WEATHER AND AVALANCHE FORECASTING: WHERE DO WE STAND?

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Introduction

Forecasting avalanches requires synthesis of weather and snowpack factors selected from a bewildering array of inputs to solve the day's avalanche forecast problem. In the U.S.A. the forecaster must either have direct access to National Weather Service (NWS) products or be in contact with a meteorologist who can provide weather information. In Canada, the Atmospheric Environment Service provides all weather services.

Forecast programs can be conveniently categorized in three groups. First, is the small scale program concerned with an area on the order of 10 km^2. Most ski areas fall into this group. Second, is the medium scale program of 10^2-10^3 km^2. Examples include the Alta-Snowbird-Little Cottonwood Canyon area of Utah and the Trans-Canada Highway in British Columbia. Third, is the large-scale program of 10^4-10^5 km^2 employing central avalanche forecasting. Examples include the warning programs in Colorado, Washington-Oregon, and Alaska. One contrast in these programs is that the smaller the scale of the program, the more specific the forecast. The ski area programs forecast for groups of avalanche paths, whereas statewide programs forecast for entire mountain ranges. Regardless of scale, the forecasters must work with the same inputs.

Formal avalanche forecasting in the United States began in the early 1950's with avalanche control programs at Alta, Utah; Berthoud Pass, Colorado; and Stevens Pass, Washington. At that time, forecasting was (as it still is) by pattern recognition, based more on empirical discoveries than on application of theory. One early outgrowth was Atwater's contributory factors to avalanche formation (Atwater, 1968). Not unexpectedly, many of Atwater's factors were meteorological.

The first large-scale avalanche forecasting project began in 1973 when the USDA Forest Service (FS) established the Colorado Avalanche Warning Program (Williams, 1978). In 1978, the FS formally assumed responsibility for the Northwest Avalanche Forecast Program, which had been run for several years under the direction of the University of Washington (LaChapelle et al., 1978). Two new programs, one in Utah and one in Alaska, will begin in 1980. These programs are based on a 1974 Memorandum of Understanding between the FS and the NWS delineating the responsibilities of the two agencies. The FS supplies and trains the avalanche forecasters, while the NWS supplies the weather information and dissemination network. The avalanche forecasters all have meteorology schooling and/or extensive field experience.

Three Avalanche Forecast Problems

Williams (1980) identified three avalanche forecast situations: direct action, delayed action, and wet snow avalanches. Direct action slides occur during or just after storms and are induced by the accumulation of fresh snow. Forecasting direct action slides is dependent primarily on forecasts of precipitation and strong winds. Delayed action slides occur during fair weather between storms and are induced by structural weaknesses in the snowpack. Weather data are of little help in forecasting delayed slides because the critical level of stress causing these slides is unaffected by short-term weather trends, with such exceptions as large rises in temperature or heavy winds. Wet snow slides occur during rain storms or thaw periods. Forecasts of wet snow slides are based on forecasts of temperatures, freezing levels, and precipitation amounts, especially rain.

Contributory Meteorological Factors

This section includes some generalizations about the important meteorological factors and considerations for avalanche formation.

1. Local climatology. Climate is average weather. A forecaster should have access to long-term weather records or a summary of these for his area (e.g., Hansen, Chronic, and Matelock, 1978). Storm climatology is especially useful. With many years of record, the forecaster can learn that storms approaching from a given direction will have similar air mass properties and can lead to similar results. Storm-typing has been done for many parts of the United States and Canada and can be a valuable forecast aid. Examples taken from Colorado climatology show that

(a) storms approaching from the northwest usually hit the Front Range and other northern mountain ranges hardest; (b) southwest storms are warmer and hit the San Juan Mountains hardest; (c) surface low pressure passing along the southern border often leads to major precipitation on the eastern slope of the Rockies; and (d) surface low pressure passing along the northern border can produce strong downslope winds along the eastern slope.

