member of one of the cluster groups. This was once again done separately for January-February and March-April.

This step resulted in seven separate sets of data (three for January-February and four for March-April), each cluster group consisting of a set of days with similar snow-weather conditions. Each of these cluster groups now contained both avalanche and non-avalanche days. Next a simple two group discriminant analysis (i.e., avalanche vs. non-avalanche days) was applied to each of the seven groups resulting in seven discriminant functions.

Operationally, the model worked in the following fashion. The snow-meteorological observations which characterize a given day (these include both historical variables (e.g., number of days since the last avalanche cycle) and the 24 hour forecast of water equivalent) are subjected to the multigroup discriminant analysis which classifies the day into one of the weather types. Next the two group discriminant function for that type is run for the day, classifying it as either an avalanche or non-avalanche day. In practice, percentage probabilities of inclusion into each cluster group are produced allowing the forecaster to choose among the most likely candidates.

To evaluate the model objectively, a 60% probability of inclusion as an avalanche day was considered sufficient to classify the day as an avalanche day. The results for a test sample of 240 days is shown in Table 3.1.

As presented by Obled and Good, the Type III models are by far the simplest. Current quantitative methods for selecting the radius of extraction in sample space were rejected as not suitable for the type of data encountered in avalanche work. Part of this is associated with the large number of different units involved in the variables. Obled and Good settled upon the criteria of taking the 40 nearest neighbors, in sample space, to the day under consideration. The reasons for selecting the number 40 are not clearly given. However, once the 40 neighbors are retrieved, the ratio of avalanche days to non-avalanche days is taken to give the probability that the current day will be an avalanche day. Further, the size of the radius (in sample space) required to obtain the 40 neighbors is used as an indication of the reliability of the forecast (see Table 3.1).

Obled and Good have introduced at least two important advances in avalanche forecasting models: discriminant analysis in combination with weather typing

TABLE 3.1 Performances on test samples.

(Number of days in sample = 240)

Type I Models (Discriminant Analysis)	
Days with probability level 60%	88
Days with avalanches.	41
Days with avalanches with forecast probability less than 60%	7
Type II Models (Cluster Analysis)	
Days with probability level 60%	80
Days with avalanches.	41
Days with avalanches with forecast probability less than 60%	7
Type III Models (Non-Parametric Models)	
Days with probability level 60%	54
Days with avalanches.	41
Days with avalanches with forecast probability less than 60%	13

and non-parametric models. The weather typing appears to be a very logical partitioning of the data. Almost all authors have broken their winter into dry and wet slide seasons and have noted that errors were introduced by the use of a single date for transition--the change being over a period of time. This error is further increased in maritime climates such as the northwest U.S., where there is not a clearly defined dry slide or wet slide season. A model which allows either type of slide to occur at anytime during the winter will have more flexibility than one that does not. The fact that little improvement in absolute forecast accuracy over simpler discriminant analysis models was realized may indicate a need for more data to better define the discriminant functions--particularly for the multi-group discriminant functions used in the weather typing. This is the singular weakness of the Type II models, i.e., partitioning the data into a number of subgroups diminishes the size of the sample for each of the groups. This in turn diminishes the accuracy of the statistical models. It seems likely that as a larger data base becomes available, the accuracy of the Type II models should increase.

The Type III models developed by Obled and Good require a great deal more work before they can be regarded as sources of truely objective guidance. The determination of the radius of inclusion and/or the number of nearest neighbors to be considered requires more theoretical development. However, the concept of examining past days with similar weather and snow situations could prove exceedingly useful as a guide to an operational avalanche forecaster. This method may possibly operate best as an identification and retrieval system.

Obled and Good used a forecasted value of new precipitation (water equivalent) as an input variable in all of their models. Surprisingly, it was not one of the variables chosen by the selection methods in any of the models. The authors, unfortunately, do not discuss this exclusion of what is thought to be a very important variable.

3.4 Discussion

Univariate regression analysis does not seem to hold much promise for use in any kind of operational avalanche forecasting methodology, as it does not present the available information in a readily usable or complete form. It is unfortunate that there has been little or no application of multivariate regression analysis to the forecasting problem. This may hold some promise, particularly considering the success of its near relative discriminant analysis, if the avalanche variable can be modified into a more compatible continuous variable. Several possibilities suggest themselves immediately. For example, it would be desirable to modify the count by the size of the avalanches occurring to give a number which is more representative of the level of avalanche activity. Also, careful selection of the index paths would probably help the behavior of the regression equations. This is a method which would be useful to explore more closely.

Of all of the techniques discussed, discriminant analysis is the most widely used and appears to hold the most promise as an operational forecast aid. Disappointingly, none of the researchers to date have addressed themselves to several of the basic difficulties inherent in this technique. The problem of non-normal distributions and highly correlated independent variables is mentioned consistently by authors, however, with the exception of some of Bovis' work and the use of non-parametric selection techniques by Obled and Good, there has been very little published effort towards quantifying the consequences of violating these basic assumptions. For example, Bovis talks about the distribution of group members as "probably looking like. . .", no attempt is made at a rigorous exploration of the nature of the distributions using such things as coefficients of skewness or kurtosis. Tests such as these could be used in conjunction with various variable transformations to arrive at an optimal form for the input data. Very closely associated with this problem is the question of sample size, that is, the paucity of avalanche days vis-a-vis the large number of non-avalanche days. Most authors equalize these numbers by choosing randomly a set of non-avalanche days which equals the number of avalanche days. The results of Bois and Obled (197x) and Salway (1976) both cast doubts on this method as they found it seemed to introduce large variations in the discriminant functions that they derived. However, in both of these cases they were working with very small sample sizes, which is symptomatic of the research to date, making their results somewhat suspect. The minimum sample which can be successfully used is normally placed between 20-30 cases and this is for well-behaved data, which is probably not the kind of data being dealt with in this situation. The type of variability that has been observed in the derived discriminant functions to date may simply be the result of sampling errors caused by too small of a sample. The only conclusion that can be safely drawn is that larger samples will be required before unique discriminant functions can be derived. This will simply require time to build up a homogeneous and consistent data base.

Several of the authors, particularly Bovis, try to draw physical interpretations from the weighting of the variables in the discriminant function. This is a suspect practice because of the inclusion of highly correlated variables into the discriminant function. Often times, closely correlated quantities will appear in a function with opposite signs which has the effect of diminishing the actual contribution of that variable information from what would be expected from a single inspection of the weights. One way to improve this situation is to examine the variables which are most closely correlated, using factor analysis for example, and eliminate all but one from the analysis. This would lead to a straightforward interpretation of the derived weights.

With the aforementioned limitations in mind, it is interesting to note the similarity in the variables chosen by the discriminate analyses of various workers, although they were working with data from widely separated areas and used differing means of choosing their variables. Generally, the short term precipitation variables dominate during dry avalanche season and the temperature variables dominate during wet avalanche season. One fruitful possibility which should be explored is the further modification of the variables that are being submitted to the selection procedures to better reflect our understanding of the physical processes at work. For example, it is interesting to note that, with the exception of Judson and Erickson's work, wind terms played no significant role in any of the derived functions. Bovis notes that this was due in his case to the fact that the wind variable differed little from the avalanche days to the non-avalanche days. This is a situation where it is known that wind alone is not the source of slope loading and subsequent avalanching but rather the transport of snow by the wind. It would seem that the wind variable should be weighted by its ability to transport snow (i.e., the use of a power law with an upper cutoff as indicated by observations) and by the availability of snow for transporting. This could be a variable such as

$$\text{TRANSPORTED SNOW} = \text{R} \times (\text{WIND SPEED})^3 + \text{S.I.} \times (\text{WIND SPEED})^3$$

where, R = depth of penetration of 1 kg ram

SI = Snow Intensity

Of course, the variables would need to be scaled properly and a more complicated power law representative of an upper limit of transport ability may be chosen, but a variable such as this would allow wind loading during times without snowfall. This type of variable could be further modified if it is known that there is a preferential wind direction for a majority of the paths. Further, it should be possible to construct other variables in this fashion that better reflect the physical processes that are taking place.

Another potential improvement, one which could be applied to multivariate regression analysis as well, is the input of high quality weather data from more varied locations within the forecast area. This should help remove noise that is introduced by applying quantities measured at one point to a large area. Additionally, better observations of the times of occurrence of avalanches, as well as more quantitative measurements of their characteristics, will aid forecast models.

One very important piece of data that has not been used sufficiently in any of the statistical forecasting schemes is a high quality weather forecast. The importance of including forecasted variables is obvious from Salway's work where the avalanche forecasting equations relied almost exclusively on forecasted variables. Obled and Good (1977) included the forecast of water equivalent for the coming 24 hours but no other forecasted variables.

Avalanche forecasts are now based upon an evaluation of conditions to the time of the forecast, or more often several hours before the forecast. This is bound to effect the accuracy of the statistical avalanche forecasts as they are working without all of the necessary information. The effects of this were seen by Bois, et al., when they noted a 24 hour lag in their avalanche activity forecasts. It would be very straightforward to include this data in the development of a set of discriminant functions.

In the maritime climate of Washington where almost all slides are direct action and/or warmup related, the inclusion of forecasted weather quantities of sufficient accuracy could give an avalanche forecaster significant objective guidance.

Still more improvements appear possible based upon the work of Bois and Obled, and Bois, et al., which showed seasonal variations in the computed discriminant functions. They worked with one month at a time which is a rather arbitrary delineation to make, as well as a very limiting one considering the reduction it makes in the data base size. It may be better, if still arbitrary, to take a month's worth of data plus 1/2 month preceding and 1/2 month following it, giving two months of data and helping to smooth sharp variations from month to month. This interval could then be "slid" along at 1/2 month intervals. Similarly, when larger data bases are available, it may be possible to identify specific types of winters which behave differently and develop separate sets of functions for each of them. It would then be a matter of recognizing the type of winter and applying the appropriate functions. Unfortunately, this approach will require much larger amounts of data than are currently available.

The introduction of weather typing by Obled and Good (1977) appears to be particularly promising for the winter situations encountered in the Cascades. Rapid and large fluctuations of freezing levels with rain extending to higher elevations at anytime during the year, almost entirely excludes an analysis which breaks the winter into a dry slide season and a wet slide season as is usually done in more continental situations. It is known that there are distinct types of weather situations which lead to avalanches in the northwest U.S. which should lead themselves to simple classification by cluster analysis. Although Obled and Good did not show any increase in accuracy over the more straightforward analyses, the distinctiveness of the weather patterns in the northwest, teamed with accurate forecasts of most of the weather variables which are now available, could make the cluster analysis models an excellent source of objective guidance for operational avalanche forecasters.

In a similar vein, the Type III models of Obled and Good may also serve as a useful source of guidance in the operational forecast situation as it allows the forecaster to examine the behavior of days in the past that had similar snow and weather conditions.

Time Series as presented to date shows little promise as a forecast aid. However, Salway's work does show the importance of both forecasted variables and historical information (in the form of lagged variables) in producing avalanche forecasts. Further work with time series giving a more complete treatment of the effects of imperfect weather forecasts and further developing the concept of an avalanche index which is an ordinal level variable may eventually produce workable models.

A very basic question remains: is there sufficient information available in the measured quantities to arrive at a completely accurate forecast even after our forecast variable is completely defined? The errors that are seen in the forecasts could conceivably just be a lack of information available rather than an inability to process the data properly. This conclusion seems to be backed up, at least partly, by the fact that all of the different avalanche forecasting techniques, both machine generated and human generated, seem to have a maximum accuracy around 80-85%. This would seem suggestive, since all of the forecasting schemes use approximately the same data for input, that some basic piece of information may be missing.

Judging from the diversity of approaches, it would seem that the definition of the subject that is being forecast is a basic conceptual difficulty in avalanche forecasting. That is to say, the quantity that is being forecast does not seem clear. The question is whether we are trying to forecast instability in the snowpack, or the avalanche frequency, or the avalanche size, etc. This simply has not been determined. There is a basic problem that avalanche observations are not uniform. Further, how much noise is introduced due to missed observations since many slides occur which are never observed. It is impossible to quantitatively evaluate forecasts when the parameter being forecast is so ill-defined. It would seem, practically, that an avalanche forecast should aim towards indicating the presence of potential instability. Unfortunately, the only clear indication available that an instability exists is the occurrence of an avalanche. It is possible that this occurrence is only a random indicator of an otherwise easily forecast condition. For example, the same antecedent weather conditions could produce a period of instability that lasts for several days, but in one instance avalanches may occur on the first day of the instability while in another it may not occur until the last day. Hence, although the variables may be capable of forecasting the existence of the instability, we are developing and verifying functions which are forecasting the probability of an avalanche being observed. Further consideration will have to be given to this basic definition before more consistent forecasts can be developed.

3.5 Conclusion

Statistical forecasting of avalanches, though still in its infancy, shows possibilities as an aid to the avalanche forecaster. Discriminant analysis is the method which shows the most promise for operational models. Discriminant analysis in combination with weather typing introduced by Obled and Good appears to be the most suitable model for application to the avalanche climatology present in the northwest U.S. The inclusion of accurate forecasts of weather variables in this type of model could produce objective avalanche guidance which can be used operationally.

Many of the problems which face statistical forecasting are the same problems which face avalanche forecasting in general. There are basic conceptual questions concerning both the suitability of the variables which are being used to forecast and the nature of the variable being forecast. The statistical methods seem "mechanically" sound; however, further testing to determine the consequences of some of the assumption violations would be reassuring. The main obstacle to avalanche forecasting now lies in the identification of the optimal independent and dependent variables.

4. OBJECTIVE METHODS IN TERRAIN ANALYSIS

4.1 Introduction

The outline of forecasting principles in section 2 excluded consideration of terrain in order to achieve a maximum generality for the principles of dealing with weather, snow structure and avalanche occurrence. For any given locality terrain, of course, plays an important role in avalanche formation and, hence, forecasting techniques. The working avalanche forecaster needs to know the terrain patterns in his forecast area and will usually become familiar with these through personal inspection in the field, compilation of photographs and reference to topographic maps and avalanche atlases. The present chapter now takes up the subject of terrain set aside in section 2 and introduces techniques for systematic and objective terrain analysis.

4.2 The Basic Methods

The essential terrain parameter about any given area is the distribution of ground surfaces in respect to altitude and orientation, with special reference to these quantities for the avalanche paths. There is further advantage in refining avalanche path terrain into release zones, tracks and deposition or run-out zones. From the forecasting standpoint the altitudes and orientations of the release zones and their distribution in respect to the overall terrain are especially important. In most situations these are known at least in rough measure from field inspection. If a good topographic map (USGS 7.5' quandrangle) is available with avalanche paths clearly identified, then more accurate analysis is possible. A map survey can compile mean altitudes and orientations of release zones, taking to a first approximation each such zone as a separate terrain element.

A much more useful terrain analysis can be made by dividing the topography into map elements considerably smaller than the area of a single release zone. Such division is possible with accuracy only on a topographic map with a larger scale than that of 1:24,000 found on the usual 7.5' maps. One way to make the division is to rule off a rectangular grid on the map with the grid spacing selected to give the desired element size. The average slope angle and orientation of each element can then be estimated by inspection, with each element additionally coded according to special features such as location within the major segments of an avalanche path. Altitude and orientation plots then show the topographic behavior of these features based on the statistical distribution of a large number of elements. This elementary technique is subject to estimation errors and becomes very laborious if a large map of varied terrain is covered by a fine grid of numerous terrain elements. A computerized analysis would have obvious advantages.

4.3 Computer-Supported Terrain Analysis

A computer program for terrain analysis originally designed by G. Maykut at the University of Washington has been adapted to the treatment of avalanche paths. This program computes the fundamental properties of mean altitude, slope angle and slope orientation for terrain elements consisting of equilateral triangles arranged as a grid overlay on a topographic map. Provisions are made for additionally characterizing the elements according to special features, in this case the location in respect to release zone, track and deposition zone of avalanche paths. Triangular elements are chosen because three map points uniquely determine a plane representing a particular segment of the terrain surface. While square or rectangular elements are simpler to rule on a map, as in the elementary case discussed above, they introduce ambiguity in computing the fundamental element properties. The scheme for generating the array of elements is shown in Figure 4.1, where the heavy dots mark triangle apices. The manual operation thus is reduced to reading out the grid coordinates from the array and the elevation from the topographic map for each apex dot, the numerical values for these features being entered on punch cards. Special features for each element, such as position in an avalanche path, are assigned by inspection. The computer program then determines the fundamental properties of each element and prints these along with the assigned special features.

4.4 An Example of Terrain Analysis

One of the principal avalanche forecasting target areas in Western Washington is the Crystal Mountain ski area. This has been selected for a demonstration of avalanche terrain analysis owing to the existence of an excellent topographic map at a scale of 1:4800 and a wide distribution of avalanche path altitudes in varied terrain. A raster of 3763 triangular elements was constructed on this map and the apex data read out as described above. Plotting the computed element properties produced the analyses shown in Figures 4.2 through 4.6.

Figure 4.2 is a hypsometric diagram showing the distribution with altitude of both the entire area under consideration and the avalanche paths within that area. At least some parts of avalanche paths are distributed throughout the full altitude range of the Crystal Mountain area. This informs the forecaster that variations of snow type with temperature, freezing level positions and snow cover metamorphism are all going to exhibit a wide spectrum of effects on avalanches, either as they form in the starting zones or are affected by snow type and temperature transitions as they fall. The frequency peak for avalanche paths occurs at a slightly higher altitude than that for the entire terrain, showing a tendency for the paths to be concentrated toward the upper parts of the area.

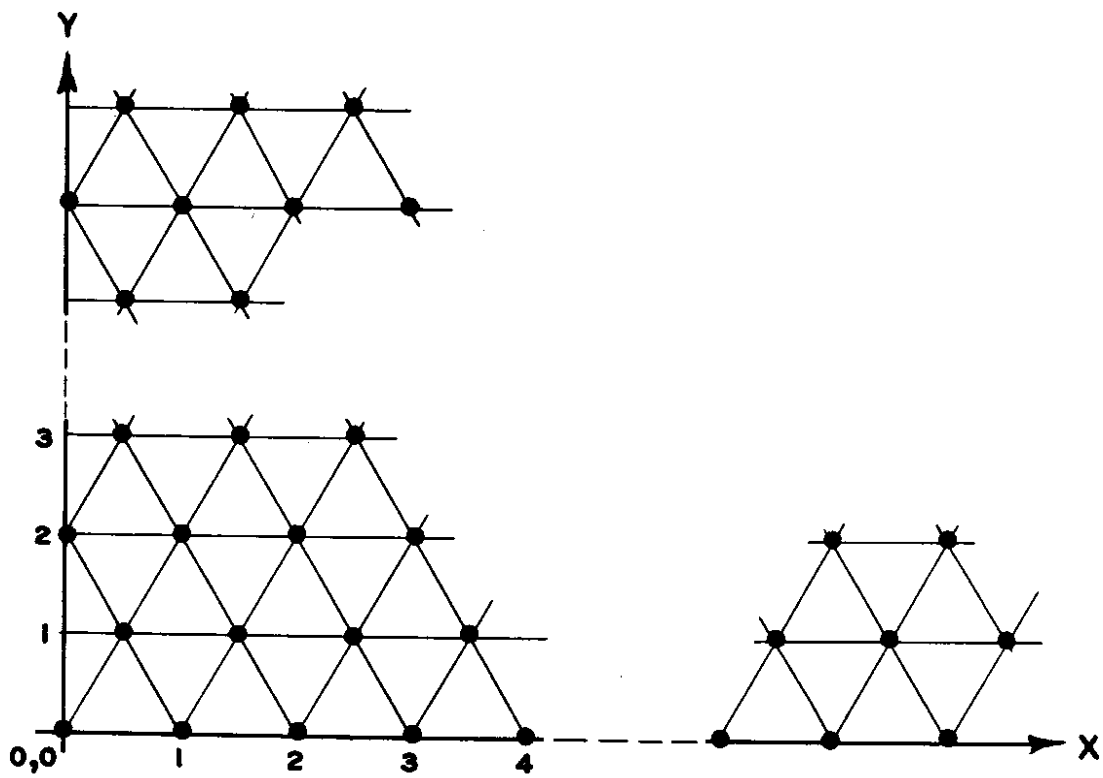


FIGURE 4.1 Array pattern for equilateral triangles used as terrain analysis elements.

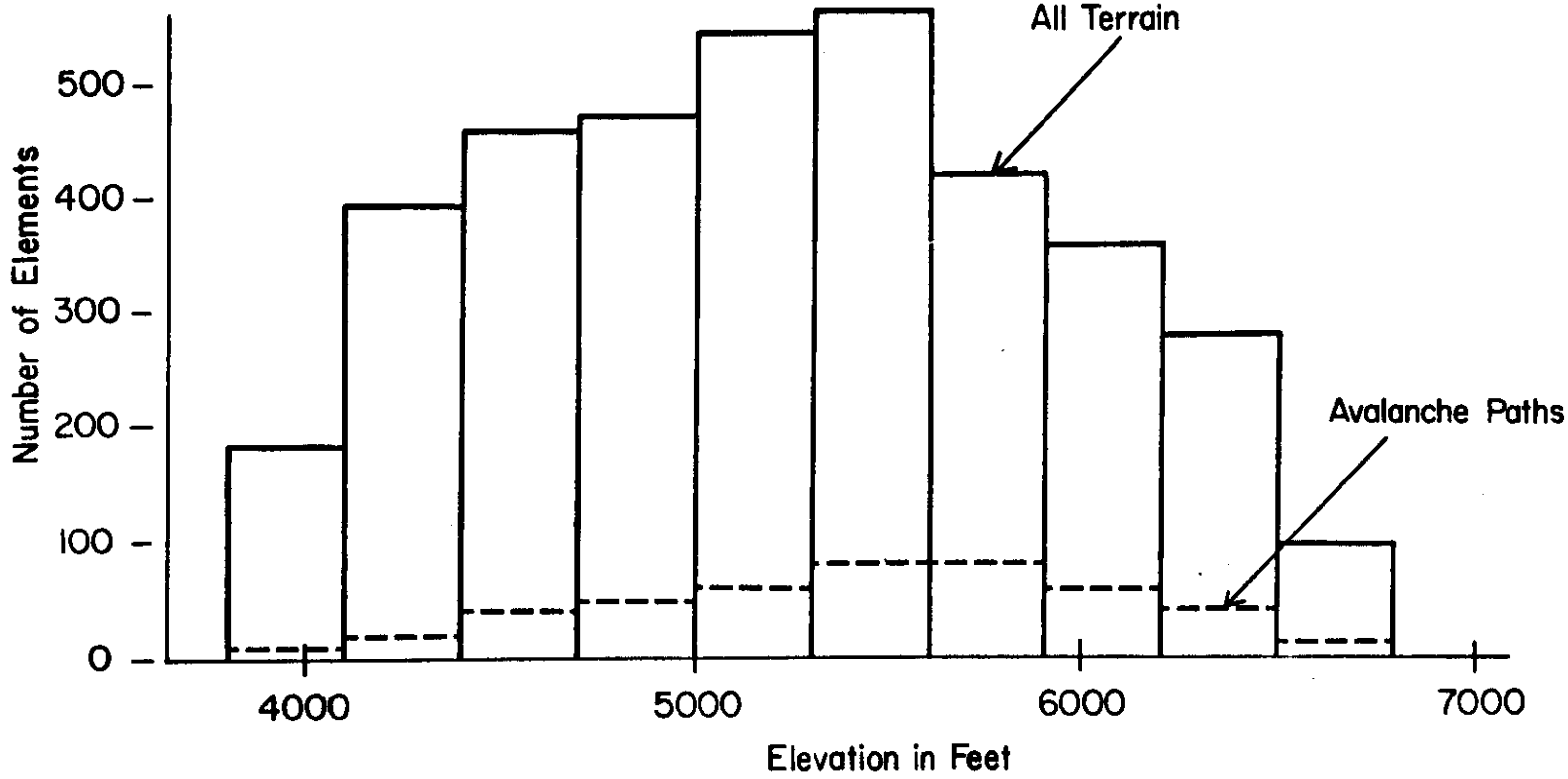


FIGURE 4.2 Crystal Mountain hypsometric diagrams showing distribution of area with altitude by 300-ft intervals for all terrain and for avalanche paths. The avalanche paths comprise 12.5% of the total terrain area.

The forecaster finds still more useful information in Figure 4.3, where the avalanche path hypsometric diagram is broken down according to the separate path segments. As would be expected, the release zone areas cluster at higher altitudes, while the tracks and deposition zones tend to be spread out over wider altitude ranges. The rather uniform altitude distribution of the deposition zones is characteristic of terrain with a wide variety of path sizes, where the avalanches predominantly originate in higher parts of the area, but the fall distance varies all the way from local short slopes to those that run clear to the valley floor. The release zone distribution is especially valuable to the forecaster, for this affects the character of avalanche formation in different weather conditions. Although there is significant clustering with a peak release zone occurrence around 5800', even more important is the fact that a significant number of release zone elements extend all the way from 5000' to 6800'. This suggests, for instance, that the effects of freezing level shifts on Crystal Mountain avalanche releases have to be considered over a range of altitudes considerably wider than is found at the highway passes.

Collection of slab avalanche fracture line data from a wide variety of climates and mountain terrain throughout the world has shown that there is a strong peak of avalanche occurrence frequency on slopes between 35° and 40°. A similar pattern for Crystal Mountain release zone terrain appears in Figure 4.4, where a pronounced peak in terrain elements appears at 39°. This suggests that by and large the release zones have been accurately mapped and, further, that most avalanches at Crystal Mountain originate as slabs. The secondary peak at 31° is probably related to local terrain patterns in this particular valley, although a climatological preference for release in this secondary slope angle range, perhaps related to wet snow conditions, cannot be ruled out. If the latter is the case, the forecaster needs to be alert to this posibility and couple it

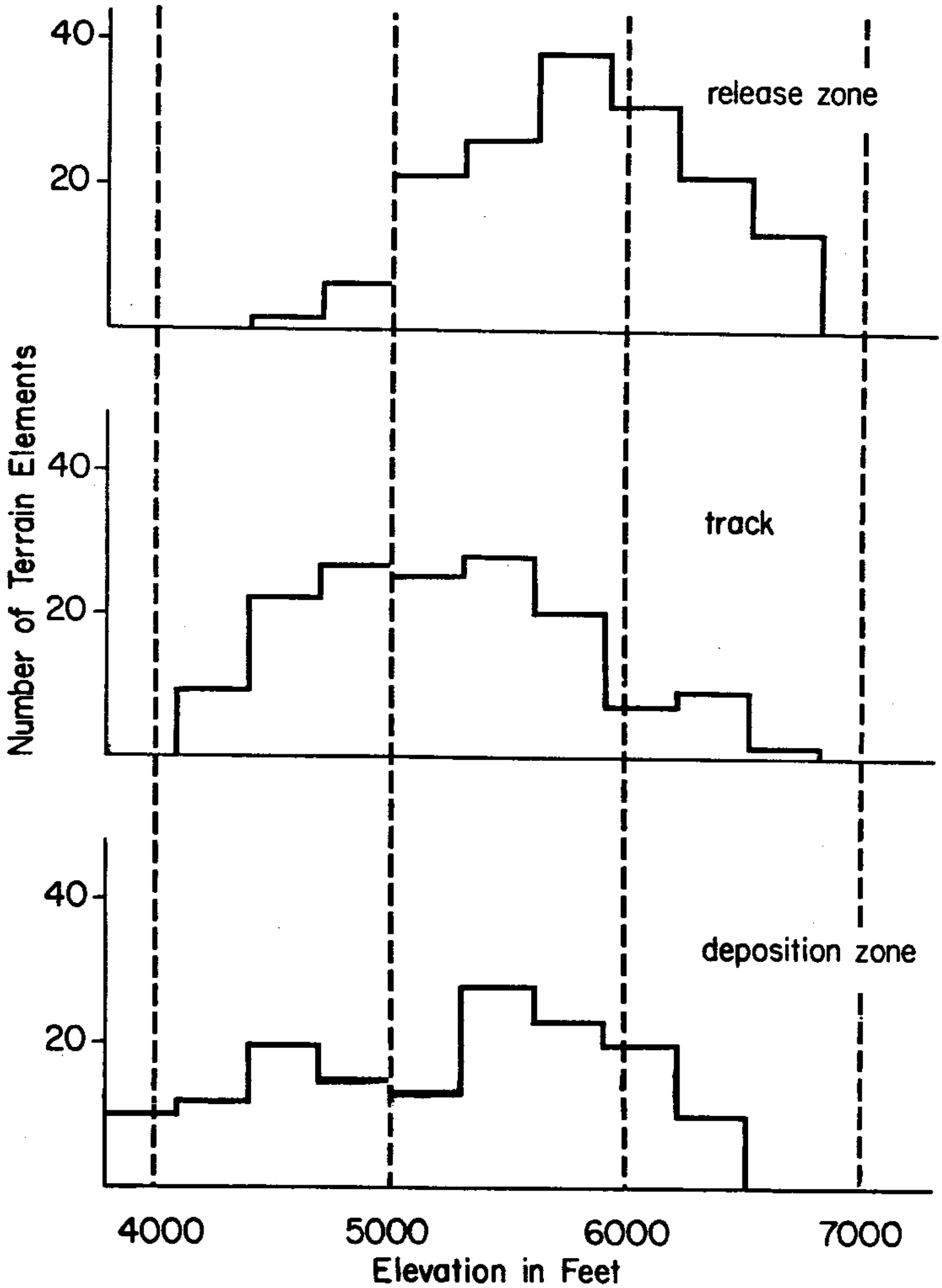


FIGURE 4.3 Altitude distribution of avalanche path terrain elements by 300-ft intervals for Crystal Mountain.

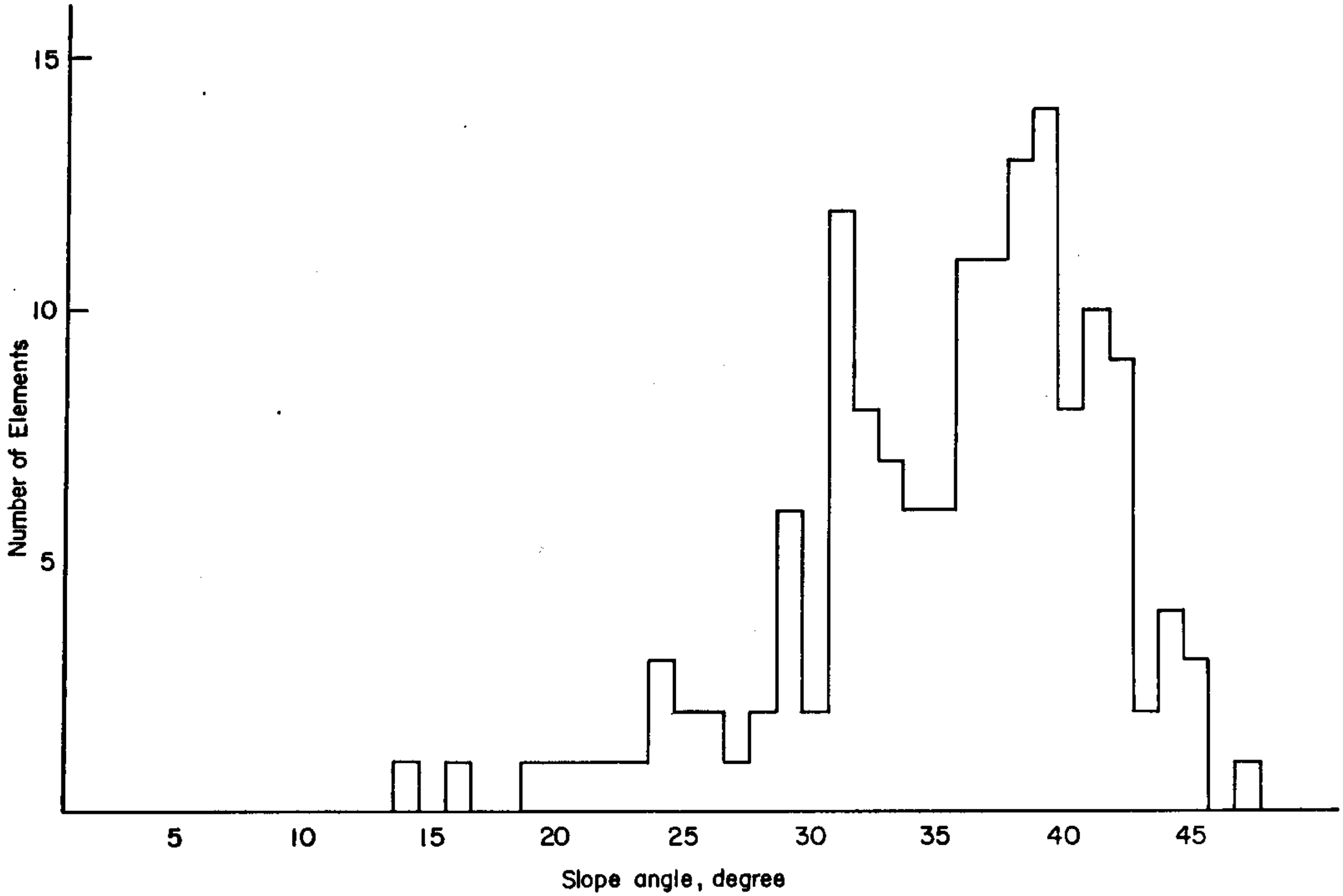


FIGURE 4.4 Slope angle distribution for Crystal Mountain avalanche release zone terrain elements by 1^{0} intervals.

with consideration of freezing levels in respect to release zone altitudes plotted in Figure 4.3.

As would be expected in a valley running approximately east-west, the predominant slope orientations for the entire area are in the north and south quarters shown in Figure 4.5. A greater number of terrain elements face in the northerly directions owing to a series of high basins on the south side of the valley that are absent on the opposite slopes. The strong aggregation of elements in the north and north-west sectors of the orientation plot immediately alert the avalanche forecaster to the likelihood that south and south-east winds are apt to be those causing the most avalanche formation through loading of lee slopes with drifted snow. This situation is confirmed by the orientation plot of avalanche release zone elements in Figure 4.6, where the clustering in the north and north-west sectors repeats that found in the overall terrain. There are relatively few paths facing the south quarter, indicating in comparison with the total terrain distribution in Figure 4.5 that there are extensive avalanche-free slopes on these exposures and informing the forecaster that spring wet-snow avalanche releases due to solar radiation are apt to be only a limited problem here.

Extension of this terrain analysis method to other forecasting target areas in the Cascades where suitable maps are available will place the central forecasting technique on an increasingly objective basis as far as terrain considerations are concerned. Such an analysis is currently being carried out for Snoqualmie Pass with a 1:4800 topographic map available from the Department of Transportation.

The computer program written in Fortran II used for this analysis is too long for convenient reproduction here but is available on request.

