WEATHER AND SNOW OBSERVATIONS FOR AVALANCHE FORCASTING:
AN EVALUATION OF ERRORS IN MEASUREMENT AND INTERPRETATION

R.T. Marriott and M.B. Moore

Abstract.—Measurements of weather and snow parameters for snow stability forecasting may frequently contain false or misleading information. Such errors can be attributed primarily to poor selection of the measuring sites and to inconsistent response of the sensors to changing weather conditions. These problems are examined in detail and some remedies are suggested.

INTRODUCTION

A basic premise of snow stability analysis for avalanche forecasting is that point measurements of snow and weather conditions over a large area. Due to the complexity of this process in the mountain environment, this "extrapolation" of data has largely been accomplished subjectively by an individual experienced with the area in question. This experience was usually gained by visiting the areas of concern, during many differing types of conditions, allowing a qualitative correlation between the measured point data and variations in the snow and weather conditions over the area.

In many instances today, the forecast area has expanded, largely due to increased public use of avalanche-prone terrain (e.g. increased backcountry skiing in developed areas, large use areas for helicopter skiing operations, or a regional avalanche forecasting center). The ultimate effect of this expanded area of concern is less direct contact with conditions by forecasters. This has resulted in greater reliance on both data gathered by instruments and on the extrapolation of these data based on physical principles rather than direct subjective experience.

In this paper, several basic problems associated with this increased dependence on instrument measurement and its interpretation are examined. Specifically, errors in the measurement of precipitation, wind, and air temperature introduced by sensor site selection are considered, as well as, limitations on the sensors' responses to the environment. Errors introduced by poor equipment maintenance, line noise, and calibration problems, although frequently serious, will not be considered.

Sources of Error

Errors which arise in instrumented snow and weather measurements can be broken into two, if somewhat overlapping, parts: those associated with the representativeness of the site where the measurements are to be taken, and those associated with the response of the instrument to its environment.

The first source of error is associated with the site chosen for measurements. The topography of mountains results in dramatic variations in conditions over short distances and often times these variations are not easily predictable. For example, temperature, which may often be extrapolated to other elevations using approximate lapse rates, may on some occasions be complicated by inversions generated by mesoscale or synoptic scale weather conditions, undetectable from a valley site. Thus measurements must be taken at a site or sites that provide information that is unambiguous regardless of the weather conditions or they must be taken at enough sites that sufficient information is available to sort out any ambiguities that might exist.

The second source of error is caused by the wide variation in sensors available to measure each parameter. Each type of sensor has a different type of response to the same environmental conditions which can result in markedly differing readings at the same location. Often times instruments are chosen without consideration of their differing traits, resulting in frustration and/or confusion in interpreting the data.

Finally, all of the above is further complicated by the fact that each of the major weather parameters (precipitation, wind, and temperature) must be combined to provide meaningful information on snowpack stability. As the best site for one type of measurement may not be the best for another, this results in the merging of data from several different areas and environments. Thus
errors introduced by either poor or unrepresentative site selection or instrument peculiarities can be additive, further confusing snow stability analysis. This further emphasizes the importance of knowledgeable selection of both measuring sites and instruments.

**PRECIPITATION**

**Site Selection**

The primary information desired from precipitation data are the amount and rate of loading of the snowpack and the density of new snow. It is well accepted that the areal variation of these quantities is affected by the interaction of wind with the topography. On the small scale (e.g., meters to kilometers) this is by wind scouring and deposition of snow and associated crystal breakage, while on the large scale (kilometers to thousands of kilometers) it is caused primarily by topographically forced lifting and altitudinal effects on temperature.

Concerns with these effects depend on the size of the forecasting area. For an area the size of most developed ski operations (<10km²) this only requires consideration of the immediate terrain around the sampling site. On this scale, the assumption can be made that an approximately equal amount of precipitation falls over the area, but is subsequently redistributed by wind interacting with the terrain. Determination of snow loading for a specific avalanche starting zone requires establishing a proportionality between the amounts received at a sensor site and that at the site in question. This proportion will be affected by winds at the starting zones, which may bear little resemblance to the winds at the measuring site (see below). Thus in order to be accurate under all conditions, measurements should be made at a site which is sufficiently protected to receive snow independent of wind speed or direction. The ideal site is usually protected by a combination of topographic features and local vegetation. Although it is possible to use data from less suitable sites, this requires estimating the magnitude of the effects of the wind at the measuring site and adds more uncertainty to the data.

