APPLICATION OF NUMERICAL WIND MODELS TO SNOW AVALANCHE FORECASTING: OVERVIEW

T.W. Tesche and M.A. Yocke

Introduction

Substantial improvement in recent years has been achieved in forecasting snow avalanches. However, the increase in loss of life and property damage in the United States and Canada in the last four years suggests that the avalanche problem is far from being solved. This increase is a result of the growing exposure to avalanches of man, his structures, and the lifelines of communications, energy, and transportation upon which he depends (Tesche, 1977). If avalanche hazards are to be mitigated, greater attention must be given to prudent development and use of avalanche-prone areas, improvement of avalanche control and defense technologies, and improvement of avalanche forecasting capabilities.

Most destructive avalanches occur during or within 24 hrs after a storm (Perla and Martinelli, 1976). Of the many factors thought to contribute to the formation of storm-induced avalanches, the one that apparently dominates is the rate of snow loading in the avalanche starting zone. This rate is a function of many meteorological processes, including snow crystal growth and structure, snowfall intensity, wind transport, and snow deposition. If mountain weather predictions could be tailored to the needs of avalanche forecasting, then it might be possible to provide the forecaster with an additional tool to augment his experience and judgment in evaluating avalanche hazards. The objective of this paper is to summarize a recent study (Tesche and Yocke, 1976) of the potential application of mountain weather predictive techniques to storm induced (direct-action) avalanche forecasting.

Characteristics of Mountain Windfields

The mathematical description of snow transport and deposition processes in a numerical model must account for several important features of airflow over mountains. Mountains modify the predominantly horizontal flow of air in the planetary boundary layer to produce variations in winds that significantly affect the drifting and redistribution of snow. Mountain effects on atmospheric flow may be categorized as kinematic, dynamic, and thermal-radiational (Lettau, 1967). These effects may be considered within the context of the two spatial scales of motion most relevant to avalanche forecasting--the mesoscale* and the microscale.

The influence of mountainous terrain on mesoscale atmospheric flow is significant. The kinematic effects of topography--orographic lifting and channelling--are probably the most well known. However, if the topography is rugged and of sufficient relief, complex dynamical interactions arise between the wind and the terrain (Nicholls, 1973). Examples of these interactions include the acceleration of flow through mountain passes (gapping), stagnation of flow upstream of ridges or promontories (blocking), formation of mountain lee waves during stable atmospheric conditions, and other inertial effects such as vortices and hydraulic jump airflow patterns (Orgill et al., 1971). In addition to the modification of the upper level wind by terrain features, secondary circulations are also observed due to thermal-radiational effects. Local wind flows in valleys and mountain passes are generated by spatial variations in surface albedo due to variable snow cover or vegetation and by varying slope aspects. These local wind currents further modify the upper level flow. During light wind conditions, thermally induced circulations (e.g., mountain-valley winds, slope winds) may be important near the ground. However, under the weather conditions generally associated with winter storms, (e.g., widespread cloud cover, an unstable atmosphere, and strong winds), thermal-radiative influences on the mesoscale flow are probably insignificant with respect to the dynamic effects (channelling, blocking, diverting, etc.) caused to topography.

Mountain windfields at the microscale (in the order of a few meters to a few kilometers) are more complex and hence more difficult to predict than the mesoscale windfield. The channelling, blocking, and gapping effects that occur at the mesoscale are also important at the microscale. In addition, atmospheric turbulence, which is prevalent at all scales of atmospheric motion, plays an especially important role in the transport and deposition of snow at the microscale. When strong winds encounter rugged topography, boundary layer separation occurs in the lee of ridges and peaks, leading to the formation of turbulent eddies and vortices. Turbulent eddies generated downwind from major terrain obstacles interact with each other, complicating the turbulent motion. Spatial inhomogeneities in surface roughness other than the general terrain features

---

*We confine our attention to the lower, γ subrange of mesoscale phenomena involving horizontal length scales on the order of 2.5 to 25 km (Randerson, 1976).

(e.g., variations in ground cover, tree spacing, and canopy height) generate additional mechanical turbulence, which is observed as gustiness and intermittancy in wind velocities.