2. Effects of terrain. Mountains greatly alter the free air wind flow. They change wind directions and accelerate or slow down wind speeds, creating scour and deposition zones. The forecaster must learn the typical loading pattern, and then be able to recognize a weather system that could produce atypical loading and, thus, unusual avalanching. Terrain also affects snowfall patterns. As wind direction varies, so will precipitation.

3. Precipitation. Amount, intensity and duration of snowfall (or rainfall) are collectively the prime architects of avalanche formation. Thus, the forecaster must have the tools to make consistently good quantitative precipitation forecasts (QPFs). One method of doing this is discussed later in this paper.

4. Wind. If precipitation is the main factor in avalanche formation, then wind speed and direction are the "follow-up" ingredients, for wind helps produce slab. Most storms have ample wind to create soft slab conditions, so it is difficult to separate the individual contributions made by snowfall and wind. Occasionally winds can be strong enough to cause problems when no precipitation is falling. A later section of this paper will include a discussion of strong wind forecasting.

5. Temperature. Temperature has a profound influence on every aspect of snow and avalanches, but this influence often cannot be observed or measured. Consider that temperature determines the type of snow crystal that forms, determines whether precipitation falls as snow or rain, influences the amount of precipitation, drives the metamorphic processes in the snowpack, and causes the snowpack to fractionally expand or contract, leading to stress changes.

Research has revealed few firm answers about the influence of temperature, leaving ample room for conjecture. Strong temperature changes appear to be more important than absolute temperature values in creating instability. When the snowpack is already critically stressed, a large temperature change in a few hours can increase stress in the topmost layers and lead to failure. Thus, temperature change can be viewed as the ultimate trigger when large stress values already exist from other processes. There is little doubt, though, of the effect of a rapid warm-up that leads to thaw. The stress/strength contest gets its most critical test with the first major thaw of spring or after a heavy snowfall.

To predict stability problems caused by temperature changes, the forecaster has had to rely on experience and intuition. Perhaps in the near future a numeric model such as the one being worked on by Judson, Leaf, and Brink (1980) will be an objective aid, but until such time, the forecaster must be content with NWS maps or other products that hint at large temperature changes (e.g., frontal passages).

6. Humidity. High humidity allows blowing snow grains to travel farther before sublimating and may lead to easier slabbing. Humidity data from a study plot could help the forecaster in his decision making, although it would carry secondary importance. Humidity (moisture) is also an input to QPFs.

7. Radiation. This form of energy exchange can cause important metamorphic and stability changes in the snowpack. Virtually no radiation data are recorded at study plots in the United States because of limited applicability. Armstrong and Ives (1976) state that for forecasting wet avalanches, radiation data provide no additional utility over air temperature.

National Weather Service Products

The forecaster uses snow study plot and ridge top wind data to get current and recent field weather readings. But making a forecast requires NWS products. Therefore, the forecaster must have access to the maps or to NWS personnel.

The NWS produces surface maps every three hours and upper air maps every 12 hours (0400 and 1600 hours, Pacific Standard Time). Data from balloons, satellites, surface stations, ships, buoys, and aircraft go into producing these maps. Standard map levels are 850 mb (approximately 1500 m), 700 mb (3000 m), 500 mb (5500 m), 400 mb (7200 m), 300 mb (9200 m), and 200 mb (11,800 m). Additionally, forecast maps (progs) are available out to 96 hours. These are generated by several computer models. The Limited-area Fine Mesh (LFM) model is the one that performs best, all things considered. There are longer range forecasts but these have marginal accuracy and are of no value to the avalanche forecaster: the "3-5 day extended forecast" is a little better than climatology, and the "6-10 day outlook" is no better than climatology.

There are dozens of other products available, but only a few are highlighted here:

1. Satellite pictures. These are available every 30 minutes as visible pictures by day and infrared imagery by night. They help forecasters determine the onset and duration of precipitation, movement of fronts and mountain wave development. They give cloud-top temperature but do not give cloud depths.

2. Radiosonde (balloon) data. The forecaster has access to any sounding in the United States for data in between the standard map levels (850, 700 mb, etc.). The soundings provide temperature, moisture, and wind data. The forecaster uses these data to determine freezing levels, inversions, stability, and as input to orographic precipitation models.