If the area of concern is greater than 10²-3km², variations due to orographically induced lifting must be considered in selecting measuring sites. Many general variations in precipitation can be estimated from climatological information (fig. 1) and/or simple orographic precipitation models. However, often, mesoscale effects of topography on the synoptic scale air flow may produce mesoscale effects which become very sensitive to small changes in the synoptic scale wind patterns undetectable by current measurements.

An example of this is shown in figure 2, which shows the differences in precipitation between Paradise at 2599m (on the south side of Mt. Rainier) and Crystal Mountain located at 2079m about 8km to the northwest. Synoptic scale winds
interacting with Mt. Rainier and the Cascade Crest strongly affect the mesoscale effects of rainshadowing and convergence in the area around Mt. Rainier. As can be seen from figure 2, there is little correlation between the measured synoptic scale winds (taken at the radiosonde station near Quillayute, Washington) and precipitation differences between the two stations. This shows that measurements of synoptic scale winds are too infrequent and too sparse to infer the location and magnitude of this type of effects. Detection of this type of mesoscale effect which is sensitive to synoptic scale winds can only be found by using a "dense" grid of stations or potentially through the use of realistic orographic precipitation models (Speers-Hayes 1984).

Sensor Errors

In snow stability analysis, precipitation data is largely used to give an indication of the amount and rate of loading of avalanche starting zones. Historically, this has been accomplished by using a snowboard: measuring the depth of new snow, taking a snow core from the board, and subsequently weighing or melting the sample to obtain the water equivalent. Increasingly, snowboard measurements have been supplemented or replaced by recording precipitation instruments, almost exclusively measuring water equivalent. A general review of the types of sensors in current use and their operation is given in Marriott and Moore (1984).

Figure 2.—Comparison of daily (12UT and 00UT) 850-mb free air wind direction and speed from Quillayute, Washington versus daily precipitation differences between Paradise (Mt Rainier) and Crystal Mountain, Washington. Winds are plotted 0-360 degrees and rounded to the nearest 5 m/sec, and water equivalents (□) indicate Paradise minus Crystal Mt. data.
All of the current methods of water equivalent measurement are subject to errors under certain conditions. In some instances these errors can be detected and allowed for; however, this is often not the case, unless information from more than one type of sensor is available from the site.

**Gauge Sensors**

The most widely used sensors for water equivalent measurements are gauge type devices. However, these sensors suffer from a number of inherent problems including missed catch (blowover), capping (for unheated gauges) and evaporation (for heated gauges).

**Missed Catch.--**Wind effects on precipitation measuring sites can introduce serious errors, and this is particularly true if the measurements are being taken using a gauge type device. Work by Larson and Peck (1974) and Goodison (1978) have shown that wind effects can introduce substantial errors in gauge measurements. The magnitude of the error is related to three factors: wind speed, wind speed vertical profile, and the obstruction to the air flow presented by the gauge. Figure 3 prepared by Larson and Peck (1974) displays the catch deficiency compared to snowboard measurements as a function of wind speed. This shows that even moderate winds at a measuring site can cause substantial errors in gauge measurements. However, figure 3 and additional work by Goodison (1977) have shown that good site selection and proper shielding can reduce or eliminate errors in the measurement due to missed catch. It is possible to develop a correction factor for the lost catch (Larson and Peck 1974); however, this requires information on wind conditions during precipitation, complicating data extraction while still producing questionable data.

**Gauge Capping.--** Often during sustained moderate to heavy snowfalls, unheated gauges will accumulate snow along the rim of the collection cylinder, especially for orifices of 30cm or less. As this accumulation grows, the effective orifice size decreases, reducing the measured precipitation, sometimes to zero when complete capping occurs. Additionally, following a capping episode, warming temperatures usually result in the eventual melting of the accumulated snow into the gauge, often resulting in an overestimate of the current precipitation amounts or indicating the occurrence of precipitation when none is occurring.