In sum, complex topography modifies the speed and direction of air flow over mountains, generates standing waves and vortices and augments atmospheric turbulence. These effects have important bearing upon the extent to which snow is transported to avalanche starting zones and consolidated in dangerous slabs.

Wind variability during winter storms affects the potential for direct-action avalanching in two important ways. First, the wind direction influences the persistence with which snow is transported to a particular slide path on the mountain. Second, the wind speed influences the intensity of snow transport and drifting. Knowledge of wind direction during a storm is useful when attempting to predict which slopes are loading up with snow and possibly reaching critical levels. Some avalanche starting zones and paths tend to experience dangerous slab formation only when winds from a certain direction prevail. If the wind changes direction, other paths may experience slab formation due to wind-transported snow. Thus, knowledge of the wind direction as it varies during a storm, when accompanied by precipitation intensity measurements for the same period, can potentially be very useful to the forecaster.

Knowledge of the wind speed can be extremely important in attempting to estimate the extent of snow transport and drifting. Mellor (1965) reported that, for wind speeds from 10 to 30 m/s, the horizontal flux of snow near the ground varies as a power law function of wind speed. Although the optimal range of wind speed for snow transport depends, to an extent, upon the type of snow crystal and the nature of the terrain, Mellor (1968) suggests that wind transport of snow and slab formation can be expected for wind speeds above 7 m/s. Wind effects on slab formation are strongly developed at speeds above 12 m/s. Thus, it appears that intermittancy and gustiness of the mean wind may play an important role in snow transport and slab formation if the gusts are strong enough to transport significant amounts of snow.

The Potential Role of Numerical Modelling in Avalanche Forecasting

Avalanche forecasts are based upon a synthesis of several factors. Among these are weather information, snow conditions, and the experience of the forecaster. Of the three, experience is most important because it forms the basis from which the forecaster interprets past and present conditions and prognoses (forecasts) the likelihood of future events. Over a period of time an experienced forecaster develops a set of "decision rules", many of which are subconscious, that allow him to recognize "patterns" in weather and snow conditions. During a storm, the forecaster might classify the existing conditions based upon one of these patterns and make a forecast accordingly. In large measure, the accuracy of the forecast depends upon how well-defined weather-avalanche patterns are and how accurately the forecaster can classify a new set of circumstances (e.g., a new storm or changes in an existing storm).

Uncertainties in forecasting direct-action avalanches are largely due to:

1. Inaccuracies in relating weather phenomena to avalanche activity.

2. Limitations on the amount and accuracy of meteorological data available to the forecaster during storm periods.

There are two main reasons for the first source of uncertainty. First, it is difficult to collect field data on winter storms and avalanches sufficient for the development of reliable deterministic or statistical relationships. Second, because the relationships between weather phenomena and avalanche activity vary from region to region and even from area to area within a region, relationships developed for one area may not be applicable to another area. The second source of uncertainty in forecasting is the lack of complete, accurate meteorological data. Regardless of whether the forecaster uses models, statistical relationships, or intuition and judgment in relating weather and snow conditions to the probability of avalanche activity, he must still have data regarding storm conditions. It is in this context that numerical modelling may be of value in avalanche forecasting.

Ideally, the forecaster would have information about wind speed, wind direction, precipitation intensity, temperature, etc., for every avalanche starting zone and track in his area. In practice, however, he is fortunate to have a recording anemometer and wind vane, a remote-reading recording thermometer, and a precipitation gauge. From limited data collected at one point, he must infer, based upon his knowledge of the area, what the storm conditions are likely to be throughout his entire area.