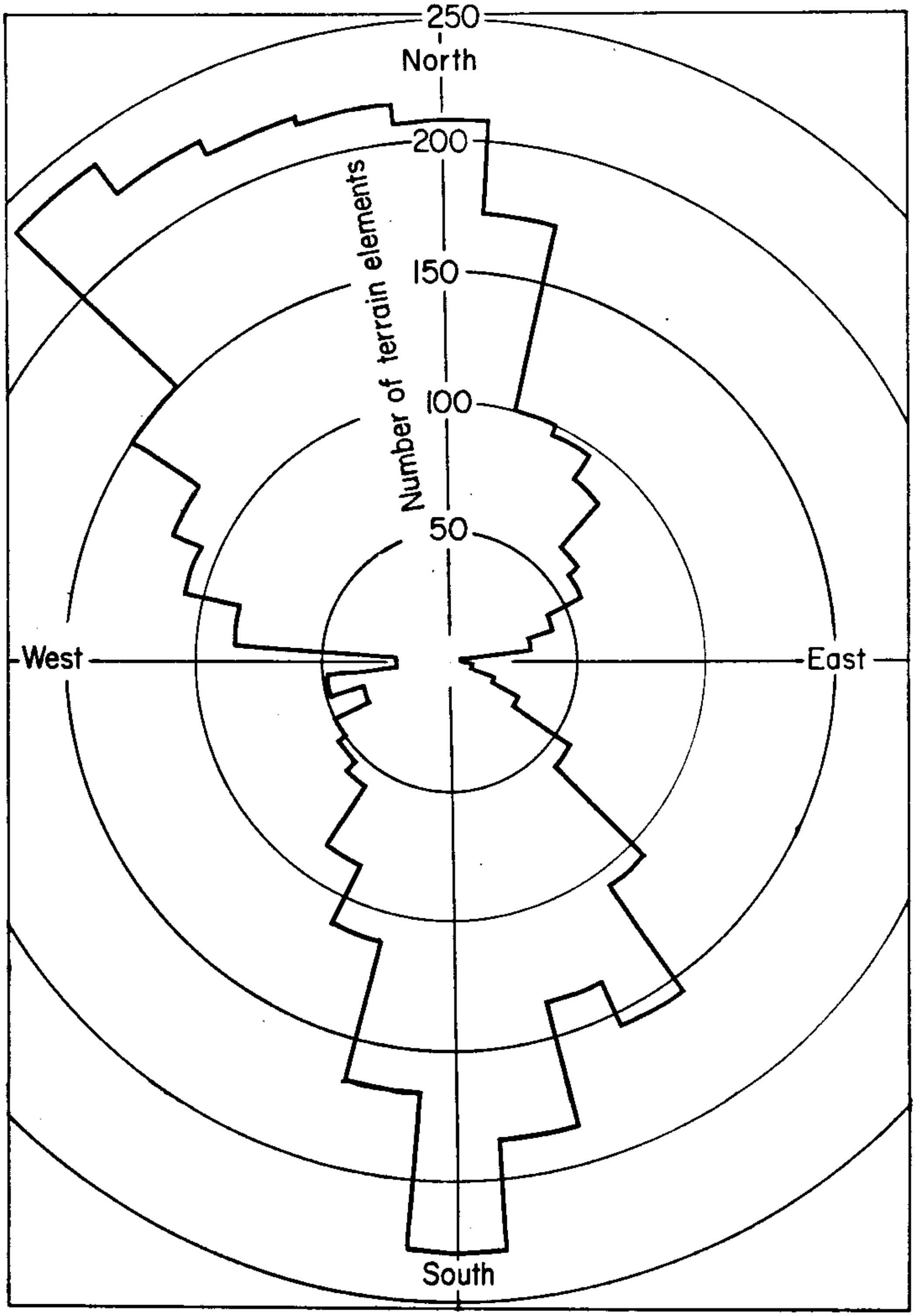


FIGURE 4.5 Distribution of terrain element orientations by 10° intervals for total Crystal Mountain terrain.

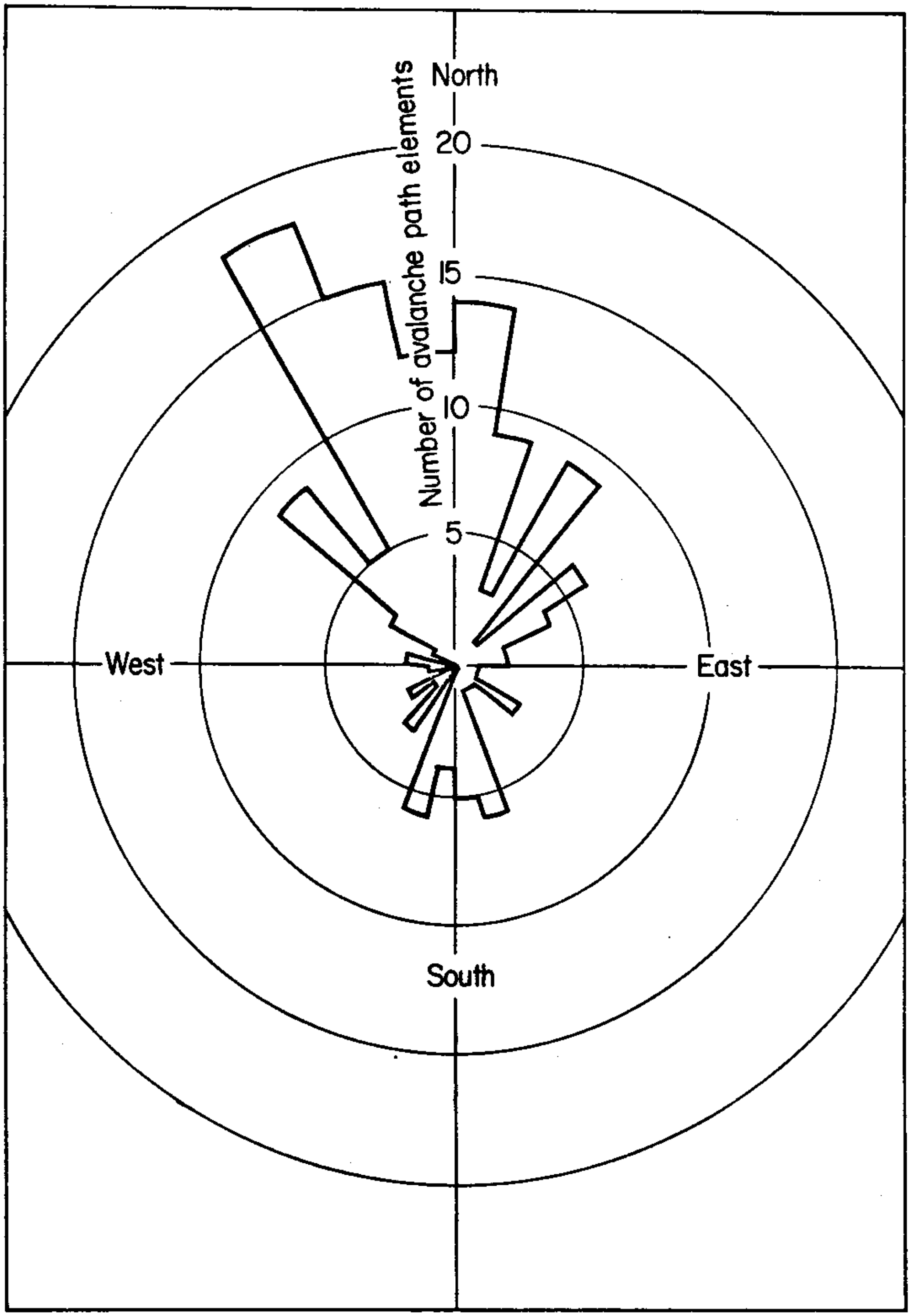


FIGURE 4.6 Distribution of Crystal Mountain avalanche path release zone orientations by 10° intervals.

5. QUANTIFICATION AND ANALYSIS OF SNOW PACK INFORMATION

5.1 Introduction

Existing snow pack structure determines how future mountain weather is going to affect avalanche formation. Analyzing this structure includes accurately measuring the snow parameters, clearly transmitting the information, and correctly interpreting the observed properties. Trained field observers collect measurement data and transfer it to the forecast office in a form similar to Figure 5.1. Effective analysis depends on the observer's field experience and the forecaster's familiarity with graphically represented data. Often a forecaster will prefer to evaluate the snow pack stability by his/her own field observation or by telephoned discussions with field personnel.

In order to improve the efficiency of evaluating snow pack stability, research has been oriented towards:

- Investigating the current methods of subjective interpretation by experienced avalanche forecasters to determine the traditional steps in evaluating snow pack stability.
- Determining the usefulness of snow pit measurements as they apply to describing stability, de-emphasizing the gathering of superfluous information.
- Optimizing the collection procedures of a snow pit investigation to reduce measurement error and increase the amount of useful information.
- Quantifying the snow pit parameters so they can be introduced into an objective, numerical analysis, not only to reduce subjectivity but also to reduce the time required to assess stability.
- Optimizing the transmission procedures for snow pit information so that a forecaster can receive such data and immediately couple it with the

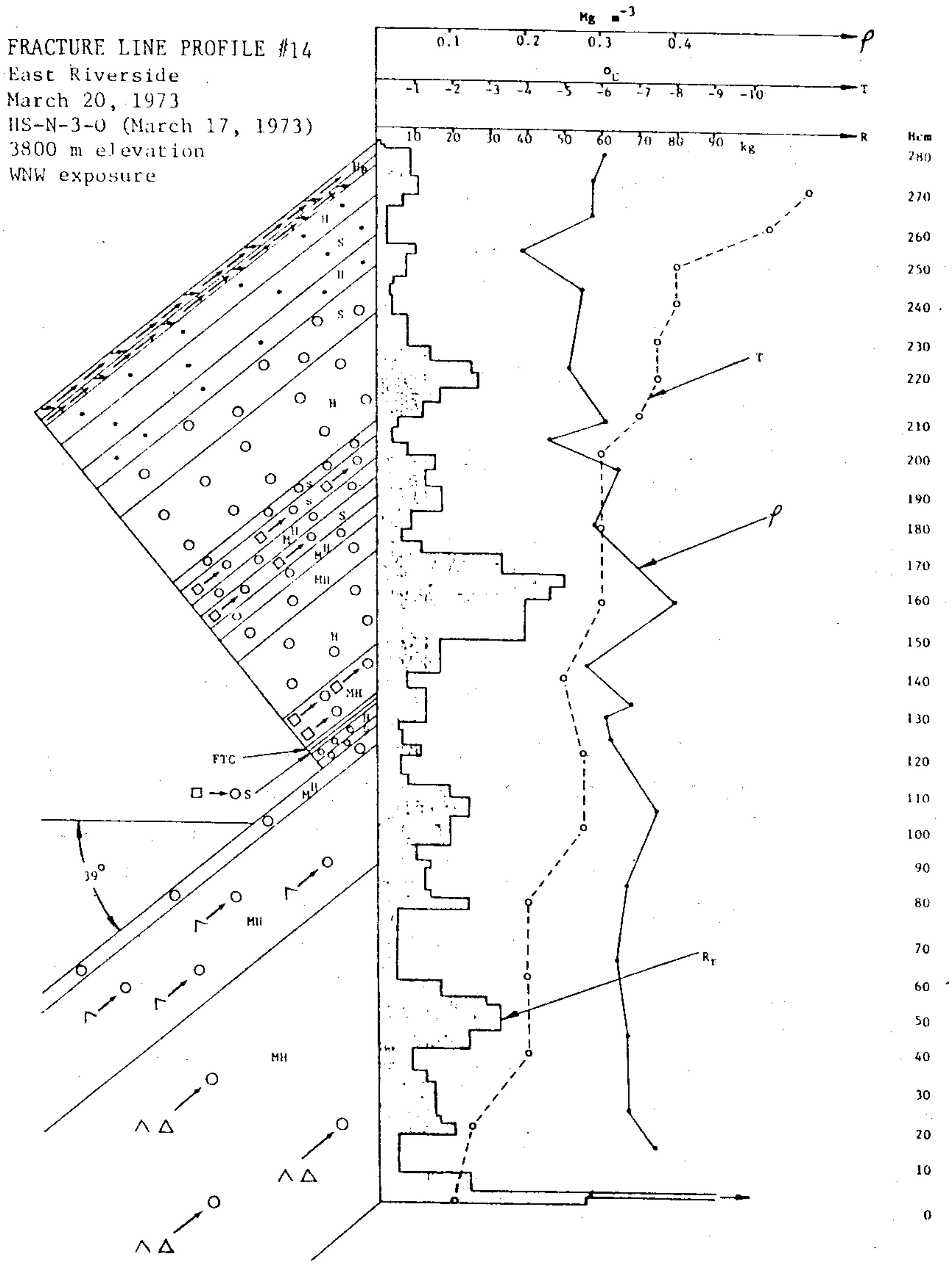


FIGURE 5.1 Fracture line profile graph. Ram resistance (R), temperature (T), density (ρ), hand test hardness (S=soft, MH=medium hard, H=hard) and crystal type (see page 79 for a list of symbols).

mountain weather forecast for an up-to-date estimation of avalanche potential.

5.2 Fracture Line Profile Testing

Subjective interpretations of fracture line profiles (FLP) were solicited from practicing forecasters. This was a simple test designed to determine the forecaster's ability to predict unstable layers in a snow pack and rate the importance of each parameter as it pertained to choice of sliding surfaces. The test consisted of 30 fracture line profiles gathered from the Colorado Rockies, Washington Cascades, Swiss Alps, Wasatch Mountains in Utah, and the Canadian Rockies. The actual bed surfaces for the observed slabs were masked and the forecasters were asked where they believed a sliding surface could exist within each snow pack. The tests were "scored" by calculating the mean error; that is, the distance of the chosen surface away from the actual bed surface. Out of 60 responses on the test the highest percentage of correct guesses was 40%.

The test profiles were grouped together by region; the first group from Colorado, the second group from Washington, etc. The test takers were also grouped according to how much experience they had and from what region they obtained this experience. The scores for each group were added and the mean and standard deviation were calculated. The results of this investigation are summarized in Figure 5.2. As with the "error" scores, the lower the mean, the better; that is, the closer a guess is to the actual bed surface. Although many of the groups do not have enough members to be statistically meaningful, the results did display a few general trends. For example, the profiles collected from the Colorado Rockies (5.2A) seemed to be more difficult to interpret (they had higher mean error scores) than those from the Wasatch Mountains in Utah (5.2C). This may be because of the character of the snow or the graphical form of the profiles. The number of years of experience seemed

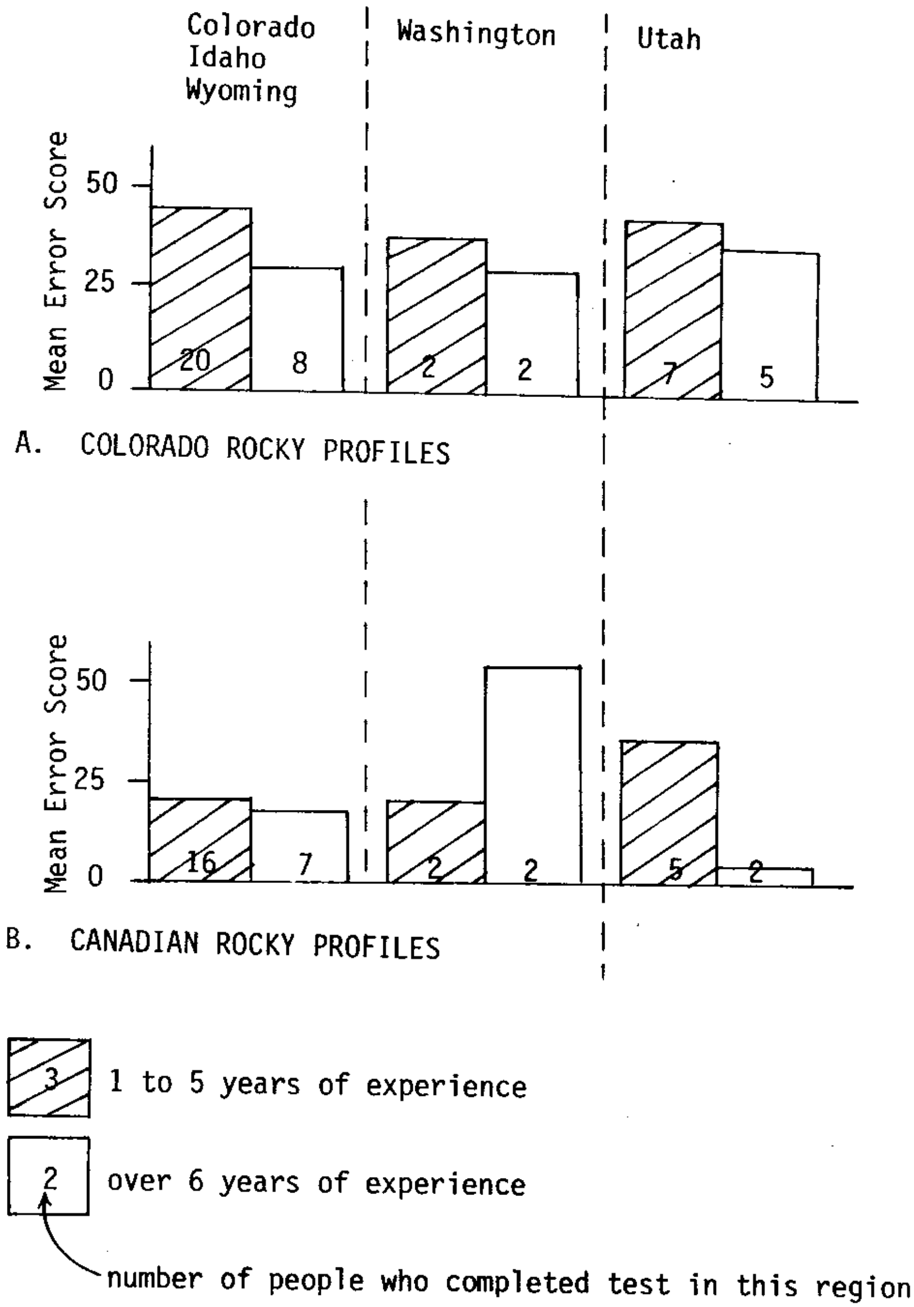
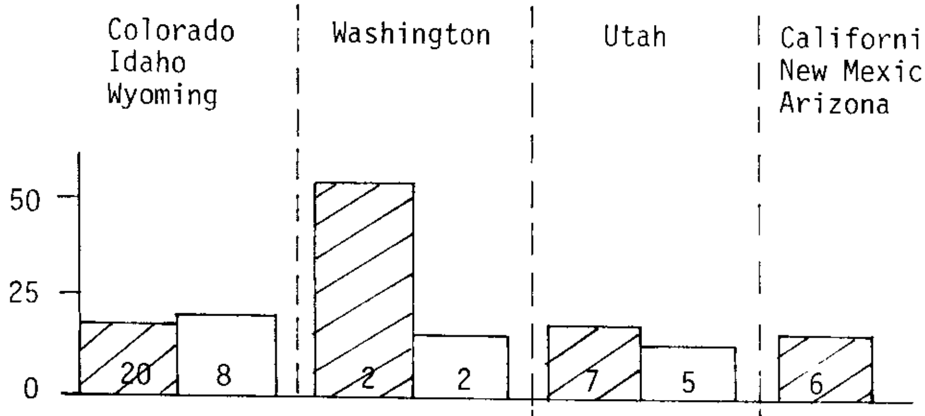


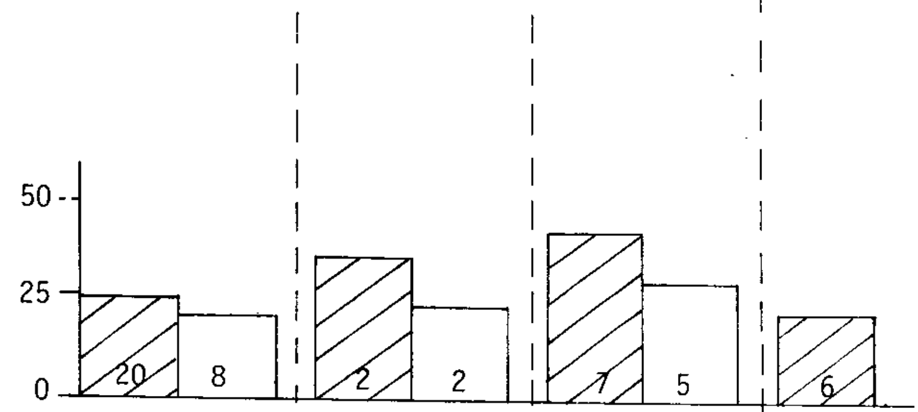
FIGURE 5.2 FLP test results. A, B, C, D, and E contain profiles from the Colorado Rockies, Canadian Rockies, Wasatch Mountains in Utah, Swiss Alps and the Washington Cascades, respectively. The dashed lines separate people with experience in those regions listed.

(continued)

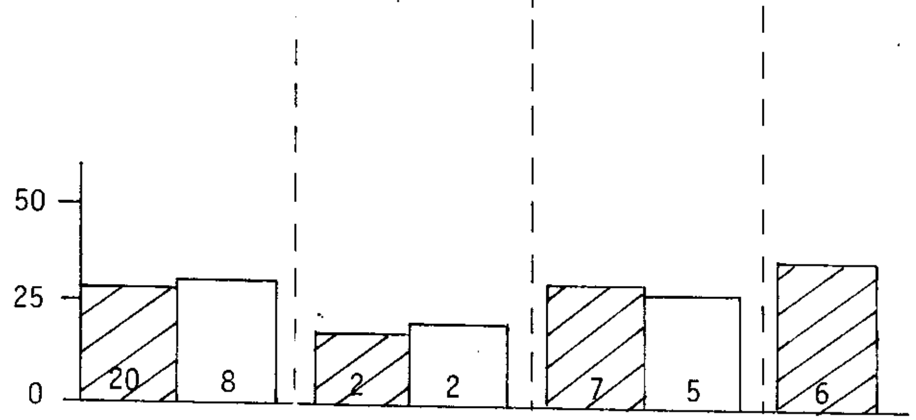
FIGURE 5.2 (continued)



C. WASATCH MOUNTAIN PROFILES



D. SWISS ALP PROFILES



E. WASHINGTON CASCADE PROFILES

to help in choosing a sliding surface from most profiles. This advantage was so slight, however, that distinctive categorization by experience is unreasonable. Also, those with experience in a certain region did not do significantly better with profiles from that region than others with experience elsewhere.

These results suggest that the teaching and understanding of physical processes in a snow pack are fairly uniform throughout the various mountain regions and differing levels of experience. For instance, when bed surfaces were identified incorrectly, it was most often due to the assumption that crusts or layers of depth hoar act as the sliding surfaces or lubricating layers of a slab avalanche. Although these are popular indicators of avalanche potential, they failed to describe a bed surface when there were more subtle instabilities elsewhere in the snow pack. However, field experience and experience with profile graphs might be separate skills that cannot be directly discriminated by this type of test.

In addition to error scores, these profile tests were helpful in assessing useful parameters. For instance, it appeared that ram resistance, crystal type, hand test hardness, and stratigraphic pattern, i.e., layer thickness and ordering of the layers, were most helpful in determining possible failure surfaces. On the other hand, temperature, geographical location, and density were continually overlooked. This type of subjective evaluation aided the subsequent introduction of these parameters into a computerized analysis system. This will become more apparent as the quantification procedures for these parameters are discussed.

5.3 Pattern Recognition

An ideal outcome for the analysis of these parameters would be a method which categorizes snow packs into stable and unstable conditions for avalanching. To do this, it is assumed that all the necessary information to describe the condition of the snow pack is available in the snow profiles. Also, because no one measurement can completely describe the snow pack structure but a combination of measured properties is necessary, the analysis of snow pit data has emphasized the use of multivariate techniques.

Pattern recognition (PR) is one such technique which allows the data to be treated as a complete unit. The form of PR employed in this research has been of the type called cluster analysis. The principles of cluster analysis involve simply the plotting of data points, whether it be on 2 dimensions or n dimensions, and categorizing those points that tend to group together, or cluster. For example, Figure 5.3 shows a simplified, 2-dimensional graph. Those points that fall to the left of the discriminant line A are in class 1 and those points that fall to the right of A are in class 2. There are several methods of plotting the points, deciding on discriminant functions, and classifying the clusters into categories. Because the _a priori_ usefulness of each of these methods cannot be directly determined for every different type of data set, it is necessary to be able to compare and, at times, combine techniques to determine the optimal analytic method. Available for the University of Washington CDC-6400 computer is a program package called ARTHUR (Duewer, et al., 1975) which is a collection of pattern recognition and general data analysis FORTRAN programs. ARTHUR is convenient for analyzing snow pit data because it allows the type of cross-checking and combining just mentioned. But careful thought about how to introduce the data has been necessary in order to achieve useful results.

5.4 Measurement Parameters

The information collected from a snow pit is designed to measure the basic properties of the snow (i.e., temperature, density, strength, and crystal type), and the environ of the snow pack (i.e., time, aspect, elevation, and slope angle).

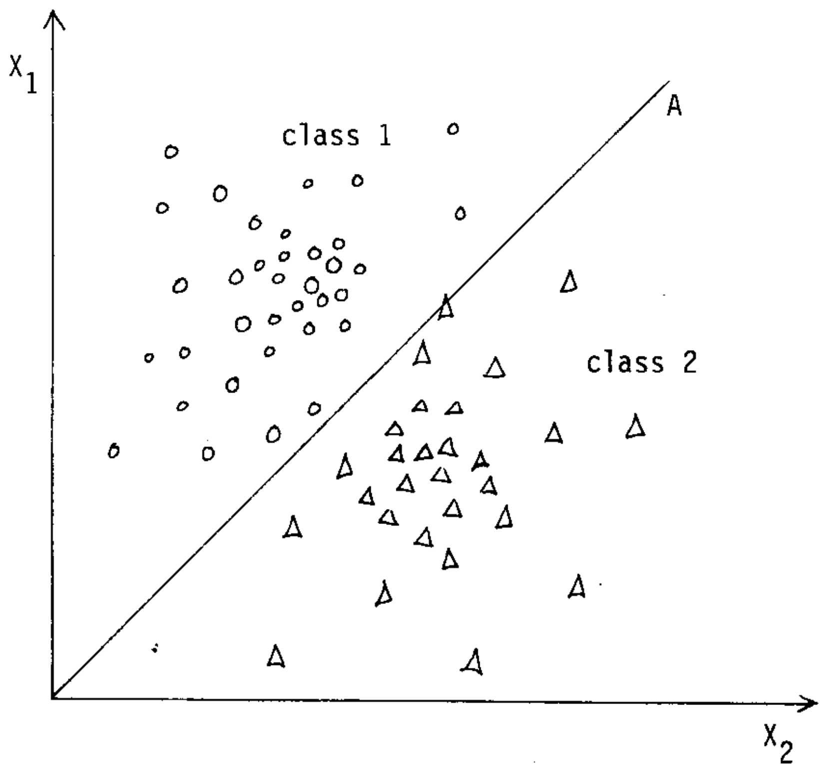


FIGURE 5.3 Schematic plot of discriminating clusters.

The latter set of parameters has been coined "location" parameters while the former set can be referred to as "measurement" parameters. The location parameters have been omitted from the introductory data matrix because they are reflected in the characteristics of the snow. What is left is a data matrix made up of measurement parameters from each profile. Out of over 100 profiles collected from Washington, Colorado, Utah, Canada, and Switzerland only 24 had a complete set of parameters, and this has limited the statistical basis for the PR routines available in ARTHUR.

Another immediate problem is the subjective nature of such measurements as crystal type and the hardness hand test. Numerical values must be assigned to these parameters to facilitate their use in the computer. This task has proven quite difficult, owing to the nominal- and ordinal-level scales upon which they are based. For example, quantifying metamorphosed snow crystals can include 1) the use of a metamorphic table, based on age and temperature; 2) redefining crystal types in terms of cohesion by plotting strength vs. viscosity; and 3) classifying crystals by means of a frequency table according to the number of times a type of crystal occurs either above or below the bed surface of a slab avalanche. Each of these produces a non-linear scale which must be adjusted for snow layers containing more than one type of crystal and for those modified by wind and temperature gradients.

An archetype of still another crystal classification scheme is shown in Figure 5.4. It is a combination of the three methods mentioned above. Values for the tensile strength and shear viscosity of crystal types were obtained from the available literature (McClung, 1974; Bradley, et al., 1977; Kojma, 1956; Shumskii, 1964). In some cases, the plotted values are averages of different experimental values. In other cases, where strength or viscosity measurements were not found in the literature, the crystal types were plotted on the graph by

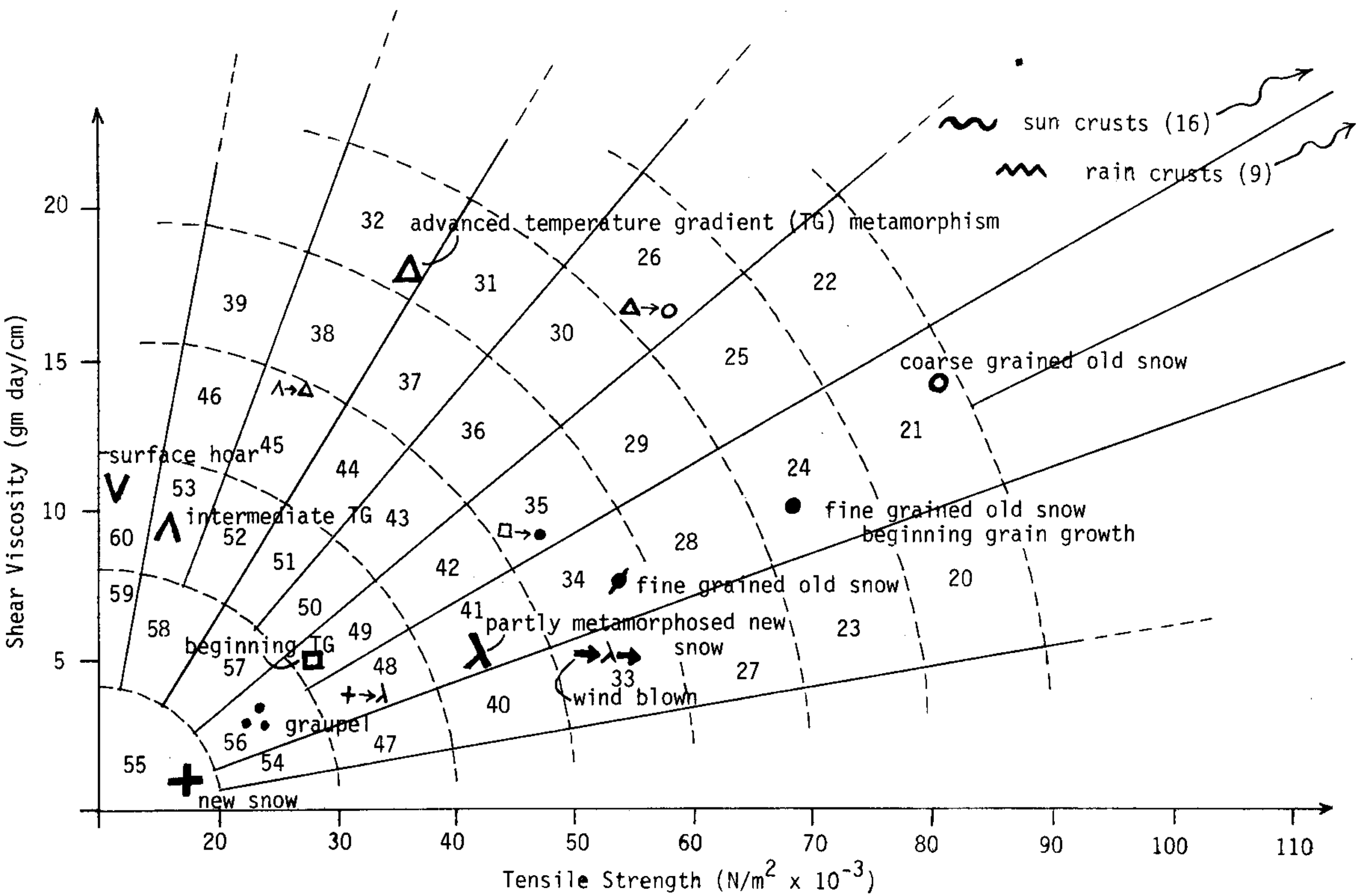


FIGURE 5.4 Tensile strength of metamorphosed snow crystals vs. shear viscosity. See text for an explanation of the numbering system. Crusts and ice layers which have tensile strengths two to three times that of coarse grained snow occupy lower numbered grid units.

interpolation. The resulting display is relative cohesion of metamorphosed snow crystals based on properties of tensile strength and shear viscosity. The grid was designed to roughly follow the natural progression of snow metamorphism. One radial section contains advancing equi-temperature (ET) metamorphism, from new snow to coarse grained old snow. Temperature gradient (TG) metamorphism, from new snow to depth hoar, produces changes in the shape of the crystal, as well as changes in size, which may contribute to the less linear progression on a strength vs. viscosity diagram. The dashed concentric lines of the grid maintain symmetry with the solid radial lines, so new snow, the starting point for metamorphism, becomes the nucleus of this cohesion graph. The grid units are sequentially numbered according to the relative frequency with which a crystal type is involved in avalanching. Frequencies were obtained from 66 fracture line profiles by counting the number of times a crystal type occurred either above or below a bed surface, divided by the number of layers containing that crystal type, then normalized to the total number of different crystal types and combinations. High numbered types most often appeared in lubricating layers. Low numbered types most often appeared in bed layers. Grid units with zero population of crystal types or combinations were not assigned a number.

Preliminary scaling of crystal type and the hand test has been developed to maximize the essential information available in each parameter, while avoiding the addition of any extraneous information inherent in the quantifying process. Each parameter was thus quantified with emphasis on describing the boundaries between snow layers where failure is most likely to occur (see Figure 5.5). The following is a list of those parameters: 1) thickness of the layer above the boundary (THCA), 2) thickness of the layer below (THCB), 3) density (DENS) - interpolated between measured points in order to assign a value at the boundary, 4) gradient of the density across the boundary (DGRD),

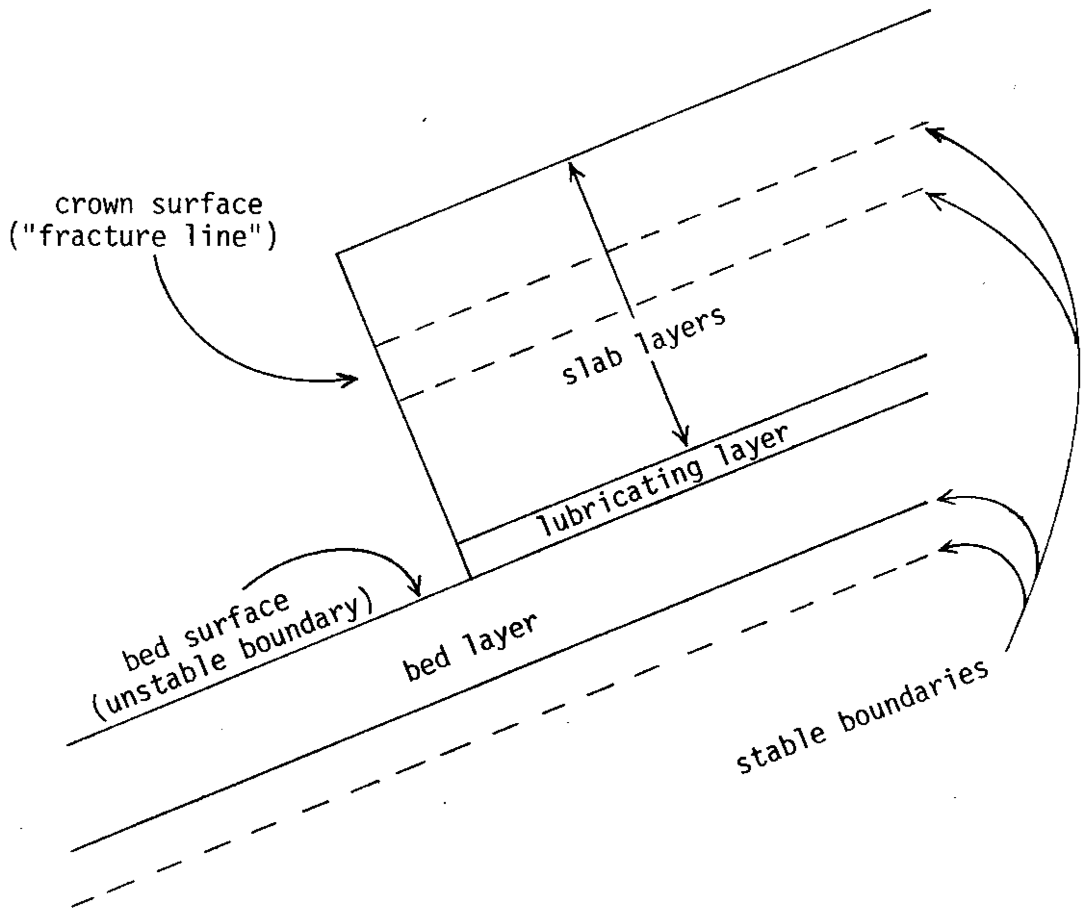


FIGURE 5.5 Schematic diagram of the slab region of an avalanche. The slab layers break away as a sliding avalanche at the crown surface owing to shear failure in the lubricating layer. The latter may at times have zero thickness, the shear failure occuring at the interface between slab layer and bed surface.