Figure 4 shows the typical results of measurements taken at the same location from both a heated and an unheated precipitation gauge during January 1984. The unheated gauge successfully measured light snowfall on the 20th (confirmed by snowboard measurements). However, increasing snowfall at cold temperatures on the 21st thru the 23rd capped the orifice of the unheated gauge stopping almost all indication of precipitation during that time, although 7 to 9 cm of water equivalent were indicated by the heated gauge and the snowboard. On the 24th, warming temperatures accompanied by rain caused the snowcap to melt causing an overestimate of the precipitation on the 24th. Obviously, any snow stability analysis prepared using the unheated gauge would be in serious error. This type of error can make unheated gauges virtually useless for measurements of moderate to heavy snowfalls at temperatures below freezing.

**Evaporation.--** As can be seen in figure 4 on the 20th and 26th and 27th, the unheated gauge indicated more precipitation than the heated gauge. This effect can be attributed to evaporation within the heated gauge. The magnitude of this effect has not yet been quantified, however, the effects appear to be largest for dry snow at low snowfall rates, especially with propane heated precipitation gauges.

Almost all heated precipitation gauges use tipping bucket mechanisms, which require that the snow must first melt and then drop into a movable bucket inside the heated gauge. This can result in evaporation at the external melting surface and, to a greater extent, within the gauge itself.

At low snowfall rates, the accumulating liquid is exposed to the internal environment of the gauge for a relatively long period of time. As the gauge is heated above the ambient air temperature, resulting humidities inside the gauge are low. For example, an ambient air temperature of -10°C and 100% relative humidity will result in an internal relative humidity of 23% if the internal temperature is kept at +10°C. Thus the environment inside of the gauge is quite dry and can lead to substantial evaporation. In the case of dry continental type snowfalls, the outside relative humidities can be well below 100% resulting in even drier conditions and more evaporation.

This effect is seen in figure 5 which shows the difference between an electrically heated precipitation gauge and snowboard water equivalents.
Figure 4.—Comparison of daily (24-hr) precipitation totals for Stevens Pass, Washington, during February, 1984. Water equivalent data are derived from electrically heated tipping bucket precipitation gauge (□) and unheated precipitation storage gauge (±) measurements.

Although Stevens Pass has a strongly maritime climate, it is obvious that at low precipitation rates, the heated precipitation gauge reads routinely lower than the snowboard. Although these differences may not always be significant, at unmanned locations, where these errors can be cumulative, this can lead to serious mistakes in judging snowpack stability.

The evaporation problem is particularly acute for gauges heated by propane as opposed to electricity. In electrically heated gauges a thermostat is usually provided allowing a certain internal temperature to be maintained independent of the cooling by the external environment. Thus a low temperature can be selected (5-10°C) minimizing the evaporation. In the case of most propane gauges on the market today, a set rise in temperature over the ambient temperature must be selected as the amount of heat delivered to the gauge is constant regardless of external changes. This requires that a large enough rise over ambient be selected to keep the gauge from dropping below freezing at low temperatures or capping over at high precipitation rates, while still not being so warm as to cause large amounts of evaporation at low precipitation rates. This necessary compromise normally results in a loss of accuracy at both extremes.

Snow Pillows

The only non-gauge type water equivalent sensor in use on a wide scale is the snow pillow. This device essentially measures the weight of the overlying snowpack which is then converted directly to the water content of the snowpack. Taking the difference between successive readings can then give information on the water equivalent of precipitation falling on the surface of the snowpack. Although these devices have proven successful for hydrological purposes (Bartee 1978), the snow pillow suffers from several inherent problems which may yield inaccurate or misleading measurements (Beaumont 1965) and limits their resolution especially for short term changes (i.e. one day or less).
Table 5.--Comparison of daily water equivalent amounts between 24-hr snow board (O) and electrically heated tipping bucket precipitation gauge (+) measurements at Stevens Pass, Washington, during February, 1984.

<table>
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<th>Date</th>
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<th>Snow Pillow (cm)</th>
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Figure 5.--Comparison of daily water equivalent amounts between 24-hr snow board (O) and electrically heated tipping bucket precipitation gauge (+) measurements at Stevens Pass, Washington, during February, 1984.