Suppose, however, that the forecaster had models capable of estimating (1) the wind patterns and (2) the snow loading throughout the area. [For convenience, we refer to the combination of these two models as a Snow Transport and Deposition Model (STDM).] To indicate how this potential modelling capability might be used, suppose that for each hour during a storm, the forecaster could determine hourly averaged wind speeds, wind directions, precipitation intensities, and temperature at a few key locations in his area. The model could be exercised with this information to provide predictions of wind velocities over each avalanche path and the snowfall distribution throughout the area. If the wind or snowfall changed significantly during the storm, the model could be operated again, this time indicating snow transport and loading on different slopes or, perhaps, in different locations within large starting zones. Throughout the storm, cumulative records could be maintained of wind direction and snow deposition for each avalanche path. An example of this type of record, called a "snow rose", is shown in Fig. 1 for three hypothetical avalanche paths. In the Figure, the length of each component in the snow rose is a measure of the persistence of the wind in a particular direction; the shading indicates the length of time that precipitation of a particular intensity occurred while the wind was in that direction. Information such as that depicted in Fig. 1 could be used to assist the forecaster in identifying which slopes in his area (if any) might be reaching a potentially dangerous slab formation stage. Also, if the avalanche starting zone is very large, snow roses might be of value in selecting preferred locations for the placement of high explosives.

Whether or not the development of a STDM is justified depends largely upon the extent to which such a capability would be useful to the avalanche forecaster. At most ski areas, the person responsible for directing the avalanche control programme normally has several other duties or responsibilities which limit both the amount of time and the resources that can be devoted to weather analysis and snow safety. It appears that the group of forecasters most likely to benefit from a STDM would be highway departments. In view of the need to keep highways open despite winter storms, and to institute control measures when conditions become dangerous, a methodology that would enable highway avalanche forecasters to more accurately and precisely evaluate the degree of hazard, which slopes should be controlled, or which closures should be made, would be valuable. The real question, it seems, is whether a numerical model can be made sufficiently simple and easy to use that it can become a part of day-to-day operations. Below, we explore the two basic components of a STDM--a mountain wind submodel and a snow transport submodel.

Appraisal of Mountain Wind Modelling Approaches

Three general approaches are available for computing windfields in mountainous terrain: objective windfield analysis, dynamic wind modelling, and kinematic wind modelling. Objective windfield analysis involves the interpolation and extrapolation of wind velocity measurements collected at a small number of unequally spaced locations to all points throughout the region of interest. In flat terrain, this technique provides an acceptable means for estimating the windfield, providing appropriate weighting and smoothing functions can be obtained (Haltiner, 1971). But, for rugged avalanche terrain, it is virtually impossible to interpolate between, and extrapolate from, measured data with confidence unless the measurement network is exceptionally dense. This requirement is not met, to our knowledge, in any area of high avalanche hazard. Thus, the use of objective analysis for providing detailed mountain windfields during storm periods appears to have limited applicability.

Dynamic wind modelling, on the other hand, involves the computation of wind patterns, based on numerical solutions to the fundamental (primitive) equations of mass, momentum, and energy. Dynamic wind models are attractive because they explicitly embody the physics of the various atmospheric processes involved. But the practical aspects of this class of models make their utility in avalanche forecasting doubtful. The computational requirements of this type of model are very large. For day-to-day avalanche forecasting, it is unlikely that this expense is justified.

The third general approach to modelling windfields over avalanche terrain is kinematic (diagnostic) wind modelling. Rather than solving the hydrodynamic equations, the kinematic details of the flow* can be computed explicitly and the dynamical interactions can be parameterized with "forcing functions" derived for a particular area. A major advantage of this approach is its minimal computational requirements compared to the dynamic wind models ($2.00 vs. $200.00). However, explicit treatment of flow dynamics is

*By kinematic details, we refer to the conservation of mass. Interactions between pressure, friction, inertial, and Coriolis forces are parameterized.

sacrificed. Of the three approaches, a kinematic wind model appears to be best suited to the description of mountain windfields for use in avalanche forecasting because it is inexpensive and simple to operate, requires only a moderate amount of input data, and can be readily calibrated for application to a specific mountain area.