3. Teletype transmissions. A wide variety of data are available via several teletype circuits. Perhaps the most useful are local and regional forecasts and hourly surface data from a dense network of observation sites.

4. Model output statistics (MOS). Climatology and the LFM model output are combined to provide the MOS products (Klein, 1978). These are more commonly referred to as FOUS (Forecast Output United States). FOUS are transmitted by teletype except for max-min temperatures and probability of precipitation (PoP), which are maps. Potential temperature, moisture, wind in the boundary layer and at 850 mb, and 1,000 to 500 mb thickness are important predictors. FOUS 43, 72, and 50 trajectory are useful in forecasting freezing levels (LaChapelle et al., 1978).

5. Radar imagery. Radar can see precipitation as it is occurring and can provide data on intensity and movement.

Precipitation Forecasting

Convection, fronts, and large, upper level cyclones produce all of the precipitation on the plains. In the mountains, forced orographic lifting produces much of the precipitation, which explains why the windward sides of mountain ranges are the wettest places on earth. Because mountains affect weather in complex ways, sometimes to the point of creating their own weather, forecasting mountain precipitation is indeed a difficult task. In addition, the LFM model poorly forecasts weather in the mountains of the western United States and Canada. There are two main reasons for this. First, because western North America lies near the western edge of the LFM model grid, there are few upwind data points to be used as model input. Second, because the LFM model assumes a topography that is much smoother than reality, the true influence of the terrain is missing from the numerical model. Overall, the LFM model overforecasts precipitation in the west. This, in turn, leads to poor (and generally too high) precipitation forecasts from the MOS data.

The skilled forecaster uses experience and memory to adjust the model outputs and arrive at a more accurate forecast. The forecaster uses knowledge of storm climatology and terrain to evaluate field data, upstream radiosonde data, satellite pictures, weather radar, and the most recent surface map. Moisture, vorticity, jet stream, thicknesses, vertical motion, and surface and upper air features are the synoptic factors used to make his forecast by conventional methods.

Rhea (1978) has developed a numerical model as an objective aid for QPFs in the Colorado Rockies. As discussed by Williams (1978), the avalanche forecasters in Colorado have used this orographic snowfall model with good results for several years. For the winter of 1979-80, Armstrong (1980) found that the mean water equivalent forecast error was 5.6 mm with a standard deviation of 5.8 mm, and that 60% of the forecasts were correct to within ±6.4 mm (0.25 in.).

The reference level for using the model in Colorado is 700 mb. If such a model were developed for other areas, the reference level would change. For example, 750 mb may be the best level for the Sierra Nevada and 850 mb for the Cascades. The forecaster picks anticipated values of wind direction, wind speed, and temperature at the reference level. These are the important factors for all mountain QPFs. Direction is important because the more perpendicular the wind flow to the mountain range, the greater the lift. Speed is important because stronger winds will produce greater amounts of condensate. Temperature is important for two reasons. First, warmer air has more ability to hold moisture than colder air; second, the growth mechanisms of snow crystals are dependent on temperature. A 700 mb temperature near 0^0 C is most efficient in the Colorado Rockies. Chappell (1970) found that a 500 mb temperature of -20^0 C corresponds to the maximum precipitation rate in Colorado. Bailey (1973) found that in the Sierra the 500 mb temperature corresponding to the maximum precipitation rate varies from -11^0 to -20^0 C depending on storm type.

Moisture is a critical input to the orographic model. When lifted, a deep layer of moist air will produce more precipitation than a shallow layer. The forecaster uses as input the thickness of the atmosphere (in mb) in which the temperature-dewpoint spread is within 5^0 C. This corresponds roughly to 65% relative humidity (or higher) and represents an air layer that will become saturated when lifted. The duration of this moist flow is the final input.

The orographic snowfall model offers the forecaster an excellent objective aid, but its output should be used only as guidance. The forecaster should be prepared to alter the model output, based on his experience with certain types of storms.

Strong Wind Forecasting

Accurate wind forecasts have benefits beyond avalanche forecasting. Two examples are closing a highway because of poor visibility, or closing a chair lift because of high winds.