The interpretation of the snow pillow data would be easier if it measured consistently greater or less than the snow board, however, due to the differing sources of error it can vary either way. In deep snowpacks, the response time of snow pillows to heavy snowfalls can be slow, ranging from 5 hours to as much as 10 days (Tarble 1968). Warming or cooling of the snowpack may result in erroneous indications of increasing or decreasing water content, respectively. Formation of crusts and ice lenses within the snowpack may result in bridging of the pillow, giving erroneously low values of water equivalent. In addition, in shallow snowpacks diurnal variations in the temperature of the snow pillow itself may give erroneous values.

The net effect of these combined errors is to limit the accuracy of short term changes measured by a snow pillow. Thus, although they may be used to estimate the magnitude of precipitation events, even this use is difficult unless information on local temperature changes and/or other independent indications of precipitation are available. Despite their lack of short term reliability, the snow pillow's widespread distribution throughout the mountains for hydrological purposes makes them a useful source of information on precipitation, but information that can only be used to substantiate information from other types of nearby precipitation sensors.

Summary

Thus selection of representative sites for precipitation measurement depends partly on the size of the area of concern and partly on the complexity of that area. In all events, the site should be protected from wind effects either by the local topography, vegetation, and/or artificial shielding so that the precipitation measured at the site is independent of local wind speed or direction. In addition, for larger forecast areas, a sufficient number of sites must be measured to detect mesoscale variations in orographically induced precipitation caused by effects such as channelling or convergence.
Additionally, all of the available methods of measuring water equivalent produce significant errors under certain conditions. Realistically, most measurement sites suffer from some type of deficiency which may cause these errors to become manifest. The practical solution to this appears to be the use of one or more types of sensors at a site. This may not be simply another precipitation sensor, but perhaps information on temperature or wind. With several pieces of information, it may become possible to recognize and correct errors when they occur.

WIND

In snow stability forecasting, wind information is primarily important for estimating the degree and nature of snow deposition over the topography of concern. Synoptic scale free air winds interacting with the mountain topography create a large variety of local winds depending on the orientation of the free air wind to the terrain. However, this problem is often further complicated by winds driven by mesoscale pressure differences across a mountain range, small scale channeling effects, and/or drainage winds.

Site Selection

Selection of sites for wind measurement requires evaluating the potential effects of all of the above winds on the avalanche starting zones of interest. The main consideration in choosing a location(s) for measuring winds is finding a site which gives wind information from which starting zone winds may be inferred.

For small scale forecasting concerns (<10km²) this often means locating the wind system close to the main starting zones minimizing the amount of inference necessary. This is particularly effective for areas whose starting zones are at approximately the same elevation with the same aspect. A wind system which gives accurate results for directions which would tend to load these slopes is usually sufficient. However, for areas with a variety of starting zone elevations and aspects, it is necessary to choose a site which is likely to give a reasonable estimate of the local free air wind speed and direction. Adding local topography to this information then allows estimating the winds for any aspect, but not necessarily any elevation (see below). A site which could satisfy this criteria would be an isolated, symmetrical peak. More often wind sites are located

Figure 6.—Comparison of daily water equivalent amounts between 24-hr snow board (□) and 24-hr snow pillow (+) data at Stevens Pass, Washington, during February, 1984.
on ridgelines or on peaks located along ridgelines which then provide a varying response depending on wind direction. This type of variation can be roughly accounted for, except in the extreme case where the ridgeline or a local obstacle blocks wind from certain directions. In some cases this may require more than one measuring location.

Small scale wind channeling, drainage winds, or winds within inversions may produce dramatic variations in winds at different elevations not derivable from measurements at any single elevations. Figure 7 illustrates the types of variation that can occur in a complex wind-terrain situation. In this example, winds at Denny Mountain (1696m), Stampede Pass (1204m), and Snoqualmie Pass (1158m) are shown. Snoqualmie Pass and Stampede Pass are located about 1.5 km and 8 km southeast of Denny Mountain, respectively. The dramatic differences between winds measured at the three sites is obvious, both in directions and speeds. Importantly, notice that there is little consistency in the differences between the stations. Thus significant variations in winds which may be loading avalanche stating zones are not easily inferable from the measurements taken at any one of these sites. Although this is an extreme case, it emphasizes the potential for major differences in the winds which are loading starting zones in a relatively small area.

