MEASURING NEAR-SURFACE SNOW TEMPERATURE CHANGES OVER TERRAIN

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ABSTRACT: The energy balance at the snow surface results in substantial diurnal temperature fluctuations within the top portion of the snowpack. These temperature fluctuations, which vary both spatially and over time, can have important effects on stability. During the winters of 2005 and 2006, field data for a near-surface warming study were collected on a treeline knoll located in the Columbia Mountains of British Columbia. Thermocouple arrays placed on the top and at different locations on the knoll side slopes recorded temperatures within the top 30 cm of the snowpack. During each test period, nearby measurements of incoming short and long wave radiation were collected, as were periodic observations of cloud cover, air temperature and the snow surface temperature at each array. The study aims to use field data to identify when, and to what extent, near-surface warming occurs on different aspects. Instrumentation challenges encountered in accurately measuring near-surface snow temperatures are also presented.

Preliminary analysis of the data shows a significant correlation between aspect and the maximum daytime increase in near-surface snow temperatures. In one experiment, the magnitude of daytime warming measured at 10 cm depth was almost 7 ºC greater on the south aspect than the north aspect. The aspect dependent differences in daily temperature change decreased with increased cloud cover.

KEYWORDS: daytime warming, near-surface temperature change, snow surface energy balance, radiation, seasonal snowcover

1. INTRODUCTION

The presence of a weak layer within the snowpack is a critical factor in the formation of a slab avalanche, as are the slab characteristics. Because near-surface temperature changes can affect both the properties of existing slabs and the potential for formation of future weak layers at the snow surface, they are an important consideration when evaluating snow stability. The objective of this study is to measure near-surface temperature changes and examine how they vary over time and space. This understanding is required prior to analysis of the spatial effects of warming on stability (e.g. McClung, 1996; McClung and Schweizer, 1997) or weak layer formation (e.g. Birkeland, 1998).

Diurnal temperature fluctuations within the top portion of the snowpack are a result of the net energy balance at the snow surface. The key energy transfer processes contributing to the surface energy balance, illustrated in Figure 1, are included in Equation 1.

$$Q_t = Q_{sw} + Q_{lw} + Q_s + Q_l + Q_c \qquad (1)$$

where Q_t = total heat flux
Q_{sw} = short wave radiation flux
Q_{lw} = net long wave radiation flux
Q_s = sensible convective heat flux
Q_l = latent convective heat flux
Q_c = conductive heat flux

The relative importance of each term will vary because of differences in location, terrain, snowpack characteristics, meteorological conditions and time of year and day. The focus in this study is on radiation fluxes (Q_{sw}, Q_{lw}), which often have the most dominant effect on the surface energy balance (Obled and Harder, 1978).

The amount of short wave radiation reaching any given location depends on the cloud cover, latitude, elevation, time of year and time of day. Short wave radiation reaching the snow surface includes a portion scattered by the earth's atmosphere (diffuse), and a portion unaffected by the atmosphere (direct). At the snow surface, both reflection and absorption of short wave radiation occur. Albedo is the ratio of reflected radiation to total incoming radiation, integrated over the short wave spectrum. Typical albedo values are 0.95 for clean, dry compact snow and 0.61 for clean, wet granular snow (Male and Gray, 1981, p. 379).