5) tangential stress (STRESS) - determined from slope angle, densities and layer thicknesses above the boundary, 6) temperature (TEMP) - interpolated to determine its value at the boundary, 7) gradient of temperature across the boundary (TGRD), 8) ram resistance of the layer above the boundary (RAMA), 9) ram resistance of the layer below the boundary (RAMB), 10) gradient of the ram resistance across the boundary (RGRD), 11) hand test above the boundary (HNDA), 12) hand test below the boundary (HNDB), 13) gradient of the hand test across the boundary (HNDO), 14) crystal type above the boundary (ATYPE), and 15) crystal type below the boundary (BTYPE).

A training set was made up of an "unstable" class of parameters that described the actual bed surface of the fracture line profiles and "stable" parameters that described surfaces within the same profiles which did not fail. Once these data were coded and introduced into the computer they were uniformly scaled so that no undue weighting was attributed to parameters with different value ranges.

5.5 Parameter Analysis

Three types of parameter selection routines from ARTHUR were employed to reduce the dimensions of the training set data matrix. WEIGHT simply weighted each parameter according to the variation from its own class (stable or unstable) and its variation from the other class. SELECT is a process which produced a set of uncorrelated, orthogonal features by beginning with the most important parameter found in WEIGHT, decorrelating it with respect to the rest of the parameters and then repeating the process with the next most uncorrelated parameter. The third reduction routine used was KARLOV which is just a Karhunen-Loeve (see Fukunaga, 1972) eigenvector transformation. It found the principle components of the data matrix and re-ordered them by the size of their eigenvalues, which is a measure of their importance. Therefore, the resulting linear combinations of parameters (features) were ordered according to the amount of information, or variance, they retained. An elaboration of this routine, one designed to improve the clustering ability of each category, is a non-linear method called NLM. NLM used an interim function to preserve interpoint distances which reduced redundancy of points mapped onto lower dimensions.

In the case of snow pit data only the first five features were retained, so instead of a 15-dimensional data space, this 5-dimensional space was more easily analyzed. Figure 5.6 is an example of the KARLOV output. The first feature shows that 22.04% of the total information has been preserved by combining parameters; 58% of the information in this feature comes from the combination of density, hand test above the boundary, tangential stress, and crystal type above the boundary. On the other hand, 55% of the information in the second feature comes from crystal type below the boundary, ram value above the boundary, thickness of the layer below the boundary and the temperature value at the boundary. This feature reduction routine preserves 70% of the total snow pit information in the first five features. This means that if the properties of the snow pack have been described correctly, trends of patterns that appear in the data will be fairly representative of the entire set with just five dimensions.

Once the number of features were effectively introduced, classification routines were employed. Discriminant techniques are used in LEAST by passing a hyperplane through the data space and categorizing the points by where they fall in relation to this plane (similar to the line in the 2-dimensional case mentioned above). Figure 5.7 is an example of the LEAST output which shows that 79.2% of the profiles were correctly classified into class 2 (the stable category), whereas only 70.8% were correctly classified into the unstable category (1). SIMCA is another classification technique which calculated the

INDEX	EIGENVALUE	VAR. PRESERVE EACH	VAR. PRESERVE SUM	FEATURE		COMP.	VAR. PRESERVED EACH	VAR. PRESERVED TOTAL
1	3.746E+00	22.04	22.04	3	DENS	-.414	17.12	3.77
				11	HNDA	-.390	15.21	3.35
				5	STRESS	-.368	13.52	2.98
				16	TYPA	-.347	12.04	2.65
				14	ATYPE	.314	9.87	2.17
				12	HNDB	-.266	7.06	1.55
				2	THCB	-.223	4.99	1.10
				8	RAMA	-.215	4.64	1.02
				4	DGRD	.213	4.54	1.00
				17	TYPB	-.199	3.96	.87
				1	THCA	-.150	2.24	.49
				9	RAMB	-.133	1.77	.39
				15	BTYPE	.130	1.69	.37
				6	TEMP	.097	.94	.21
				13	HNDD	-.053	.28	.06
				10	RGRD	.037	.14	.03
				7	TGRD	-.004	.00	.00

INDEX	EIGENVALUE	VAR. PRESERVED EACH	VAR. PRESERVED SUM	FEATURE		COMP.	VAR. PRESERVED EACH	VAR. PRESERVED TOTAL
2	2.672E+00	15.72	37.75	15	BTYPE	.441	19.42	3.05
				8	RAMA	.395	15.62	2.46
				2	THCB	.325	10.55	1.66
				6	TEMP	.308	9.49	1.49
				13	HNDD	-.298	8.85	1.39
				17	TYPB	-.272	7.39	1.16
				14	ATYPE	.270	7.28	1.14
				9	RAMB	.260	6.75	1.06
				12	HNDB	-.204	4.16	.65
				1	THCA	.200	3.99	.63
				3	DENS	.144	2.08	.33
				5	STRESS	.127	1.61	.25
				4	DGRD	-.089	.79	.12
				7	TGRD	-.084	.70	.11
				16	TYPA	-.078	.61	.10
				10	RGRD	.064	.41	.06
				11	HNDA	-.056	.31	.05

FIGURE 5.6 The first two principle components from the linear combination of 15 parameters. See page 79 for a list of features (TYPA and ATYPE are variations of crystal classifications). The respective columns are; eigenvalues of the covariance matrix of the snow pit data (listed by decreasing magnitude), amount of variance preserved, list of parameters (ordered by decreasing magnitude of their preserved variance), eigenvector component values, amount of variance preserved by each eigenvector for their respective eigenvalues, amount of variance preserved by each eigenvector out of the total variance of the respective eigenvalues.

MY INDEX	YOUR INDEX	NAME	CATEGORY TRUE	CATEGORY CALC	CLASS	WEIGHT	CLASS	WEIGHT
1	*****	COLOAIN	1	1	1	7.972E-01	2	2.028E-01
2	*****	COLOAIN	1	1	1	1.046E+00	2	-4.555E-02
3	*****	COLOAIN	1	1	1	8.424E-01	2	1.576E-01
4	*****	COLOAIN	1	1	1	1.001E+00	2	-1.392E-03
5	*****	COLOAIN	1	2	2	7.325E-01	1	2.675E-01
6	*****	COLOAIN	1	1	1	7.0[illegible]E-01	2	2.950E-01
7	*****	COLOAIN	1	1	1	8.740E-01	2	1.260E-01
39	*****	WASHAIN	2	2	2	7.193E-01	1	2.807E-01
40	*****	WASHAIN	2	2	2	8.354E-01	1	1.646E-01
41	*****	COLOAIN	2	2	2	9.170E-01	1	8.297E-02
42	*****	COLOAIN	2	2	2	7.604E-01	1	2.396E-01
43	*****	COLOAIN	2	2	2	6.397E-01	1	3.603E-01
44	*****	COLOAIN	2	1	1	6.051E-01	2	3.949E-01
45	*****	COLOAIN	2	1	1	7.690E-01	2	2.310E-01
46	*****	COLOAIN	2	2	2	9.201E-01	1	7.993E-02
47	*****	COLOAIN	2	2	2	5.617E-01	1	4.383E-01
48	*****	WASHAIN	2	2	2	9.060E-01	1	9.400E-02

```
MISCLASSIFICATION MATRIX
COMPUTED CLASS .      1     .      2    .
               .+-----------+-----------+
TRUE CLASS     .     17     .      7    .
             1 .   70.8     .   29.2    .
               .+-----------+-----------+
               .      5     .     19    .
             2 .   20.8     .   79.2    .
               .+-----------+-----------+

PERCENT CORRECT. TOTAL.....   75.0
                 AVERAGE...   75.0
```

FIGURE 5.7 Output from LEAST (only 17 of the 48 profiles are shown). The respective columns are; profile index numbers and names, the assigned category, the calculated category, and weights determined for each class.

principle components of the cluster center of mass of each category and classified the points by their closeness to these centers of mass. SIMCA's output (Figure 5.8) displays 75% of the profiles correctly classified into both categories. Although LEAST may be better able to classify known stable profiles than SIMCA, this data set does not seem to provide the necessary information for more accurate classifications. A unique routine is a hierarchical method which computes the distance of a point to its closest neighbors called K-Nearest-Neighbor. KNN classified points by how many neighbors they had within a certain pre-determined distance. But Figure 5.9 shows that KNN did even worse at properly classifying the profiles than either SIMCA or LEAST.

5.6 Observable Relationships

None of the classification routines could distinguish stable and unstable layer boundaries better than 79%, even after ratios of the parameters were introduced. But by viewing 2-dimensional plots of the selected features and cross-checking the misclassified layer boundaries with results from the profile test mentioned earlier, some characteristics of the data set were unveiled. For instance, crystal type and the hand test for hardness are parameters which have shown some interesting trends when plotted together. Figure 5.10 is a plot of crystal type below the boundary vs. gradient of the hand test across the boundary. It has been divided into three sections for clarity. Section I is characterized by large numerical values of crystal type (see Figure 5.4) and small values of the hand test gradient. It also is predominantly populated by unstable (1) snow layer boundaries. This means that a snow type like new snow or depth hoar which is similar in hardness to the adjacent layer above the boundary acts as a sliding surface or lubricating layer in an unstable situation. On the other hand, Section II is predominantly populated by stable (2) snow layer boundaries. The smaller values of crystal type indicate that

```
HERE IS THE TRAINING SET...
 MY    YOUR    NAME     TRUE    ***************************************** CALCULATED
INDEX INDEX              CAT     CAT...FIT...  DISTANCE     CAT...FIT...  DISTANCE
    1*****  COLOAIN       1       1****     0  8.462E-02    2****      0  1.599E-01
    2*****  COLOAIN       1       1****     0  7.988E-02    2****      0  8.173E-02
    3*****  COLOAIN       1       2****     0  6.003E-02    1****      0  1.277E-01
    4*****  COLOAIN       1       1****     0  6.408E-02    2****     34  1.826E-01
    5*****  COLOAIN       1       1****     0  8.389E-02    2****      0  1.138E-01
    6*****  COLOAIN       1       1****     0  3.648E-02    2****      0  1.402E-01
    7*****  COLOAIN       1       1****     0  1.157E-01    2****      0  1.271E-01
   39*****  WASHAIN       2       2****     0  3.903E-02    1****      0  1.454E-01
   40*****  WASHAIN       2       2****     0  7.133E-02    1****      0  9.782E-02
   41*****  COLOAIN       2       2****     0  5.827E-02    1****      0  1.275E-01
   42*****  COLOAIN       2       2****     0  8.487E-02    1****      0  2.679E-01
   43*****  COLOAIN       2       2****     0  1.367E-01    1****      0  1.384E-01
   44*****  COLOAIN       2       1****     0  6.098E-02    2****      0  8.209E-02
   45*****  COLOAIN       2       2****     0  2.302E-02    1****      0  8.111E-02
   46*****  COLOAIN       2       1****     0  7.506E-02    2****      0  1.036E-01
   47*****  COLOAIN       2       2****     0  3.319E-02    1****      0  9.121E-02
   48*****  WASHAIN       2       2****     0  1.018E-01    1****      0  1.749E-01

MISCLASSIFICATION MATRIX
COMPUTED CLASS .     1    .     2   .
                .+---------+---------+
TRUE CLASS      .    18    .     6   .
              1 .   75.0   .   25.0  .
                .+---------+---------+
                .     6    .    18   .
              2 .   25.0   .   75.0  .
                .+---------+---------+

PERCENT CORRECT. TOTAL.....   75.0
                 AVERAGE...   75.0
```

FIGURE 5.8 Output from SIMCA (only 17 of the 48 profiles are shown). The respective columns are: profile index numbers and names, the assigned category, the calculated category and the distance from its center of mass to the profile data point.

```
****************************************************************  1-NN   *****

MISCLASSIFICATION MATRIX
COMPUTED CLASS .      1   .      2   .
              .+---------+---------+
TRUE CLASS     .     16   .      8   .
             1 .   66.7   .   33.3   .
              .+---------+---------+
               .      9   .     15   .
             2 .   37.5   .   62.5   .
              .+---------+---------+

PERCENT CORRECT, TOTAL.....   64.6
                 AVERAGE...   64.6

****************************************************************  3-NN   *****

MISCLASSIFICATION MATRIX
COMPUTED CLASS .      1   .      2   .
              .+---------+---------+
TRUE CLASS     .     13   .     11   .
             1 .   54.2   .   45.8   .
              .+---------+---------+
               .      8   .     16   .
             2 .   33.3   .   66.7   .
              .+---------+---------+

PERCENT CORRECT, TOTAL.....   60.4
                 AVERAGE...   60.4

****************************************************************  4-NN   *****

MISCLASSIFICATION MATRIX
COMPUTED CLASS .      1   .      2   .
              .+---------+---------+
TRUE CLASS     .     16   .      8   .
             1 .   66.7   .   33.3   .
              .+---------+---------+
               .      9   .     15   .
             2 .   37.5   .   62.5   .
              .+---------+---------+

PERCENT CORRECT, TOTAL.....   64.6
                 AVERAGE...   64.6
```

FIGURE 5.9 Output from K-Nearest-Neighbor. 1-NN is the category of the closest data point to that being classified. 3-NN and 4-NN are categories which are represented most often in the first three and four closest data points to the data point being classified. The program continues to 10-NN.

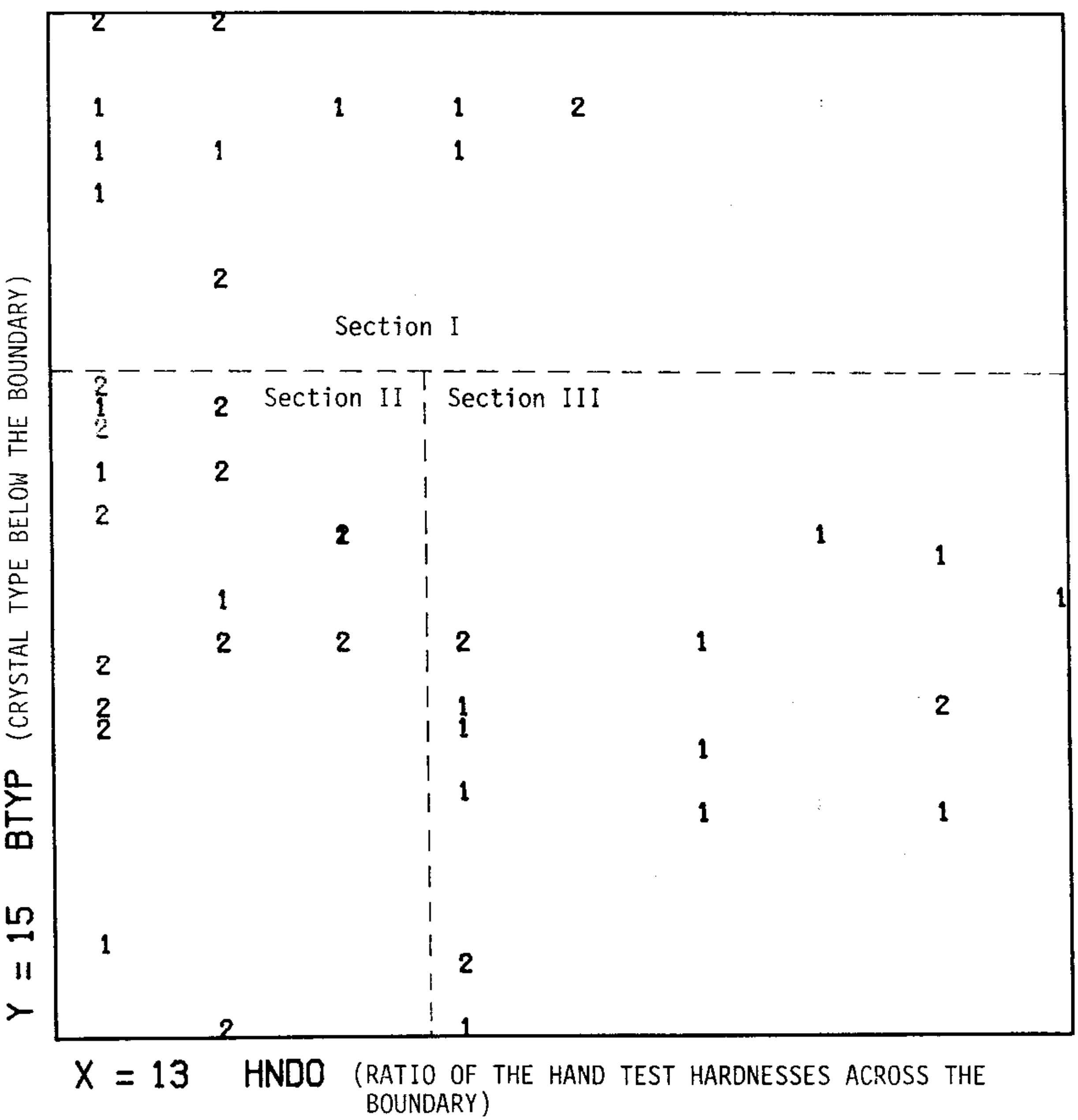


FIGURE 5.10 Crystal type of the snow layer below the boundary vs. the ratio of hand test hardnesses across the boundary (irrespective of direction). Dashed lines divide the plot into three arbitrary regions containing clusters of bed surface boundaries (1) and stable layer boundaries (2).

older snow or crusts are present which are, again, similar in hardness to the adjacent layer above. Section III is predominantly unstable, as in Section I, but while the crystal types are like old snow and crust, as they are in Section II, the hardness values are dissimilar between adjacent layers. These findings are consistent with field observations but no such trends can be distinguished for crystal types above the snow layer boundary of a slab region. This implies that the distinction between a lubricating layer and a sliding surface may be a necessary refinement for this program.

The misclassified profiles were ones which had no distinctive parameter change across the true bed surface. Wrong estimates of the bed surface on the profile test also had this trait. When recording the observations and methods of analyzing the snow profiles exhibited by some people as they took the FLP test, it was often noted that they searched the data for obvious changes in certain parameters. These obvious changes were then reinforced and justified as bed surfaces by what might be described as unstable characteristics in other parameters. But ARTHUR had the advantage of simultaneously looking at all the parameters. In this manner, it was the obvious feature differences that reinforced the characteristic unstable traits, so it was less likely to miss those bed surfaces which did not exhibit distinctive changes.

5.7 Reordering the Data to Describe Snow Layers

Because current research in snow mechanics has dealt with the failure of a snow layer as the cause of slab avalanching and not the bonding properties at a snow layer boundary, the next step in our analysis has been to reorganize the training data set so that it describes the condition of snow layers above and below a boundary rather than at the boundary itself. This set of parameters consists of: 1) thickness of the layer (THCK), 2) tangential stress at the base of the layer (STRS), 3) temperature of the layer (TEMP), 4) temperature gradient across the layer (TGRD), 5) ram resistance value of the layer (RAMO), 6) the layer's hand test value (HNDO), and 7) crystal type within the layer (TYPE). The layers were classified as: 1) failure - the layer directly above the bed surface which has slid away with the slab, 2) hard bed - a layer directly below the bed surface characterized by hard, cohesive snow, and 3) soft bed - another type of layer directly below the bed surface characterized by a less cohesive form of snow. These are subjective labels introduced only to test the program for its ability to distinquish stable properties within snow layers. At this point the physical descriptions of these three classes are not clearly defined, the important distinction being whether the layer is above or below the bed surface of a slab region.

The feature plots of these parameters are shown in Figures 5.12 through 5.14. The same reduction routines were used for these seven parameters as was used for the previous 15 parameters. These plots, then, are a 2-dimensional view of a 5-dimensional space. Figure 5.11 explains the combinations for the first three features: Figure 5.12 shows feature 1 vs. feature 2, Figure 5.13 shows feature 1 vs. feature 3, and Figure 5.14 shows feature 2 vs. feature 3. Figures 5.12 and 5.13 illuminate the separation between hard bed layers (2) and failure layers (1); an arbitrary line has been drawn on the plots for clarity. Soft bed layers (3) cannot be distinguished from failure layers. ARTHUR also provides these same plots (not shown here) with sequence numbers of the profiles instead of their class numbers. This way a cross-check of profiles which were incorrectly classified is available. A rotation about the second feature axis provides a third view of this 5-dimensional feature space, shown in Figure 5.14. Here the class separation is very difficult to see, which reaffirms the necessity for retaining as many dimensions as feasible. Failure layers and hard bed layers clearly can be distinguished. The next research step, yet to

INDEX	EIGENVALUE	VAR. PRESERVED EACH	VAR. PRESERVED SUM	FEATURE	COMP.	VAR. PRESERVED EACH	VAR. PRESERVED TOTAL
1	2.244E+00	32.05	32.05	6 HNDO	.550	30.26	9.70
				7 TYPE	-.515	26.52	8.50
				5 RAMO	.384	14.73	4.72
				2 STRS	.317	10.02	3.21
				3 TEMP	-.298	8.85	2.84
				1 THCK	-.265	7.03	2.25
				4 TGRD	-.161	2.59	.83

INDEX	EIGENVALUE	VAR. PRESERVED EACH	VAR. PRESERVED SUM	FEATURE	COMP.	VAR. PRESERVED EACH	VAR. PRESERVED TOTAL
2	1.195E+00	17.07	49.12	4 TGRD	.609	37.07	6.33
				1 THCK	.553	30.58	5.22
				2 STRS	.349	12.20	2.08
				3 TEMP	.347	12.01	2.05
				7 TYPE	-.210	4.39	.75
				6 HNDO	.168	2.83	.48
				5 RAMO	.095	.91	.16

INDEX	EIGENVALUE	VAR. PRESERVED EACH	VAR. PRESERVED SUM	FEATURE	COMP.	VAR. PRESERVED EACH	VAR. PRESERVED TOTAL
3	1.097E+00	15.67	64.80	3 TEMP	-.609	37.03	5.80
				5 RAMO	-.524	27.46	4.30
				2 STRS	.434	18.86	2.96
				4 TGRD	.345	11.90	1.86
				6 HNDO	-.176	3.08	.48
				1 THCK	-.129	1.67	.26
				7 TYPE	-.001	.00	.00

FIGURE 5.11 The first three principle components from the linear combinations of 7 snow pit parameters (see page 79 for a list of parameter abbreviations). The respective columns are; eigenvalues of the covariance matrix of the snow pit data (listed by decreasing magnitude), amount of variance preserved by each eigenvalue, sum of variances preserved, list of parameters (ordered by decreasing magnitude of their preserved variance), eigenvector component values, amount of variance preserved by each eigenvector for their respective eigenvalue, amount of variance preserved by each eigenvector out of total variance of the respective eigenvalues.

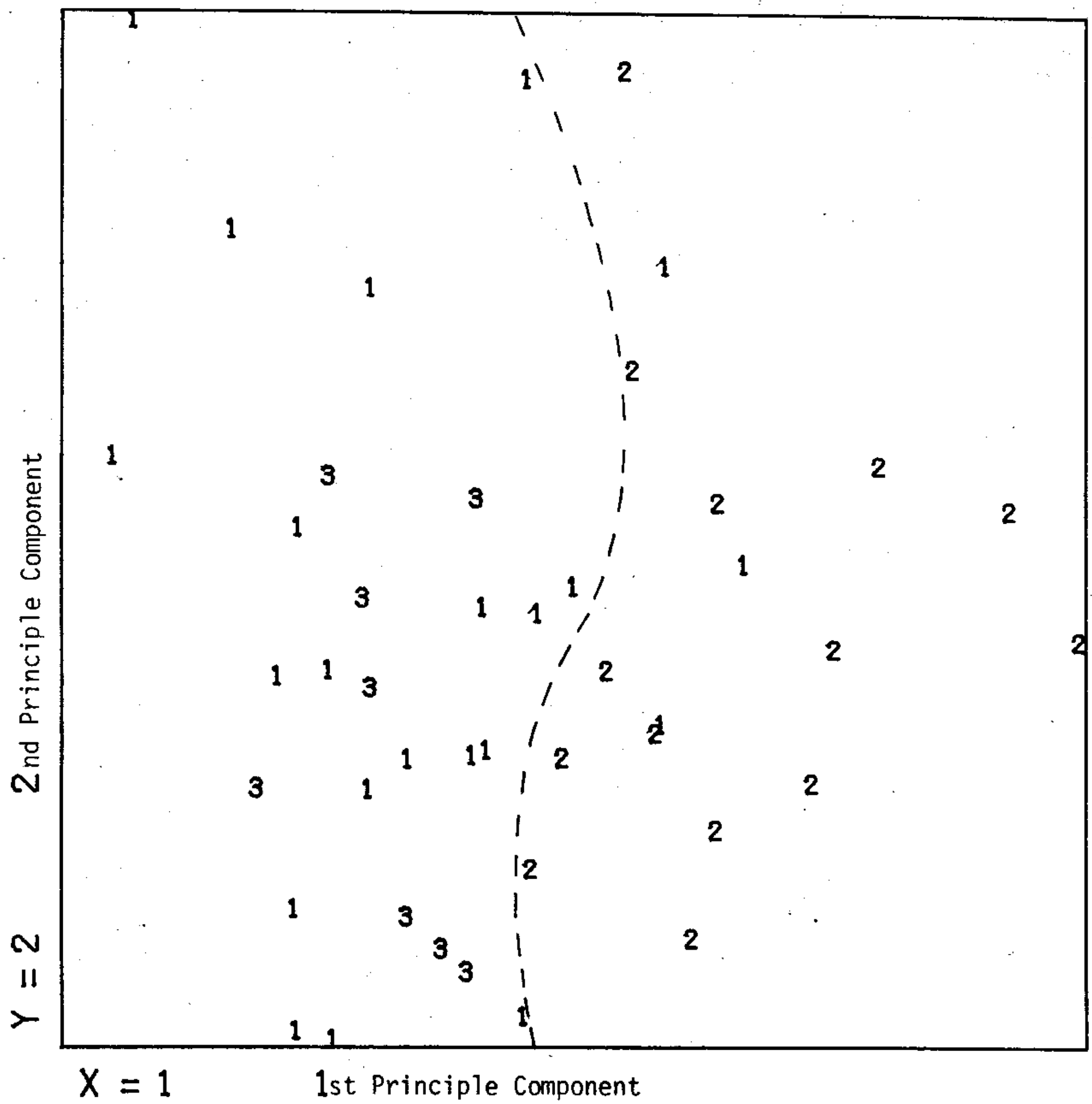


FIGURE 5.12 First principle component of the covariance matrix of the snow pit data vs. the second principle component. The dashed line is arbitrarily drawn to illustrate the separation of classes 1 and 3 (failure layers and soft sliding layers) from class 2 (hard sliding layers).

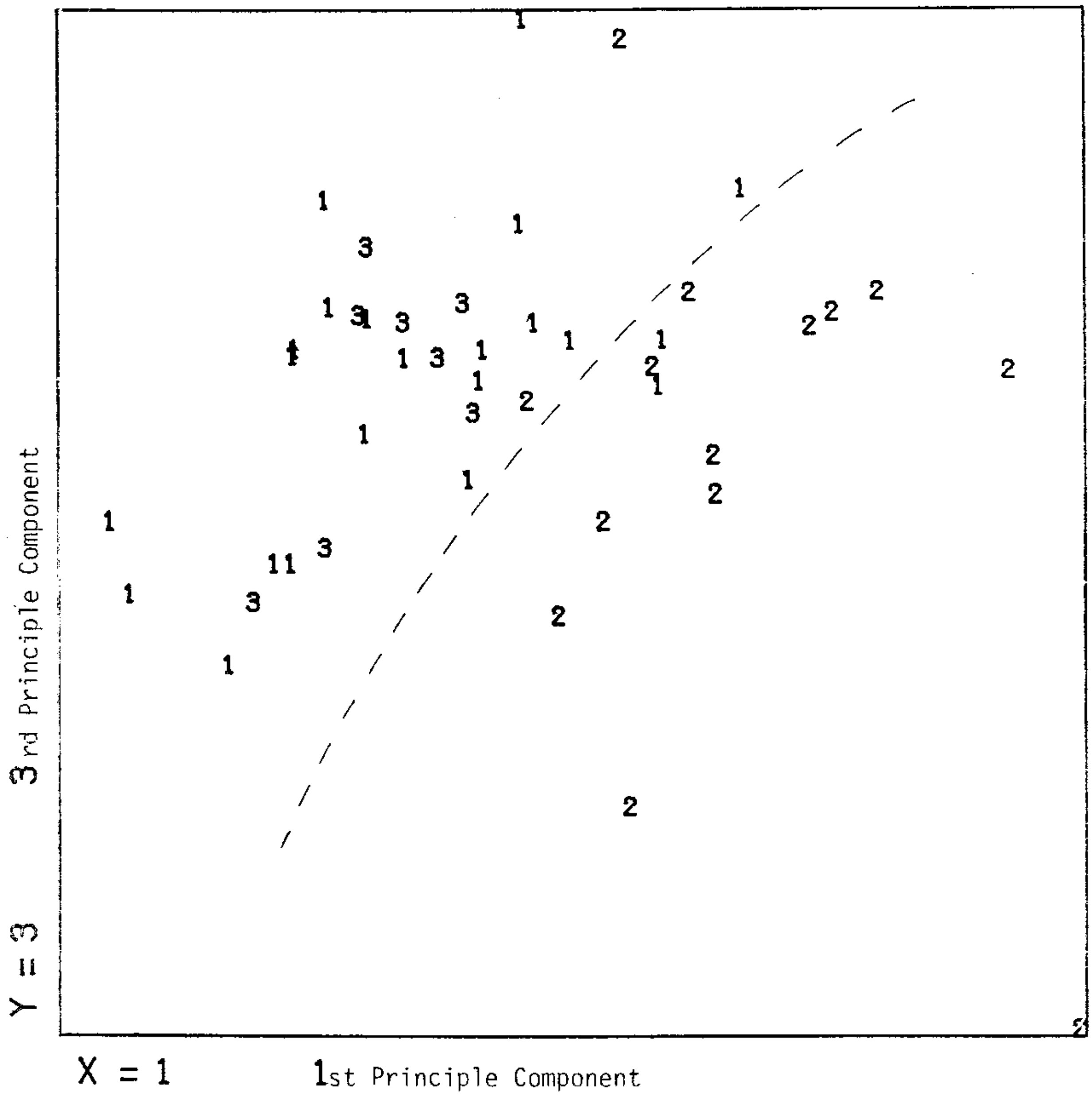


FIGURE 5.13 First principle component of the covariance matrix of the snow pit data vs. the third principle component. The dashed line is arbitrarily drawn to illustrate the separation of classes 1 and 3 (failure layers and soft sliding layers) from class 2 (hard sliding layers).

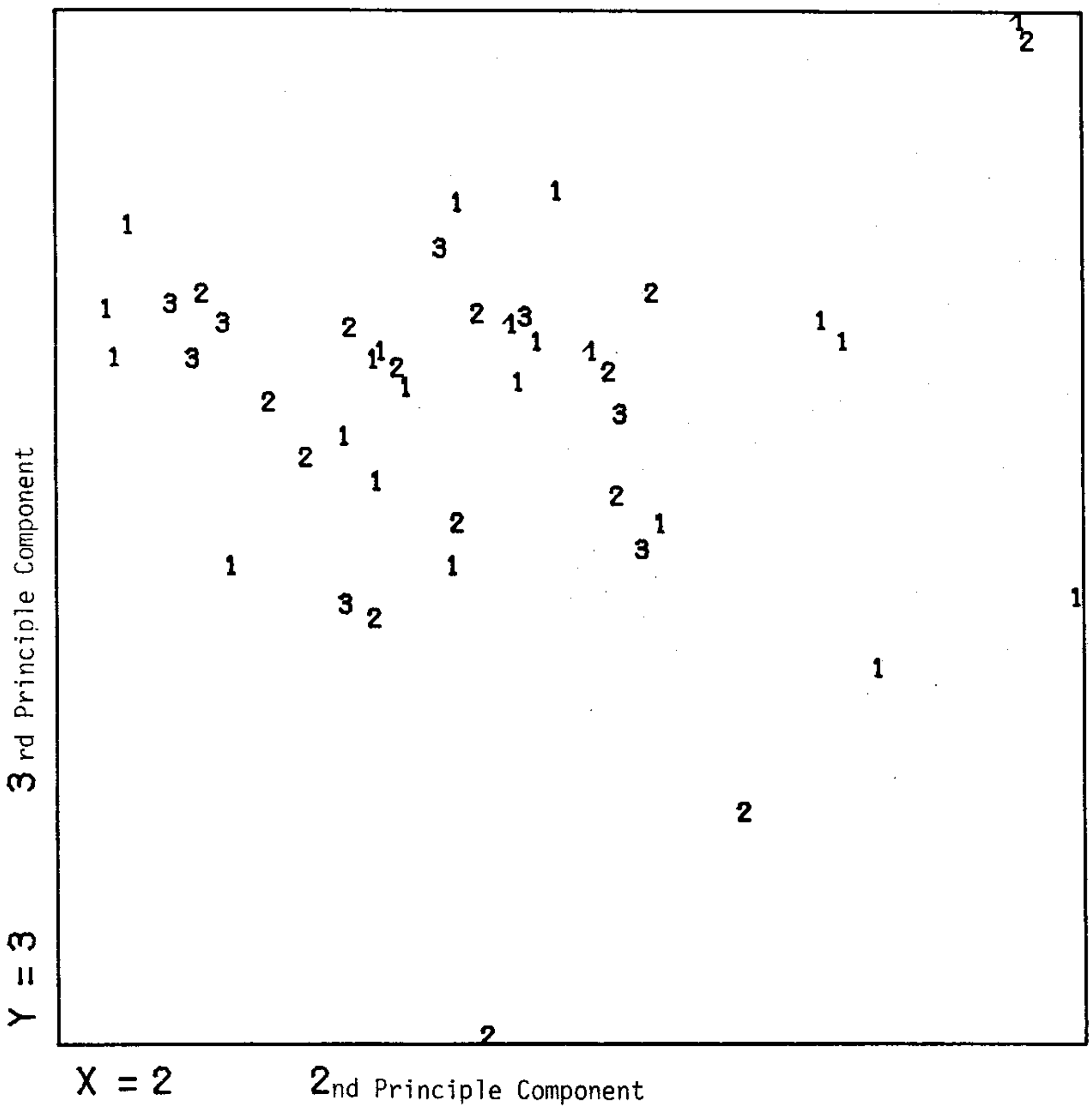


FIGURE 5.14 Second principle component of the covariance matrix of the snow pit data vs. the third principle component. Values are plotted for failure layers (1), hard sliding layers (2), and soft sliding layers (3).

be completed, is to find the proper parameters or cluster techniques that will allow distinction between a failure layer and a soft bed layer.

