THE RELATIONSHIP BETWEEN SYNOPTIC WEATHER PATTERNS AND SNOWPACK STABILITY IN A HIGH-LATITUDE MARITIME SNOW CLIMATE

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ABSTRACT

Weather is considered to be the architect of avalanche formation. Understanding its effects on snowpack properties is an important tool in avalanche forecasting. This study investigated regional synoptic weather patterns and their correlation to near-surface faceted crystal formation and snowpack stability in a high-latitude maritime snow climate. Regional synoptic variables were classified from charts published by the National Weather Service into three types 1) on-shore, 2) off-shore, and 3) split flow. Synoptic patterns were compared to plot scale meteorology and snowpack measurements collected at two study plots located at 700 m and 720m above sea level near Juneau, Alaska. Here we report on three episodes in January and February of 2004 in which vapor pressure gradients measured in the upper 25 cm of the snowpack were in excess of 45 mb m^{-1}. During all three periods, faceted crystals 1-2 mm in diameter formed near the surface of the snowpack. In one case, wet grains comprising a low density crust at the surface of the snowpack metamorphosed into a weak layer of faceted crystals. Snowpack stability measurements following all three episodes revealed near-surface instabilities and avalanche cycles were observed after each of the events. Analysis of synoptic charts showed a correlation between synoptic weather events and the formation of near-surface faceted crystals. The results of this research are being used to improve avalanche forecasting in Juneau and are applicable to other high-latitude maritime snow climates.

INTRODUCTION

Snow avalanches are a major hazard, endangering human life and infrastructure in mountainous areas throughout the world. Predicting avalanche events is difficult and reliable warning systems rely, at best, on probability occurrences of weather and snowpack interactions with localized terrain (Schweizer et al., 2003). Understanding the complex interactions between large-scale atmospheric circulation and topography is an important prerequisite for snow avalanche forecasting (Burak and Davis, 2001). In addition, understanding the relationship between synoptic weather patterns and snow crystal metamorphism within the stratographic composition of mountain snow covers can further aid in avalanche forecasting.

The development of layers with low shear strength in the snowpack is a primary cause of the release of slab avalanches (McClung and Schaerer, 1999). Past studies have shown that faceted snow crystals can develop rapidly in low density snow subject to high temperature gradients, and that these poorly bonded crystals are a common weak layer associated with avalanche release, particularly in continental snow climates (Gray and Male, 1981: McClung and Schaerer, 1999). While much past research has focused on faceted crystal weak layer growth in the basal layers of the snow pack, recent attention has been given to the role of faceted grains that form in the near-surface layers of the snowpack (Birkeland, 1998; Scheler et al., 2003). These near-surface faceted (NSF) crystals have been shown to contribute to weak layer formation and snowpack instabilities in a wide range of snow climates (Fukuzawa and Akitaya, 1993; Birkeland, 1998; Hardy et al., 2001; Hood et al., in press).

Near-surface crystals are formed under conditions with strong vapor pressure gradients near the snow surface. Birkeland (1998) delineated three processes that can result in the formation of NSF crystals: *radiation recrystallization, melt-layer recrystallization,* and *diurnal recrystallization.* Each of these processes is dependent on a specific balance of either diurnal temperature cycling or solar radiative inputs at the snow surface (Colbeck, 1989). As a result, the formation of NSF crystals is intimately tied to the snow surface energy balance. Previous research in snow hydrology has shown that the synoptic weather patterns are useful for predicting shifts in the snowpack energy balance (Cline, 1997). Thus we hypothesize that there is a link between synoptic weather patterns and the conditions that lead to the formation NSF crystals near the snow surface.

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The purpose of this study is to investigate storm categories and the direct correlation with avalanche activity associated with near-surface faceted crystal growth within a defined study area. Identification of these categories can further aid avalanche forecasting in the Juneau Area where avalanches commonly affect populous areas.