For snow stability analysis for larger scale areas (>10^1-3 km^2) of concern, it is necessary to measure winds which are representative of the largest area possible. Since local effects have such a strong influence on measured winds, site selection becomes critical. This usually requires placing the wind site at a location which measures the mesoscale free air winds. Although this often requires sacrificing important information on local effects, it is required by the need to apply the information to areas beyond the immediate vicinity of the wind site. In this case, it is usually necessary to infer significant local effects from experiential knowledge of local behavior (when available) with a commensurate increase in possible errors.

Sensor Errors

Although a variety of wind sensors are commercially available (Marriott and Moore 1984), the most commonly used are variations on the cup anemometer and wind vane or the single unit “bird” which uses a plane-like body with a propeller and a tail. The only serious problem with wind sensors themselves occurs during periods of rime formation. In light rime situations heat lamp deriming has shown some effectiveness, however, moderate to heavy rime deposition on the sensors, inhibiting their motions, and producing false readings. Rime deposition can be overcome by heating the sensors or, in some cases, by locating the sensors at a relatively rime free site.

AIR TEMPERATURE

Air temperature measurements supply significant information to snow stability forecasters, allowing judgements to be made about such things as: the likely types and rates of metamorphism in the snowpack, crystal types and densities of snowfalls, surface melt and crust formation, and occurrence of rainfall, etc., all of which relate intimately to the strength of the snowpack.

Site Selection

Although temperatures in the mountains are largely controlled by a combination of free air freezing levels and diurnal variations, these factors are sometimes overpowered by more localized effects such as terrain induced inversions. Temperature variations caused by topographic effects may act on the scale of a few meters and be of only minor significance or, in some cases, may operate on the scale of hundreds of kilometers.

A single air temperature sensor does not provide sufficient temperature data for either local or regional snow stability analysis, particularly in the case of inversions. Inversions of 10°C to 20°C between the top and bottom of a ski area are not unusual, and in some instances, may be maintained for days. A single measurement taken at
Figure 7.--Comparison of hourly wind speed and direction data from three different elevations in the Washington Cascades. Data are derived from wind sensors at Snoqualmie Pass (1158m, □), Stampede Pass (1204m, +) and Denny Mountain (1696m, ◊), December 30, 1983.
either the top or the bottom of the area could be misleading, however, measurements at both can show the existence and the magnitude of the inversion. Measurements at intermediate levels may be of interest when the top of the inversion lies within the elevation range of the forecast area, as this will help to locate the top of the inversion, which is often a relatively, sharp boundary and can lead to rapid localized temperature variations.

Inversions are especially important for temperatures near freezing as variations in temperature in this range can have strong and immediate effects on snowpack stability. However, even at temperatures well below freezing inversions may have significant effects on snowpack metamorphism and the formation of surface hoar.

For snow stability forecasting for areas on the scale of less than about 10km², temperatures should be measured near the elevation of the starting zones of concern as a minimum, or in the case of starting zones at multiple elevations, temperatures should be taken both at the highest and lowest elevations. Temperature measurements at additional elevations will improve the vertical resolution of temperature but are probably only essential in areas where inversions at intermediate levels may exist for extended periods.

Long lasting inversions (hours to days) can have a significant effect on the timing of warming induced avalanches. Figure 8 illustrates the complexity that can result within a single ski area. The time variation of temperature sensors located at 914m, 1341m, and 1646m in the Alpental ski area are shown. Initially, a relatively normal lapse rate exists with temperatures cooling with increasing elevation. At about 1300 PST, warming at higher elevations produces an inversion somewhere between the stations at 1341m and 1646m, although, a normal lapse rate continues to exist between the two lower sensors. Around 2100 PST the sensor at 1341m begins to warm as the top of the inversion gradually lowers. Finally around 0100-0200 PST, the inversion drops completely below the middle sensor, while a normal lapse rate develops between the two upper sensors. In this example it is obvious that one or even two temperature sensors in this situation could result in an erroneous impression of the temperatures in the area and consequently could lead to a poor estimate of avalanche stability, if temperature sensors were not located near the elevation of the starting zones. Thus for stability analysis, the vertical temperature resolution required will depend on the distribution of

![Figure 8](image.png)

Figure 8.--Hourly air temperature at three elevations—914m (□), 1204m (+), and 1646m (○)—at Alpental ski area near Snoqualmie Pass, Washington, December 29-30, 1983.
avalanche starting zones with elevation and to some extent on the longevity of inversions in the area, which may be controlled by local or regional topography.