5.8 Experimental Instrumentation

The consistent selection of the hardness hand test and crystal type as valuable contributions to these clustering and classification routines is significant with respect to their evaluation as useful measurements. These two parameters have also proven popular for recognizing sliding surfaces on the FLP test. It is somewhat distressing that the most subjective measurements could have the greatest ability to influence clustering in this type of analysis. Subjectivity in these parameters has made them difficult to quantify, so they have become unreliable as absolute measurements. This may be a reason for the poor clustering ability of the data points. It suggests that some vital re-organization of data collection procedures be implemented to improve the quantitative measurements of these parameters. When this is done, it is quite reasonable to expect an improvement in classifying and recognizing unstable layers from snow profiles.

Alternative measurement techniques designed for field use have focused on strength tests (compressive, tensile, shear, and bending). Up to now these have been either too cumbersome, time consuming or inconsistent, whereas other snow properties, such as the energy of disaggregation, may be more amenable to instrument requirements. In order to develop a coherent program of experimental instrumentation, serious consideration has been given to the difference between a property measurement and an empirical type of measurement. Temperature would be a property measurements for it is a direct measure of a physical state of a snow layer. Ram resistance is an example of an empirical measurement. It is an indirect measure of strength based on complicated properties of compaction and disaggregation. The design and use of property measurements would greatly improve the development of theoretical relationships to the mechanics of slab failure. But empirical measurements should not be disregarded for they often provide the necessary simplicity for field use. As long as the empirical measurements are quantitative, and there are sufficient property measurements gathered, multivariate methods, like those available in ARTHUR, may enhance the understanding of snow slab mechanics through snow pack feature analysis.

5.9 Conclusion

Given the subjective nature of available data, the pattern recognition techniques described above are obviously preliminary in nature. But they have been instructive in providing the groundwork for reorganizing and improving the collection and transmission procedures from snow pit investigations. Future collection techniques might concentrate on gathering information about layer boundaries, not just the layers themselves. Also, more quantitative measurement techniques, both in collection and transmission, would aid numerical classification methods. Although the effectiveness of pattern recognition for establishing a stability index has not yet been proven, it does provide the ability to seek and describe relationships among parameters as they pertain to the physics of avalanching. This is an advantage, not available in other analytic techniques, which should be pursued.

6. THE RATING OF FORECASTING SKILLS

Only minor changes were made in the Forecasting Office product during the third year of operation. The time of issuance of the morning forecast was generally a half hour later than in previous years due to changes in NWS forecast models which delayed their arrival in the Forecasting Office. Additionally, a little greater emphasis was placed on the backcountry weather and avalanche forecasting in hopes of generally improving the forecasts by considering the Cascades as a whole rather than as individual passes. The results discussed in this section are an extension of those discussed in last year's report, as well as a review of improvements in forecast accuracies over the last three years.

6.1 Weather and Weather Trends

Weather and weather trends were given as a narrative forecast for the present to 48 hours and in a less detailed form from 48 to 96 hours. A greater effort was made to treat individual areas separately whenever the situation required. This consisted of giving forecasts for "south of Snoqualmie Pass" or "from Stevens Pass northward," as examples.

The consensus of field personnel was that the general forecast accuracy continued to improve as forecasters gained increasing knowledge of the peculiarities of the various areas. Particularly, forecasters showed an increased ability to forecast the formation and movement of heavy post-frontal precipitation associated with the Puget Sound Convergence Zone. This improvement is due primarily to better high resolution radar and satellite imagery, as well as access to weather observations from the Puget Sound Air

Pollution Stations at 15 minute intervals which allowed forecasters to better pinpoint the location and motion of the convergence zone.

The usefulness of the 48-96 hour forecasts was improved by modifying the temperature information. In the past forecasts of temperatures were given in relation to the climatological norm for the period (e.g., above normal temperatures). As many people were not familiar with the climatological norms, it was decided to express temperatures as a range of freezing levels or snow levels, for example, "snow level 3-5000 feet at the beginning of the period lowering to 1-3000 feet by the end of the period." Ranges were given in 2000 foot increments, but this was expanded to 3000 feet when there were uncertainties in the long range progs. Field personnel reported good forecast accuracy, as well as much greater utility from this system.

6.2 Freezing Levels

Free air freezing levels were forecast for the Cascades and Olympics with geographical variations noted when appropriate. Verification was carried out between the freezing levels forecast for the Olympics and those measured at the Quillayute radiosonde station located just west of the Olympics. The mean monthly error and mean total error for the season are given in Table 6.1.

Monthly forecast errors are greatest in December due largely to extremely high freezing levels (in excess of 10,000 feet) which were underforecast during the early December floods. The monthly averages show improvement in January and February and then some degeneration in March as periods with very large fluctuations of freezing levels occur. The average error for the season shows

TABLE 6.1 Mean errors in free air freezing level forecasts winter 1977/78.

Mean Monthly Error

December	1093 ft.
January	800 ft.
February	725 ft.
March	980 ft.

Mean Season Error

1975/76	1500 ft.
1976/77	1056 ft.
1977/78	904 ft.

a significant improvement over the three seasons, with 1977/78 showing a 40% improvement in accuracy over the 1975/77 season.

Additionally, the local freezing level problem of the Cascade passes associated with cold easterly flows was handled with increasing accuracy. This allowed much better timing of local warmups in the passes. This was associated with the development of forecasting algorithms discussed in Sections 7 and 8.

6.3 Wind Forecasts

Free winds at the 850 mb level (5000 feet) and winds through the Cascade passes were routinely forecast twice daily.

As in previous years a qualitative comparison of the forecasted free air wind speed and direction forecasted was made with the Quillayute measurements. Quite good agreement between the observed and forecasted values were noted. Some improvement was noted over the previous two years, particularly in wind direction accuracy. This is probably due to new NWS forecast guidance that is now available specifically for the 850 mb level. Most errors in free wind direction occurred during periods of light winds and in the immediate vicinity of fronts where timing errors of a few hours drastically alter the measurements taken at the radiosonde station. Wind speeds, which are given as 10 mile ranges, were generally correct to within $\pm$10 mph with most errors associated with poor 850 mb progs.

Forecasts of pass winds were made based on forecast pressure gradients across the Cascades, as well as expected 850 mb winds. Project forecasters have been able to improve the timing of wind shifts, which are frequently critical in timing warmups within the passes, largely due to increased experience and improved forecasting algorithms. Unlike last year, pass wind speeds were most often underestimated when they were in error. There appears to be no particular source for this, although some of the errors may be due to ridge accelerations which are present at some of the reporting stations.

6.4 Quantitative Precipitation Forecasts (QPF)

The estimated water equivalents for two consecutive 24 hour periods beginning at 0400 PST on the day the forecast is issued were made twice daily for eight points in the Cascades (Washington, Stevens, Snoqualmie, White, Chinook, and Cayuse Passes and Paradise and Crystal Mountains). Reliable records of water equivalent are only available from Washington, Stevens, and Snoqualmie Passes due to lack of staff and/or instrumentation at the other locations. Tables 6.2-6.4 summarize the accuracy of the QPF's for the 1977/78 winter. Each Table has nine numbered columns which describe the following:

Column 1--the number of days with measurable precipitation for which observations were available;
2--the mean error of the forecasts in inches of water equivalent;
3--the standard deviation of the mean error (68% of all of the forecast errors lay within one standard deviation of the mean);
4--the percentage of days on which the observed value lay within the forecast ± 1/8 inch range;
5--the percentage of days that lay within ± 1/4 inch range;
6--the percentage of days that lay within ± 3/8 inch range;
7--the percentage of days on which the observed value lay more than 1/2 outside the forecast range;
8--the accumulated error in inches; and
9--the total observed precipitation.

TABLE 6.2 Accuracy of QPF's - Washington Pass.

	1*	2	3	4	5	6	7	8	9
December									
1st 24 hrs AM	21	0.49	0.58	19%	38%	48%	52%	10.29	14.76
PM	21	0.48	0.52	14%	29%	38%	62%	10.11	
2nd 24 hrs AM	20	0.48	0.62	14%	33%	43%	52%	9.67	
PM	21	0.45	0.56	19%	33%	43%	57%	9.47	
January									
1st 24 hrs AM	15	0.18	0.35	40%	73%	87%	13%	2.64	4.67
PM	15	0.16	0.32	33%	73%	87%	13%	2.40	
2nd 24 hrs AM	15	0.24	0.27	33%	47%	53%	47%	3.64	
PM	15	0.28	0.30	40%	47%	53%	47%	4.19	
February									
1st 24 hrs AM	12	0.19	0.19	25%	58%	67%	33%	2.31	2.92
PM	12	0.13	0.18	33%	75%	83%	17%	1.62	
2nd 24 hrs AM	12	0.26	0.21	0%	42%	67%	33%	3.08	
PM	12	0.23	0.21	8%	42%	67%	33%	2.73	
March									
1st 24 hrs AM	13	0.17	0.21	38%	62%	62%	38%	2.27	3.72
PM	13	0.14	0.19	46%	69%	69%	31%	1.81	
2nd 24 hrs AM	13	0.32	0.20	8%	23%	46%	54%	4.14	
PM	13	0.32	0.20	8%	23%	46%	54%	4.14	
Season									
1st 24 hrs AM	61	0.29	0.43	30%	56%	64%	36%	17.51	26.07
PM	61	0.26	0.40	30%	57%	66%	34%	15.94	
2nd 24 hrs AM	60	0.34	0.41	15%	37%	52%	48%	20.53	
PM	61	0.34	0.39	20%	36%	51%	49%	20.53	

*See text for explanation of column labels.

TABLE 6.3 Accuracy of QPF's - Stevens Pass.

	1*	2	3	4	5	6	7	8	9
December									
1st 24 hrs AM	21	0.65	1.14	38%	43%	48%	52%	13.65	21.79
PM	21	0.73	1.07	19%	29%	38%	62%	15.43	
2nd 24 hrs AM	20	0.70	1.11	10%	24%	29%	67%	13.96	
PM	21	0.64	1.10	14%	24%	38%	62%	13.37	
January									
1st 24 hrs AM	14	0.27	0.42	43%	64%	71%	29%	3.72	6.33
PM	14	0.28	0.42	50%	57%	71%	29%	3.97	
2nd 24 hrs AM	14	0.39	0.36	14%	29%	50%	50%	5.47	
PM	14	0.42	0.37	14%	36%	43%	57%	5.84	
February									
1st 24 hrs AM	15	0.23	0.25	33%	47%	60%	40%	3.39	4.58
PM	15	0.18	0.21	40%	47%	67%	33%	2.68	
2nd 24 hrs AM	15	0.27	0.29	13%	47%	60%	40%	3.98	
PM	15	0.25	0.30	27%	47%	60%	40%	3.76	
March									
1st 24 hrs AM	12	0.24	0.31	42%	58%	67%	33%	2.93	3.28
PM	12	0.24	0.31	42%	58%	67%	33%	2.93	
2nd 24 hrs AM	12	0.33	0.32	25%	42%	42%	58%	4.00	
PM	12	0.36	0.33	17%	33%	50%	50%	4.33	
Season									
1st 24 hrs AM	62	0.38	0.74	39%	52%	60%	40%	23.69	35.98
PM	62	0.40	0.72	35%	45%	58%	42%	25.01	
2nd 24 hrs AM	61	0.45	0.71	15%	34%	44%	56%	27.41	
PM	62	0.44	0.71	18%	34%	47%	53%	27.30	

*See text for explanation of column labels.

TABLE 6.4 Accuracy of QPF's - Snoqualmie Pass

		1*	2	3	4	5	6	7	8	9
December										
1st 24 hrs	AM	18	0.85	1.67	17%	33%	61%	39%	15.36	22.69
	PM	18	0.93	1.73	17%	28%	44%	56%	16.74	
2nd 24 hrs	AM	17	1.04	1.86	28%	28%	33%	61%	17.62	
	PM	18	1.07	1.82	22%	28%	33%	67%	19.19	
January										
1st 24 hrs	AM	20	0.33	0.48	25%	30%	60%	40%	6.56	8.01
	PM	20	0.33	0.48	25%	30%	60%	40%	6.56	
2nd 24 hrs	AM	20	0.38	0.44	25%	40%	50%	50%	7.66	
	PM	20	0.38	0.44	25%	40%	50%	50%	7.52	
February										
1st 24 hrs	AM	12	0.28	0.28	17%	33%	67%	33%	3.40	6.60
	PM	12	0.27	0.29	25%	42%	67%	33%	3.25	
2nd 24 hrs	AM	12	0.27	0.30	25%	42%	67%	33%	3.27	
	PM	12	0.27	0.30	25%	42%	67%	33%	3.28	
March										
1st 24 hrs	AM	15	0.39	0.37	27%	27%	53%	47%	5.85	7.02
	PM	15	0.37	0.37	27%	33%	53%	47%	5.59	
2nd 24 hrs	AM	15	0.45	0.41	27%	27%	40%	60%	6.76	
	PM	15	0.47	0.45	27%	27%	40%	60%	7.01	
Season										
1st 24 hrs	AM	65	0.48	0.97	22%	31%	60%	40%	31.17	44.32
	PM	65	0.49	1.01	23%	32%	55%	45%	32.14	
2nd 24 hrs	AM	64	0.55	1.06	27%	34%	47%	53%	35.31	
	PM	65	0.57	1.07	25%	34%	46%	54%	37.00	

*See text for explanation of column labels.

A separate verification was carried out for the first and second 24 hour QPF's. The verification was further broken up into QPF's issued in the morning forecasts (AM) and those issued in the afternoon forecasts (PM).

The accuracy of the results for Washington Pass (Table 6.2) seen in December is much less than that seen in the other three months. This has two sources. First, a period of relearning appears to take place at the start of every season as forecasters refamiliarize themselves with the various areas. Second, extremely large precipitation quantities occurred in December associated with the early December floods. Project forecasters have little or no guidance which allows accurate forecasts of QPF's above 1 to 1 1/2 inches of precipitation. Twenty-four hour quantities as great as 2.60 inches were recorded at Washington Pass during these floods. This effect is also seen at Stevens and Snoqualmie Passes. With the exception of December, the other months showed comparable or better accuracy than the 1976/77 season, particularly in the percentage accuracies.

Table 6.3 shows the results for Stevens Pass. The effects of the December floods are seen once again in terms of the poor December forecast accuracy. Other months show accuracy comparable to that seen for the previous two seasons and a notable improvement is seen over the three years in the percentage of forecasts that were within ± 1/8 inch of the recorded value.

Table 6.4 shows the results for Snoqualmie Pass. Even more than the other two stations, the effects of the heavy precipitation in December can be seen. Unlike the other stations, Snoqualmie Pass does not show any improvement in forecast accuracy over the three years. Although part of this may be due to instrumentation deficiencies, it most likely points out the level of QPF accuracy for this area cannot be further increased until better guidance is available to forecasters.

Table 6.5 summarizes the season statistics for the three years of the project for the first 24 hour forecasts of QPF. Only PM forecasts are compared as only one forecast was issued each day during the first year of the project. Although the season statistics for 1977/78 are somewhat biased by the poor December accuracies, there does not seem to be a truly consistent improvement in the seasonal forecast accuracy over the period. A consistent level appears to have been attained with average errors of 0.20 to 0.30 and a percentage accuracy in the $\pm$ 1/8 inch range of 30% to 40%. It appears doubtful that further significant improvement will be possible until better mesoscale guidance, such as an orographic precipitation model, is available.

6.5 Avalanche Advisories

Avalanche advisories continued to be issued premarily as a narrative part of the forecast; however, forecasters kept a verification sheet for in-house use. For purposes of verification, sluffs and slides have been combined together as one phenomenon due to the uncertainties in observations. Significant numbers of avalanches affecting the highway were reported at Washington, Stevens, and Snoqualmie Passes, but reliable observations were not available from Snoqualmie Pass; hence, verification was only carried out for Washington and Stevens Passes.

Tables 6.6 and 6.7 show the results for Stevens Pass and Washington,

TABLE 6.5 Summary of seasonal statistics 1975-1978

Stevens Pass

	1	2	3	4	5	6	7	8
1975-76	70	0.19	0.24	34%	57%	69%	13.52	38.65
1976-77	59	0.20	0.31	34%	63%	78%	11.86	27.48
1977-78	62	0.40	0.72	35%	45%	58%	25.01	35.98

Washington Pass

	1	2	3	4	5	6	7	8
1975-76	- - - - - - - - - - - - No Data -							
1976-77	69	0.16	0.22	43%	61%	77%	10.92	19.90
1977-78	61	0.26	0.40	30%	57%	66%	15.94	26.07

Snoqualmie Pass

	1	2	3	4	5	6	7	8
1975-76	48	0.28	0.26	19%	40%	48%	13.65	31.58
1976-77	61	0.26	0.35	31%	54%	66%	15.80	38.10
1977-78	65	0.49	1.01	23%	32%	55%	32.14	44.32

1 Number of days with measurable precipitation
2 Average error
3 Standard deviation of average error
4, 5, 6 % of days with precipitation forecast correctly within $\pm$ 1/8, $\pm$ 1/4, and $\pm$ 3/8 respectively.
7 Accumulated error (inches)
8 Total precipitation (inches)

TABLE 6.6 Accuracy of avalanche advisories for Stevens Pass (December-March). Tabulated in terms of the number of days forecast and observed.

FORECAST \ OBSERVED	NO SLIDES	SLIDES	SLIDES AFFECTING HIGHWAY
NO SLIDES	76	2	0
SLIDES	19	8	4
SLIDES AFFECTING HIGHWAY	8	3	1

TABLE 6.7 Accuracy of avalanche advisories for Washington Pass (December-March). Tabulated in terms of the number of days forecast and observed.

FORECAST \ OBSERVED	NO SLIDES	SLIDES	SLIDES AFFECTING HIGHWAY
NO SLIDES	45	2	3
SLIDES	23	4	9
SLIDES AFFECTING HIGHWAY	14	2	19

respectively. Statistics are based on reports of avalanche activity sent into the Forecast Office. The numbers represent the number of days for which a given level of activity was forecast and for which it was observed. For example, there were 19 days at Stevens Pass when slides were forecast but no slides were observed. The results show a fair level of accuracy--there being only three instances at Washington Pass out of 31 when avalanches reaching the road were reported at times when no slide activity at all was forecast. The conservative nature of the forecasts is seen from the number of over-forecasts, that is, the number of instances when avalanches affecting the highway were forecast but did not occur (8 at Stevens, 14 at Washington Pass).

With the exception of Washington Pass, the number of serious avalanches reported during the three years of the project was exceptionally low (particularly during the drought year of 1976/77). However, it appears that the conclusion set forth in the previous reports holds true:

> The avalanche advisory serves as a general evaluation of current snowpack conditions and stability. It can serve as an aid or a starting point for the evaluation of the local avalanche hazard by WSDT avalanche crews or ski area control teams. However, detailed evaluation of the current hazard on a path by path basis still requires a trained observer on the spot.
>
> Many times the advisory can serve these individuals by informing them of activity and snowpack structure observed elsewhere, thus allowing them to better interpret their local situation. The advisory does not provide sufficient information for individuals involved in determining regional avalanche hazards, such as those covered in public advisories and warnings issued for the National Forests.

7. CASCADE MOUNTAIN WEATHER FORECASTING

7.1 Introduction

Avalanche occurrences have long been known to be intrinsically related to the winter mountain weather. Given the predominance of direct action slab avalanching in the Washington Cascade mountain passes and nearby areas, the importance of accurate and reliable quantitative precipitation, wind and temperature forecasting for these areas cannot be over-emphasized. Timely knowledge of the expected amounts and rates of snowpack loading, expected wind transport problems, and expected freezing level variations is often critical to successful avalanche control missions on the highway or in the ski area. Such knowledge is also necessary for efficient scheduling of highway maintenance crews and related personnel, and provides important input for consideration in public avalanche warnings.

This section of the report attempts to formulate an improved forecasting algorithm for the Cascades through compilation in specific and quantitative form the basic criteria for evaluating the normal spectrum of snow and weather conditions encountered during a Cascades winter. This treatment takes as a starting point the preliminary guide to forecasting methodology developed during the second year of the Central Avalanche Hazard Forecasting Project (see Figure 8.1 on p. 145) and attempts to give some quantitative guidelines for the key meteorological variables (boxes C-E in Figure 8.1) influencing stability of the mountain snowpack.

The principles of data management developed in section 2 are applied here for the selection of meteorological quantities used in avalanche forecasting. Rating schemes for several weather parameters are introduced in order to apply the principle of minimizing potential information or entropy. Instead of carrying specific values like 17 knots wind speed or 27°F. air temperature into the avalanche algorithm, the available spectra of values for each parameter are divided into rating categories. These categories are scaled as LOW, TRANSITIONAL and HIGH according to their relative contribution to avalanche formation. The basic meteorological forecast decisions for each parameter then need to be made among only a very limited number of choices, usually three. As will be developed further in section 8, this same principle is then in turn carried over into the avalanche forecast. The key problem here is to select the dividing points between rating levels for each parameter; for instance, should the division between LOW and TRANSITIONAL wind velocities be set at 15 knots or at some other value? The dividing points presented here are highly preliminary ones based largely on empirical experience and are subject to future revisions as these concepts are further developed. They also are specific to the weather and avalanche conditions of the Cascade Mountains; the rating categories might well be divided differently in other mountain ranges and climates. Further analysis of weather and avalanche records, underway but yet incomplete, may suggest further category revisions. The choice of three categories for each weather parameter is in some measure arbitrary, being based largely on local forecasting experience developed during the course of this project. The theoretical optimum is to define categories so that each decision is made as a choice between two options of approximately equal occurrence probability, for this leads to eliminating a maximum amount of entropy or uncertainty at each step in the forecasting process. Ideally, each weather parameter should be divided into 2^n rating categories with entropy elimination most rapidly when n=1.

7.2 Precipitation Forecasting

Factors to consider in making quantitative precipitation forecasts for various points in the Washington and Oregon Cascades are based on both the current synoptic weather situation and climatological data. That is, the forecaster must not only consider what is and will be happening meteorologically in the mountains using maps, satellite pictures and current field data, but also needs to have a good working knowledge of the past local and regional responses of various mountain stations to given large-scale weather conditions.

Focusing first on the climatological aspect of mesoscale quantitative precipitation forecasting, the forecaster needs information describing the local precipitation climate at the mountain stations of interest. Daily, weekly, monthly and annual precipitation and snowfall characteristics for selected Cascade mountain stations are shown in Table 7.1 and Figure 7.1. These are useful guides in characterizing absolute precipitation regimes as well as regional or local variations in precipitation and snowfall characteristics within the Cascade mountains. For example, Snoqualmie Pass receives approximately three times as much annual precipitation (water equivalent) as Seattle's 35 inches/year and slightly more than Paradise on Mt. Rainier, which is generally considered the winter precipitation capital in the continental United States. But as Table 7.1 shows, Snoqualmie Pass received much less annual snowfall than Paradise, since a much higher percentage of precipitation falls as snow at Paradise than at Snoqualmie Pass. If rates or amounts of loading on a marginally stable snowpack are to be considered, knowledge of regional variations such as this are basic to quantitative precipitation forecasting.

Given this basic working knowledge of precipitation climatology in the forecast areas, the forecaster must next consider the current and expected weather situations and how these will affect the areas of interest. To reach a reliable confidence level in his/her precipitation forecasts, the forecaster often consults with NWS forecasters while assessing NWS data from satellite pictures, weather maps, temperature/dew-point soundings, precipitation forecast

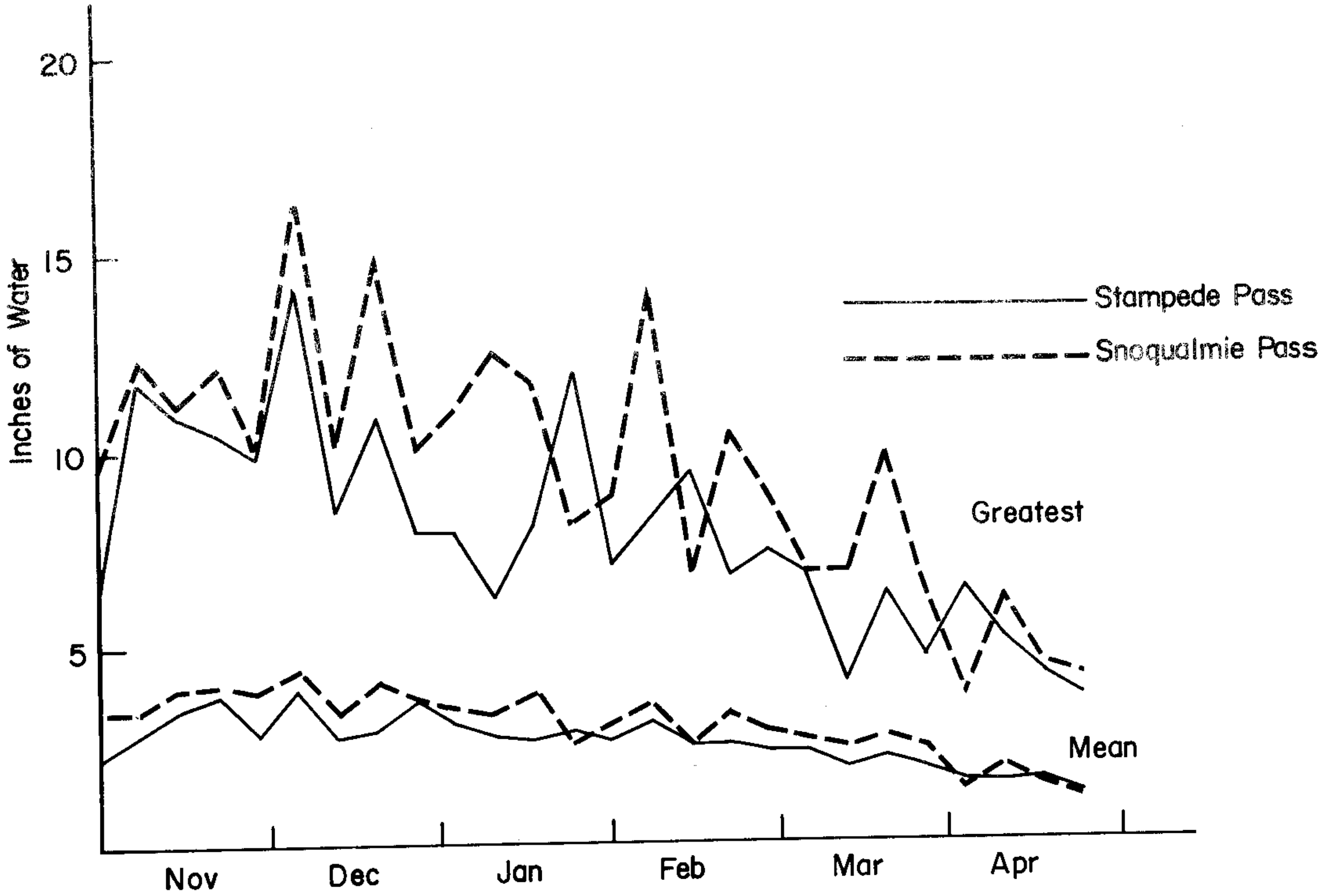


FIGURE 7.1 Stampede and Snoqualmie Passes weekly precipitation totals in water equivalent, 1931-1965. Data are from Climatological Handbook, Columbia Basin States, Precipitation, Vol. 2, September 1969.

TABLE 7.1. Selected monthly precipitation and snowfall characteristics for Rainier-Paradise, Snoqualmie Pass, Stevens Pass and Stampede Pass. (From Climatological Handbook, Columbia Basin States, Precipitation, Vol. 2, Sept., 1969.)

A. Means, Monthly and Annual Precipitation, 1931-1960, in inches.

STATION	#YEARS	JAN	FEB	MAR	APR	NOV	DEC	ANN
Rainier-Paradise	32	14.90	11.22	10.65	6.43	13.64	16.51	103.73
Snoqualmie Pass	27	14.77	12.74	11.72	6.39	15.41	18.06	107.60
Stampede Pass	30	12.03	10.15	10.60	5.60	12.58	16.19	92.19
Stevens Pass	18	10.65	8.77	7.47	4.18	11.86	11.69	75.55

B. Medians, Monthly and Annual Precipitation, 1931-1965, in inches.

STATION	#YEARS	JAN	FEB	MAR	APR	NOV	DEC	ANN
Rainier-Paradise	34	14.11	13.06	11.45	6.41	13.41	15.71	100.28
Snoqualmie Pass	34	14.80	13.24	11.33	6.55	14.27	19.26	104.44
Stampede Pass	21	10.38	9.91	9.24	6.39	12.05	11.76	79.87
Stevens Pass	23	9.54	8.54	7.92	4.61	9.84	11.94	71.12

(continued)

TABLE 7.1 (continued)

C. Number of Days Exceeding .01, .10, .25, .50 and 1.00 Inch Totals--Averages by Months, 1931-1965. (Data not available for Rainier, Paradise and Stevens Pass.)

STATION	LIMIT	JAN	FEB	MAR	APR	NOV	DEC
Snoqualmie Pass 1931-1962	0.01	18.5	16.7	18.6	14.2	15.6	19.6
	0.10	16.2	14.2	15.6	10.8	13.9	17.6
	0.25	13.3	11.6	12.1	6.9	11.7	14.8
	0.50	10.1	8.0	8.5	4.4	9.1	11.3
	1.00	4.7	4.2	3.8	1.8	5.3	5.9
Stampede Pass 1944-1966	0.01	22.5	20.3	21.3	18.9	18.0	20.5
	0.10	17.5	15.0	16.3	12.7	14.4	16.0
	0.25	12.9	10.7	11.5	8.3	11.0	12.4
	0.50	8.7	7.7	7.1	4.1	7.7	8.4
	1.00	4.6	3.3	2.6	1.2	4.1	4.6

D. Mean, Median, Greatest, Least Monthly and Seasonal Totals, Snowfall, 1931-1965, in inches

STATION	STATISTIC	JAN	FEB	MAR	APR	NOV	DEC	SEASONAL
Rainier-Paradise (27 years data)	Mean	117.0	99.8	98.7	47.6	67.9	98.9	578.3
	Median	109.5	100.2	106.0	38.5	75.0	107.5	-
	Greatest	260.0	227.5	203.7	116.1	190.0	168.0	998.5
	Least	42.0	20.5	22.0	7.0	6.0	37.0	313.0
Snoqualmie Pass (32 years data)	Mean	104.9	85.8	78.7	24.6	42.2	86.8	435.7
	Median	95.0	82.3	76.4	18.5	40.7	79.5	-
	Greatest	265.0	190.5	222.0	87.4	107.0	157.0	797.0
	Least	24.5	8.0	2.0	T	T	21.0	173.0
Stampede Pass (33 years data)	Mean	84.1	79.0	76.3	41.2	60.3	76.9	448.1
	Median	76.8	74.8	72.2	40.2	52.3	60.6	-
	Greatest	192.9	181.7	154.8	90.9	138.5	163.3	632.7
	Least	26.1	24.5	23.7	11.7	5.8	22.7	333.5
Stevens Pass (22 years data)	Mean	102.8	81.0	78.6	30.5	64.7	90.9	475.5
	Median	103.4	76.8	64.0	26.0	54.5	85.5	-
	Greatest	233.0	166.0	148.0	78.5	139.3	158.5	691.5
	Least	26.5	15.5	8.5	2.0	6.5	22.1	229.6

products (which yield general numerical guidelines for expected precipitation), and current and recent past hourly precipitation intensities (PI) from reporting mountain stations. A specific list of the more important NWS products and field data sources considered by the forecaster in estimating the ranges of expected precipitation for mountain stations is given below. This same list applies to forecasting procedures for other weather variables discussed in sections 7.3 through 7.5.

Associated variable abbreviation	Data Source	Application/Useful derived information
P = precipitation, W = wind, FL = freezing level, G = general weather trend		
P W FL	Remote telemetry - Stevens Pass	Current values of PI, wind speed and direction, and temperatures (upper and lower). Important for verification of maps and current weather forecasts (or indications of changes in same), and for information about possible snow loading, wind transport and temperature inversion problems.
W FL	Remote telemetry - Hurricane Ridge	Current values of wind speed and temperature. Good for indication of freezing levels, temperature trends to appear later in Cascades.
P W FL G	NWS Stampede Pass hourly weather data	Current values of all meteorological parameters from the NWS synoptic mountain observation station, including sky cover, visibility, wind transport, etc. Important for forecast and map verification.
P W FL G	Mountain data network	Current values of important meteorological parameters, generally once daily (more often as needed). Useful for trends in weather and indication of possible regional (or horizontal) precipitation gradients. Indirect indication of freezing level through temperature and rain/snow reports. Very important for snowpack information.
P W FL	WSDT Sno-line reports; Oregon road reports	Teletype pass road information good for verification of current forecasts or indications of changes in same.

P W FL G	Radiosonde data (UIL, SEA, GEG, GRF, SLE, C7P, YVK, YZT)	Gives current vertical sounding of air temperature, dew point and wind speed and direction at the indicated station. Useful in determining freezing level, stability, drying and wetting trends, cloud layers and possible orographic precipitation magnitude. These form an integral part of any freezing level forecast though all are not used in any given situation. Advection of temperature and moisture important for freezing level forecasts.
P W FL G	Ship reports (NWS teletype)	Form ship weather reports, may often infer frontal motion, precipitation and wind values; also from simple lapse rate estimates of ship surface air temperature, may infer freezing level at that point.
FL G	FOUS 43 (especially for SEA, PDX, GEG)	Primarily for forecasting freezing level heights above the station level for SEA, PDX, MFR, GEG, YVR. Forecast relative humidity values are useful for drying trends.
P FL G	FOUS 72 (& 76) (for SEA, PDX, GEG, MFR, YVR)	Forecast freezing level heights may be derived from listed 1000-500 mb thicknesses and boundary layer potential temperature (using NWS graph). Precipitation timing, amounts, trends, frontal timings and surface wind values also indicated (point estimates).
W FL G	FOUS 50 Trajectory	Useful in freezing level forecasts and east-west pressure gradients SEA-YKM. Gives 24 hour forecast of 850-mb temperature. By using this and looking upstream at station reports near the forecast trajectory, forecaster gains a feel for any ongoing modifications (in wind and temperature fields).
G	FP3	NWS Lead forecaster's assessment of current and expected weather situation in terms of reliability and trend of NWS computer-generated weather products.
P	Columbia Basin QPF forecast (quantitative precipitation forecast)	NWS Lead forecaster's estimate of expected 24-hr precipitation for mountain and western Washington stations for first and second days.