METHODS AND SITE DESCRIPTION

Juneau Climatology

Juneau is situated on the northwest coast of the Gulf of Alaska in a high-latitude maritime climate. Immediately to the northeast of Juneau lies the Coastal mountain range and Juneau ice field, a source area for continental polar/artic air masses during the winter season. During winter, onshore flow typically brings warm, moist air and can result in rainfall at elevations up to 1500 m. In contrast, northerly air flows are a result of cold and dry air spilling over the coastal mountains. When the northerly pattern collapses, warm moist maritime air moves back over southeast Alaska where it can be forced aloft by established cold air that is blocked against the Coastal Mountains. This transition may last for several days and is responsible for very heavy snowfalls occurring at sea-level (Colman, 1986).

In this study, we categorized Juneau's synoptic weather patterns into three categories: 1) Onshore (coastal) flow, 2) Offshore (northerly) flow, and 3) Split flow (Figure 1). Weather charts collected from the National Weather Service and weather data collected from the Eaglecrest Ski Area study plot and the Fish Creek Knob study plot were analyzed over the winter season (2003-04). Meteorological conditions during the study period were grouped into the categories mentioned above.

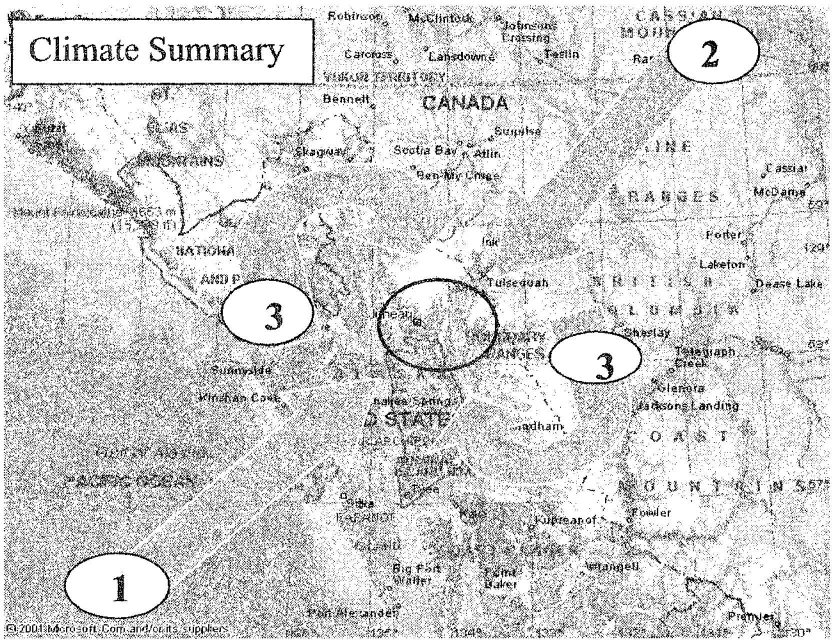

Figure 1. Synoptic weather pattern classifications: 1) Onshore: Typically resulting from S/SE maritime air flows, 2) Offshore: Typically resulting from N/NE artic air flows, 3) Spilt-flow: Typically resulting from a transition period between 1&2.

Study Area

This study was conducted at two sites on Douglas Island located 8 km southwest of Juneau, Alaska: 1) Eaglecrest Ski area and 2) Ben Stewart Backcountry area (Figure 2).

Eaglecrest Ski area is comprised of 640 acres of north/northeasterly facing terrain. A large part of the inbound terrain is avalanche prone and an aggressive avalanche control program is maintained to deal with new snow instabilities. The top of the highest lift is located at 780 m above sea level and provides access to the Eaglecrest snow study plot located on an undisturbed flat bench just south of the top of the ski lift. Information collected at this site included: height of snow, new snow accumulation during storms, near-surface temperature gradients, wind speed and direction, storm categories, and avalanche activity with in the ski area boundaries.