Wind Modelling Studies in Avalanche Terrain

To explore the feasibility of modelling mountain windfields for the purpose of avalanche forecasting, we performed preliminary modelling studies at the Sugar Bowl-Donner Pass area, approximately 25 km (14 miles) northwest of Lake Tahoe in the rugged California Sierra Nevadas using a two-dimensional kinematic model developed by Liu et al. (1975). The Donner Pass region normally receives unusually heavy snowfall (approximately 10.0-11.5 meters of snow per year) relative to the surrounding areas. Partly for this reason, the U.S. Forest Service maintains its Central Sierra Snow Research Laboratory in this area. The heavy snowfalls and steep mountainous terrain in this area lead to intermittent high avalanche hazard. The modelling grid selected for studying airflow patterns over the Sugar Bowl was based on a 12 × 14 grid composed of cells 500 m on a side superimposed on a 7 1/2 minute series U.S. Geological Survey topographic map as shown in Fig. 2.

Winter storms at the Sugar Bowl are typically accompanied by 10-20 m/s southwest winds observed at the Mt. Lincoln weather station. Based on the general wind features observed at Mt. Lincoln and the snow laboratory, we simulated a hypothetical southwest-wind snow storm with the kinematic wind model. Southwest winds of 13.4 m/s at Mt. Lincoln, westerly winds of 6.6 m/s at the snow laboratory, a neutrally stable atmosphere, and a uniform surface temperature distribution were assumed.

The computed windfield is given in Fig. 3. Wind directions and speeds are represented by the length and orientation of the wind vectors in the Figure. Perusal of the estimated flow field in Fig. 3 and the topography in Fig. 2 yields the following qualitative observations:

1. Flow near the boundaries of the modelling grid is clearly influenced by the boundary conditions that are used.

2. Flow is channelled up Summit Valley toward Donner Pass.

3. Flow is blocked slightly upwind of Mt. Lincoln, then diverted around the peak.

4. Flow is accelerated over the ridges southeast of Mt. Lincoln, (where extensive cornice buildup is commonly observed).

5. Flow is diverted around Crow's Nest.

Insufficient data are presently available with which to assess the accuracy of the computed windfield presented in Fig. 3. Although the windfield appears to be generally consistent with the large-scale ($\sim$1/2-1 km) flow patterns over the Sugar Bowl under southwest wind conditions, the spatial resolution of 500 m is far too coarse to provide the detailed wind information necessary for avalanche forecasting.

The above results underscore three research needs with respect to mountain wind modelling for avalanche forecasting:

1. Improved methods for specifying boundary conditions in data-sparse mountain regions.

2. Finer spatial resolution of the surface and upper level windfield.

3. Representation of three-dimensional wind flow over complex terrain.

A promising approach toward resolving the first two problems is to employ nested diagnostic models. For example, a mesoscale model could provide the general flow pattern to a spatial resolution of approximately 1-5 km, and a fine-grid model with much finer resolution (say 50-100 m) would be applied to a smaller area of interest. This would permit a finer approximation to the wind flow over individual avalanche starting zones and tracks while still enabling a description of the general windfield over a larger area. Secondly, nesting the models reduces the influence of uncertainties in boundary conditions on the specific areas of interest by removing these areas from the boundaries of the overall modelling region.

The third research need is by far the most complicated. Over smooth or gently rolling terrain, where vertical velocities are small, a two-dimensional wind model may often be quite useful. However, in avalanche terrain, mountain slopes between 30°-60° are common; consequently, vertical wind velocities are significant. Thus it appears that a three-dimensional model is required for estimating flow over very rugged topography. Currently, efforts are underway to develop a three-dimensional diagnostic wind model for application in complex terrain (Liu et al., 1977). Should this model (or any other) prove successful, it could then serve as the basis for developing the snow transport model.

Snow Transport Model

In recent years, a number of numerical models have been developed to describe the processes governing the fate of solid precipitation during winter storms (MBA, 1976). Generally speaking, these models have been (1) confined to mesoscale applications and (2) focussed either on the treatment of wind flow over an idealized mountain (the transport problem), or the rate of formation of snow crystals in the atmosphere (the microphysics problem). To our knowledge, modelling of snow erosion, transport and deposition in mountainous terrain on spatial scales of 2.5-25 km has not been attempted.