On the scale of about 10^1-3 km^2, smaller scale inversion effects such as valleys or basin are usually ignored with temperatures from the tops of peak or ridges and from balloon soundings being more representative of the temperature near most major starting zones. However, additional measurements may be necessary in situations where geographical conditions produce inversions over wide areas. In this case additional measurements on carefully selected ridges and in valleys can give important information on the depth and trends of this cold air which may affect snow stability.

Sensor Errors

Numerous types of temperature sensors are in current use (Marriott and Moore 1984), although the most popular recording temperature sensor continues to be the thermistor. The single biggest contributor to errors in air temperature measurements, aside from poor line maintenance, is lack of shielding from heat and radiation sources. Locating sensors close to heated buildings or in direct sunlight without proper shielding produces errors in measurement which change during the day as the temperature inside the building or the sun exposure changes, making observations difficult to interpret and correct. Positioning of sensors on trees or towers a substantial distance from any heat sources and the use of simple double walled radiation shields for the probe can eliminate most measurement errors.

In some poorly placed or exposed sites, it is possible that the temperature sensors may become rimed or encrusted in ice or snow. This ordinarily results in a slower response to temperature changes, and in the case of temperatures fluctuating around freezing, the sensors will continue to read 0°C until all of the ice or snow melts from the sensor. Locating the sensor at a site reasonably protected from direct wind should minimize or eliminate the problem.

Summary

Selection of temperature sensor location depends both on the scale of the area under consideration and on the complexity of the associated terrain. Snow stability analysis for a small area (10 km^2) may be accomplished with a single temperature sensor if inversions tend to be weak or short lived. However, if inversions are strong and persistent, it may be necessary to measure the temperature near the elevation of all major groups of starting zones to obtain sufficient vertical temperature resolution.

For larger scale areas of concern (10^1-3 km^2), sensors should be located on ridges or at sites unaffected by local temperature effects such as drainage winds or trapped cold air, allowing extrapolation of the information over a wide area. When geographical conditions can produce regional inversions, however, it is desirable to obtain measurements from several elevations to determine the depth and trend of the inversion.

CONCLUSIONS

Assuming proper sensor maintenance and calibration and a reliable telemetry and data recording system, errors in measurement and interpretation of precipitation, wind, and temperature quantities arise from two primary sources: 1) improper or inadequate site selection(s) for the measurements and 2) inconsistent response of sensors to varying weather conditions. Although these deficiencies have always existed, increasing reliance on instrumentation, especially at remote, unmanned sites has made recognition and, where possible, correction of the problems more imperative. Although the optimal situation for snow stability analysis remains a combination of sensors and direct human observation, where this is not possible or impractical, sensors can provide useful information, provided a suitable combination of proper sensors and sites and appropriate site density are achieved for the intended forecast area.

In those instances where sensor data alone must be relied upon, the best solution appears to be a number of measuring sites with several types of sensors at each site. This type of input often helps to resolve potential ambiguities produced by individual sites or sensors. The use of multiple sensors, gathering information on the same parameter or on several different parameters (e.g. precipitation and temperature) at each site can elucidate effects which are artifacts of the sensors. Similarly an increase in the number of measuring sites can overcome deficiencies at individual sites and provide information on mesoscale weather features.

Practically, the optimal data system for snow stability analysis and forecasting varies markedly from area to area, depending on the scale of the operation and upon the peculiarities, both meteorological and topographical, of the specific area. Although basic considerations outlined in this paper can aid in initial site and sensor selections, experience with an area and a data system are necessary to produce an optimal system.

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