Ben Stewart Backcountry area is comprised of roughly 1280 acres of backcountry terrain located just north of the Eaglecrest ski area. The close location and ease of access from the ski area makes this area popular with backcountry users. Located within the Ben Stewart study area was the Fish Creek Knob Study Site. This site was located at 700 meters above sea level on a flat, open bench just below tree line. A meteorological tower at the site monitored wind speed and direction, temperature, relative humidity, and net radiation. Additionally, a sonic snow depth sensor allowed observation of real time snow accumulation during storms.

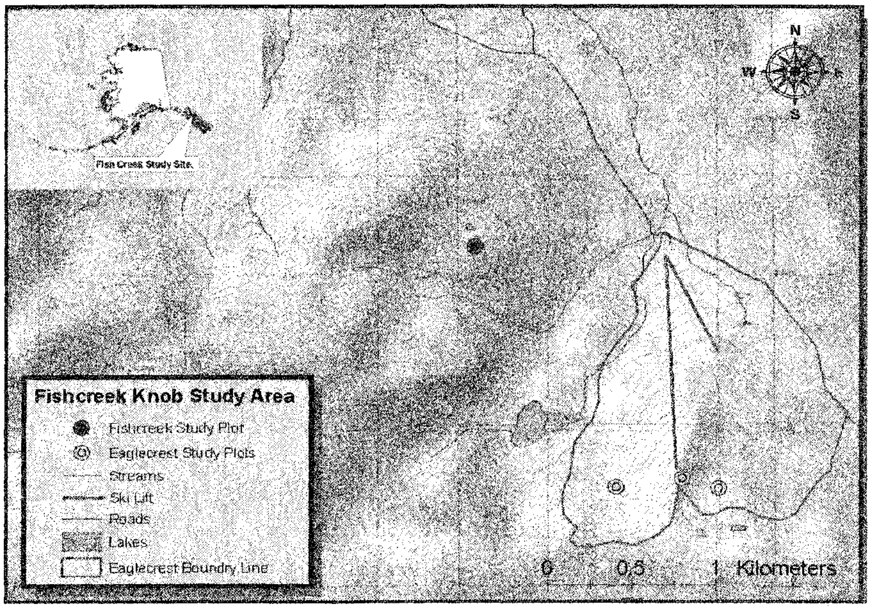

Figure 2. Study area on Douglas Island near Juneau, Alaska.

Snowpack Measurements

Stability ratio: A stability ratio was derived during each new storm cycle using a shear frame test. The shear frame test uses a frame placed just above a weak layer that is pulled with a gauge, which records the maximum force. The shear strength is calculated by dividing the maximum force by the area of the frame. Each shear frame test was conducted at least five times to ensure shear results were accurately reproducible. The equipment used for the shear frame test included a 100cm^2 shear frame, 2kg and 5kg Imada pull gauges, digital and mechanical weigh scales, two sampling tubes and a large putty knife. Shear frame test results were used to calculate a stability ratio that can be used to formulate stability indices for the triggering of avalanches (naturally or artificially). Snow stability is a ratio of strength to stress on a weak layer or interface. The shear frame measures strength. The weight of the snow above the layer being tested measures stress. A dimensionless stability ratio is then calculated as shear strength divided by the weight of snow per unit area (Observation Guidelines and Recording Standard, 2002).

Snow temperature gradients: Near-surface temperature gradients in the snowpack were measured using a 30cm temperature probe consisting of a thermocouple array mounted in white PVC pipe. Holes were drilled in a spiraling line around each probe every 5cm. A high accuracy thermocouple protruded from each hole. The remaining void space inside the probe was filled with insulation foam. The spiraling array around the temperature probe was designed to minimize interference between thermocouples. The probes were inserted into the snow pack with the bottom sensor flush with the snow surface and the remaining sensors were left exposed to collect natural snow deposition. Once buried, the probes sensors recorded temperature gradients in the top 30 cm of the new snow. Upon complete burial the probes were reset so the first sensor was again flush with the surface of the new snow and ready for the next storm cycle. Two temperature probes were deployed, one at Eaglecrest study plot and the other at Fish Creek Knob study site. At both sites, the position of the probe relative to the snow surface was carefully monitored throughout the study period.