P W FL G	NWS Cascades/Olympics zone forecast	NWS lead forecaster's general mountain weather forecast, including general timing and magnitude of precipitation, winds, and freezing level variations. Good overall guide.
P	Weather Radar images (Auburn)	Gives estimate on locations, motion, and magnitude of substantial convective activity.
P G	Satellite pictures (visible and infared)	Indications of timing of precipitation, potential magnitude of post-frontal precipitation, frontal motion and strength, wave development, cloud heights, verification of map prognoses.
P W FL G	Pacific surface analysis	Frontal position and relative magnitude (pressure-wise), storm center pressure changes and relative motion, wave development (frontogenesis). Close companion to 2-mile satellite pictures.
G	US surface analyses	Same as Pacific analysis but less useful in forecasting as upstream developments not shown.
P W FL	PE & LFM surface pressure and 1000-500 mb thickness (4-panel-12, 24, 36, & 48-hr prog)	Frontal positions, surface troughs and ridges (position), pressure gradients, particularly east-west across Cascades. Freezing level trends from thicknesses giving indications of any horizontal freezing level gradients expected in Cascades. In interpretation of PE thicknesses, use straight thickness vs. freezing level chart. There is an envelope of values plotted on this chart which is helpful in judging ranges of possible freezing levels with a given thickness. The most likely position in the envelope (i.e., high or low freezing level range) is usually indicated (for at least 24 hours) by comparing current thickness freezing level forecasts with the current observed freezing level.
P W FL	LFM 850-mb heights/ temperature prog. (4-panel -- 12-24-36-48 hr)	Indicates expected wind flow (speed and direction) and general magnitude of possible orographic precipitation. Following motion of 0°C isotherm good for freezing level forecasts (temperature advection is seen clearly here). Watch form of 0°C isotherm between panels. Frequently useful in judging reasonable-ness and potential errors of other freezing

		level forecasts (e.g., is the forecast area on the fringe of closely packed isotherms so that a small forecast error will make a large difference in correct value in the forecast freezing level -- for example, in the FOUS 43?)
WS FL	24-hr 850-mb heights/ temperature prog	Indicates forecast pressure and temperature fields at 850-mb level.
P W	LFM 700-mb heights and relative humidity prog (12-24-36-48-hr-- 4-panel)	Gives guidance for estimate of higher elevation (approx 9000 feet) winds and magnitude of possible orographic precipitation. Relative humidity values good for timing onsets of orographic precipitation, particularly when used in conjunction with similar 850-mb progs.
WS FL	700-mb and 850-mb current heights/ temperature	Current flow patterns (winds) and temperature fields at approximately 9000 ft. and 5000 ft., respectively. Can be misleading (occasionally) if all necessary data not included in analysis or is mis-analyzed.
P	PE & LFM vertical velocity and precipitation prog (4-panel-- 12-24-36-38 hr)	Vertical velocities helpful in precipitation forecasting, particularly in warm front situations (with overrunning). Precipitation generally much overforecast, but can be good for large-scale trends, and as guide to a real extent of precipitation coverage.
G	30-hr hand drawn surface analysis prog (including aviation cloud and weather depiction)	General idea of weather trends, expected frontal motions, and current thinking at NMC (National Meteorological Center)
G	36 & 48-hr surface progs and related weather (#39, 52, 102, and 115)	Guidance for frontal motions, associated precipitation and timing, and current thinking at NMC.
P G	LFM 500-mb heights and vorticity prog 4-panel -- 12-24-36- 48-hr)	Ten vorticity line usually approximates beginning of precipitation in areas of PVA (positive vorticity advection). Position and shape of 5580-meter pressure height line is good as general guide for trough-ridge position.
G	500-mb hemispheric analysis (current)	Good for long-range feel of wave-pattern changes up and down-stream. Can give early indications of changing situations.

G	500-mb (standard) analysis (current)	Current trough and ridge line positions and associated temperature-weather trends.
G	200 & 300-mb analyses and progs	Jet-stream positions and expected positions; may compare jet max position with satellite picture information.
G	72 & 84 hr 500-mb height progs	Good guides for future trough and ridge line positions. Gives good ideas of expected weather trends.
G	96-hr 500-mb and surface package prog	Weather trends, particularly regarding departure from earlier progs.
G	Baroclinic & Barotropic 500-mb heights and vorticity progs (4-panel--00-12-24-36-hr)	Forecast trough and ridge line positions from numerical models, also regions of PVA and NVA (negative vorticity advection) useful for precipitation timing when correlated with other models (LFM).

With the climatological base serving as a background of prior knowledge, the array of data inputs from the sources listed above are then used to develop an evolving hypothesis about expected precipitation in the Cascade Mountains. The diversity of data sources, ranging widely in character from complex numerical forecasting maps generated by the NWS to ad hoc local observations of snow conditions in the passes, lends a strong element of redundancy to the data flow. Because the precipitation forecast is not an isolated, unique event each day, but continually evolves from the previous days forecasts and weather situations, a constant process of revision and testing by observation (daily precipitation reports) ensues, leading to repeated convergence on daily forecast decisions. Like the general approach to avalanche forecasting outlined in section 2, the empirical process of quantitative precipitation forecasts operates by the application of inductive logic.

The forecasts benefit not only from inductive logic applied to general and local synoptic observations, but also from experience developed with local terrain and weather patterns in the Cascade Mountains. The data inputs outlined above (or their equivalent) and the manner in which they are analyzed could apply equally well in other mountain ranges of the world. The local patterns peculiar to the Cascade Mountain passes are now outlined below:

- In most significant storm systems (excluding warm-frontal over-running situations), 60-70% of the precipitation is post-frontal orographic, though this is at times difficult to separate out with a series of storms in a zonal flow. Extent of potential orographic precipitation is judged by strength of westerly component of wind at 850 and 700-mb level, amount and trend of moisture in radiosonde soundings at UIL, SEA, SLE, C7P, GRF, and amount of moisture as forecast by LFM or PE relative humidity. Forecast precipitation amounts are then determined through consideration of climatology and precipitation guidelines given above.
- Most precipitation in the Cascades results from the upslope snow-fall (or rain) following a frontal passage. Forecasters ask them-selves the questions: What is the upper (500 mb) and lower (850 mb) air flow behind the front? West? Southwest? Northwest? West winds will produce the greatest lift, southwest winds the most moisture, and NW winds the driest conditions. How unstable is the air mass? That is, are cumulus or cumulo-nimbus visible in the satellite pictures off the coast, following a front? Many times moist air masses are shallow but super unstable; i.e., an arctic air mas flowing offshore in northern British Columbia and onshore along the Washington coast. This is extremely unstable and can produce copious amounts of snow in the mountains with 3000 feet of lift while mostly sunny skies prevail in Seattle and the Puget Sound Basin.

- Rebuilding surface high pressure over western Washington behind a strong front coupled with westerly 850-mb winds gradually shifting northward will often result in strong convergence zones in the Cascades beginning near Stevens Pass and shifting southward with time.
- The heaviest precipitation amounts in the Cascades are usually produced by a strong W-SW flow at low levels which is tapping sub-tropical moisture (i.e., coming from vicinity of Hawaii) and raising it to high elevations. A cold polar maritime air mass often exists to the north of fronts imbedded in this flow. These fronts are often broad and become nearly stationary over Washington or along the coast, with frontal movement identifiable only by onset of heavy precipitation. Heavy over-running precipitation ahead of fronts such as these occurs often and is enhanced by cold air pooled in either western Washington (additional upslope effect) or eastern Washington (wedge of cold easterly air flow over the Cascade passes).
- Empirical evidence indicates that orographic (upslope) precipitation is not too important if the westerly component of the wind at the 850-mb level is under 15 knots. However, with a good supply of moisture available, upslope precipitation is usually quite significant with the westerly component of wind (at the 850-mb level) from 15-25 knots and is usually heavy with the westerly component from 25-35 knots or greater (see quantitative wind guidelines below). The fetch of the westerly component is also important to estimate the duration of the possible upslope wind, and the NWS FOUS forecasts usually handle this situation fairly well. The question asked here is how many hours do moderate-to-strong westerlies continue?

- The potential for heavy (1-2 inches WE) precipitation ahead of a front is greatest with air of tropical origin with high freezing levels and strong vertical velocities to release available moisture (freezing level and vertical velocity forecasts available from LFM and PE forecasts at NWS).

Along with the basic concepts in Cascade precipitation forecasting listed above, the following list of major precipitation categories used in project weather forecasts provides a useful guide to the more important weather situations and associated precipitation regimes observed in the Cascades:

- $<$1/4 inch WE--no frontal activity or dissipating weak frontal activity, stable air mass, winds less than 10 knots at the pass level, <u>or</u> weak upper disturbance passing mostly to north or south of the state. Mostly cloudy conditions, could produce drizzle or light snow.
- 1/4 - 1/2 inches WE--weak frontal activity during 24-hr period of forecast with weak upslope following, <u>or</u> moderate front but precipitation split between two 24-hr periods.
- 1/2 - 3/4 inches WE--moderate frontal activity with moderate upslope following, <u>or</u> strong front split between two 24-hr periods.
- 3/4 - 1 inches WE--moderate to strong frontal activity with only short fetch between short waves, winds shifting and upslope for short to medium duration.
- 1 - 1-1/2 inches WE--strong front with medium duration upslope winds following frontal passage, usually associated with the jet-stream over Washington.
- 1-1/2 - 3 inches WE--strong jetstream over Washington and strong upslope winds of long duration. Air mass of sub-tropical origin.

- >3 inches WE--heavy rains, high freezing levels, very strong jet-stream over Washington with stationary front of sub-tropical origin near or over Cascades and strong westerly, low-level flow.

To augment this general summary of Cascade precipitation situations, a working guide to hourly precipitation data is also considered very useful for quantitative precipitation forecasting in the Cascades. Observed statistical summaries for the major precipitation categories (listed in the previous paragraph) and the mean PI for each precipitation category are given in Table 7.2. Using this table in conjunction with the related forecasting principles above, the forecaster should have a good idea of the range of precipitation intensities (PI) he may expect from a given weather situation. The expected 24-hr WE (and hence precipitation category) for each mountain station may then be forecast utilizing the precipitation rate ranges in Table 7.3, along with the following general precipitation equation:

$$\text{24-hr WE} = WE_{24} = WE_1 + \sum_{i=1}^{n} P_i T_i$$

where WE_{24} = forecast 24-hr water equivalent, WE_1 = water equivalent already received at time of forecast for particular station (may be estimated for certain situations) in inches or mm, P_i = precipitation intensity for given time period, T_i, in inches/hr or mm/hr, and T_i = duration of expected precipitation intensity, P_i, in hours. The summation portion of the equation is often divided into pre-frontal, frontal, and post-frontal periods, depending on magnitude and timing of over-running pre-frontal precipitation, width, speed and strength of the frontal band, and magnitude and timing of the post-frontal orographic precipitation. In any case, the calculated value of expected 24-hr WE often done mentally by forecasters should corroborate the estimated range of 24-hr WE (precipitation category) which was based on the forecaster's initial assessment of the general weather situation and the climatology of each mountain

TABLE 7.2. Selected hourly precipitation characteristics of Stampede Pass, Washington. Based on fifteen months (544 days) of hourly winter precipitation data, 1971-77. Characteristics are derived for indicated ranges of 24-hr. water equivalents listed below.

Precipitation Characteristic	24-HR WATER EQUIVALENT RANGE IN INCHES							
	0 or TRACE	.01-.25	.25-.50	.51-.75	.76-1.00	1.01-1.50	1.51-3.00	≥ 3.01
Total days with indicated W.E.	100	139	72	42	52	72	56	11
% total days with indicated W.E.	18	25	13	8	10	13	10	2
% of total hours each day with measurable precipitation when 24-hr precipitation lies within given W.E. range	0	25	49	61	73	78	98	99
Total hourly precip. occurrences	0	843	855	611	910	1355	1247	262
Total observed W.E. (inches)	0	16.5	27.34	25.32	44.70	87.77	117.06	45.44
Mean P.I. for hours when precipitation fell, inches/hr.	0	.019	.032	.041	.049	.065	.094	.17
Mean P.I. for all hours of days with indicate W.E. range	0	.005	.016	.025	.036	.051	.087	.17

TABLE 7.3. Precipitation rating categories for the Cascade Mountains.

Precipitation Rating	General Precipitation Category	Approximate ranges of mean P.I.		Approximate ranges of 24-hr snowfall amounts		Approximate range of 24-hr water equivalent	
		(inches/hr)	(MM/hr)	inches	CM	inches	MM
LOW	very light	* T - .02	T - .50	T - 3	T - 7	T - .25	T - 7.0
LOW	light	.02 - .03	.50 - .75	3 - 5	7 - 12	.25 - .50	7.0 - 12.0
TRANSITIONAL	moderate	.03 - .04	.75 - 1.00	5 - 7	12 - 17	.50 - .75	12.0 - 17.0
TRANSITIONAL	mod. heavy	.04 - .05	1.00 - 1.25	7 - 10	17 - 25	.75 - 1.00	17.0 - 25.0
TRANSITIONAL	heavy	.05 - .07	1.25 - 1.75	10 - 15	25 - 37	1.00 - 1.50	25.0 - 37.0
HIGH	very heavy	.07 - .12	1.75 - 3.00	15 - 30	37 - 75	1.50 - 3.00	37.0 - 75.0
HIGH	extreme	≥ .12	≥ 3.00	≥ 30	≥ 75	≥ 3.00	≥ 75.0

*T - indicates trace amount W.D.

station. Regional variability of precipitation from station to station may often be explained on the basis of topographic or other influences and is also derived through operational forecasting experience, but its inclusion here is beyond the scope of this current report and this topic must be reserved for future research.

The relative effect of various forecast precipitation categories and precipitation intensities on the avalanche forecast is discussed in section 8. Precipitation rating categories are given in Table 7.3; these relate to the general effect that various PI's have on the avalanche forecast when considered in conjunction with similar rating variables of wind and temperature.

7.3 Wind Forecasting

Wind forecasting for the Cascade Mountains of Washington comprises two major considerations: free air wind speed and direction and pass wind speed and direction. Free air winds at the elevations of interest for the majority of avalanche situations in the Cascades are determined and forecast primarily through large-scale map and up-wind radiosonde (raob) analysis. Pass winds, on the other hand, are generally much more localized and are assessed and forecast largely through consideration of local east-west pressure gradient magnitudes, although other factors such as magnitude and direction of free air flow are also important. The two wind forecasts must be treated separately, as weather situations often arise in the Cascades when free air winds are markedly different from surface pass winds in both speed and direction. Both types of winds are at least somewhat amenable to statistical analysis and a discussion of derived quantitative guidelines follows.

For the Cascades, observed values of free air wind speed and direction at the 5000 ft. (1525 m.) level (approximately the 850-mb level) from Quillayute (radiosonde), when considered in conjunction with current 850-mb maps, give forecasters a useable though rough guide to the current state of winds at the higher release zone levels in the Cascade mountains. These winds are largely responsible for the heavy upslope precipitation occurring with moist, unstable, post-frontal air over Washington and are also those winds which the forecaster must assess for possible snow transport problems in areas or elevations not dominated by local pass winds.

Forecast wind speed and direction of free air winds for the next 24-48 hours are commonly derived from the LFM 850-mb 4-panel prognostic package of height gradients and thicknesses. At this level of the atmosphere, winds may be considered geostrophic and so blow along the height contour lines; hence, expected wind direction is fairly readily avalable through visual inspection of the forecast products. Free air wind speed, however, is not so easily determined without a numerical guideline. Spacing of height contours at this atmospheric level is more or less directly proportional to wind speed, and Figure 7.2 exhibits a correlation between number of north-south 30-m height isopleths at 850 mb between 45° and 50° north latitude and observed wind speeds at 850 mb at Quillayute. This correlation considers only wind cases having directions of W-NW to W-SW (approximately 245° to 295° on 360° wind direction scale), since westerly winds are the dominant precipitation-producing and generally strongest transport winds at this level in the free atmosphere over Washington. However, theory and experience indicates that these numerical free wind guidelines could be extended, at least in general fashion, to all wind directions at the 850-mb level in western Washington (terrain modifications excluded).

Figure 7.2 indicates that there is a strong linear correlation between observed wind speed (WIND850 -- in knots) at 850 mb at Quillayute and the north to south 850 mb height gradient (NSIPGRAD). The Statistical Program for the Social Sciences (SPSS) subprogram SCATTERGRAM was utilized to plot these data and calculate the various given bivariate correlation statistics. In this

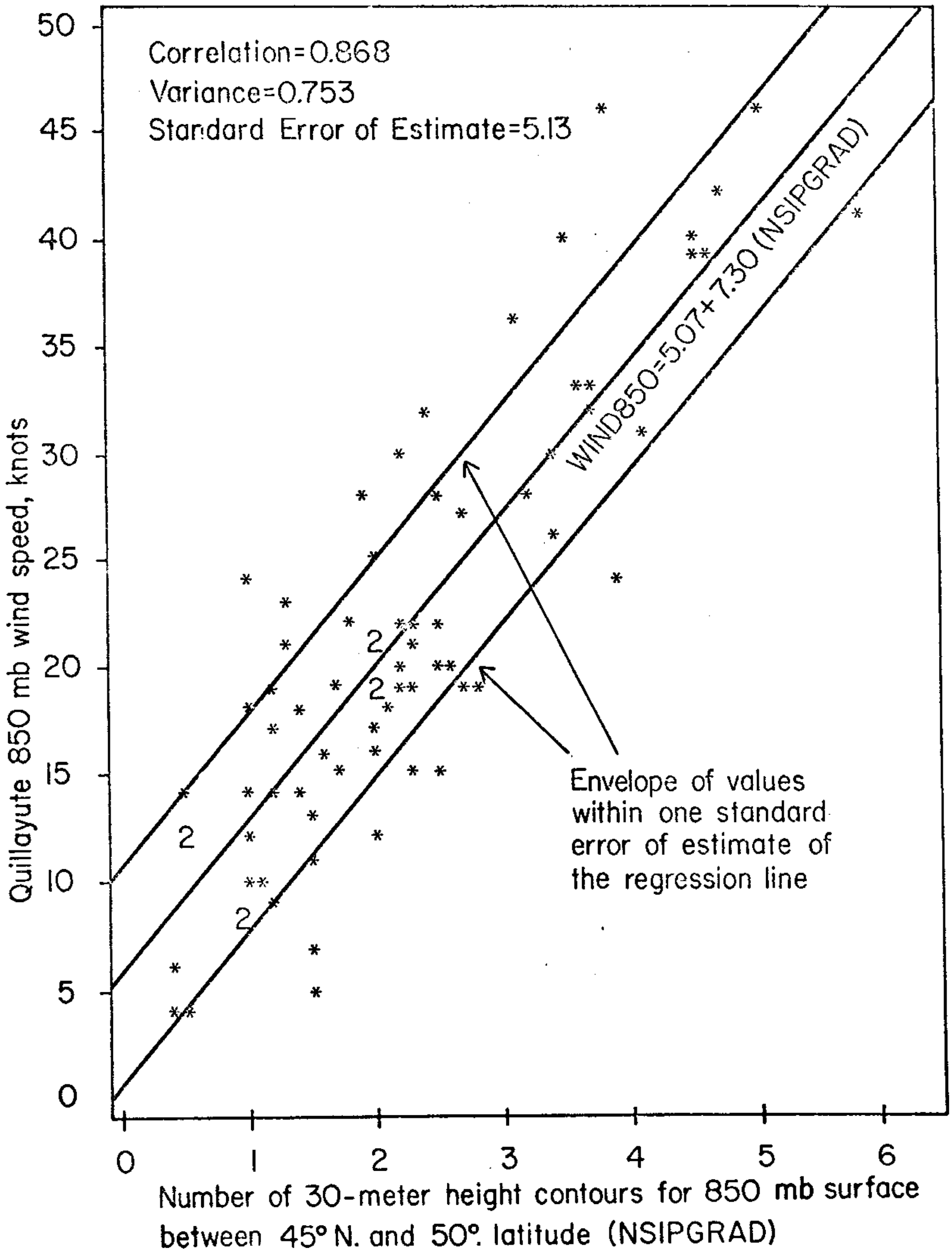


FIGURE 7.2 Correlation between observed 850 mb wind speeds at Quillayute (UIL) and north-to-south 850 mb height gradient in number of 30-meter height isopleths between 45° and 50° N. latitude. Free air wind speed guidelines for inclusion in avalanche forecasting (section 8) are: LOW--0-15 knots; TRANSITIONAL--15-25 knots; HIGH--over 25 knots.

case the relatively high correlation (R = .868) and variance (R^2 = .753) indicate a fairly strong linear relationship between WIND850 and NSIPGRAD. The resulting linear relationship WIND850 = 5.07 + 7.03 (NSIPGRAD) then defines a useful forecast tool for deriving expected mean free wind speeds from prognostic weather maps. Topographical effects on the free winds resulting in local areas of accelerated or decelerated flow must still be considered by field personnel in their interpretation of wind speed forecasts. Free air wind speed ratings also shown in Figure 7.2 are defined by considering wind transport of snow and orographic precipitation.

Numerical guidelines for Cascade pass wind speed and direction forecasting are based primarily on horizontal east-west pressure gradients across the Cascades which govern the flow of air through the passes. In Table 7.4, pass-level wind directions at Stampede Pass are clustered around east and west. From 11 years (1948-59) of records, pass winds were either E or W (east or west) 55-60% of the time and E-SE, E, E-NE, W-SW, W or W-NW 90-95% of the time studied. Experience indicates that this type of direction limitation at the pass level is also largely true for Stevens, Snoqualmie, White and Washington Passes. At higher elevations, free air winds begin to play an important role and channeling effects, particularly for cold, easterly air flow, become less important.

Given the fact that pass winds over the Cascades are basically east or west, the timing of directions becomes important. From a study of Stampede Pass wind directions and the observed Seattle to Yakima (SEA-YKM) pressure gradient, Table 7.4 gives the most probable wind directions for the given gradients. Forecasting experience indicates that SEA-YKM gradient results for Stampede Pass can be extended to wind direction forecasts for Snoqualmie Pass, Stevens Pass, and to a lesser degree White Pass. Occasionally, Stevens Pass lags behind Stampede and Snoqualmie Passes in east to west wind shifts due to pools of cool air (local high pressure) lingering in the Wenatchee - Leavenworth area, creating

TABLE 7.4. Stampede Pass Wind Direction Guidelines. Based on empirical studies of three-hourly teletype and mountain station observational data.

PRESSURE GRADIENT, SEA-YKM, MB	MOST PROBABLE WIND DIRECTION AT STAMPEDE PASS
+2, +3, +4, +5, +6	wind west
+1, 0	wind west, except east if east aloft
-1, -2, -3	wind east, but will reverse to west if west aloft, and near zero if winds south aloft
-4, -5, -6, -7......-14	wind east

strong north to south horizontal temperature gradients on the east-side of the Cascades and resulting in lower (more negative) Seattle to Wenatchee (SEA-EAT) pressure gradients for a longer period of time. However, this is not often the case, and Table 7.4 may be followed for all the major Cascade passes except Washington Pass, where no long-term, pass-level wind data are available.

The statistical analyses performed on Stampede Pass wind speed versus SEA-YKM pressure gradient give less straightforward results. For both positive and negative SEA-YKM pressure gradients, there is no strong linear correlation between the pressure gradient and the wind speed, especially for positive pressure gradients (PPG). For the PPG case, a correlation of only 33% and variance of approximately 11% indicate that a linear regression for this case is not particularly valid. From further analysis of the raw data and the weather situations surrounding low values of PPG, it appears that strong frontal and post-frontal winds prior to build-up of large PPG values may account for a large part of the low PPG scatter. In addition, the presence of strong free air winds often accompanying or immediately following frontal passage further complicates the situation. The reduced scatter and higher correlation (approximately 63%) with the negative pressure gradient (NPG) case further supports this possibility. In any case, the pressure gradient data give forecasters a rough but useable guide to the range and general magnitude of response of free-air wind speeds to the associated pressure gradients. Further studies could yield more definite guidelines if certain high scatter-prone weather situations could be filtered out of the analysis, but this aspect must be reserved for future research.

In conclusion, the following special wind situations peculiar to the mountain passes have been identified during the evolution of the forecasting project:

- With a series of relatively weak storms (i.e., not strong enough to scour out cold air on the east-side) there is generally a pronounced but short-lived east to west, then back to east pass wind progression, with average speeds seldom exceeding 15-20 knots west and 10-15 knots east, except just prior to or during the frontal passage. The easterly flow seems to be quite persistent in this situation, lasting until frontal passage and returning fairly soon thereafter. This is probably due to weaker westerly 850-mb winds associated with the front.
- With a series of stronger fronts (i.e., front scours out east-side), easterly flow is of shorter duration, and is relatively weaker <u>for the same gradients</u>, probably due to good westerly 850-mb winds. The East-west gradients are generally higher with strong fronts.
- The depth of easterly flow and consequently the strength of the pass-level inversion seems to be associated with strength of easterly flow, particularly when easterly winds are gusty, probably due to associated higher surface pressure in eastern Washington with colder denser air.

7.4 Temperature (Freezing Level) Forecasting

From an avalanche forecasting point of view, temperature forecasting for the Washington Cascades has been largely supplanted by freezing level forecasting. The forecast height of the 0°C constant temperature surface appears more easily assimilated by, and is more useful, to field and forecast office personnel than the range of expected temperatures for several reasons:

- Solar radiation often plays a misleading role in correct assessment of air temperatures, while not affecting the actual freezing level.

The forecast freezing level effectively covers temperature variations at all elevations while not specifically listing them (as would be necessary with temperature ranges).

Freezing or snow level forecasts are more easily applied values than temperature ranges for estimation of snow/rain levels, and estimates of maximum elevation of potential snowpack melt.

In weather situations of cold, easterly winds at the passes under warm westerly flow at higher levels with associated high freezing levels, forecasts of pass temperature ranges alone may give misleading information to field personnel as to actual freezing levels. With freezing level forecasts in this situation, the existence of temperature inversions is obvious, especially as forecasters stress the fact that cold, easterly, surface winds are responsible for the anomalous temperature values.

Freezing level forecasts for the Cascades are based on a combination of NWS data and mountain station temperature observations. In order of most frequent usefulness, the following NWS products --FOUS 43, FOUS 72, PE/LFM 1000-500 mb thickness, radiosonde observations, FOUS 50 Trajectory, 850-mb height/temperature analyses, ship reports of surface temperatures -- are used in conjunction with reports of current mountain temperatures (data network and remote telemetry) in determining a freezing level forecast. Which of the above is used depends strongly on which one has been most accurate in the immediate past. Forecasters arriving for the first day of a forecast period will usually check back and see which model has been doing the best job, and if any errors present are consistent. Then the best forecast model will be used accordingly, modified by satellite picture trends of frontal motion wherever appropriate.

Guidelines defining the freezing level ranges and ratings to be utilized in the avalanche forecasting discussion following are shown in Table 7.5. These ratings have been operationally derived for the Washington Cascades through several years experience and are based on general starting zone elevations for each area of interest and types of slides considered (i.e., cutbank sluffs versus major slide paths). The relevant starting zone elevations are summarized in Table 7.6. The freezing level ratings may often differ from area to area during any given storm situation.

7.5 Freezing Rain

An infrequent but important forecasting problem is freezing rain in the Cascade passes. This has serious effects on road conditions and hence is included in the specialized weather forecasts prepared for the passes. If the conditions extend to higher elevations, they can have a critical effect on subsequent avalanche development owing to the very smooth and slippery ice coating formed on exposed snow surfaces.

Basically, freezing rain is indicated at the passes when there is overrunning precipitation, freezing levels 3000 ft (915 m) or more above the pass level, and a sufficiently cold easterly air flow through the passes to supercool the rain drops. As a reasonable example, consider the free air temperature for transition from snow to rain as 1-2^{0}C on the average. Assuming a temperature inversion about 1000 ft deep with a minimum lapse rate of approximately +4^{0}C/1000 ft (which may be considerably higher, depending on surface air temperature in eastern Washington and associated strength of the easterly flow within the inversion) and assuming a lapse rate within the air above the inversion of about -1.8^{0}C/1000 ft, then a freezing level 3000 ft above the pass level allows about 1000 ft for warming of precipitation after it has gone from snow to rain. If there is no warming of the precipitation (freezing level lower than 3000 ft above pass level),

TABLE 7.5. Freezing level ratings. Low, transitional or high freezing level ratings are based on approximate starting zone elevations for each individual mountain area and individual avalanche paths.

LOW - Current or forecast freezing levels at or below the lower starting zone elevation limit for the given mountain station avalanche area.

TRANSITIONAL - Current or forecast freezing levels within the starting zone elevation range for the given mountain station avalanche area.

HIGH - Current or forecast freezing levels above the upper starting zone elevation limit for the given mountain station avalanche area.

TABLE 7.6 Starting Zone Elevation Guide

Location	Feature	Approximate Starting Zone Elevations Range (ft/m)
Washington Pass (N. Cascades Highway, especially pass area and east)	- cut-bank sluffs	4500-5500/1370-1675
	- major paths	5000-7000/1525-2135
Mt. Baker (vicinity ski area)		5000-7000/1525-2135
Stevens Pass (U.S. 2)	- cut-bank	3500-4000/1065-1220
	- major paths, east side	3500-5000/1065-1525
	- major paths west side	3500-6000/1065-1830
Tumwater Canyon (U.S. 2)		2500-4500/ 760-1370
Snoqualmie Pass (I-90)	- cut-banks	2500-3500/ 760-1065
	- major paths	3000-5500/ 915-1525
Snoqualmie Pass (vicinity ski areas)		3500-5500/1065-1675
Crystal Mountain ski area (and vicinity ski area)		5000-7000/1525-2135
Cayuse Pass		4500-6000/1370-1830
Chinook Pass		5000-6500/1525-1980
Paradise	- major paths	5000-7000/1525-2135
	- cut-banks	4000-5500/1220-1675
Mt. St. Helens		5000-7000/1525-2135
Mt. Hood, Oregon		5000-7000/1525-2135
Olympic Mountains		4000-6000/1220-1830

it will probably refreeze quickly and give either snow pellets or ice pellets at the pass. Otherwise, warmed precipitation may become freezing rain if the inversion is strong enough. Other factors which need to be taken into account are the character of precipitation (higher precipitation intensity with larger drops and higher fall rates should require a larger transition and warming zone) and strength or depth of the inversion layer.

8. CASCADE MOUNTAIN AVALANCHE FORECASTING

8.1 Introduction

Methods for avalanche forecasting developed during the life of this research project have evolved along two parallel paths. One of these paths is the investigation of underlying principles summarized in section 2. The other path is the operational forecasting scheme developed through empirical experience. It is important at the start to emphasize that the theoretical investigation did not precede the operational system, and, thus, did not provide a rationale for the design of that system. The two approaches developed side by side, the operational methods evolving from conventional forecasting traditions and the basic principles emerging from the analysis of widely diverse data about these traditions. It is equally important to point out that the two paths have converged. Once the basic principles had been identified, they were found to describe accurately the manner in which the operational scheme actually executed an avalanche forecast.

The following outline presents the way in which the forecasting scheme actually is applied on a daily basis by the central forecast office developed under this project. The presentation follows the framework and terminology outlined in section 2. Quasi-numerical methods, based on rating schemes for weather parameters identified in section 7, are introduced for calculating the daily evolution of avalanche conditions. Some obvious extensions of the methods can be made in the light of the principles from section 2 and these are outlined as a base for future inprovements in the central forecasting scheme.

8.2 The Concept of Avalanche Potential

It is a fundamental premise of all avalanche forecasting that, given a convergence of factors favorable for their formation, avalanches do not actually fall through spontaneous circumstances. Instead, they are understood to be triggered by some overt agent that communicates an extra increment of energy to the unstable snow pack and pushes it past the point of failure. The real problem in forecasting is to determine the amount of energy required to trigger an avalanche in any given circumstance. The spectrum of trigger energies required to release a given avalanche may range all the way from a few joules associated with random natural perturbations in the environment, to a hundred million or more joules ensuing from an earthquake. Any body of snow lying on an inclined surface may be dislodged if sufficient energy is communicated to it; hence, there is no such thing as a completely stable snow pack, only varying degrees of relative stability.

A snow stability index based on relative trigger energies is introduced in Table 8.1. This provides a quantitative anchor for a scale of snow stability, with the logarithmic scale of energy magnitudes compared to typical triggering agents both natural and artificial. The situation of absolute instability is the one which leads to widespread natural avalanche falls and occurs only for very short periods of time. It is relatively easy to forecast, for the causal factors usually become overwhelmingly obvious in number and intensity. (High altitude rain following deep accumulations of cold snow is a typical case in the Cascade Mountains.) It is in the middle ranges of conditional stability that the avalanche forecaster is put to a test of his mettle, for the trigger magnitudes lie within the range that involve skier accidents or merit artificial release measures, yet the snow is stable enough that conclusive evidence from natural falls is usually absent.

Forecasting practices developed by this project have subsumed the trigger magnitude concept under the designation avalanche potential. This term refers to the likelihood that the snow is unstable and categorizes the degree of instability. The avalanche potential refers to the prospects of avalanches falling, but it explicitly does not refer to avalanche size. The latter factor must be estimated separately, then combined with the avalanche potential to determine the degree of

TABLE 3.1 Snow stability indices in terms of avalanche trigger magnitudes. See text for additional discussion.

Stability Index	Energy Required to Trigger Slab Release, Joules		
0	under 10^0j.	Random natural perturbations	(absolute instability)
1	10^1j.	Falling snow clod	(conditional stability)
2	10^2j.	Man walking in snow	↓
3	10^3j.	Small cornice fall, fall of standing skier	
4	10^4j.	Medium cornice fall, fall of skier moving 5 m/s	
5	10^5j.	Large cornice fall	
6	10^6j.	1 kg TNT, dynamic loading by small avalanche	
7	10^7j.	10 kg TNT, major cornice collapse	
8	10^8j. or more	Earthquake, dynamic loading by a major avalanche	

risk to be expected. The currently-used scale of avalanche potential is summarized below, along with the corresponding stability indices (see Table 8.1).

1. Low avalanche potential: No slopes are expected to slide naturally or artificially. Stability Index 8.

2. Moderate avalanche potential: No slopes are expected to slide naturally. Artificially-triggered slides are not likely, except on isolated steep slopes where pockets of instability may exist. Stability Index 7.

3. High avalanche potential: Natural slides are possible. Artificially-triggered slides are likely, especially on steeper, open terrain and steep gullies. Stability Indices 4, 5 and 6.

4. Very high avalanche potential: Natural slides are likely. Artificially-triggered slides are certain; in some area at some time during the forecast period, artificial triggers would release a slide. Stability Indices 2 and 3.

5. Extreme avalanche potential: Natural and/or artificially-triggered slides are certain. No artificial triggers are necessary for slides to occur. Stability Indices 0 and 1.

The distribution of stability indices in this list is *ad hoc*, based on practical experience. It lacks rigor in that Category 3, high avalanche potential embraces trigger energies covering two orders of magnitude. Strictly from the forecasting standpoint, this is unsatisfactory, for a rather wide range of snow stability must be considered, but from a practical standpoint it does cover the spectrum of stabilities that are likely to offer risks to mountain travelers of all kinds. This spectrum includes the stabilities associated with artificial release measures.

In the context of the forecasting interation scheme discussed below, *current avalanche potential* is understood to be a forecaster's present evaluation of snow stability in terms of the likelihood avalanches can be released by a given size of trigger. This evaluation serves as a starting-point to prepare an avalanche forecast.

8.3 Forecasting by Iteration

The underlying principle of inductive logic was introduced in section 2 as the basis for avalanche forecasting. It commonly works by accreting elements of information about the snow and weather environment and processing these through a series of iterations converging on an estimate of current or future snow stability. Redundancy plays an essential role and the forecasting technique is conditioned by the available level of informational entropy. Ideally, the iteration process begins with the first winter snowfall and provides an evolving and constantly revised picture of snow stability.