To simulate the rate of snow loading in avalanche starting zones and tracks, it is necessary to (1) predict the mountain windfield, and (2) describe the formation and fate of snow crystals over complex topography during winter storms. The primary goal of this paper has been to investigate various aspects of the first need. Considering the second need, a model capable of simulating the transport and redistribution of snow over complex terrain must describe several complex physical processes, i.e., the microphysics of snow crystal formation, and the mechanics of turbulent suspension and diffusion, sublimation, snow deposition, and snow erosion. The interested reader is referred to Tesche and Yocke (1976) for a more complete discussion of these processes and how they might be represented in a numerical transport model.

Assessment of the Feasibility of Modelling Snow Transport and Deposition

Can a snow transport and deposition model actually be developed in view of the extremely complex nature of winter storms, precipitation processes, and atmospheric turbulence over avalanche terrain? Clearly, a detailed treatment of boundary layer turbulence and transport processes over complex terrain would be very difficult to achieve (if it could be done at all) and a sophisticated model of this sort is well beyond the scope of the forecasters' needs.

However, to estimate the general flow and deposition patterns of snow by means of a model does appear to be feasible if one is willing to parameterize certain physical processes (snow formation, sublimation, and flow separation, etc.).

Assuming that it is possible to mathematically model the general features of mountain winds and snow transport, is there sufficient observational data with which to verify and subsequently operate the model? Ideally the data base for model validation would include:

1. Surface and upper level wind velocities at several prominent locations.

2. Precipitation intensities at several locations including the slopes and starting zones.

3. Surface temperatures and atmospheric mixing depths.

4. Concurrent records of avalanche activity and weather data.

To our knowledge, such a data base does not currently exist although portions of the wind and transport models might be tested with available data (Armstrong et al., 1974; Judson and Erickson, 1973).

Conclusions

In this paper, we have considered whether numerical models for predicting mountain winds and snow transport can be developed and applied to avalanche hazard forecasting. Attention has been confined to direct-action avalanches because they are primarily weather-induced and are the most frequent type of avalanche in the coastal and inter-mountain ranges. Because the snow loading rate appears to be the single most important factor in direct-action avalanching, it follows that an improved understanding of the factors affecting this rate in avalanche starting zones and paths could result in an improved capability for forecasting avalanche hazards. To develop a mathematical model for describing snow loading rates, it is essential that the general airflow patterns over rugged avalanche terrain be predicted since local surface wind speeds and directions are intrinsic to the description of snow erosion, transport, and deposition. Although it appears feasible to develop a highly parameterized snow transport and deposition model, consideration must be given to the extent to which such a model, if developed, can be made suitable for routine use in avalanche forecasting.

References

Armstrong, R.L. et al. 1974. Development of methodology for evaluation and prediction of avalanche hazard in the San Juan Mountain area of southwestern Colorado. Final report INSTAAR-14-06-7155-3. 141 p.

Haltiner, G.J. 1971. Numerical weather prediction. John Wiley and Sons, Inc., New York, N.Y. 317 p.

Judson, A., and Erickson, E.J. 1973. Predicting avalanche intensity from weather data: A statistical analysis. U.S. Forest Service Research Paper, RM-112, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo. 12 p.

Lettau, H.H. 1967. Small to large-scale features of boundary layer structure over mountain slopes. Proc. Symp. on Mountain Meteorology, Fort Collins, Colorado, eds. E.R. Reiter and J.L. Rasmussen. pp. 1-74.

Liu, M.K., Mundkur, P., and Yocke, M.A. 1975. Assessment of the feasibility of modelling windfields relevant to the spread of brush fires. Systems Applications, Inc., San Rafael, Calif. 142 p.

Liu, M.K., Yocke, M.A., and Tesche, T.W. 1977. Modeling wind distributions over complex terrain. Systems Applications, Inc., Interim Report to Environmental Monitoring and Support Laboratory, Environmental Protection Agency. 44 p.

MB Associates. 1976. Weather modification design study for stream flow augmentation in northern Sierra Nevada. Volume I--Meteorology and hydrology of the northern Sierra Nevada. Report No. MB-R-76/65A. 151 p.

Mellor, M. 1968. Avalanches. Cold Regions Science and Engineering, part III: Engineering, Section A3: Snow technology. U.S. Army Material Command, Cold Regions Research and Engineering Laboratory, Hanover, New Hamp. 213 p.