Snowpit observations: The Fish Creek Study Site was visited at least weekly, and the Eaglecrest site was visited on a daily basis during normal operation. Pits were dug at both plots in close proximity to the temperature probes. In each pit, snow stratigraphy including grain size and type was recorded following the international standards. A series of standard field stability tests to identify weak layers within the snowpack were also performed at the study plots and within the general study areas. Additionally, avalanches within the Eaglecrest area that were either released naturally or by explosives were documented. Backcountry avalanches were also closely monitored and fracture profiles were investigated when ever possible.

RESULTS AND DISCUSSION

Synoptic Weather Patterns and Snowpack Stability

Snowpack stability ratios and synoptic weather patterns were analyzed from December 26th 2003 through March 26th 2004. During this period, it was observed that synoptic weather patterns preconditioned avalanche conditions as measured by the stability ratio (Figure 3). Changes in snowpack stability were often associated with shifts in the synoptic weather regime. In particular, the shift from an offshore continental regime (weather pattern 2) to a split flow regime (weather pattern 3) was associated with several dramatic decreases in the snowpack stability ratio. It was also observed that during periods when synoptic weather pattern stayed constant, the snowpack stability ratio would increase with time (Figure 3).

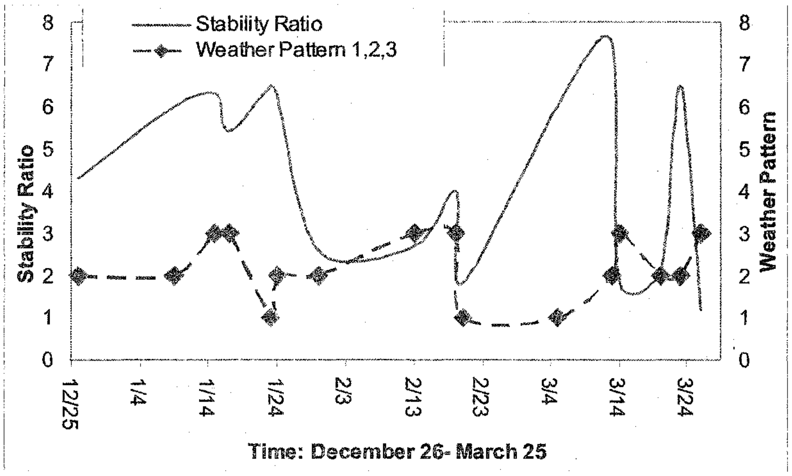

Figure 3. Stability ratios compared to synoptic weather patterns as observed from December 26- March 25. Lower stability ratio values indicate greater instability. Weather patters are defined by 1, 2, and 3 as described previously and are represented on the right axis.

Synoptic Weather Patterns and NSF Crystal Formation

Here we report on three synoptic events during the winter of 2004 during which near-surface temperature gradients in the snowpack exceeded 150°C m^{-1}. These large temperature gradients resulted in the growth of well-developed near-surface faceted crystals and were responsible for widespread snowpack instabilities.

Event 1- January 14-27, 2004

The first event was characterized initially by a split flow weather pattern that was present around January 14th and resulted in 25 cm of snowfall. This was followed by onshore flow which brought wet weather and above-freezing temperatures. On or around January 23rd a strong offshore flow brought an extended period of cold, clear, and windy conditions. Both study sites recorded temperatures that were consistently below -15° C and no new snow was recorded during this period. Additionally, blowing snow was observed in both study areas.