The main guide for forecasting wind is the gradient flow on the 850, 700, and 500 mb analyses and progs. The forecaster should predict gusts at least 50% over average mountain-top speeds. MOS tends to underestimate winds stronger than 11 m/s (Klein, 1978). Mountain terrain can deflect and channel wind around a mountain, through a pass, or up or down a valley so that the resultant wind has no resemblence to the free air flow. The forecaster's experience is the only recourse in these situations.

The strongest mountain winds result from waves. A mountain wave can cause an acceleration and dowward transport of momentum. As explained by Scheetz, Henz, and Maddox (1976), the prediction technique relies on forecasting a mid-tropospheric (600-400 mb) inversion or stable layer accompanied by moderate to strong gradient winds perpendicular to the mountains. The mountain barrier initiates the wave, which tries to flow upward but strikes the impenetrable stable layer. This bounces the wave downward, increasing its amplitude. Damaging winds can result. Sites directly downwind from a higher mountain range are most susceptible to these severe winds.

The forecaster looks for a large vorticity change at 500 mb, either positive or negative, moving toward the mountains. If this is accompanied by strong flow at 850, 700 and/or 500 mb (and often a strong surface pressure gradient), strong downslope winds should be forecast. One other synoptic clue can be used: surface low pressure passing north of the forecast area is likely to produce considerable wind and little precipitation. LaChapelle et al., (1978) offer additional techniques for wind forecasting in the Cascades.

Freezing Level Forecasting

Avalanches on the West Coast are more influenced by fluctuations in the freezing level than are avalanches in the Rocky Mountains. Forecasters on the West Coast must always be alert for a warm front passage which raises the freezing level, changes snow to rain, and destabilizes the snowpack. LaChapelle et al., (1978) provide some forecasting guidelines for the Cascades. They use all available field data plus the following NWS products: FOUS 43, FOUS 72, FOUS 50 trajectory, and LFM 1000-500 mb thickness progs, 850 mb analysis, radiosonde data, and ship reports of surface temperatures.

Conclusions

This paper has included a discussion of the current status of weather and avalanche forecasting and a brief description of applicable NWS products. State-of-the-art techniques on three critical forecast problems were included: precipitation, strong wind, and freezing levels. The paper is not intended as a comprehensive treatise on weather forecasting. Rather it is a guide to information sources that forecasters need for daily decision making. Whether responsible for a ski area, mountain highway, or a vast mountain range, the forecaster is a skilled technician who must combine weather and snowpack information into an avalanche forecast. The forecaster's weather skills include the ability to grasp and diagnose a weather situation and project it into a picture of tomorrow's weather.

The ideal situation is to have direct access to (1) field data and (2) weather service products. The forecaster can then pore over the information, make a forecast, and still get second opinions from other forecasters. But many forecasters do not have direct access to both data sources. The ski area forecaster, for example, has plenty of field data but only indirect NWS data. Such forecasters should develop the skill to communicate with a weather office forecaster (i.e., to ask the right questions and to interpret the data received) and develop a good working relationship with Weather Service personnel.

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Discussion

Hamre:

If the LFM model doesn't work really well in Western Canada and Washington, is there any reason to believe that an orographic precipitation model would work better?

Williams:

Yes, because if you have the ability to alter the LFM output to improve your forecast, based on experience and storm climatology, then you can alter the inputs that an orographic model would need. An orographic model gives you a second opinion, very good guidance on what range of precipitation to expect. In spite of poor LFM performance, I think there is hope.

Hamre:

Secondly, I would like to take exception to your statement that radiation can be excluded and air temperature might be sufficient. I think as you move into more northerly latitudes, radiation becomes a bigger factor. I don't personally feel that air temperature alone is sufficient for wet slab prediction.

Williams:

I have no quarrel with that. In Colorado, we have not yet found a use for radiation data.

Reynolds:

LFM underpredicts precipitation in Alaska for the big storm events. Also the MOS products are new in Alaska being initiated by the new spectual model.