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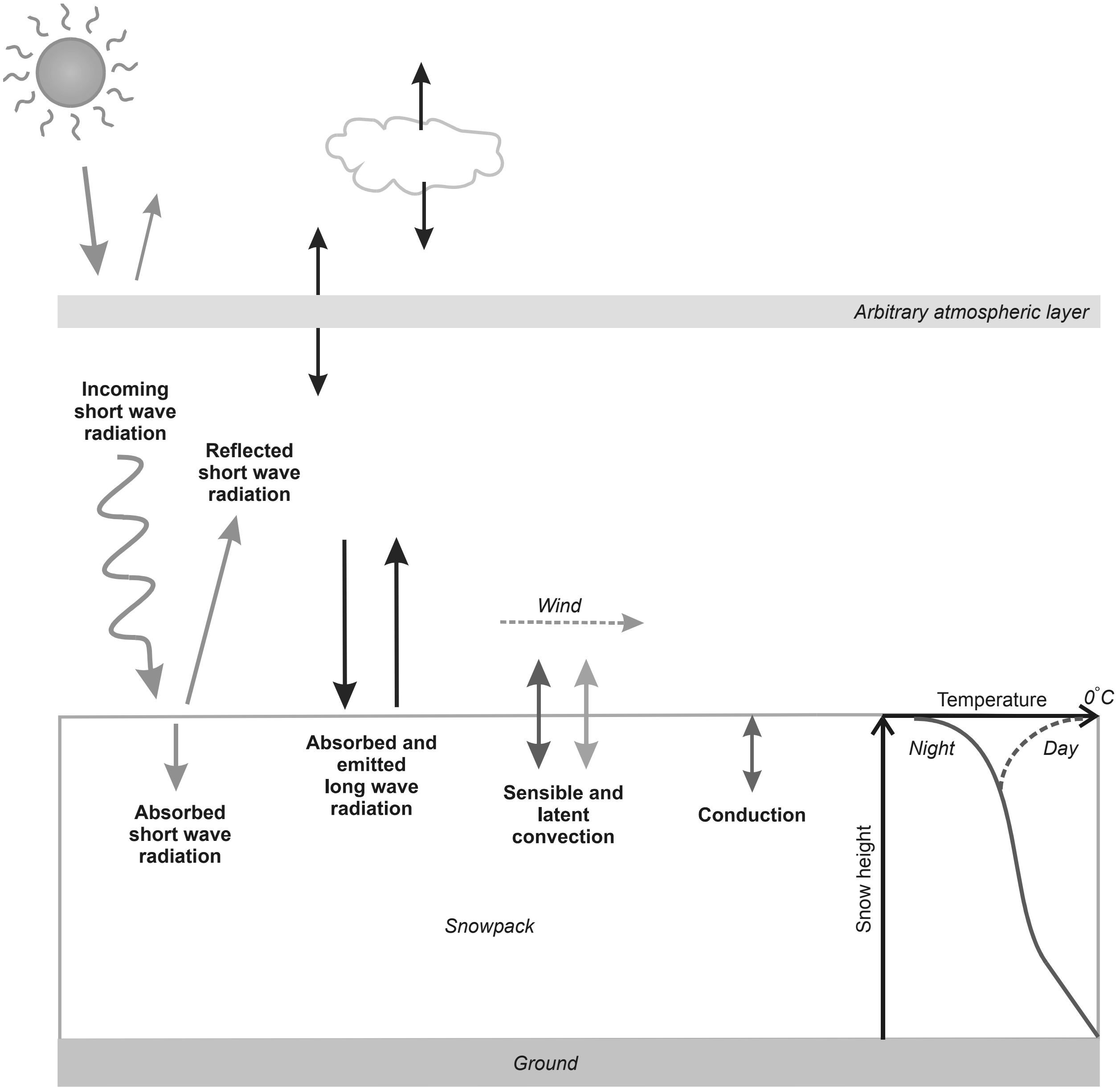

Figure 1: Key components of the snow surface energy balance, with an example of the resultant diurnal temperature fluctuations in the top portion of the snowpack (after McClung and Schaerer, 1993, pp. 34, 45).

Albedo will vary with factors such as solar zenith angle, cloud cover, snow grain size, surface roughness and the presence of impurities (Warren, 1982). Short wave radiation not reflected at the snow surface penetrates approximately 10-20 cm below the surface of the snowpack, decreasing in intensity with depth (McClung and Schaerer, 1993, p. 33). The depth of short wave penetration, over which the incoming short wave radiation will contribute to warming, depends on the properties of the surface snowpack layers.

In addition to long wave radiation emitted by the snow itself, the net long wave radiation flux at the snow surface includes incoming long wave radiation emitted from clouds, the atmosphere, nearby terrain and other objects like trees. Because the net long wave radiation flux at the snow surface consists of both incoming and outgoing radiation, it can result in either warming or cooling of the snow surface. Cooling due to outgoing long wave radiation can be strong under clear sky conditions, particularly overnight.

2. METHODS

2.1 Field site

Field data were collected at Gopher Butte knoll, located approximately 300 m northwest of the Mt. Fidelity research station in Glacier National Park (Figure 2). This location offered a treeline study site (approximately 1940 m) in close proximity to an automated weather station maintained by the Avalanche Control Section of Parks Canada. Mt. Fidelity is located in the Columbia Mountains of British Columbia, Canada, which Hägeli and McClung (2003) describe as having a transitional snow climate with a strong maritime influence.