The onset of the offshore weather pattern chilled the relatively-warm snowpack, creating a cold wave that quickly penetrated the near-surface of the snowpack (<15cm). Snowpack temperature profiles recorded by the probe located at the Eaglecrest study plot recorded extreme temperature gradients within the snowpack surface, with a maximum value of -160° C m^{-1} on January 24 (Figure 4a). As time progressed, the temperature gradients decreased as the cold wave penetrated deeper into the snowpack causing temperatures to become more uniform through the snowcover surface. Vapor pressure gradients calculated for this time period showed gradients in excess of -40 mb m^{-1} with the largest gradients occurring initially at the onset of the cold event (Figure 4b). Vapor pressure gradients in the 0-15 cm layer of the snow pack were 2-6 times the threshold of -5 mb m^{-1} commonly associated with faceted crystal growth and large facets were observed. As the snowpack cooled larger temperature gradients were required to maintain the vapor pressure gradients necessary to form NSF crystals (Figure 4b), and overall vapor movement decreased as the snowpack become colder. Typically, temperature gradients are known to be strongest in the immediately below the snow surface (Birkeland et al., 1998; Fukuzawa and Akitaya, 1993). This was demonstrated here with the largest gradients recorded 5 cm below the snow surface.

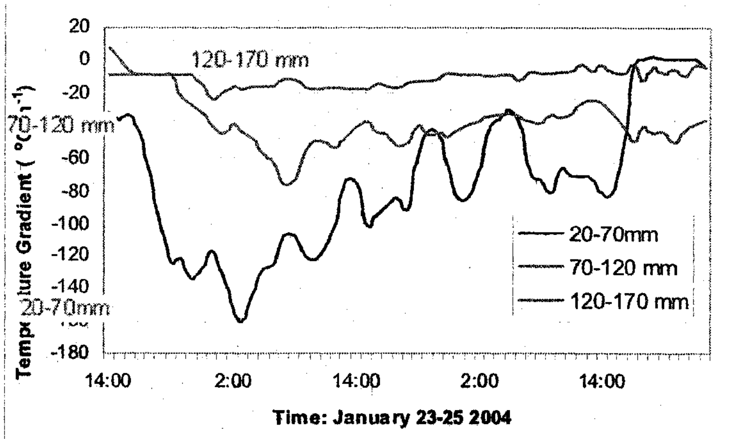

Figure 4a. Event 1: Temperature gradients as observed at the Eaglecrest study plot, January 23-25.

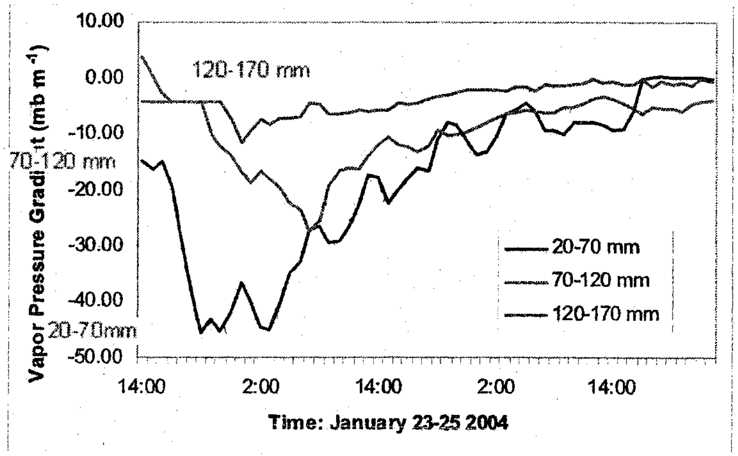

Figure 4b. Event 1: Calculated vapor pressure gradients as observed at the Eaglecrest study plot, January 23-25.

Field observation during and following this event documented the growth of large NSF up to 3 mm in diameter in the upper layers of the snowpack (<20cm). On January 27th a large avalanche cycle occurred in both study areas that consisted of a stiff wind slab over faceted crystals. This demonstrated that instabilities were associated with the newly formed facets in the upper layers of the snowpack. Furthermore, weather patterns leading up to the avalanche cycle were consistent with the development of NSF crystals, and the instability resulting from these crystals was reflected in the stability ratio tests performed at the Eaglecrest study site.