Mellor, M. 1965. Blowing snow. Cold Regions Science and Engineering, part III: Engineering, Section A3c. U.S. Army Material Command, Cold Regions Research and Engineering Laboratory, Hanover, New Hamp. 79 p.

Nicholls, J.M. 1973. The airflow over mountains, research 1958-1972. World Meteorological Org. Tech. Note No. 127, WMO-No. 355, Geneva, Switzerland. 73 p.

Orgill, M.M., Cermak, J.E., and Grant, L.O. 1971. Laboratory simulation and field estimates of atmospheric transport-dispersion over mountainous terrain. Report CER70-71MMO-JEC-LOG40, Fluid Dynamics and Diffusion Laboratory, Col. of Engineering, Colorado State Univ., Fort Collins, Colo. 302 p.

Perla, R.I. and Martinelli, M. Jr. 1976. Avalanche Handbook. U.S. Dept. Agric., Agric. Handbk. 489. 238 p.

Randerson, D. 1976. Overview of regional-scale numerical models. Bull. Am. Met. Soc., 57, pp. 797-804.

Tesche, T.W. 1977. Avalanche zoning: current status, obstacles and future needs. Proceedings 45th Annual Western Snow Conference, Albuquerque, New Mexico, April 18-21, 1977. 10 p.

Tesche, T.W. and Yocke, M.A. 1976. Application of numerical wind models to snow avalanche forecasting: theoretical considerations and preliminary investigations. Systems Applications, Incorporated, San Rafael, California. Report SAI ES76-100. 42 p.

Discussion

GEISLER: It seems that the most useful information on wind transport comes from visual observations of drift patterns made by an observer on the spot.

TESCHE: Visual observations are important for day-to-day operations in a limited area. However, most of us would agree that wind instrumentation and analysis of wind records are needed to supplement the visual observations.

PERLA: What inputs are required for your model?

TESCHE: A few well-placed anemometers--3 or 4 if possible--located on the upper ridges and in the lower parts of the mountain are needed. In addition, the precipitation intensity over the area must be known.

BURR: Do you have any suggestions for reliable wind instrumentation?

TESCHE: Because we are primarily concerned with winds during storm periods, the riming problem must be solved before a reliable wind sensing system is obtained.

LANG: Now that you have a wind velocity model, are you planning to add precipitation transport?

TESCHE: First, we have to validate the mountain wind model for winter storm conditions. This appears to be a very challenging problem. If this can be done, we could then turn our attention to the development of a precipitation transport and deposition model.

LANG: Three-dimensional codes are expensive to run on computers. Will costs limit the practicality of your model?

TESCHE: Three-dimensional dynamic models are expensive. However, we are experimenting with kinematic models which, if perfected, may provide a sufficiently good approximation to the mountain windfield to be of use to forecasters. Of course, the computer costs are an important consideration. Our computational costs with the present wind model vary from $2-$5 per run.