Earlier work on the central forecasting project evolved an algorithm showing the paths by which a forecaster reasoned about the effects of current and future weather on snow stability. This algorithm appeared in Report No. 23.3 (LaChapelle, et al., 1977) and is shown here as Figure 8.1. The reader is referred to an extensive discussion of this algorithm in the earlier report for a review of its significance for weather parameters in avalanche formation. It is reproduced here in order to introduce the basic nature of the iteration process developed for Cascade Mountains avalanche forecasting. Figure 8.1 takes as a starting point the current snow pack stability and shows the paths to determine whether this current stability is going to increase or decrease. The example of an i^{th} iteration described in detail below follows this principle and refines it by introducing specific rating shcemes to determine the direction and magnitude of expected change. The end-product is a new estimate of snow stability which, when compared with subsequent field reports on actual snow behavior, becomes the starting point for the $(i+1)^{th}$ iteration. An iteration does not determine an absolute value of snow stability, but rather the trend in this property.

8.3.1 Nature of the Rating Scheme

The scheme for rating the expected trend in snow stability (avalanche potential) is based on a fundamental premise about snow behavior: In the absence

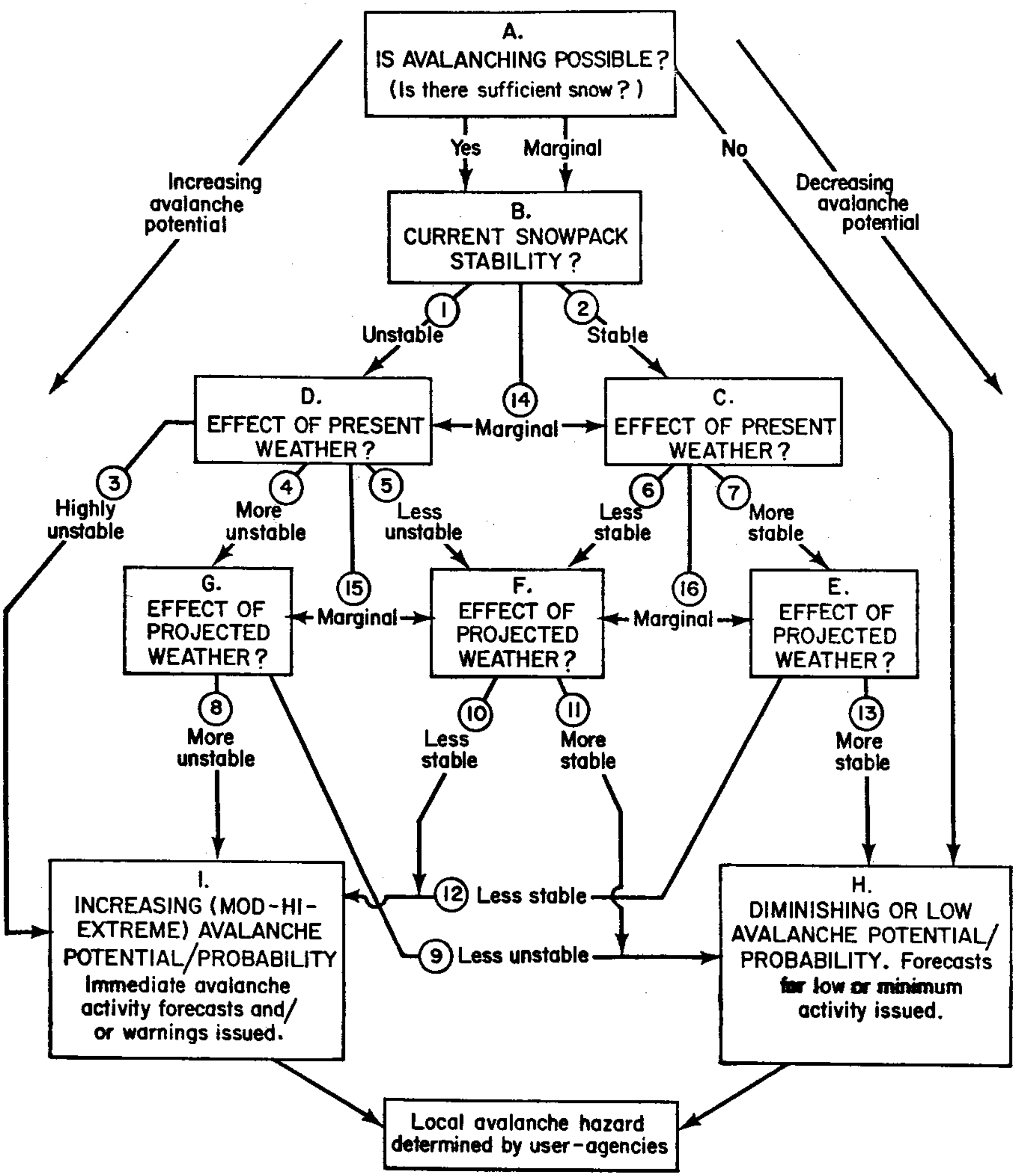


FIGURE 8.1 Avalanche forecasting algorithm.
(See Note on page 146 for explanation of numerals.)

NOTE: Explanation of numerals appearing in Figure 8.1 (Avalanche forecasting algorithm). Numerals describe the state of the the snowpack.

1--a currently unstable snowpack (mod-hi potential, possibly extreme)
2--a currently stable snowpack (lo potential)
3--an unstable snowpack which is becoming highly unstable through the effects of the present weather (hi-extreme potential, increasing)
4--an unstable snowpack which is becoming even more unstable through the effects of the present weather (mod-hi potential, increasing)
5--an unstable snowpack which is becoming more stable (less unstable) through the effects of the present weather (mod-hi potential, diminishing)
6--a stable snowpack which is becoming less stable through the effects of the present weather (lo potential, increasing)
7--a stable snowpack which is becoming more stable through the effects of the present weather (lo potential, decreasing)
8--an unstable snowpack which is becoming more unstable through the effects of the present weather and is expected to become even more highly unstable through the effects of the projected weather (mod-hi potential, increasing with time)
9--an unstable snowpack which is becoming more unstable through the effects of the present weather but is expected to stabilize through the effects of the projected weather (mod-hi potential, diminishing with time)
10--a stable snowpack which is becoming less stable through the effect of the present weather and is expected to become more unstable through the effects of the projected weather (lo-mod potential, increasing with time); or
--an unstable snowpack which is becoming more stable through the effect of the present weather, but is expected to become more unstable through the effect of the projected weather (mod-hi potential, currently diminishing, but increasing again in time)
11--a stable snowpack which is becoming less stable through the effect of the present weather, but is expected to become more stable through the effect of the projected weather (lo-mod potential, currently increasing, but diminishing with time); or
--an unstable snowpack which is becoming more stable (less unstable) through the effect of the present weather and is expected to become even more stable through the effect of the projected weather (mod-hi potential, currently diminishing, and further diminishing with time)
12--a stable snowpack which is becoming more stable through the effect of the present weather but is expected to become less stable through the effect of the projected weather (lo potential, currently diminishing, but increasing with time)

(continued)

NOTE: (continued)

13--a stable snowpack which is becoming more stable through the effect of the present weather and is expected to become even more stable through the effect of the projected weather (lo potential, currently diminishing, and further diminishing with time)

14--16 these are all indications of a borderline (marginal) snowpack, which is neither decidedly stable or unstable, but could become either as a result of current (14) or projected (15-16) weather. For example, this marginal category could refer to a snowpack whose upper layer consists of a large amount of recently deposited, fairly homogeneous, unconsolidated cold snow which has experienced some sluffing, a snowpack situation which may occur fairly often in the Cascades. It is not really stable as it has not yet consolidated (settled or densified), nor is it really unstable as sluffing has brought about some stabilization through tension release. However, a rapid warm-up with or without significant rain or snow could quickly make this snowpack very unstable, while prolonged near but below freezing temperatures with little or no precipitation could be a very stabilizing influence allowing the snowpack to rapidly settle without further sliding. Such borderline stability may also be the case with wind slabs whose stability and possible release is often closely related to temperature trends during and following formation, as well as bonding to underlying layers and rates of build-up.

of any external influences, the natural tendency of snow is to become more stable with the passage of time. These external influences may be mechanical, such as the weight of a new snow fall, or they may be thermal, such as loss of heat by surface radiation cooling or its gain from sunlight. The purpose of the rating scheme is to provide a numerical basis of estimating the extent to which external influences will modify or reverse the natural stabilizing tendency. If the influences are few or weak, a natural increase in stability can be expected. If they are many or strong, the tendency is reversed and the snow is seen to become less stable with time.

Numerical rating values of 1, 2 or 3 are assigned to the individual snow and weather parameters according to whether their modifying influence on the natural stabilizing trend is perceived to be, respectively, LOW, TRANSITIONAL or HIGH. A summation of all the relevant rating values then gives an overall rating number ranging from 9 to 27 for the 9 parameters chosen as significant for the Cascade Mountains. There are three fundamental parameters: Precipitation Intensity (PI), Wind Speed (WS) and Freezing Level (FL). Each of these is sub-divided according to current values: 24-hour predicted values and anticipated effect on the existing snow pack. The basis for assigning the numerical rating values to the current and predicted fundamental weather parameters was introduced in section 7 on weather forecasting. The effects on the existing snow pack are rated under the heading of snow pack susceptibility. This refers to the likelihood that, for a given state of the snow, any of the fundamental parameters with a high rating is apt to have an adverse effect on stability. In other words, it is a rating of snow structure according to how susceptible it is to stability reduction by presence or persistence of high-rated weather parameters. Guidelines for assigning Cascade Mountains snow pack susceptibility ratings are outlined in Table 8.2.

TABLE 8.2 Ratings for Cascade Mountains snow pack structure according to its susceptibility to influence by the major weather parameters.

RATING	TYPICAL SNOW PACK CHARACTERISTICS
P I Susceptibility (snow)	
Low	Well consolidated snowpack with no major weak layers.
Transitional	Partially consolidated snowpack above marginally weak layers or crusts.
High	Unconsolidated snowpack above crusts or weak layers (with potentially poor inter-layer bonding)
P I Susceptibility (rain)	
Low	Well consolidated snowpack with no major weak layers.
Transitional	Partially consolidated snowpack above marginally weak layers or crusts.
High	Unconsolidated cold snowpack above crusts or weak layers (with potential poor inter-layer bonding)
F L Susceptibility Rating	
Low	Well consolidated cold snowpack with no major refrozen melt-freeze crusts or major weak layers
Transitional	Partically consolidated cool or cold snowpack with no major weaknesses or well consolidated warm snowpack above some marginally weak layers and/or melt-freeze crusts.
High	Unconsolidated snowpack above strong crusts or weak layers (with possible poor inter-layer bonding)
W S Susceptibility Rating	
Low	Snowpack with firm cohesive snow surface such as melt-freeze crust or wind slab; also well consolidated warm or cold frozen snow surface.
Transitional	Partially consolidated cool surface snow amenable to transport only by high winds.
High	Snowpack with loose, unconsolidated surface snow with possible poor bond to underlying layers.

Terms are defined as follows:

unconsolidated--snow density < 100 kg/m^3; partially consolidated--snow density 100-200 kg/m^3; well consolidated--snow density > 200 kg/m^3.

Warm--mean snow temperatures 0 to 1°C; cool-- -1° to -3°C; cold-- $<$ -3°C.

The summation of the nine individual rating values gives a total rating guide. If this total value is 11 or less, the net effect on the normal stabilizing trend is deemed LOW; if the total lies within the range of 12 to 19; it is deemed TRANSITIONAL; from 20 to 27 it is deemed HIGH. These figures serve as guidelines by which the forecaster completes the iteration step and arrives at a forecast avalanche potential. The following rules of thumb help to evaluate the total rating guide.

Low Total Rating: (9-11, with no high rating in any column) -- indicates to the forecaster that diminishing or low avalanche potential for the area under consideration may be expected.

Transitional Total Rating: (12-19, with only one high rating for all columns) -- is generally re-analyzed by the forecaster in light of current and projected weather and snowpack susceptibility for the area in question until either a low or high total rating is reached. The usual immediate effect of a transitional rating for a given snow-pack is toward an increase of low avalanche potential, maintenance of moderate or high avalanche potential, and a decrease of very high or extreme avalanche potential.

High Total Rating: (20-27 or 19 with more than one high rating) -- indicates to the forecaster that increasing or high to extreme avalanche potential at the area under consideration may be expected. When high susceptibility and weather ratings concide, this combination may result in a very fast rise in avalanche potential.

Additional Guidelines

When individual or summed rating values increase with time, so does the avalanche potential.

Watch for rapid rises in avalanche potential when transitional weather ratings are coupled with high snow pack susceptibilities.

High weather ratings plus high susceptibility ratings equal maximum increase in avalanche potential.

The effects of freezing level rise are felt immediately; the effects of wind and precipitation intensity take a little longer.

8.3.2 An Example of Iteration by the Rating Scheme

Iteration starts with an existing estimate of current avalanche potential. It should be remembered that this current potential does not materialize out of thin air, nor is it an isolated stability evaluation. On any given winter day it is a composite of the previous day's forecast, verifications through field reports and the integrated sum of previous knowledge and experience diminishing in importance with distance into the past.

An actual forecasting example is chosen from 14 December 1978. Winter snowfall to this point has been relatively light, especially at lower elevations. The avalanche potential is estimated to be moderate above 5000' elevation and low below this. The next iteration step takes place early in the morning on the 14th after the following new and total snow depths have been reported: Snoqualmie Pass 2", 33"; Stevens Pass 3", 45"; Mt. Baker 6", 40"; Crystal Mountain top 1", 42", Paradise 3", 63". There have been strong SW winds for the past 12 hours and a weak frontal passage around 0400 in the Seattle area. Very unstable cold air characterizes westerly flow from the Pacific following this front, and this is expected to persist through the day. Twenty-four hour water equivalent precipitation of 1 to 2" is expected in the passes. The freezing level is low and expected to fall close to sea level by the evening. The snow pack has experienced considerable wind transport at higher elevations, depositing lee drifts on top of a melt-freeze crust extending up to 6000' or higher. Considerable surface hoar had been observed around Stevens Pass on the 13th, but the effects of the wind on this are not known. Below 5000' the snow pack thickness decreases rapidly and good sliding surfaces have not yet developed on the lower avalanche release zones.

The forecaster chooses to prepare two separate iterations, one for avalanche paths originating above 5000' and one for those below. Entries in the rating scheme matrix are made as follows:

<u>Above 5000'</u>

	Snow Pack Susceptibility	Current Weather	Expected Weather	
PI	2	3	3	
WS	1	3	3	$\sum = 19$
FL	2	1	1	

Below 5000'

	Snow Pack Susceptibility	Current Weather	Expected Weather	
PI	1	3	3	
WS	1	3	3	$\sum = 17$
FL	1	1	1	

Above 5000' the scheme has produced a total rating just reaching the HIGH category, and this is seen to raise the predicted avalanche potential to a higher level. Coupled with estimates of the amounts of snow apt to be involved in avalanching, this leads to a warning of high avalanche danger in the Cascades above the specified level. For the iteration of conditions at lower altitudes, only a transitional total rating is reached and the estimate of a low avalanche potential is left to stand as the forecast for areas below 5000'.

8.3.3 Scope of the Rating Scheme

The method of forecasting by iteration outlined and illustrated above is to be seen as universal only in principle. The choice of parameters, the distribution of their rating values and the critical points in the total rating number are all peculiar to the avalanche conditions of the Cascade Mountains in Western Washington. In other mountain ranges and climates a different set of parameters might well be chosen and certainly the criteria for their classification will be different. Mid-winter in the Colorado Rockies, for instance, the freezing level might be largely irrelevant as a forecasting tool because it stays far below the altitude of avalanche release zones, but data on radiation cooling of the snow surface could be significant.

The iteration process described here has been an attempt to set down in concrete form the practices which have largely evolved through empirical insights and intuitive methods. The rating scheme presents the outlines of the process but obviously does not reduce to an organized plan all of the details. As implied in the rules of thumb mentioned above in section 8.3.1, there is a considerable amount of "fine-tuning" of the iteration by the forecaster. As the understanding of underlying principles continues alongside identification of practices, considerable further improvements in formalizing avalanche forecasting techniques can be expected in the future.

8.4 Paths for Future Development

Iteration forecasting by means of a rating scheme has been presented here in a simplistic form. There are several features about it that can now be identified as a basis for improving the method and lending it greater sophistication. Such identification comes at the end of the present research project and hence must serve as the basis for future progress in avalanche forecasting research. Some of the developments suggested below are already being explored and will subsequently be treated in separate publications.

8.4.1 Contributory Factors

Inspection of the rating scheme described in section 8.3 shows that is has much in common with the familiar avalanche forecasting method known as Contributory Factor Analysis (CFA) first enunciated by Atwater and Koziol (1951). CFA in its earlier forms sought to generate a stability evaluation on the basis of a number of weather and snow parameters, usually ten, which contributed to avalanche formation. It was biased toward soft slab avalanche formation in cold climates and aimed for a true forecast only in a limited fashion. It did not recognize the basic inductive logic process since identified as fundamental to forecasting. The main innovation of the rating scheme outlined here is to explicitly recognize inductive logic applied through iteration and explicitly strive for true forecasts. It also assigns numerical values to the chosen parameters in a way that reflects the relative degree of their contribution to modifying snow stabi ity.

The present method and the classic CFA approach to forecasting have in common the weakness of assigning equal weight to the chosen parameters. Even the most cursory examination of physical principles underlying avalanche formation suggests that, in fact, any chosen set of contributory parameters is apt to carry unequal weight in creating avalanches. This truth has long been recognized, but a quantitative basis for assigning weights has been lacking. The principles enunciated in section 2 can provide such a basis by establishing informational entropy as the weighting criterion. By this standard, high-entropy parameters would receive less weight than low entropy ones. An obvious corollary would be the shifting of entropy values and hence weighting schemes with climate and season. Inspection of the examples for calculating data entropy given in the Appendix will clarify the reason for such shifts.

8.4.2 Probability Analysis

The concept of snow pack susceptibility rating according to the effects of the weather parameters obviously is a statement of conditional probability. This suggests that the application of Bayesian statistics could provide a more sophisticated means of introducing rating values. In fact the whole rating scheme is actually an exercise in probability analysis which should lend itself to a more rigorous treatment than is possible with ordinal-scale rating values. This aspect of the forecasting technique is presently being explored and will be developed in subsequent separate publications.

8.4.3 Introducing Avalanche Occurrence

The iteration method outlined here has a singular weakness in the omission of avalanche occurrence data as one of the rating parameters. As explained in section 2, such data has a very low informational entropy and hence is a highly desirable input for forecasting. The present rating scheme does incorporate such data implicitly in the final revision of the estimated avalanche potential which serves as the starting point for the next iteration step. The method would be strengthened considerably if these data were also incorporated explicitly in the iteration. This is especially true when the snow stability on a given group of avalanche paths depends heavily on whether or not avalanches have removed the unstable layers. Methods for including avalanche occurrence are under discussion.

8.4.4 Seasonal Adjustments

There is no a priori reason why the criteria for setting the rating values for the different weather parameters should be constant throughout the winter. The reasonable expectation, in fact, is that they would shift with the seasons. Clearly the choice of the key parameters themselves is apt to be modified from one part of a winter to another. As an example, the effect of solar radiation on deep falls of new snow becomes very important to avalanche formation on south exposures in the spring, but does not appear at all in the rating scheme. For a given forecasting area, seasonal modification of the iteration process should lead to improved forecasting models.

9. ORGANIZATION AND PROCEDURES FOR CENTRAL FORECASTING IN WESTERN WASHINGTON, 1977/78

9.1 Mountain Weather and Avalanche Data

The mountain weather and avalanche data network (see Figure 9.1) employed in the previous seasons of operation was re-established this past year, along with improvement of field instrumentation following recommendations included in last year's report. In the station by station outline below, only instrumentation modifications, problems or other significant changes from last year's data network are discussed in detail. For a more in-depth description of these stations, refer to previous reports. An equipment operating manual, describing telemetry equipment and associated non-standard instrumentation utilized on the project has been prepared by project staff.

9.1.1 Primary Reporting Stations

a) Stevens Pass (WSDT). Primary communication with this site was by SCAN-line telephone or eight-level teletype link. Quality and reliability of all snow, weather and avalanche observations continued to be high. Snowpit data were available from time to time or upon request.

New Weather-Measure remote recording heated, tipping-bucket type snow gage (model P511-E), wind baffle, and event recorder (Weather-Measure model P521) were installed at this area. The gage functioned well with one exception: a conduction-heated funnel caused substantial water evaporation during periods of low precipitation intensity. A similar problem exists for the same model at White Pass. Some modifications are indicated.

b) Snoqualmie Pass (WSDT). Primary communication was by SCAN-line telephone or Forecast Office recording device. A substantial number of observations were missed due to a combination of personnel and instrumentation problems, and a relatively low snow year for this area.

The avalanche control supervisor for this area has indicated that a new precipitation gage will be installed which should greatly alleviate precipitation measurement problems. This area has usually been a high quality snow, weather and avalanche observation site. Snowpit data generally are available on request.

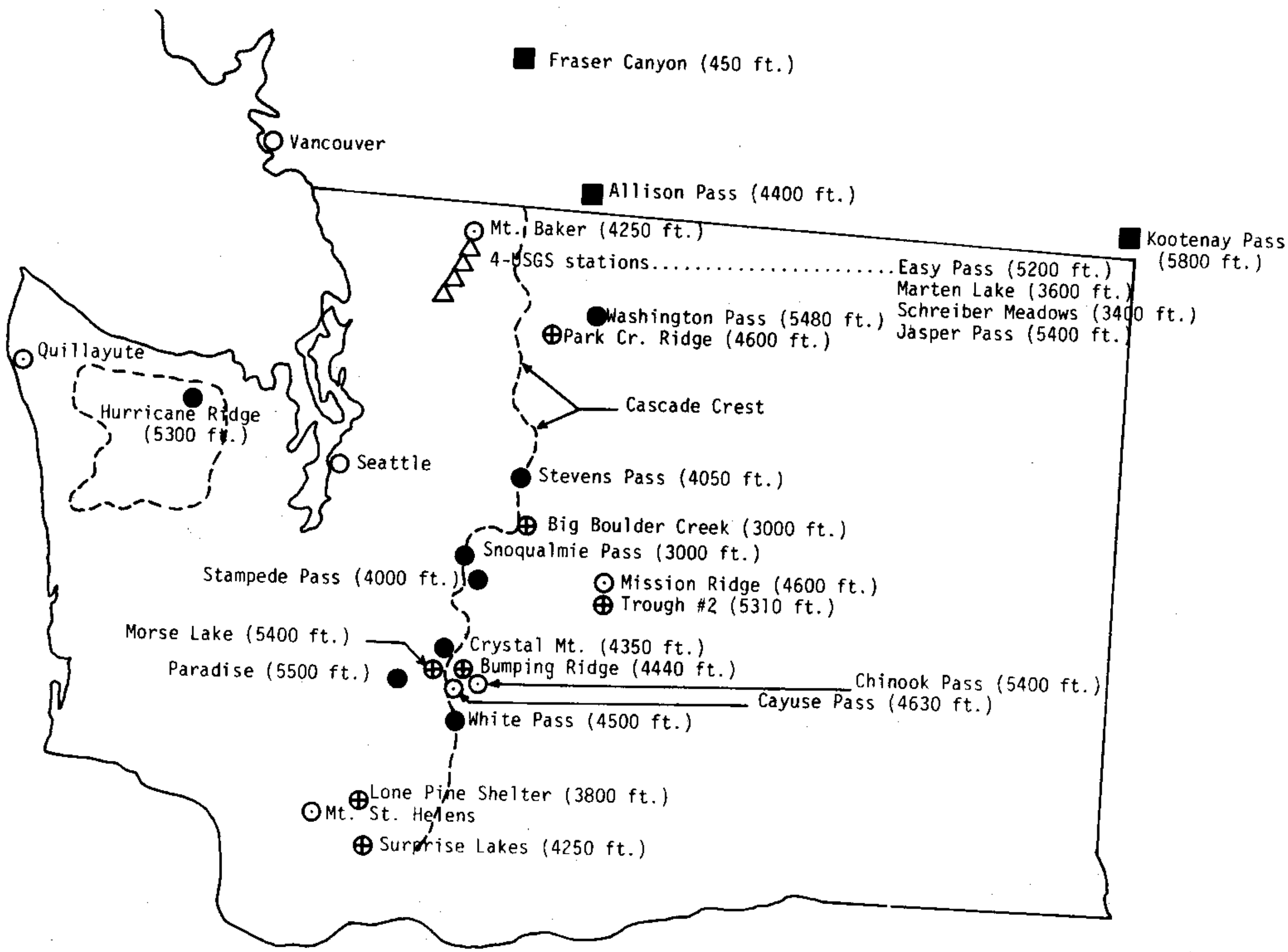


Figure 9.1 Location and elevations of primary (●) and secondary (⊙) reporting stations in Washington. Also shown are British Columbia Department of Highway stations (■), USGS stations (△), and SCS remote telemetry stations (⊕) which may be included in future data collection schemes. The SCS stations appear particularly important if hourly or 4-hourly real-time data becomes available, while B.C. Department of Highways (through AES) and USGS stations could prove to be valuable for future forecasting efforts involving Washington Pass.

c) Crystal Mountain. Primary communication was by UW WATS system or Forecast Office recording device (by commercial telephone from the area). A phone link to the summit house, installed by the area management was again available.

Project instrumentation was not available this past year due to shipment delays in replacement instruments, but USFS equipment from previous years gave relatively reliable snow, weather and avalanche data. Upgrading and replacing portions of snow sample collection and weighing equipment at both upper (Green Valley) and lower (base) study plots is recommended. Snowpit data are available periodically from USFS Snow Rangers or professional ski patrol.

d) Paradise, Mt. Rainier (NPS). Communication was by SCAN-line or Forecast Office recording device (commercial telephone from area). Reliable snow, weather and avalanche observations were generally available.

Line and/or recorder problems at Paradise resulted in some loss of wind and temperature data during season. These problems will hopefully be solved by NPS personnel in cooperation with project staff.

NPS personnel also indicate a possibility that Park funds may be available for a temperature and wind speed telemetry system from Camp Muir (approx. 10,000 ft.) on N-NE slope of Mt. Rainier to Paradise Visitor Center. This system should aid forecasters substantially in assessing the local avalanche potential for the Mt. Rainier area, and possibly for a larger area as well.

(e) Washington Pass (WSDT). Communication with this site was generally by radio relay link at the WSDT Okanagan office during weekdays, by Wenatchee radio operator on weekends. All data were generally reliable and accurate.

The expected removal of the Washington Pass summit house and observers in the future will make specific forecasting for this site impossible, and will also limit data input from the north Cascades. A general meteorological reconstruction of the snowpack may give a rough estimation of current avalanche potential for this area. Nearby SCS remote telemetry site (Park Creek Ridge) data may partially compensate for the loss of Washington Pass data, if SCS is able to solve their instrumentation/power problems.

(f) White Pass (WSDT). Communication was by micro-wave system from the Pass to a Yakima radio operator, then by SCAN-line to Forecast Office phone or recording device (the reverse applies for forecaster initiated call).

Instrumentation upgrading at this site during past season: installation of Weather-Measure remote recording, heated, tipping-bucket type snow gage (model P511-E), wind baffle, and event recorder (Weather-Measure model P 521) in WSDT Pass maintenance area. Same evaporation problem as for Stevens Pass gage. Precipitation recorder reading problems should be solved by re-writing observation instruction manual.

g) Stampede Pass (NWS). The reliability of all snow and weather data from this station by NWS teletype was excellent, except hourly precipitation intensity values at times were in error or misleading when correlated with 6-hourly water equivalent values. Conversations with the Chief Observer (Ken Fahey) At Stampede Pass indicates that problems with the precipitation gages and/or recording devices do exist.

h) Sno-line Reports (WSDT). These reports of road and weather conditions at major highway passes were utilized extensively by project forecasters in verifying or updating snow, weather and avalanche forecasts for the various pass areas. At times, these reports gave forecasters the only early-morning information obtainable on new-total snow depths and temperatures in certain pass areas, especially following a major storm (when avalanche crews were involved in control). As a result of this often heavy reliance on WSDT Sno-line reports by project forecasters, some strongly recommended guidelines regarding their content are included in this report.

i) Remote Telemetry -- Stevens Pass. Significant problems were encountered with this part of the very valuable remote telemetry system in both existing land-lines and in the precipitation gage.

The land-line problem is associated with one portion of telemetry line installed several years ago by Forest Service personnel within the confines of the ski area. To minimize heavy equipment (bulldozer, tractor) damage, the line was left on the surface and flagged, at the request of the ski area, so that the lines would be visible. The problem is either pressure exerted by snow creep and glide on the lines resulting in breakage or shorts, or faulty junction soldering during installation, also resulting in breakage or shorts -- or both. Considering the age and current condition of the line, replacement is the best solution to the problem. WSDT personnel at Stevens Pass have indicated that sufficient telemetry line exists for replacement of this line section. This replacement of line must be done to ensure that this valuable telemetry system data is available.

The precipitation gage problem is associated with air bubbles in the drain line between the heated water-oil bath and the bucket mechanism which measures the precipitation intensity. At present a small upward bend in the drainage line (in addition to the siphon bend) within the lower anti-freeze solution is necessary to accomodate existing transfer tubing between the water-oil bath and the tipping bucket mechanism. When an air bubble (possibly due to heating of the water which forces air out of solution) forms in this upward bend, it severely retards or stops water flow until sufficient pressure head builds up to dislodge it. Such irregularities in fluid flow obviously have adverse (misleading) effects on the recorded precipitation intensity and cannot be tolerated. The basic design of the system is sound and appears to be very reliable in terms of de-riming, and accuracy of measurement (excluding the above problem). Attention is now focusing on re-design of the tubing and heating apparatus to eliminate the upward line bend, and a workable solution to the problem should be achieved.

j) Remote Telemetry -- Hurricane Ridge. Due to a malfunctioning part in the power supply of the Hurricane Ridge transmitter, and a shipping delay of over two months for the replacement part, the Hurricane Ridge telemetry system was not operational at all during the past season. However, the system was finally made fully functional in mid-spring, and the Olympic National Park Service utilized the temperature/wind speed system for a fire warning program.

A recommended modification of the telemetry system input at the Forecast Office from manual on-call to automatic all-hours reception (through a strip chart recorder also utilized for Stevens Pass data reception) was completed through re-design of the data transmitter (to send the same type of signal as from Stevens Pass). The wind speed voltage scale was also modified to cover the entire range of voltages (for a one-to-one corresondence on the strip chart recorder), a new radiation shield for the temperature sensor was installed, and an RF filter was installed in the anemometer telemetry line to eliminate much undesired noise.

Olympic NPS is also considering making funds available at some time in the future for upgrading the telemetry system both at Hurricane Ridge and possibly throughout the Park. This instrument upgrading should be strongly encouraged with maximum project staff cooperation.

9.1.2 Secondary Reporting Stations

a) Stevens Pass Ski Area. Primary communication was by UW WATS-line telephone. Reliable back-up information to WSDT observations was provided regarding new snowfall, temperature, winds, current weather and avalanche occurrences during morning avalanche control by either area Snow Ranger or professional ski patrol.

Although insurance liability problems eliminated Forecaster lift access during non-public operating hours for most of the season, a Hold-harmless Agreement worked out between the ski area, WSDT and UW personnel late in the season again allowed project Forecasters to accompany the ski patrol on morning control missions. This arrangement again gave Forecasters the needed access (also available at Alpental, Crystal Mountain and Mt. Hyak) not only to study the snowpack and its susceptibility to artificial control methods, but also to gain the necessary feel for the general snowpack stability in this area.

b) Mt. Baker Ski Area. Snow and weather data from this area was received by WSDT- Snow-line reports. Direct contact with USFS personnel (or an after-hours phone recording) regarding wind, temperature, and snowfall for the Mt. Baker area was also utilized by project Forecasters for information relative to the timing and magnitude of storms which tracked primarily from the northwest and for specific avalanche and weather forecasting for this area and for the north Cascades.

c) Mission Ridge Ski Area. Although the ski patrol director expressed interest and willingness to participate in a cooperative exchange of information (between ski area and Forecast Office), a working arrangement to do so was not forthcoming from the ski area. A consideration in the usefulness of Mission Ridge data (except for avalanche and physical snowpack information) is that roughly equivalent data should be available from a nearby SCS station at Trough #2.

d) Soil Conservation Service. Discussions with the snow survey supervisor (Bob Davis) at the SCS office in Spokane in the winter and spring of 1978 indicated that power problems in data transmission were still being worked out by the contracting agency for the meteor-burst telemetry system. It is strongly hoped that these problems will be worked out and that associated data will be available either by WATS telephone or teletype (eight level).

e) U. S. Geological Survey. Weather (temperature and precipitation) data from USGS stations (locations and elevations given in Figure 9.1) continues to be available through the USGS office in Tacoma. At present, the need for such data in the Mt. Baker area has not yet been defined by project staff. If and when the need arises, however, such data, interrogated at least twice daily, could be obtained through either a phone call to the USGS hydrological office in Tacoma (through John Cummans) or through NWS teletype.

f) Atmospheric Environment Service, Canada. The British Columbia Department of Highways contributes daily weather observations to AES from three southern mountain passes (Allison, Fraser Canyon and Kootenay -- see Figure 9.1). If future forecasting projects attempt real-time avalanche and weather forecasting for Washington Pass on the North Cascades Highway in a normal winter situation, important data could be obtained from these stations through the cooperation of AES.

g) Government Camp and Mt. Hood Meadows, Oregon. Generally reliable snow, weather and avalanche observations were received from these areas by USFS Snow Rangers on most days and on any significant weather/avalanche days. In turn, short weather and avalanche forecasts for the Mt. Hood or southern Cascade area were available to these same personnel on the recording or directly from the Forecaster.

A definitely different weather, snowpack and avalanche pattern from the Washington Cascades emerges in the Cascades south of the Columbia River Gorge. Forecasters have begun to consider and analyze the reasons underlying these differences, but much more in-depth study and a large body of weather, snow and avalanche data is needed before real-time avalanche forecasting for all of the Oregon Cascades becomes accurate and effective.

h) Red Mountain and Mt. St. Helens, southern Washington Cascades. To aid in avalanche forecasting for the southern Washington Cascades (especially the Mt. St. Helens area), periodic abbreviated snow, weather and avalanche observations were instituted at these areas during the past season (utilizing both USFS and WSDT personnel). Communication with these areas was usually initiated by the observer by radio or radio-phone to an intermediary who then reported to the Forecast Office.

With the noticeable lack of any other mountain stations in this area, data received from these areas became quite useful to forecasters in operational forecasting for the southern Cascades and as an aide in the preparation of any necessary (USFS) avalanche warnings or bulletins for this area.

Continuation of this (or a similar) reporting program for the southern Cascades is urged for future forecasting seasons to support avalanche forecasts for this area. The existence of two nearby SCS remote telemetry stations, hopefully operational by the Fall of 1978, may help to alleviate the shortage of data from this region, but instrumentation alone cannot provide all the data necessary for consideration in avalanche forecasts.

i) Oregon Road Reports (Oregon State Division of Highways). A cooperative data exchange between the Portland, Oregon (PDX) NWS office and the Avalanche Forecasting group (at the Seattle (SEA) NWS office) was instituted during the past year to share information on mountain road and weather conditions. Data was exchanged via the PDX-SEA local teletype unit (Coast Guard circuit), generally by 0900 PST each morning. WSDT Sno-line reports were typed by forecasters and sent to PDX, who in turn sent Oregon road reports. These Oregon road reports included current air temperature, new and total snow depths, and general sky and road conditions, and proved to be an interesting and informative weather forecasting aid for the Mt. Hood area. This data should become increasingly important if and when future avalanche forecasting efforts extend to all of the Oregon Cascades.