Event 2- December 20, 2003- February 19, 2004

The second event was characterized by the development of a weak layer during a period of cold offshore flow in mid-December. The weak layer formed during this event did not become reactive until early February. On December 17th, onshore flow caused the surface of the 120-160 cm deep snowpack to warm substantially. Air temperatures at Eaglecrest during this time often above freezing while snow profiles from both sites on December

20th revealed large wet grains 2-3 mm in diameter in the upper layers (<30cm) of the snowpack. This warming pattern was then followed by persistent cold, clear weather (-2°C to -11°C) beginning on the 24th of December which froze the surface of the snowpack. As the cold weather continued over the next few days, field observations showed large 2-3 mm faceted crystals forming near the surface of the existing wet grain layer. By December 28th , a profile in the Ben Stewart backcountry area showed that the frozen wet grain layer consisted of very large 3-4 mm faceted crystals now buried 20cm below the surface. This layer was of some concern as a possible weak layer, however no avalanche cycle occurred and by January 15th the now deeply buried layer became less of a concern, but remained suspect as a possible sliding layer.

On February 29th a fracture profile was done within the Ben Stewart study area on a large avalanche that had been naturally triggered by a section of falling cornice approximately 7-10 days before. The cornice release was caused by a sudden change in weather patterns; a split flow pattern that deposited 20-30 cm of new snow and was quickly replaced by a strong onshore flow that brought warm temperatures. Additionally during this time, stability ratios decreased drastically and an avalanche cycle occurred on or around February 19th (Figure 3). The fracture profile revealed the sliding layer to be 5 cm of faceted crystals 1-3 mm in diameter buried 92 cm below the surface of the snow. On further investigation the layer was identified as the melt-freeze layer that was formed during the December freeze.

While the process that initially formed the faceted layer in this event is somewhat similar to melt-layer recrystallization, we believe that the formation of this weak layer occurred by a different mechanism than that described by Birkeland (1998). Melt-layer recrystallization is a process in which a melt-layer is formed by either solar radiation or rain, followed by a new snow event. The colder new snow that accumulates over the warmer wet snow results in strong temperature gradients at the interface. This process is further enhanced when the new snow layer is thin, has a low density and is subject to clear, cold weather (Birkeland, 1998).

In comparison, the faceted weak layer formed in the December event developed not in new snow but in the upper portion of an existing layer of wet-grain crystals that had a relatively low density (~250 kg/m^3). We hypothesize that the latent heat released during the freezing of the wet grain layer set up a strong near-surface temperature gradient. In this scenario the faceted layer and the frozen wet grain layer beneath it would have formed at the same time similar to the process by which faceted crystals form above crusts (Colbeck and Jamieson, 2001). However, since the development of this faceted layer occurred before the deployment of the temperature probes we can only speculate about mechanisms and further research is needed to accurately describe this near-surface faceting process.

Event 3- February 24-27, 2004

The third event can be characterized by a generally colder and dryer onshore weather pattern with large diurnal temperature fluctuations during the increasing daylight hours. Temperature gradients in the snowpack showed a diurnal shift with temperatures decreasing toward the snow surface during night time hours and increasing toward the snow surface during the day (Figure 5a). During this time, the diurnal fluctuations caused temperature gradients in the top 20cm of the snowpack to be in excess of 50° C m^{-1} and vapor pressure gradients to exceed 15 mb m^{-1} (Figure 5b). Subsequent to this event, a snow profile dug at the Eaglecrest study plot showed NSF 1-2 mm near the surface (0-2cm) and 10 cm down from the surface of the snow. Following this cold spell a storm on or around the 27th deposited 30 cm of snow and a small avalanche cycle occurred where a backcountry skier was involved. Stability ratios derived during this time fluctuated widely and did not accurately reflect instability with in the upper 40cm of the snowpack.