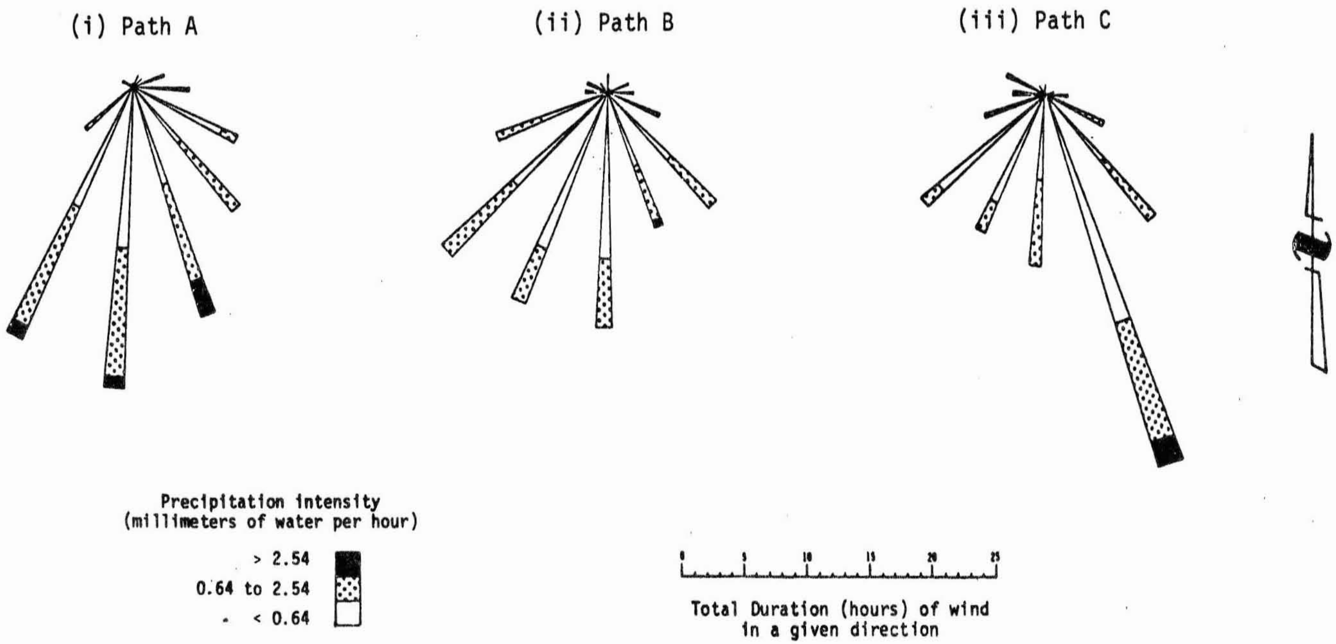

FIGURE 1 HYPOTHETICAL OUTPUT FROM A SNOW TRANSPORT AND DEPOSITION MODEL APPLIED TO THREE AVALANCHE PATHS DURING A STORM

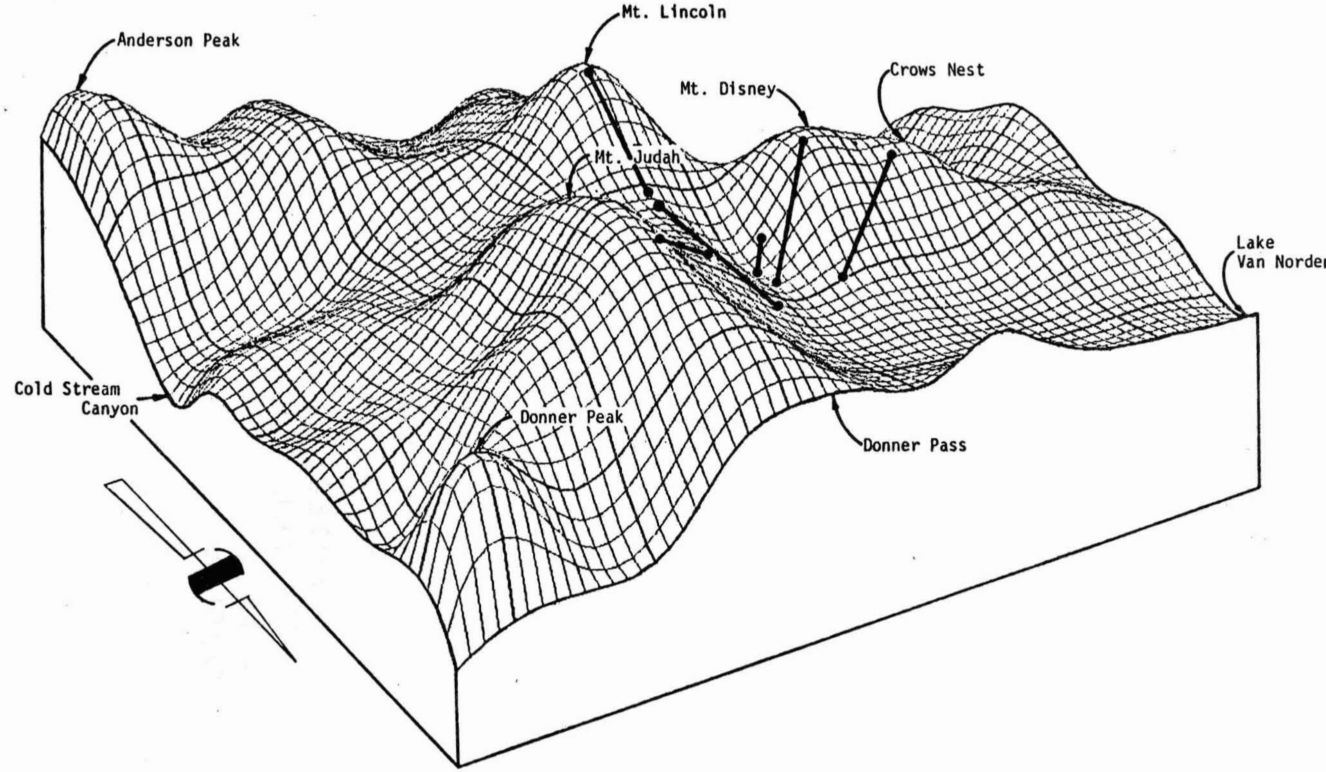

FIGURE 2 THREE-DIMENSIONAL REPRESENTATION OF THE COMPLEX TERRAIN SURROUNDING