9.2 Field Snowpack Data

Field snowpack studies by both project staff and cooperating field personnel (WSDT, USFS and professional ski patrol) continue to be a very critical part of the data acquisition element of the avalanche forecasting system. Throughout the past three years of the Central Avalanche Hazard Forecasting project, a good working knowledge of the snowpack by the Forecasters has been essential for meaningful discussions with cooperating agencies. First-hand snowpack knowledge by project forecasters has assured rapid assimilation and analysis of new snow test and weather data provided by field personnel. An in-depth discussion of how field snowpack data is utilized in the avalanche forecasting methodology for the Cascades is contained in section 4.3 of last year's report and more briefly in section 8 of this report. Research on the underlying principles of snowpack analysis is reported in section 5.

9.3 Meteorological Data

Reliable quantitative mesoscale weather forecasting is indispensable to avalanche forecasting. NWS maps, satellite pictures and teletype data (see Table 9.1), along with current and past weather data from areas of interest,

TABLE 9.1 Facsimile charts, teletype and satellite products. Schedule of charts and products used at the Forecasting Office, received on the National Weather Facsimile Circuit (NAFAX) or Forecast Center Facsimile Circuit (FOFAX).

Time (PST)	No.	Facsimile Chart
0011	F038C	24-h Sfc Prog (PE)
0022	F048C	Prog 24-h 850/700mb
0025	N43	Prog 36-h 500mb
0027	F039C	Baroclinic 500mb Hgts & Vort at initial, 12, 24, 36-h progs
0045	N45	Prog 48-h 500mb and Vort
0053	N46	Prog: 24-h 850mb, 24-h 700mb
0101	F055C	4 Panel PE QPF Progs--12, 24, 36, 48-h
0107	F056P	Pacific Surface Analysis
0127	F035C	36-h Sfc Prog (PE)
0149	F036C	48-h Sfc Prog (PE)
0154	N52	Prog 30-h Sfc and 36-h 1000-500mb Thkns
0206	F047C	Prog 84-h 500mb
0213	F043C	0, 12,24, 36-h mean RH 6, 12, 24, 36-h VV progs
0309	F069C	Prog 12-h 500mb
0339	N63	300mb Analysis
0349	N64	12-12Z QPF, First day, second day
0359	N65	Prog 36-h 300mb
0420	N67	Prog 72-h 500mb
0525	N74	Temperatures: Minimum
0533	N75	Surface Analysis (6-hourly)
0626	N78	700mb Analysis
0636	N79	Barotropic Progs of 4-Panel of 500mb Hgt and Vort for initial, 12, 24, 36-h
0650	F083C	24-h 500mb Hgt Change and 12-h Surface Pressure Change
0652	N80	850mb Analysis
0702	N81	24-h Precipitation
0712	N82	500mb Analysis
0715	F084P	Pacific Surface Analysis
0736	N84	300mb Analysis
0746	N85	LFM Initial 500mb & Vort, Sea-level Press & 1000-500 mb Thkns
0753	N86	LFM 12-h 500mb Hgt & Vort, 700mb Hgt and RH, Sea-level Press, 1000-500mb Thkns, QPF and VV
0807	N87	LFM 24-h as above (N86)
0821	N88	LFM 36-h as above (N86)
0835	N89	LFM 48-h as above (N86)
0850	F093C	LFM Progs, 850mb Hgt and Temp, 12, 24, 36, 48-h
0850	N90	Surface Analysis (3-hourly)
0858	F094C	LFM Progs, Lifted Index, Initial, 12, 24, 36-h
0920	N92	Surface Analysis with 1000-500mb Thkns

(continued)

TABLE 9.1 (continued)

Time (PST)	No.	Facsimile Chart
0930	N93	Prog 12-h & 24-h Surface, Clouds, Pcpn, Low-lvl Sgfct Weather
1038	F092C	300mb Analysis
1112	F101C	12-h Surface Prog (PE)
1115	N102	Prog: 36, 48-h Surface, Clouds, Pcpn
1116	F102C	24-h Surface Prog (PE)
1123	N103	Pcpn Probability Progs
1139	N105	Surface Analysis (6-Hourly)
1143	F107C	24-h Trajectory Forecast (4-Panel)
1205	F099C	36-h Surface Prog (PE)
1210	F103C	Baroclinic 500mb Hgt & Vort at Initial, 12, 24, 36-h progs
1214	N106	Progs: 36-h 500mb Hgt and Isotachs
1217	F110C	12-h Surface Pressure Change
1223	F100C	48-h Surface Prog (PE)
1227	F108C	0, 12, 24, 36-h Mean RH; 6, 12, 24, 36-h VV Progs
1239	F120C	4-Panel PE QPF Progs, 12, 24, 36, 48-h
1244	N109	Daily Extended Outlook, 24-h Pcpn Charts, Maximum Temp Charts
1300	F121C	Daily Extended Outlook: Surface Prog Chart
1302	N110	Prog 48-h 500mb and Vort
1311	F116P	Pacific Surface Analysis
1319	N112	Prog 72-h 500mb
1327	N114	Prog: Maximum-Minimum Temp
1347	N115	Prog 30-h Sfc and 36-h 1000-500mb Thkns
1413	N117	500mb Analysis
1415	F130C	Prob of Pcpn from 7-Lvl PE
1443	N120	Surface Analysis (3-Hourly)
1503	N121	Prog 36-h 300mb
1505	F111C	24-h 850/700mb Prog
1532	F129C	12-h 500mb Prog
1539	N125	Prog 12 & 24-h Sfc, Clouds, Pcpn, Low-level Sgfct Weather
1604	N1	Daily Extended Outlook, 500mb Prog 96-h, Sfc Prog, 5-day Mean Temp Anomaly and Total Pcpn
1654	N4	Prog: 24-h 850mb, 24-h 700mb
1725	N7	Temp: Maximum
1735	N8	Surface Analysis (6-Hourly)
1820	N10	Barotropic Progs, 4-Panel of 500mb & Vort for Initial, 12, 24, 36-h
1846	N12	700mb Analysis
1858	N13	850mb Analysis
1859	F013C	24-h 500mb Hgt Change & 12-h Sfc Press Change
1903	F016P	Pacific Surface Analysis
1918	N14	500mb Analysis
1940	N17	300mb Analysis

(continued)

TABLE 9.1 (continued)

Time (PST)	No.	Facsimile Chart
1950	N18	LFM Initial 500mb Hgt & Vort, Sea-lvl Press and 1000-500mb Thkns
2000	N19	LFM 12-h Progs, 4-Panels of 500mb Hgt & Vort, 700mb Hgt & RH, Sea-lvl Press, and 1000-500mb Thkns, QPF & VV
2015	N20	LFM 24-h Prog as above (N19)
2030	N21	LFM 36-h Prog as above (N19)
2045	N22	LFM 48-h Prog as above (N19)
2046	F024C	LFM Progs, Lifted Index, Initial, 12, 24, 36-h
2054	F023C	LFM Progs, 850mb Hgt & Temp, 12, 24, 36, 48-h
2059	N23	Surface Analysis (3-Hourly)
2159	N27	Prog 12 & 24-h Sfc, Clouds, Pcpn, Low-lvl Sgfct Weather
2209	N28	Surface Analysis w/ 1000-500mb Thkns
2221	N32	500mb Analysis
2252	F042C	24-h Trajectory Forecast (4-Panel)
2306	N37	Prog: Maximum-Minimum Temp
2315	F030C	300mb Analysis
2326	N39	Prog: 36 & 48-h Sfc, Clouds, and Pcpn
2340	N41	Surface Analysis (6-Hourly)
2340	F050C	12-h Sfc Press Change
2347	F037C	12-h Surface Prog (PE)

Schedule of Products Received via Teletype
(Dedicated Circuit or Service C)

Time (PST)	Teletype Product	
0730	FOUS 72	Forecast--6-Hourly data from LFM Numerical Model, including temperature, relative humidity, wind speed and direction, vertical velocity, precipitation, etc.
1930	FOUS 72	See above
1000	FOUS 43	Forecast--6-Hourly values derived from LFM Numerical Model including freezing level and relative humidity
2200	FOUS 43	Same as above
1040	FOUS 50	Trajectory Forecast--700, 850mb and surface temperature and dewpoint
2240	FOUS 50	Same as above
Hourly	Weather observations (clouds, visibility, pressure, temperature, dewpoint, wind, weather, precipitation amount, etc.) from Canadian and NWS Washington, Oregon and other northwest reporting stations	

Schedule of Satellite Products Received

Half-hourly	Satellite pictures (IR or Visual with various resolution or enhancement)--received every half-hour at 15 and 45 minutes after the hour

provide a basis for such mesoscale weather forecasting, but many of the application techniques and statistical handling processes necessary for accurate mesoscale forecasts of important meteorological variables are only beginning to be developed.

At this point, only approximate numerical guidelines are available for forecast meteorological variables over mountainous terrain -- and these only for general regions. Since techniques for tailoring these more general forecasts to fit a specific mountainous area are still in their infancy, empirical methods still play a significant role in mountain weather forecasting. To eliminate as much subjectivity as possible in future mesoscale weather and avalanche forecasting for this area, a discussion of Cascade weather forecasting is presented in section 7.

Several basic changes in important numerical NWS forecast products were instituted this past season by the National Numerical Center of the NWS. Briefly, the Primitive Equation (PE) forecast model, previously based on a six-layer analysis with 300 km grid spacing, was refined to a 7-layer model with a 150 km grid spacing. Similarly, the Limited Fine Mesh (LFM) numerical model grid spacing was reduced from 150 to 100 km. These changes appear to reduce some differences in forecast values between the two models, although certain inherent model-related differences remain. Some of the differences between the major numerical prognosis models include: PE is generally slow with frontal (storm) motion, but better with amplitude; LFM is usually a little fast and usually too large with amplitude; and baroclinic is good for 12, possibly 24, hours but misses a lot of detail. In general, the prognosis which has been behaving the best for the past few days is the one to follow until it obviously goes awry.

Another important forecasting consideration which has not yet been given proper emphasis is freezing rain, which often results in significant hazard to mountain travel and may play an important role in avalanche formation through the creation of relatively impermeable ice layers. A consistently accurate and workable algorithm for the occurrence of freezing rain in the Cascade passes has not yet been devised, but the state of knowledge to date is discussed in section 7.

9.4 Staffing and Equipment

As in the past years of operation, the forecasting staff was occupied early in the season with establishing the field reporting network and planning the office organization. The field network required recalibration and reinstallation of instruments used during past years, the modification of new sites, and instruments, and replacement of telemetry lines at Stevens Pass, Hurricane Ridge and White Pass. Minor revisions and improvement of the Forecasting Office operation were undertaken based on experience gained during previous years and to accomodate new data and communications equipment.

During the operational phase, the office was manned from 0600 to 1500 PST during periods of low avalanche potential. Scheduling was established to give effective 24-hour coverage during high avalanche potential periods. During the months of September-December and April-June, the forecasting staff consisted of Mark B. Moore, UW Research Scientist, and Richard T. Marriott, UW Associate Research Scientist. During the months of January-March when the greatest avalanche activity is expected, the staff was augmented by the addition of Frank W. Reanier, Consultant/Senior Meteorologist. Flexible hours and staff rotation were utilized to handle the heavy workload during all but the most quiescent weather situations.

After three years of avalanche forecasting, it is our unanimous recommendation that a minimum of three full-time forecasters is necessary to adequately staff the Forecasting Office during all hazard periods, especially if project forecasters are to gain any significant firsthand field input. During past forecast seasons, project forecasters have attempted to spend a minimum of one or two days per week in the field to maintain familiarity with snowpack conditions, to increase their knowledge of local snow and weather features, and to conduct occasional instrumentation inspection and maintenance. In our opinion improved weather and avalanche forecasts can be produced when forecasters have regular personal contact with the areas for which they are forecasting. This is particularly true in the present program where detailed forecasts for small areas are being produced. The forecasting of meteorological quantities on the relatively small scales involved require intimate knowledge of local topographic effects. This kind of knowledge requires that personal observations under all conditions be developed to an optimal level on an on-going basis. The necessity of firsthand experience with the current snowpack in evaluating the potential effects of forecast weather on the avalanche probability is a fact of current avalanche forecasting technology. Even during a very light snow year (such as 1976/77), the project staff were often overworked, since technically only two and one-half full time positions were provided, requiring large amounts of uncompensated overtime. This problem is not unusual in research situations but cannot be sustained in an operational program.

The project forecast desk at the NWS office was located this past year adjacent to the NWS staff research area and the Flood, Satellite and Air Pollution Focal Points. This location provided adequate wall and floor space, and was situated substantially closer to teletype and weather map data areas, which are consulted continuously by project staff.

Communications equipment, both for the receipt of data and for the dissemination of forecasts, continued to comprise the bulk of the Forecasting Office hardware. Based on previous recommendations, four phone lines (combined WATS and SCAN) were installed. Two were used for voice communication (mandatory touch-tone dialing system for maximum speed and efficiency) and two were used for machine data transmission or receipt.

Of the two phones used for voice communication, one was used for conservations between the forecaster and field personnel and the second line was hooked into an automatic answering and recording system (described in section 4 of the 1976 report), which contained the latest weather and avalanche forecasts and allowed for the recording of incoming observations or comments from field personnel. Additionally, the forecaster telephone was equipped with an automatic forwarding device which transferred incoming calls to the recording line when the forecaster was unavailable. Two phone extensions in the teletype and map rooms were also utilized to allow for the fact that the duty forecaster spends a significant portion of time examining map, satellite and teletype data, and in preparing the twice-daily teletype forecast sheet for transmission to users.

This telephone arrangement appears satisfactory for the current scope of the forecasting system, allowing individuals access to the current forecasts at all times without interrupting the NWS forecasters, while still allowing field personnel direct contact with the avalanche forecaster. The problem of busy phone lines, which was a frequent complaint during the first year, was alleviated in most situations even though the number of users of the project forecasts has expanded to groups outside of the regular reporting network (e.g., maintenance crews from Chinook and Cayuse Passes, ski areas, etc.).

As in the second year of operation, a teletype link to the third phone line to the Stevens Pass Maintenance Camp at Berne and the WSDT regional office in Wenatchee was installed in the NWS communications room using one of the two data lines. The system simply required the sender to dial the number of the other teletype which then automatically answered and was ready to receive any messages. Ordinarily, the forecaster punched the forecast onto a paper tape prior to phoning Berne. This tape could then be fed through the teletype at a great speed, minimizing the length of the long distance phone call.

Instruments for the receipt of weather data telemetered from the project sites on Hurricane Ridge and Stevens Pass constituted the remainder of the Forecasting Office hardware. Starting this past year, both the Stevens Pass and Hurricane Ridge telemetry were received at the Forecast Office on one (the fourth) phone line, separate from all other functions. Two "one-number dialers" were triggered automatically once hourly or on demand in the Forecast Office. These in turn sequentially called automatic answering devices at Stevens Pass and Hurricane Ridge which set a series of events in motion leading to the receipt of various meteorological quantities on a chart recorder on the forecaster's desk. When functioning properly, the Stevens Pass and Hurricane Ridge telemetry has proved to be an invaluable aid in weather and avalanche forecasting. Unfortunately, significant problems were encountered in the operation of both telemetry sites during the past year. These problems were mainly field-oriented and are discussed in section 9.1.

9.5 Daily Routine

Operation of the Forecasting Office in Seattle for the 1977/78 winter began on November 21, 1977, and ended on April 15, 1978. As previously noted, the office was ordinarily manned from 0600 to 1500 PST during low avalanche potential periods with provisions for up to 24-hour effective coverage during high hazard or rapidly changing conditions. The daily routine followed closely that established during the second year of operation, which is discussed in depth in section 4.2 of last year's report. As in the past, compilation and assessment of information from many and varied data sources was an ongoing process in formulation of weather-avalanche forecasts issued by the Forecast Office. The data sources listed in Table 9.1 plus others discussed in section 7 were major information sources consulted during compilation of the daily worksheet guide (Figure 9.2) and the hourly log form (Figure 9.3). Knowledge derived from all these sources was assessed in preparing the weather-avalanche forecast (Figure 9.4). Quantitative forecasting of the important meteorological variables is discussed in section 7 along with a semi-quantitative outline of the effect of these parameters on the stability of the snowpack in section 6.

The general daily routine (including compilation of forms) and guidelines for the preparation of the weather-avalanche forecasts follows:

- Log Stevens Pass temperatures, precipitation, and wind velocity from the paper chart record at three-hour intervals (one-hour intervals during strom periods), beginning at midnight Greenwich Mean Time (1600 PST). Log present and past values of temperature and wind speed (similar intervals) from the Hurricane Ridge sensors off the paper chart record. Enter appropriate time marks on the paper record for both Stevens Pass and Hurricane Ridge.

- Log Stampede Pass temperatures, precipitation, wind velocity, and the surface pressure gradient between Sea-Tac Airport and Yakima (SEA-YKM) at three hour intervals (hourly intervals during strom periods) beginning at midnight Greenwich Mean Time (1600 PST). The pressure gradient gives a general indication of the direction and magnitude of pass winds.

- Log temperatures and present weather from the 0630 PST highway pass reports received at NWS via teletype from WSDT Station #10. Unfortunately, new snow and total snow on the ground were not usually available until the 0930 PST pass report, at which time they were logged. These reports regularly included Snoqualmie, Blewett, Stevens, White, Satus and Sherman Passes. Mt. Baker reported on the 0930 report only. Additionally, NWS estimated 24-hour water equivalents for the next two days for Stampede Pass and Diablo Dam were noted, if needed.

AVALANCHE CENTER WORKSHEET

Date ____/____/____ Time ________ PST Revised 10/1/77

SNOW-LINE AND NWS DATA (0630/0930/1130/1800)	Temp(°F)	Wx.	New snow"	Total snow"	W.E.	Remarks or QPF-Tda/tmrw 0400-0400 PST
Snoqualmie.......	/	/	/	/		
	/	/	/	/		
Blewett..........	/	/	/	/		
	/	/	/	/		
Stevens..........	/	/	/	/		
	/	/	/	/		
White	/	/	/	/		
	/	/	/	/		
Baker............	/	/	/	/		
Cayuse...........	/	/	/	/		(Diablo Dam)
Chinook..........	/	/	/	/		. / .
Stampede.........						. / .
Paradise.........						
Washington.......	/	/	/	/		

RADIOSONDE DATA:

1200Z/0000Z	Frzg Lvl (ft)	5000' (850 mb) Wind Direction/Speed
UIL(797)	/	/
GEG(785)	/	/
ZT(109)	/	/
VK(115)	/	/
GRF(207)(1500Z)		
SLE(594)	/	/
C7P(50N145W)	/	/

Depth Arctic Air ________

SEA(793)(1500Z) ________ (Frzg lvl)

FOUS 72 — 1200Z (Date) ____/____/____ | 0000Z (Date) ____/____/____

Time		RH%	.VV	HH	DDFF	TB°	PTT	RH%	.VV	HH	DDFF	TB°	PTT	Time	
16P	SEA													04P	
22	18													10	
Tmrw 04	24													16	
10	30													22	
16	36													04	Tmrw
22	42													10	
Next day 04	48													16	

FOUS 43 (Frzg lvls): 1200Z | 0000Z

Time		SEA(+400')	GEG(+2400')	PDX	SEA(+400')	GEG(+2400')	PDX	Time	
16P	12							04P	
22	18							10	
Tmrw 04	24							16	
10	30							22	
16	36							04	Tmrw
22	42							10	
Next day 04	48							16	

850 mb chart (1200Z)(0000Z) Advection?? WARM / COLD / NONE

NWS Cascade / Olympic Mtn. Forecast (0430 - 1030 - 1630 PST):

FIGURE 9.2 Forecast office daily worksheet.

Dates		AVALANCHE FORECASTING HOURLY WEATHER LOG 1977-78													
-		Stevens Pass Telemetry					HR Telemetry		Stampede Pass						
Date	Time	Temp °F		Wind		Precip In.	Temp °F	Wind	Temp °F	Wind		Precip In.	Snow Depth	Press Grad	
Mo/Da	Z/PST	4050'	4800'	Dir 0-360	Speed mph	4750'	5300'	Speed mph	4000'	Dir 0-360	Speed kts	4000'	In. & Wx.	Sea-Yka Mb.	
												2			
	09Z/01											3			
												4			
												5			
	12Z/04											24			
	15Z/07											3			
	18Z/10											6			
	21Z/13											3			
	00Z/16											6 24			
	03Z/19											3			
												4			
												5			
	06Z/22											6			
												1			

FIGURE 9.3 Forecast office hourly weather log.

WEATHER AND AVALANCHE TELEPHONE RECORDING Revised 9/30/77

"Department of Transportation Research Project, For Official Use Only"

__________ AM/PM __________ __________ __________
(time) (day) (month) (date)

Wx. Synopsis:

Includes current weather map synopsis, weather trends, reasons for trends, timing of future weather disturbances or other weather patterns of significance, regional effects of weather (if any), and reports of any significant weather events.

• • • •

Wx. Forecast (day 1 & 2): ______ - ______

Includes timing and type of precipitation (if any), temperature trends, cloud cover, cloud type (e.g., low, middle, high), and local or regional variations (e.g., east vs. west side, temperature inversions, fog, freezing rain, etc.).

Snow / Freezing level nr.__________ft. rsg / lwrg to_________ft.__________________.

Winds thru the Cascade passes_____ __________knots, becmg________________________.

Free winds at 5000 ft. level___________ ________knots, becmg____________________.

24-hr precipitation forecast ending at 4 AM_________/ 4 AM__________

Wash. Pass________/________Inches W.E.
Stevens Pass_______/________Inches W.E.
Snoq. Pass________/________Inches W.E.
White Pass________/________Inches W.E.
Paradise__________/________Inches W.E.
Chin. Pass________/________Inches W.E.
Cayuse Pass_______/________Inches W.E.
Crystal Mtn.______/________Inches W.E.

Extended Weather Forecast (day 3,4 & 5): ______-______

Includes general forecast of precipitation and temperature trends.

Avalanche Advisory:

Includes Forecaster's evaluation of present and possible future condition of the snowpack based on past, present, and forecast future weather conditions, the observation network, and in-situ snowpack observations by Forecasting Office staff. Also includes summary of avalanche activity and/or snow structure reported from various areas when applicable.

FIGURE 9.4 Weather and avalanche telephone recording form.

- Note the latest NWS forecast, normally issued at 0430 PST (and thereafter at six hour intervals), for the Olympics and Cascades.

- Check moisture patterns and log freezing levels, inversions, and 850 mb level winds (approximately 5000 feet) from the following radiosonde observatories: Quillayute, Washington (UIL), Spokane, Washington (GEG), Vernon, B.C. (YVK), Port Hardy, B.C. (YZT), Salem, Oregon (SLE), and the Canadian Weather Ship (C7P) located near 50° North and 145° West. Frequently, on weekdays additional soundings were available from Seattle (Portage Bay), Washington (SEA) and Gray's Field/Fort Lewis, Washington (GRF). The depth of the arctic air mass at Vernon and Prince George, B.C., was noted, if present.

- Log FOUS 43 and 72 data, forecast values of various weather parameters for Seattle generated by the NWS-NMC LFM computer model for six-hour intervals out to 48 hours from 0400 PST. These data include the forecast freezing levels, average relative humidity (RH) for the layer from the surface up to 700 mb (approximately 9000 feet), the forecast vertical velocity (VV), the forecast thickness value (HH) between the surface and the 500 mb pressure surface (approximately 18,000 feet) from which freezing levels can be approximated, direction and speed of the mean wind in the boundary layer (DDFF) (this extends from the surface to near 4000 feet for Seattle), the mean potential temperature of the boundary layer (TB), and the six-hour precipitation amount (PTT). All of the above data are forecast a second time early in the evening for 48 hours starting at 1600 PST.

- Check satellite pictures which are received several times per hour. Note location and speed of frontal bands, cloud types, and trends in motion and intensity.

- Check all current analyses of weather conditions at the surface and upper levels of the atmosphere. Check all available hand and computer generated maps of forecast weather conditions (normally for 12 hour intervals out to 48 hours, plus 72, 84, and 96 hours).

- Based on the above, plus discussions with other forecasters, write a brief synopsis of current and projected weather patterns, including location and velocity of weather fronts, trends of upper air patterns that may effect their motion, temperature trends, etc.

- Make a detailed weather forecast for the Cascade and Olympic Mountains to 48 hours and formulate a general outlook for 48-96 hours. The first 48 hours should include sky cover, precipitation (type and intensity), timing of frontal passages, wind velocity and expected changes at both the pass level and in the free air at 5000 feet, freezing (snow) levels, 24 hour water equivalent of new snow or rain expected during the next two days for six individual passes, plus Paradise and Crystal Mountain and Mt. Hood, Oregon. The 48-96 hour outlooks contained indications of temperature and precipitation trends for that period. Estimates of timing of any precipitation or temperature changes were also given. Included with all of the above were indications of any expected geographical variations.

- Based on most recent pass reports, weather trends, avalanche activity, snowpack analyses, reports from field personnel, etc., formulate an avalanche advisory. This takes the form of an area by area narrative when necessary. Include any pertinent reports of avalanche activity experienced as an indicator of possible trends throughout the Olympics and Cascades.

- Place new forecast on tape recording. Punch forecast onto teletype tape and send to Stevens Pass and Wenatchee.

- Continue to log incoming data from various stations in the field network. Participate in NWS map discussion, where forecasters and meteorologist specialists discuss the present weather situation, weather trends, reliability of numerical forecast products, etc. Continue to review new forecast packages from NWS-NMC as they come in and update the forecasts as necessary.

- Write summary of present and forecast weather and avalanche conditions, including important details that may have influenced the forecast or which may be of concern to future forecasts. This report is used in-house both as an aid to forecasters when there is a personnel change and as an aid in evaluating forecast accuracy after the season ends.

- Complete various forecast verification forms. These include estimates of the freezing level and avalanche activity for 6 hourly periods, a qualitative evaluation of the previous day's weather forecast, and a daily evaluation of the water equivalent forecasts. All of these data are used in-house to aid forecasters.

- Constantly update or amend the present forecast as the situation warrants. Under extreme conditions of severe weather or avalanche activity, issue special alerts to user agencies by telephone. These are normally issued when rapid changes in the weather are expected to lead to avalanche-generating situations.

- Interspersed with all of the above, receive user phone calls, discuss forecasts, and receive observations.

With this daily routine forecasters were able to have a completed forecast available between 0800-0900 PST. A second complete forecast was normally issued at about 1500 PST, based on information received during the day. In changing situations this forecast was sometimes delayed until after 1600 PST to allow forecasters to examine new radiosonde data that becomes available at 1600 PST. Updates of the forecasts were issued at anytime the situation warranted.

Experience gained from three years of operation has indicated that continuity and familiarity with existing weather and avalanche conditions requires several hours of overlap between forecasters when it is necessary to staff the office for extended periods. Often under changing conditions it is required that forecasters be on duty at least through 1600-1800 PST to examine radiosonde observations and to monitor continuing field data input and issue alerts when necessary. It has been the practice under these circumstances for a single forecaster to cover the entire day. If it appears that the situation may become critical and require extended staffing of the office, the forecaster on duty may contact a stand-by forecaster who would be briefed on the present situation. If the situation continues to develop, the duty forecaster then informs the stand-by forecaster that he/she will be needed at the Forecasting Office. The stand-by forecaster is briefed after arrival and the two forecasters work together for several hours to insure the necessary continuity and familiarity with the existing and forecast weather and avalanche conditions. The importance of maintaining this continuity in producing reliable forecasts is increasingly recognized by workers in this field.

10. FIELD TESTS OF STEVENS PASS TELEMETRY

During the summer of 1978, a field test was carried out using the sensors from the remote telemetry package located at Stevens Pass during the previous two winters. The purpose of this experiment was to compare the measurements taken by this package with those obtained using conventional meteorological instruments. This type of study was quite useful, for the general system, as well as the wind speed and precipitation sensors, were experimental. Although the package had been tested extensively in the laboratory, it had never been field tested alongside conventional instruments.

10.1 Experimental Set-Up

The experiment was carried out at the University of Washington's Blue Glacier Research Station, located at 6800 feet in the Olympic Mountains of Washington. This site was chosen as it is located above the permanent snow line and frequently experiences winter-like weather during the summer months. The station is located on a rock ridge north of Mt. Olympus, adjacent to the Snow Dome accumulation area for the Blue and Black Glaciers.

The Stevens Pass telemetry package was modified to run on 12 V battery outputs and to be triggered hourly by a local clock; otherwise, the system was kept in a configuration closely approximating that used during winter operation. The telemetry package sensors consisted of wind speed, wind direction, precipitation, and temperature. These sensors were mounted as close to conventional sensors as was practicable. All of the instruments were located directly to the west of the station on a ridge dropping steeply westward down about 2500 feet to the Glacier Creek drainage. A conventional Aerovane anemometer was mounted on the same 12 foot mast as the telemetry package wind sensors and its readings were recorded continuously. A conventional total wind anemometer was mounted about

30 feet southeast of the main mast, 20 feet in the air, placing it at the same elevation as the other wind sensors. The experimental precipitation gage was located approximately 10 feet north of a Weathermeasure heated tipping bucket precipitation gage (the same unit used at White pass during the winter of 1977-78). Additionally, a standard Weather Service 8" rain gauge was located about 30 feet south and 8 feet higher than the experimental gage. All three gages had roughly the same wind and topographic exposures.

The telemetry package temperature sensor was located on the main anemometer mast in the usual double-shielded container. A Weathermeasure thermograph was located about 12 feet south of the mast in a weather instrument shelter.

Observations began on June 27 and continued until August 23, with occasional gaps due to equipment failure and staff changeovers.

10.2 <u>Wind Speed</u>

Wind tunnel tests on the experimental anemometer had indicated a stall speed of approximately 4 mph; however, it was immediately noted by comparison with the Aerovane anemometer that the effective stall speed for a west wind was approximately 10-11 mph and somewhat lower for an east wind. These values were considered unacceptably high. To account for this unexpected development, paper streamers were attached to the mast to ascertain the approximate vertical component of the winds. It was found that a west wind, which accelerates directly up a steep ridge face, frequently blew at an angle of 45° or greater from the horizontal. This indicated that the vertical component of the wind was as great or greater than the horizontal component. East winds, which blow over a more gradual slope approaching the mast, had a significantly smaller vertical component. As the wind tunnel tests were performed with essentially horizontal winds, this indicated that the experimental anemometer was insensitive to a vertical wind component.

Consideration of the shape of the experimental anemometer led to a simple modification of the sensor. This consisted of adding a half circular piece of sheet metal to the top of each of the cylindrical cups (Figure 10.1). This modification lowered the stall speeds to about 5 mph for both directions, which is in the acceptable range. This modification is particularly significant when it is noted that the Stevens Pass sensors are located on a ridge and frequently experience winds with large vertical components. This modification should allow the sensor to give more representative values for the wind speeds affecting the avalanche paths at the Pass. Further research into alternate design shapes could lead to even more accurate observations.

In a separate part of the work, a qualitative comparison was made between the continuous readout of the Aerovane anemometer, the total wind anemometer and the hourly observations of instantaneous wind speed recorded by the telemetry package. It was found that the once-hourly readout of 45 seconds of wind speed can be misleading. During this test, the winds during the 45 second period were generally lower than those which were representative of the whole hour. Undoubtedly, a more lengthly study would show the reverse to occur frequently, so that, statistically, the two would balance out; however, for a given hour, the 45-second window can be very misleading, causing errors in such things as estimated snow transport.

The simplest way to combat this problem is to simply lengthen the window of the wind speed observations, although there are obvious practical limits to this solution. A more satisfactory solution may be to substitute a total wind anemometer for the instantaneous readout. This could then give an average wind speed for the hour, although it would have the disadvantage of not indicating any gustiness which may be present. A possible combination of the two may be the optimal solution. Further quantitative study of this problem should be performed.

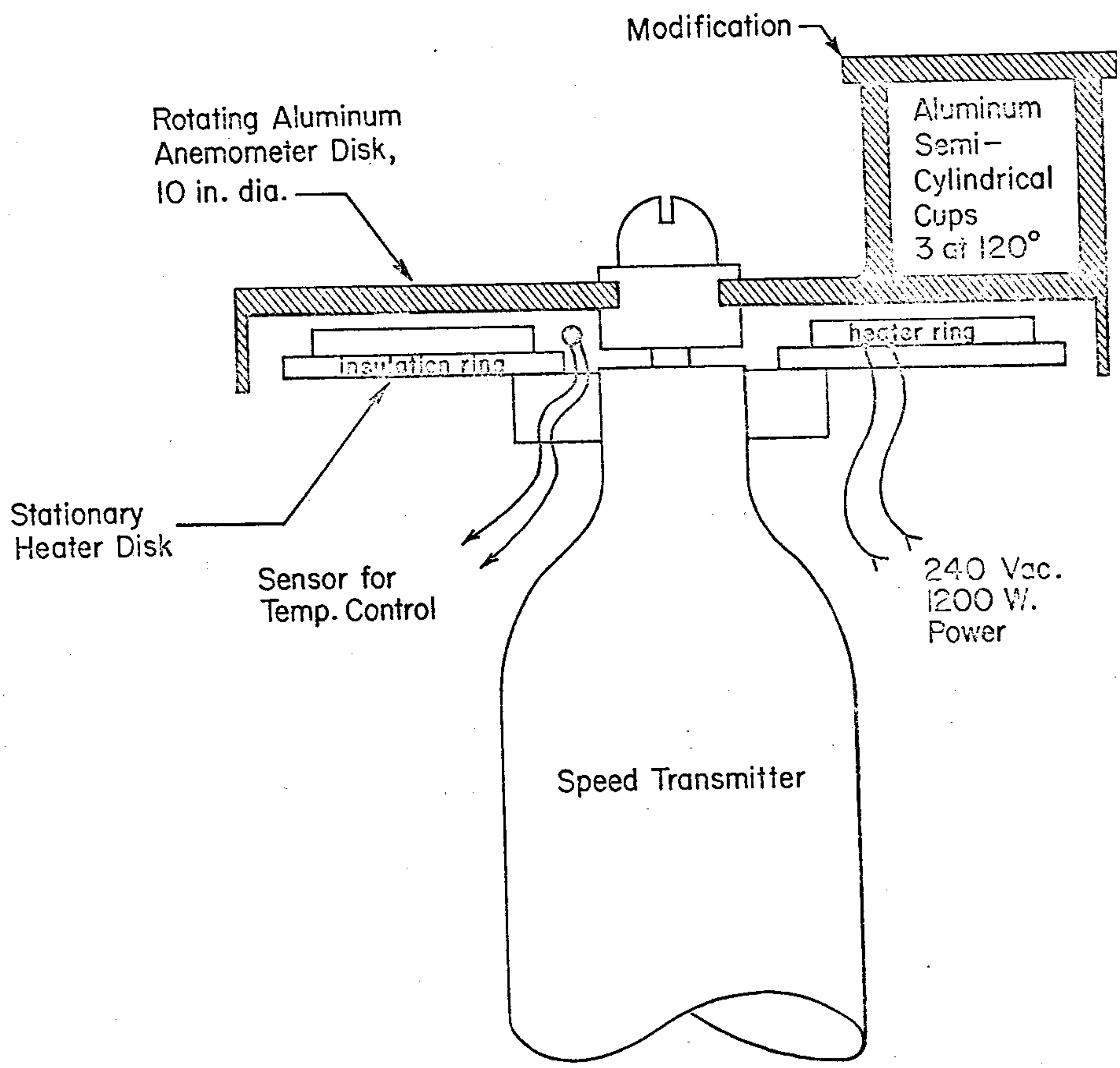


FIGURE 10.1 Wind speed sensor.