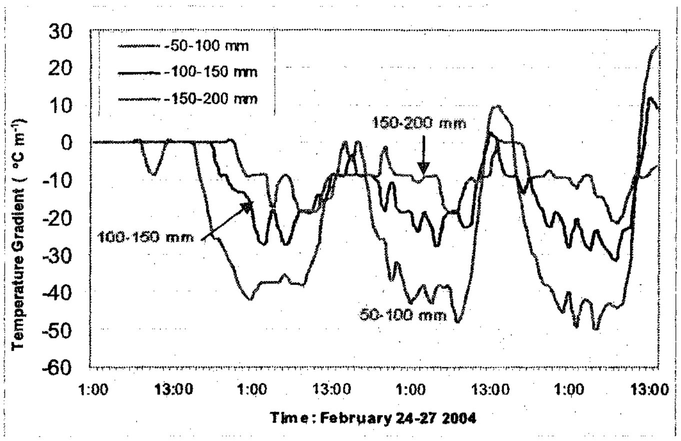

Figure 5a. Event 3: Temperature gradients as observed at the Fish Creek Knob study plot, February 24-27.

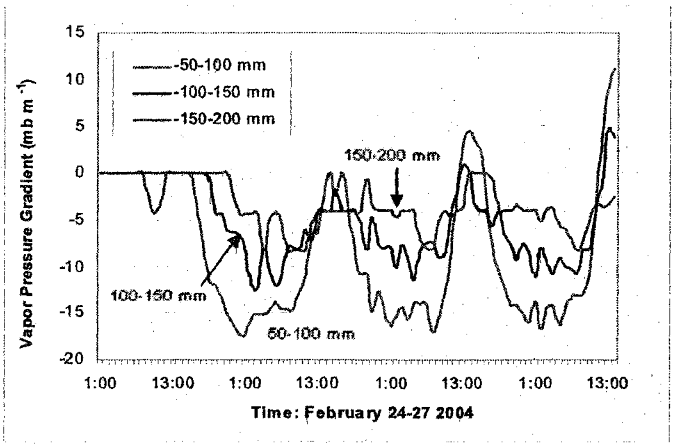

Figure 5b. Event 3: Calculated vapor pressure gradients as observed at the Fish Creek Knob study plot, February 24-27.

The strong diurnal fluctuation in surface temperature in conjunction with relatively constant temperatures below 20 cm resulted in a strong temperature gradient near the snow surface. Again the strongest gradients were recorded in the upper 5cm of the snowpack where NSF crystals were observed. While temperature gradients were only about half the values described by Birkeland et al (1998), a strong enough gradient existed to promote the growth of faceted crystals in upper (0-10 cm) layers of the snowpack. Once buried the NSF crystals became a weak layer upon which new snow was deposited. This process has been well documented in many mountain ranges and is clearly an important process for weak layer formation in high-latitude maritime snow climates.

CONCLUSIONS

The research described here examined the effectiveness of monitoring synoptic weather patterns in relationship to the growth of near-surface faceted crystal weak layer formation in the maritime snowpack of Southeast Alaska. Previous studies performed within the study area showed that temperature probes were an effective way to monitor snowpack temperature gradients resulting in near-surface faceted crystal growth. During this study, temperature probes observed snowpack temperature gradients in excess of -160° C m^{-1} that resulted in the rapid growth of NSF crystals 1-3 mm in the upper layers of the snowpack. These NSF crystals contributed to three separate avalanche cycles. Additionally, stability ratios were calculated to establish a stability index for near-surface snow layers and were later compared to weather patterns. A correlation was found between the sequence of synoptic weather patterns and snow stability as measured by a snow stability index. Large avalanche cycles were associated with either clear, cold conditions resulting in strong temperature gradients resulted in NSF crystal growth or large, wet precipitation events that loaded weak near-surface layers. Furthermore, wet-grain faceting was found to be a new type of near-surface faceting crystal that can exhibit deep, long-lasting instability once buried. Understanding the correlation between near-surface weak layer formation with in the snowpack and weather patterns that dictate snowpack stability is a valuable key in avalanche forecasting for Juneau, AK.

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