THE SUGAR BOWL SKI AREA. (VERTICAL COORDINATE NOT TO SCALE; SOLID LINES INDICATE CHAIR LIFTS)

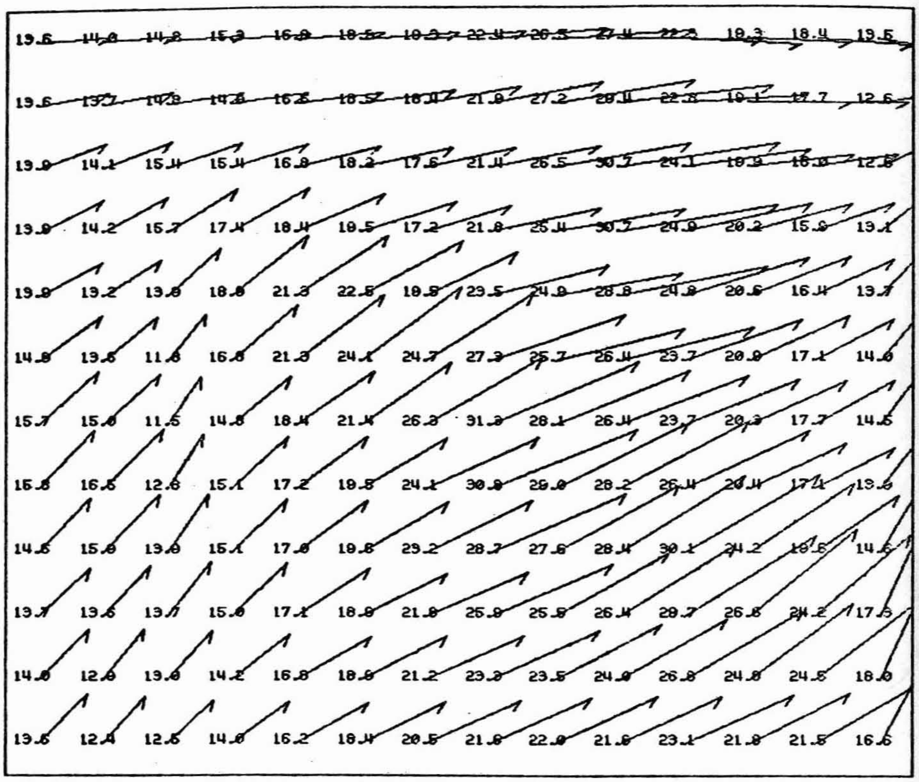

FIGURE 3 COMPUTED WINDFIELD IN (METERS/SEC) OVER THE SUGAR BOWL SKI AREA DURING A 13.4 m/s SOUTHWEST STORM AS OBSERVED AT THE TOP OF MT. LINCOLN