Collection of field data on a knoll allowed for comparison of near-surface temperature changes on different aspects. Tree cover on Gopher Butte, however, limited selection of sites for measurement of near-surface temperatures. To minimize the effects of trees on the surface energy balance, through shading from direct incoming short wave radiation and increased long wave radiation emitted by the trees, sites without trees in close proximity were preferred. Because the west-facing knoll slopes have more tree cover than the relatively open east-facing slopes (Figure 3), less data were collected on west-facing slopes.

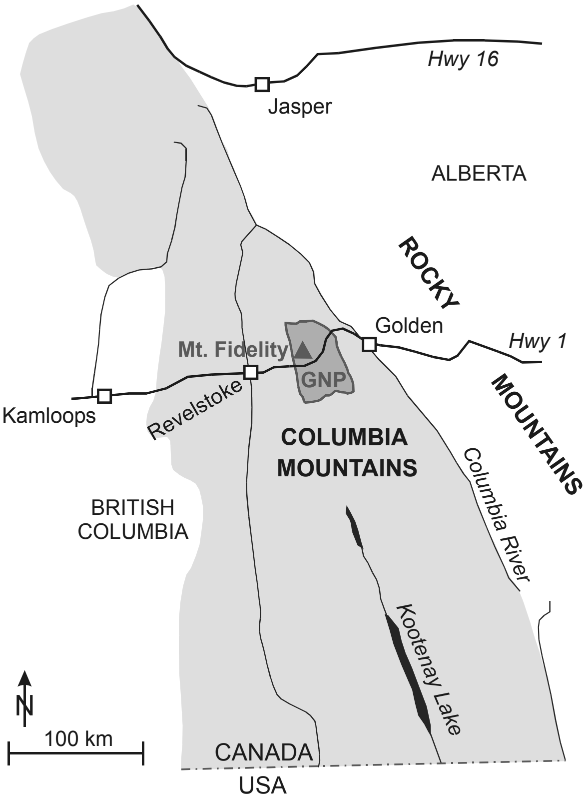

Figure 2: Map showing the location of the study site at Mt. Fidelity in Glacier National Park (GNP).

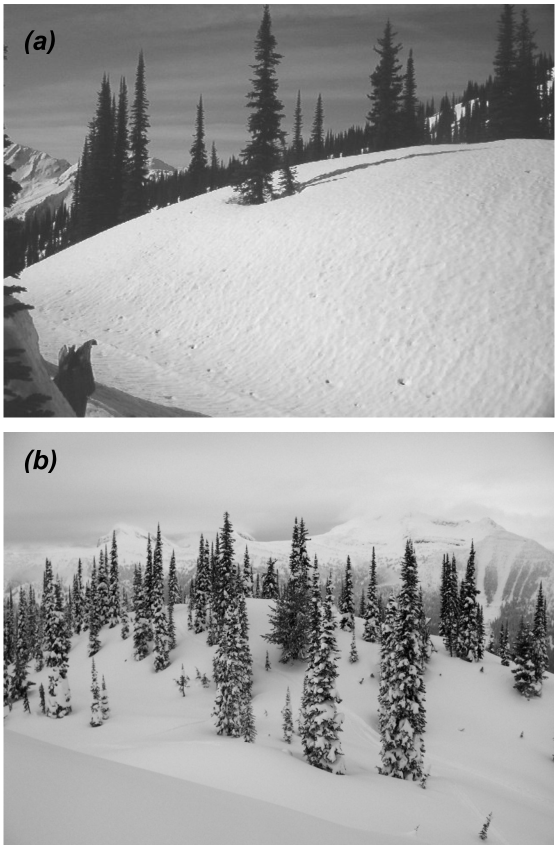

Figure 3: Photographs of Gopher Butte showing tree cover on the (a) east- and (b) west-facing knoll slopes.

2.2 Instrumentation

Parks Canada provided hourly air temperature, precipitation and relative humidity data from the Mt. Fidelity study plot (1905 m). Incoming short and long wave radiation measurements were collected in the study plot with a pair of radiometers on loan from the University of British Columbia Avalanche Research Group. An RM Young Wind Monitor, also located in the study plot, measured wind speed and direction every hour.