10.3 Precipitation Gages

During the 1977-78 winter, project personnel found that air bubbles frequently formed in the siphon in the experimental precipitation gage that ran from the water reservoir to the overflow (Figure 10.2). This often prevented the flow of precipitation to the tipping bucket until a sufficient pressure head could be built up to push the air blockage out. This problem was solved during the summer study by replacing the siphon tube with a shorter, wider diameter tube. After this substitution no air bubbles were observed to form.

For the summer experiment the heaters on both the experimental precipitation gage and the Weathermeasure heated gage were left off unless capping by new snow was anticipated.

Unfortunately, the summer of 1978 proved to be quite dry during the period of observations--only three days with significant precipitation were recorded. However, several interesting points were noted. In all three instances, the experimental gage showed substantially less precipitation than either the Weathermeasure tipping bucket or the 8" gage (both of these gages recorded values within .02" of each other). The experimental precipitation gage was low by as much as 30%. In the three available cases, it was found that the experimental gage did not indicate anything for several hours after the onset of precipitation. The difficulty was traced to the area of the overflow tube. This is the only section of the system where the water reservoir is exposed directly to the air. Apparently, sufficient evaporation occured during periods without precipitation to lower the level of the water reservoir significantly. Hence, whenever a precipitation period began, no water could reach the tipping bucket mechanism until the evaporated water was replenished. This problem should be comparable, or possibly greater, during the winter when the reservoir heaters are left on continuously, accelerating the evaporation.

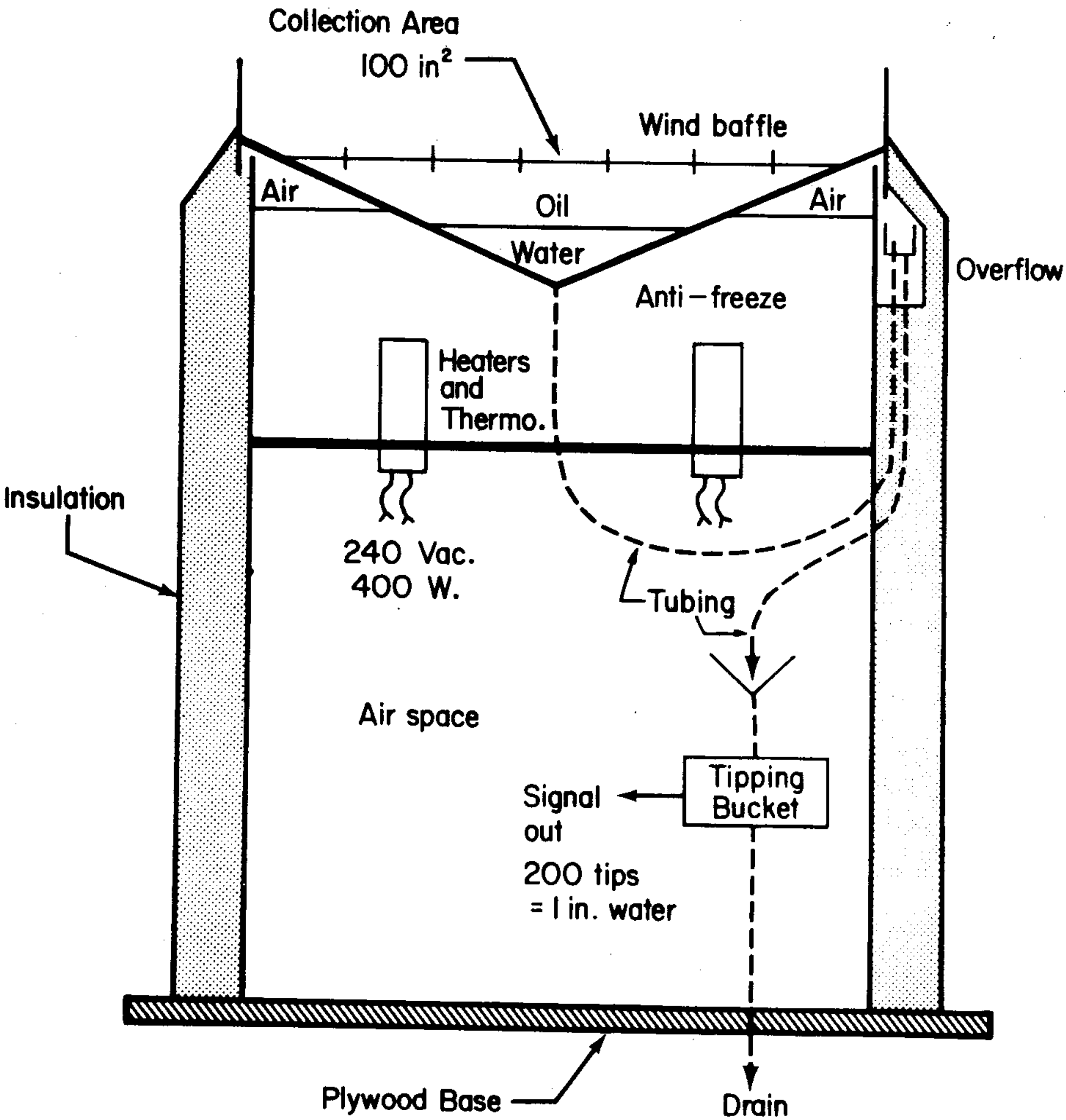


FIGURE 10.2 Heated Precipitation Gage

No immediate solution to the problem is apparent. Some way must be found to seal the overflow area without inhibiting the siphon action. Even if this is accomplished, there can still be evaporation at the end of the tube leading to the tipping bucket, although it will require tests to determine if this evaporation is significant. In the interim, it was concluded that the experimental gage should be replaced by a standard heating tipping bucket gage for future use at Stevens Pass.

10.4 Temperature

A comparison of the hourly temperatures recorded by the telemetry package thermistor and those recorded by the Weathermeasure thermograph was carried out. The two instruments were found to agree to within 1°F except for occasional discrepancies of approximately 2°F during times of rapidly changing temperatures. The source of these differences appeared to lie in the characteristics of the radiation shields of the two systems.

During periods of calm winds, the thermistor sensor ran approximately 1°F warmer than the thermograph which was better protected from solar insolation by being in the instrument shelter. During periods with any wind, there was little difference between the reading of the temperature sensors, evidently due to good aspiration of the thermistor radiation can. During periods of rapidly falling or rising temperatures, the thermograph tended to lag behind the thermistor sensor, probably due to the greater thermal inertia of the instrument shelter.

It seems that the double-shielded thermistor used in the telemetry package is quite comparable to a conventional thermograph and, in fact, appears to be somewhat more responsive to rapid temperature fluctuations. Its tendency to read slightly high during sunny, windless periods can probably be corrected by placing the sensor in a shaded location.

11. BIBLIOGRAPHY

Atwater, M.M. Snow Avalanches, Scientific American, 190, No. 1, p. 26, 1954.

Atwater, M.M. and F.C. Koziol. Avalanche Handbook. USDA Forest Serv , 1952.

Bois, B. and Obled, C. An Analysis of Nivoclimatological Data with Regards to the Forecasting of Avalanches, 1970 (unpublished).

Bois, B., Obled, C., and Good, W. Multivariate Analysis as a Tool for Day-by-Day Avalanche Forecasting, Proceedings of the Grindlewald Conference, IAHS Publication No. 114, 1975.

Bovis, M.J. Statistical Analysis, Avalanche Release and Snow Characteristics, INSTAAR Occasional Paper No. 19, University of Colorado, 1976.

Box, G.E.P. and Jenkins, G.M. Time Series Analysis, Forecasting, and Control. San Francisco, Holden-Day, 1970.

Bradley, C.C., Brown, R.L., and Williams, T.R. Gradient Metamorphism, Zonal Weakening of the Snow-Pack and Avalanche Initiation, Journal of Glaciology, Vol. 19, No. 81, pp. 335-342, 1977.

Climatalogical Handbook, Columbia Basin States, Precipitation, Vol. 2, September 1969.

Duewer, D.L., Koskinen, J.R., and Kowalski, B.R. "ARTHUR," available from B.R. Kowalski, Laboratory for Chemometrics, Department of Chemistry BG-10, University of Washington, Seattle, WA 98195, 1975.

Fukunaga, K. Introduction to Statistical Pattern Recognition, Academic Press, New York, 1972.

Garner, W.R. The Processing of Information and Structure. Lawrence Earlbaum Associates, Patomac, MD, 194 pp., 1974.

Garner, W.R. Uncertainty and Structure as Psychological Concepts. Wiley, New York, 369 pp., 1975.

Judson, A. and Erickson, B.J. Predicting Avalanche Intensity from Weather Data: A Statistical Analysis. USDA Forest Service Research Paper RM-112, 1973.

Kojma, K. Viscous Compression of Natural Snow Layer, II. Institute of Low Temperature Science, Series A, No. 15, pp. 117-136, 1956.

McClung, D.M. Avalanche Defense Mechanics. Ph.D. Dissertation, University of Washington, 1974.

Obled, C. and Good, W. Recent Developments of Avalanche Forecasting by Discriminant Analysis Techniques: A Methodological Review and Some Application to the Parsenn Area. (Submitted to the Journal of Glaciology, 1979.)

Perla, R.I. On Contributory Factors in Avalanche Hazard Evaluation, Canadian Geotechnical Journal, 7, No. 4, pp. 414, 1970.

Perla, R.I. and Martinelli, M., Jr. Avalanche Handbook. USDA Forest Service, 489, 1975.

Rivett, P. Principles of Model Building. John Wiley & Sons, London, 141 pp., 1972.

Salway, A.A. Statistical Estimation and Prediction of Avalanche Activity from Meteorological Data. Ph.D. Dissertation, University of British Columbia, 1976.

Shannon, C.E. A Mathematical Theory of Communication. Bell System Technical Journal, July 1984, p. 379; October 1948, p. 623.

Shumski, P.A. Principles of Structural Glaciology. Dover Publications, Inc., New York, 1964.

Wilson, N. Everything You Wanted to Know about Snow. Mariah, pp. 26-28, 82-84, 104-106, Winter 1977.

APPENDIX A. Examples of Calculating Avalanche Data Entropy

The entropy (information content) of a message or data transmission depends on the number of possible message or data elements and the probabilities of these elements.

$$H = \sum_{0 \rightarrow i} -p_i \log_2 p_i,$$

where p_i is the probability of the i^{th} element.

If N messages or elements are equally probable, this reduces to the simpler expression

$$H = \log_2 N$$

Ordinary calculators do not usually have a $\log_2$ function key. The values of $\log_2$ can be found from the relation

$$\log_2 N = \frac{\ln N}{\ln 2} = 1.44 \ln N$$

Example No. 1

Data about avalanche occurrence on a single path comprises the 25% probability that an avalanche has occurred ($p = 0.25$) and 75% probability that one has not occurred ($p = 0.75$).

$$\begin{aligned} H &= (0.25 \log_2 0.25) + (0.75 \log_2 0.75) \\ &= (0.50) + (0.31) \\ &= 0.81 \text{ bits} \end{aligned}$$

If the occurrence and non-occurrence are equally probable, the entropy then is given by

$$H = \log_2 2 = 1 \text{ bit}$$

Entropy is maximum when events are equally probable.

Example No. 2

A common range of densities in a typical winter snow cover is 50 to 450 kg/m^3. An incremental change of 20 kg/m^3 is thought to be significant for purposes of evaluating snow stability. Suppose by late winter there is an equally probable chance of finding in the snow cover any given density within the range.

$$H = \log_2 \left(\frac{450-50}{20}\right) = 4.31 \text{ bits}$$

If the significant incremental change is 50 kg/m^3, then H = 2.99. Entropy can be minimized by keeping the significant increment no smaller than absolutely necessary.

Example No. 3

The hand test for snow hardness given five possible values for this snow parameter ranging from very soft to very hard. It can reasonably be assumed that each value has the following probability of being encountered in a certain mid-winter snow cover: VS = 0.15, S = 0.20, MH = 0.30, H = 0.20, VH = 0.15.

$$H = (0.41) + (0.46) + (0.52) + (0.46) + (0.41)$$
$$= 2.25 \text{ bits}$$

The hand test for hardness is associated with lower entropy than the density measurements introduced in Example No. 2.

Example No. 4

At a certain ridge-top observation site, one-hour average wind speeds exceeded 20 mph on 550 occasions during a winter extending from November through mid-April. The wind directions for these 550 observation intervals were distributed around the compass by 45° segments as follows:

Direction	Number of Observations	p	$-p \log_2 p$
S	204	.37	0.53
SW	95	.17	0.43
W	125	.23	0.49
NW	87	.16	0.42
N	33	.06	0.24
all others	5	nil	0

The second column of numbers, p, gives the probability that any given observation selected at random will fall in the corresponding direction segment. The third column gives the calculated values of $-p \log_2 p$ for these probabilities. If the 45° segments are taken as the different elementary events of wind direction, eight possible events in all, then the entropy is given by

$$H = \sum -p \log_2 p = 2.11$$

If a wind direction shift of a half-segment, or 22.5°, is thought to be significant for avalanche formation, and the chance that an observation within any given segment will fall in either 22.5° sub-division is equal, then there are 16 elementary events instead of 8, with probabilities distributed proportionate to those in the table above, and the entropy is H = 3.11.

APPENDIX B. Glossary of Useful Avalanche/Snowpack Terms

artificial avalanches--those avalanches triggered directly by man or his equipment (skier, explosives, etc.).

artificial control--the stabilization of avalanche areas by hand charges (explosives), artillery, ski testing or other non-natural means. This control method usually results in slope stability through reduction or elimination of stresses within the snowpack by either avalanche release, sluffing, or snow settlement.

aspect--the direction toward which an (avalanche) slope faces. For example, north aspect slopes face toward the north. Slope aspects are particularly important when considering the effects of solar radiation or wind loading on the snowpack.

avalanche hazard--measure of the probability of avalanche release in a given area at a particular time, considered together with the threat to people and property.

avalanche path--areas in mountainous terrain where avalanches are known or suspected to occur. These areas include, but are not limited to, steep, open slopes, gullies and bowls.

avalanche potential--measure of the probability of avalanche release in a given area at a particular time, regardless of threat to people or property.

climax avalanche--an avalanche which occurs at the culmination of slow load buildup during several storms and/or results from metamorphism in the snow cover. Generally, this avalanche involves snow layers from more than one storm.

compression zone--an area of compression at the base of a slide path where terrain steepness decreases. This zone is concave in profile, and subject to gravitational pressure from the snow above.

cornice--an overhanging snow structure resulting from the accumulation of (large) quantities of wind-drifted snow over and in the lee of sharp terrain bends. Natural cornice releases during warm-ups often trigger slab avalanches on the slopes below.

creep--the slow, continuous, glacier-like downhill deformation of the snow cover, as a result of gravity-induced internal snow motion. This does not include the downhill motion of the snow cover relative to the ground, which is known as glide.

density--the mass per unit volume of a given quantity of snow, usually expressed in grams per cubic centimeter (gm/cm^3). The density of water, 1 gm/cm^3, (or 1000 kg/m^3), is a convenient reference. In the absence of wind, new snowfall densities usually range from .07 to .12 gm/cm^3, (70 to 120 kilograms per cubic meter), while in areas exposed to wind densities are often from .20 to .30 gm/cm^3 (200-300kg/m^3). In general, high densities of new snowfall correlate with warm air (rimed crystals) or high winds (breakage of crystals), while low densities correlate with cold air (no riming) or low winds (cystals intact). Snowpack settlement also results in increasing snow density.

deposition zones--see lee slopes (as relating to wind transport); see runout (as relating to avalanche paths).

direct-action avalanche--an avalanche occurring during or immediately after a storm, which involves only the snow deposited during that storm.

equitemperature (ET) metamorphism--the process of changes in snow texture from complex crystal shapes toward rounded snow (ice) grains in the absence of large temperature gradients. Technically this is known as destructive metamorphism (it destroys crystal shapes), and it results in a strengthening of the ice skeleton and a general rounding of snow grains largely through a preferential transfer of water vapor within the snowpack.

exposure--see aspect

fracture line--a well-defined line where the moving snow cover breaks away from the stable snow in a slab avalanche release.

fracture-line profile--a snow profile obtained by excavating a snowpit at a recent slab avalanche release site. Normally, measurements of temperature, density, ram resistance and stratigraphy at various depths are taken in order to understand the snow layering leading to the avalanche release.

free water--liquid water present in a snow layer.

ice lens, ice layer--a very hard layer in the snowpack produced by freezing of meltwater into solid ice.

lee slopes--those (avalanche) areas on the down-wind side of ridges and other terrain obstacles, where deceleration of wind flow often deposits deep accumulations of snow. Also, usually refers to those slopes sheltered or protected from the wind. An east-facing slope is in the lee of a west wind.

loose snow avalanche (L)--a progressive rupture of snow cover, starting at a point and fanning out downhill. Loose snow grains start to slip from a point near the surface in this type of avalanche, sweeping progressively more grains with them as they move downhill leaving an inverted V-shaped scar. Loose slides may be sub-classified as dry or wet, according to whether or not liquid water is present.

lubricating layer--the snow layer involved in avalanche release which, due to its weak internal strength and/or poor bonding to adjacent layers, facilitates the mechanical failure of a snow slab. Two examples of this lubricating layer are graupel or light, wind-deposited snow sandwiched between two more cohesive slab layers. A clearly defined lubricating layer may not always be present in a slab avalanche release.

melt-freeze (MF) crust--a usually hard layer within the snowpack which has undergone at least one melt-and-freeze cycle, and has gained strong intercrystalline bonds through refreezing of interstitial liquid water.

metamorphism--as applied to a mountain snowpack, metamorphism refers to changes in snow texture caused by pressure and temperature conditions. The temperature of the snow layer determines the rate of metamorphism, and the temperature change (gradient) across the layer largely determines the type of metamorphism.

natural avalanches--those avalanches not triggered directly by man or his equipment (e.g., cornice fall, earth tremors, etc.).

percolation--the downward motion of meltwater through interstitial air spaces in a snowpack due to gravity.

pocket of instability--an isolated area of potentially unstable snow.

rain crust--a melt-freeze crust where the source of liquid water is rain.

ram resistance (ram number)--a measure of the relative mechanical strength of snow layers. This number is obtained by utilizing a device known as the ram penetrometer.

riming--the deposition of supercooled water droplets directly on snow crystals or terrestial objects. Riming on snow crystals may also play an important role in avalanche formation through either its higher density or its promotion of a more slablike snow texture.

runout--the bottom boundary of an avalanche path, often identifiable by forest damage or avalanche deposition.

settlement--the progressive densification (consolidation) of a snowpack due to gravity, overburden pressure (of overlying snow) and metamorphism. In general, substantial settlement (>25%) of new snow layers is a stabilizing influence on a mountain snowpack.

shear strength--in a snow slab, the slope parallel component of gravity tends to pull the slab downhill while friction and cohesion between snow surfaces act to hold the slab in place. Slippage between the slab and its undersurface can result, and avalanching can result if gravity induced shear stress between layers exceeds shear strength bonding layers together. Snow layers composed of surface hoar, graupel, low-density snow, etc., have very low shear strengths.

slab--a layer of snow held together by internal cohesion between snow grains.

slab avalanche--the simultaneous rupture of a coherent mass of snow over an extended area. A distinct fracture line is left at the upslope limit of the avalanche, and a clearly defined sliding surface is often revealed. Slab avalanches may be sub-classified as either soft slab (SS), if during motion the avalanche breaks into a formless mass, or hard slab (HS), if hard angular blocks of snow are left in the final avalanche debris. Wet slabs are slab avalanches that have free water present at the fracture line and generally result from rain or appreciable surface snow melt.

slide cycle--a period of time during which instability in the snowpack is high and substantial avalanching occurs naturally or artifically. A given slide cycle may be variously referred to as a wet slab cycle, soft slab cycle, etc., depending on the nature of the predominant avalanching.

sliding surface--the usually hard snow surface below a possible lubricating layer upon which a slab avalanche slides. This may be a sun crust, a rain crust, an ice layer, a wind-slab surface or other strong snow surface.

sluffing--the progressive stabilization of steep snow slopes by small, usually harmless avalanches of either point or slab origin. Technically, a sluff is any snow slide that moves less than 150 ft. (50 m) slope distance.

slope loading--the increase in stress (shear and tensile) within an inclined snowpack by the addition of new snowfall.

snow decomposition--the mechanical weakening of a melt-freeze crust by the action of a strong temperature gradient, where the gradual separation of previously bonded snow grains into individual loose snow grains, or the recrystallization of new snow grains, often occurs.

snowpack instability--see unstable snow conditions.

snowpack stratigraphy--layering within the snowpack.

snowpit--a hole dug into the snow surface to obtain certain physical properties of the snowpack.

spring avalanches--avalanches that typically occur after an extended period of warm weather saturates the snowpack with melt water. Usually this water will flow down through the snowpack until it either reaches the ground or an ice layer where it spreads out and lubricates the layer causing the snow above to slide. True spring avalanches are always wet snow avalanches.

starting zone--that portion of an avalanche path where a slide originates. Generally, starting zones are bare of trees, steeper than about 30° and receive large amounts of snow. Gullies and bowls are particularly efficient collectors of snow (especially on lee slopes where wind transport occurs) and the tops of these areas make up a large portion of the most active starting zones. Many starting zones are also bounded by cliffs or rock outcrops.

steep slopes--those avalanche areas where large slab slides are most likely to start during conditions of high to extreme avalanche potential. In general, dangerous slabs most often occur on slopes in the 30°- 45° range. The upper limit of 45° reflects the tendency of snow to sluff gradually off steep slopes. However, windpacked snow often accumulates on steeper terrain (45°- 60°) and here, too, slab slides may occur. Also, slab avalanches can propogate from high angle slopes to slopes of less than 30°, and loose snow avalanches that would otherwise be harmless may spill onto lower slopes, triggering dangerous slab avalanches.

sun crust--a melt-freeze crust where the source of liquid water is due to solar radiation.

surface hoar--also hoarfrost; the ice equivalent of dew surface ice crystals resulting from vapor deposition onto a cold surface. These crystals are quite intricate, extremely weak and cohesionless, and generally form on cold, clear nites.

temperature-gradient (TG) metamorphism--the variation of temperature per unit depth of the snow cover; also, constructive metamorphism of deposited snow crystals in response to a strong vertical temperature gradient (generally greater than 0.1° C/cm) in the snowpack and accompanying differences in vapor pressure with depth, where marked crystal growth occurs without appreciable intergranular bond growth. The grain growth generally has an adverse effect on mechanical properties of snow.

tensile strength--the slope-parallel component of strength in a snow layer which prevents it from fracturing across the slope. Tensile strength of a snow slab together with shear strength between the slab and the underlying snow surface prevents the slab from avalanching.

tension zone--a snow slab is placed in tension by the straining and stretching of the snowpack over terrain irregularities. The tension zone of a slab occurs at the top where the slab is trying to pull away from the stable snow, largely through the effects of varying snow creep.

track--that part of an avalanche path between the starting zone at the top and the runout zone at the bottom. In general, avalanche tracks have an inclination of at least 15°, more commonly 20°- 25°, and can be subdivided into channeled (gullies, gulches, couloirs, etc.) or unconfined (plane, open slopes) tracks.

trigger--the type of activating agent which results in an avalanche. The trigger types for a slide may be natural (cornice fall, snow from tree, internal stress build-up, etc.) or artificial (ski, explosives, etc.).

unstable snow conditions--physical characteristics of the snowpack which may result in avalanching. The presence of TG metamorphism, surface hoar or graupel may indicate an unstable snowpack in old snow. In new snow, instability often results from a heavy strong layer (e.g., wind slab) deposited over a relatively light (low density) or weak layer (e.g., surface hoar, low wind deposited snow). Rising temperatures, winds or snowfall intensity during a storm usually lead to unstable snow conditions.

wet-snow avalanche (or wet avalanche)--an avalanche consisting of snow which contains liquid water. In many instances, an avalanche will begin as a dry snow avalanche but turn into a wet snow avalanche as it descends to lower elevations.

wind loading--the wind transport of snow onto lee slopes in addition to the accumulation due to snowfall. In this interpretation, wind loading may occur without precipitation, by scouring of snow on exposed windward slopes and subsequent deposition of this scoured snow on lee slopes.

wind slab--a firm snow slab resulting from deposition of wind-pulverized or wind-transported snow. Although wind slabs usually occur on lee slopes, hard wind slabs may also occur on windward slopes. Wind slab deposited over weak, low density, snow layers represents a particular dangerous unstable snow condition.

wind transport--see wind loading.

windward slopes--those (avalanche) areas on the upwind (facing into the wind) side of ridges or other terrain obstacles, where accelerating wind-flow can erode surface snow, redepositing it in areas of low wind stress (lee slopes).

APPENDIX C. Job Description for Avalanche Forecaster

This is a U.S. Civil Service description of the position of Meteorologist GS-1340-11 which was developed as a direct result of the Central Avalanche Hazard Forecasting project.

A. DUTIES

The incumbent is in charge of the Northwest Avalanche Forecasting Program on a rotating scheduled operational shift. As Forecaster, the incumbent interprets current and expected weather situations to produce mesoscale forecasts for assigned areas. The working title is Avalanche Weather Forecaster.

-- Based on National Weather Service forecaste products and snow, weather and avalanche reports transmitted to the Forecast Office from numerous field observers, the incumbent assesses the current degree of stability of the snowpack and forecasts future snowpack stability. This includes preparation of twice-daily avalanche bulletins with updates as required and specialized forecasts for highway maintenance, back-country travelers, and others who work or play in snow.

-- Makes detailed analysis of present and expected meteorological parameters (temperature, wind, precipitation, freezing and/or snow levels, and avalanche potential) over a wide geographical spread. (Washington Cascades to the Northern Oregon Cascades and Olympic Mountains.)

-- Exercises the general supervision of the forecasting program during his shift and is responsible for insuring that all professional products and services are provided on a timely basis and in such manner that maximum responsiveness to public and all other needs is maintained.

Specific jobs concerned with the Avalanche Forecasting Program include:

-- Selects and establishes observation and reporting sites to best sample the variety of weather and snow conditions in the Washington and Northern Oregon Cascades.

-- Trains and maintains a close working relationship with observers.

-- Maintains a close working relationship with cooperating agencies.

-- Develops and maintains a close working relationship with the National Weather Service Forecast offices in Seattle and Portland.

-- Supervises and trains an assistant avalanche forecaster who helps man the Forest office and maintains the field observation and reporting stations.

-- Evaluates National Weather Service Forecast Products and observations from field observers to determine snow stability conditions.

-- Conducts regular field snowpack observations in support of mountain meteorological and avalanche data.

-- Prepares small-scale mountain weather forecasts daily.

-- Prepares and issues avalanche bulletins daily and warning as warranted.

-- Determines when avalanche conditions have abated enough to issue a bulletin to terminate existing avalanche warnings.

-- Selects and supervises installation and maintenance of all field instrumentation and automated telemetry equipment.

-- Makes periodic checks in field of automated telemetry system and other field equipment.

-- Conducts forecast improvement studies and develops theoretical basis for forecasting improvements.

-- Contacts the public and cooperators to explain the Forest Service program and to increase avalanche and mountain weather awareness among National Forest users, especially the ski mountaineering group.

B. <u>FACTORS</u>

1. <u>Knowledge Required</u>

Professional knowledge in the theories, principles, practices, and techniques of meteorology, mountain meteorology and snow cover stability evaluation supplemented by experience in combining meteorological processes and snow cover information with past and current avalanche activity to forecast <u>decision</u> on avalanche hazard.

2. <u>Supervisory Controls</u>

Work is performed under the supervision of the leader of the Recreation Management Group, R-6, Recreation, who indicates the immediate objectives, degree of accuracy required, and nature of results expected. The incumbent is responsible to independently plan and organize the work in order to make timely stability evaluations. The employee also determines the timing, wording, and extent of the avalanche bulletins and warnings issued in the name of the Forest Service. Completed work is reviewed for adequacy in meeting objectives.

3. Guidelines

Guidelines include manuals, handbooks, established procedures, policy statements and research. The employee is considered to be a specialist in the field and is expected to interpret guidelines and actual conditions (meteorological-snowcover) prior to issuing bulletins and warnings. Guidelines generally apply but improvement and modification of guidelines is an ongoing responsibility and the employee must recognize when adaptations are necessary to deal with unique conditions.

4. Complexity

Assignments involve preparing twice-daily mesoscale mountain weather forecast and comprehensive real time avalanche bulletins with updates and warnings when needed. Meteorological processes and snowpack conditions must be combined with past and current avalanche activity to reach a judgmental decision. This must be routinely accomplished for a mountainous area larger than, for example, a country the size of Switzerland. The process for performing the work was developed recently from research and will require monitoring to determine forecast accuracy. If necessary, forecast improvement studies will be conducted to develop a theoretical basis for forecasting improvements.

5. Scope and Effect

Avalanche bulletins and warnings are prepared and issued on a real time basis to cooperators and the public. This includes preparation of a twice-daily mesoscale mountain weather forecasts and avalanche bulletins with updates as required for highway maintenance, back-country travelers and others who work or play on snow. Bulletins and warnings will have considerable impact on a wide range of National Forest users and cooperators, and are very important to their safety.

6. Personal Contacts

Contacts are with the public, media, cooperators and personnel within several National Forests in Oregon and Washington.

7. Purpose of Contacts

The purpose of the public and media contacts is to primarily enhance evalanche - awareness among the public in general and the mountaineering group in particular. Contact with cooperators will be for information exchange.

8. Physical Demands

Though the job is mainly a sedentary one, but regular field checks of both equipment and conditions involve physical exertion, sometimes extreme, during severe winter conditions in high mountainous terrain. Therefore, the incumbent must be in excellent physical condition and agile enough to negotiate steep snow covered slopes on skis, and capable of withstanding physical stress.

9. Work Environment

Much of the work is performed in an office setting although frequent field observations may provide exposure to severe winter weather and hazardous conditions.

APPENDIX D. Project Participants (in addition to those from the University of Washington).

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CRYSTAL MOUNTAIN
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Hugh Koetje (USFS Snow Ranger)
White River Rnager Station
Enumclaw, Washington

GOVERNMENT CAMP
Government Camp Snow Rangers
Zig-Zag Ranger Station
Government Camp, Oregon

MISSION RIDGE
Pro Patrol
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MT. BAKER
Mike Dolfay (USFS Snow Ranger) also Mt. Baker Ski Area Management
Glacier Ranger Station
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MT. HOOD
Mt. Hood Meadows Pro Patrol
and Snow Rangers
Mt. Hood, Oregon

MT. RAINIER NATIONAL PARK
Walt Dabney and Visitors Center Staff
(Rick Kirschner, Bill Swift, John Leohr),
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NATIONAL WEATHER SERVICE
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OLYMPIC NATIONAL PARK
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US GEOLOGICAL SURVEY
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WASHINGTON PASS

Frank Almquist and Donna Daniels
Winthrop, Washington

WHITE PASS

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Maintenance Crew, Washington State Dept. of Transportation
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APPENDIX E. Avalanche Reports prepared by the University of Washington for the Washington State Highway Commission during the period 1971/78.

LaChapelle, E.R. Avalanche Atlas: North Cascades Highway SR-20. Washington State Highway Commission, Olympia, Washington, 1971. (Prepared under Agreement Y-1301)

LaChapelle, E.R. Avalanches on the North Cascades Highway (SR-20), Summary Report. Washington State Highway Commission, Olympia, Washington, 1971. (Prepared under Agreement Y-1301)

LaChapelle, E.R., C.B. Brown and R.J. Evans. Avalanche Studies (1971-1972). Report 8.3, Washington State Highway Commission, Olympia, Washington, 1972. (Prepared under Agreement Y-1301)

LaChapelle, E.R., C.B. Brown, R.J. Evans, T. Fox, D.M. McClung and L. Smith. Avalanche Studies (1972-1973). Report 8.4, Washington State Highway Commission, Olympia, Washington, 1973. (Prepared under Agreement Y-1301)

LaChapelle, E.R. Avalanche Atlas Supplement: North Cascades Highway SR 20. Washington State Highway Commission, Olympia, Washington, 1974. (Prepared under Agreement Y-1301)

LaChapelle, E.R., C.B. Brown, R.J. Evans, D.M. McClung, and M.B. Moore. Avalanche Studies (1973-1974). Report 8.5, Washington State Highway Commission, Olympia, Washington, 1974. (Prepared under Agreement Y-1301)

LaChapelle, E.R., C.B. Brown and R.J. Evans. Methods of Avalanche Control on Washington Mountain Highways, Summary Report 1970-74. Report 8.6, Washington State Highway Commission, Olympia, Washington, 1974. (Prepared under Agreement Y-1301)

LaChapelle, E.R. Avalanche Atlas, Cascade Passes: Part 1 (Chinook, Cayuse, White and Snoqualmie Passes). Washington State Highway Commission, Olympia, Washington, 1974. (Prepared under Agreement Y-1301)

LaChapelle, E.R. Avalanche Atlas, Cascade Passes: Part 2 (Stevens Pass and Tumwater Canyon). Washington State Highway Commission, Olympia, Washington, 1975. (Prepared under Agreement Y-1301)

LaChapelle, E.R., C.B. Brown, R.J. Evans, J.B. Johnson, J.A. Langdon, M.B. Moore and P.L. Taylor. Alternate Methods of Avalanche Control, Interim Report. Report 19.1, Washington State Highway Commission, Olympia, Washington, 1975. (Prepared under Agreement Y-1637)

LaChapelle, E.R., R.T. Marriott, M.B. Moore, F.W. Reanier, E.M. Sackett and P.L. Taylor. Central Avalanche Hazard Forecasting, Interim Report. Report 23.2, Washington State Highway Commission, Olympia, Washington, 1976. (Prepared under Agreement Y-1700)

LaChapelle, E.R., J.B. Johnson, J.A. Langdon, C.R. Morig, E.M. Sackett, and P.L. Taylor. Alternate Methods of Avalanche Control, Interim Report. Report 19.2, Washington State Highway Commission, Olympia, Washington, 1976. (Prepared under Agreement Y-1637)

LaChapelle, E.R. Alternate Methods of Avalanche Control, Executive Summary Report. Washington State Highway Commission, Olympia, Washington, 1977 (unpublished). (prepared under Agreement Y-1637)

LaChapelle, E.R., R.T. Marriott, M.B. Moore, F.W. Reanier, E.M. Sackett and P.L. Taylor. Central Avalanche Hazard Forecasting, Final Report. Report 23.3, Washington State Highway Commission, Olympia, Washington, 1977. (Prepared under Agreement Y-1700)

LaChapelle, E.R., D.B. Bell, J.B. Johnson, R.W. Lindsay, E.M. Sackett, and P.L. Taylor. Alternate Methods of Avalanche Control, Final Report. Report 19.3, Washington State Highway Commission, Olympia, Washington, 1978. (Prepared under Agreement Y-1637)

LaChapelle, E.R., S.A. Ferguson, R.T. Marriott, M.B. Moore, F.W. Reanier, E.M. Sackett, and P.L. Taylor. Central Avalanche Hazard Forecasting, Summary of Sci. Investigations. Report 23.4, Washington State Highway Commission, Olympia, Washington, 1978. (Prepared under Agreement Y-1700).

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