Balsa wood sections, 30 cm in length, were constructed to place and hold the chromel-alumel thermocouple wires used to measure near-surface temperature (Figure 4). Requirements for a light material with thermal properties somewhat similar to snow lead to the selection of balsa wood for construction of the sections. Holes were punched in

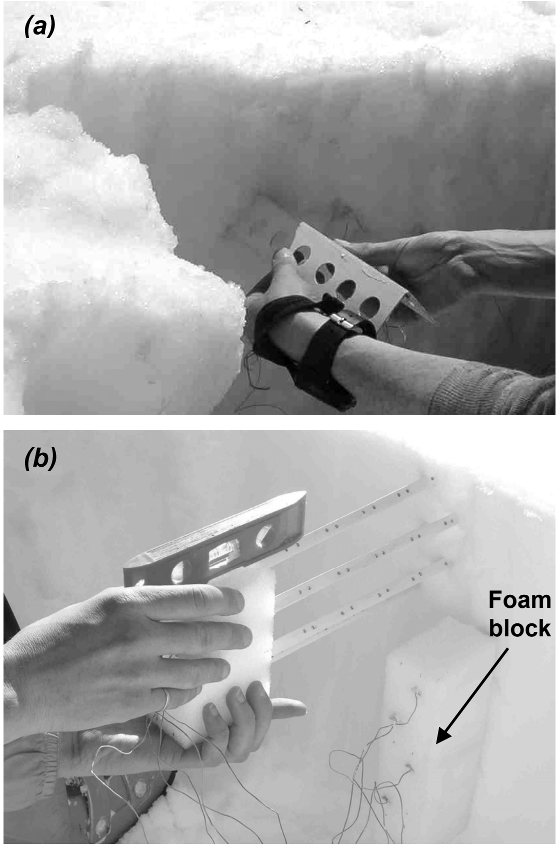

Figure 4: Photographs of balsa wood sections used to place and hold thermocouples: (a) 2005, (b) 2006.

the balsa wood to make the sections even lighter and more comparable to the density of new snow. After gluing a single thermocouple wire to the underside of each section, the apparatus was painted with white acrylic spray paint in an attempt to mimic the highly reflective properties of snow and minimize absorption of incoming short wave radiation.

Each array included ten thermocouples placed at different depths within the top 30 cm of the snowpack. Four Campbell Scientific AMT25 multiplexers (one for each array) connected to a single Campbell Scientific CR10X datalogger allowed for placement of the thermocouple arrays at different locations on the knoll while minimizing the individual thermocouple lengths (<1.6 m). Based on thermocouple measurements made at 30 or 60 second intervals, the datalogger recorded average temperature values every 10 or 15 minutes.

2.3 Field procedure

For each experiment, one array was placed at a flat location on the knoll top, with the remaining three placed in undisturbed areas on varying aspects. After recording the aspect and slope angle at each array location, field staff dug a shallow pit and installed the thermocouples at the desired depths. The multiplexer was then placed in the pit and backfilled with snow. To maintain measurements close to the snow surface and reduce difficulties in tracking thermocouple depths, the temperature measurement equipment was only set up during periods without forecast precipitation.

Throughout each measurement period, which varied in length from one to six days, manual measurements of daytime air temperature and snow surface temperature (using a handheld infrared thermometer) were made at approximately hourly intervals. Observations of cloud cover, estimated wind speed and snow surface condition (i.e. sunny or shaded) were also recorded. Near the beginning of each measurement period, a shallow snow profile, approximately 40 cm deep, was completed in an undisturbed area representative of each array site. Snow profile observations followed the procedures outlined in the Canadian Avalanche Association Observation Guidelines and Recording Standards (CAA, 2002,13-19).

3. RESULTS AND DISCUSSION

Field data were collected during eleven different measurement periods in February, March and April of 2005 and 2006 (Bakermans, in prep.). Three sets of field data are presented to illustrate variation in near-surface temperature changes due to differences in terrain, snowpack characteristics, weather and time of year.

3.1 28 February 2005

Of interest from the first of the eleven field experiments is a comparison between the near-surface temperatures measured on an east-northeast aspect (ENE, 063°) and those measured on a north-northeast aspect (NNE, 032°). The array sites were both relatively open, with the same slope angle of 17°. No nearby terrain features were directly opposite either array location. Sky conditions over the two day period varied from clear skies to a few clouds.

Figure 5 illustrates the temperatures measured at different depths below the snow surface for these two arrays. It is evident that temperatures were warmer on the ENE aspect, with a greater difference at midday than overnight. The magnitude of daytime warming on the ENE is also greater than that measured for the NNE array. The term daytime warming (ΔT_d) is used to represent the daytime increase in temperature, at a given depth, from sunrise to the maximum afternoon peak (see Figure 5a). This daytime fluctuation is primarily the result of incoming short wave radiation absorbed within the top portion of the snowpack and, as expected, the magnitude decreases with depth. Table 1 summarizes the daytime warming differences between the two arrays.

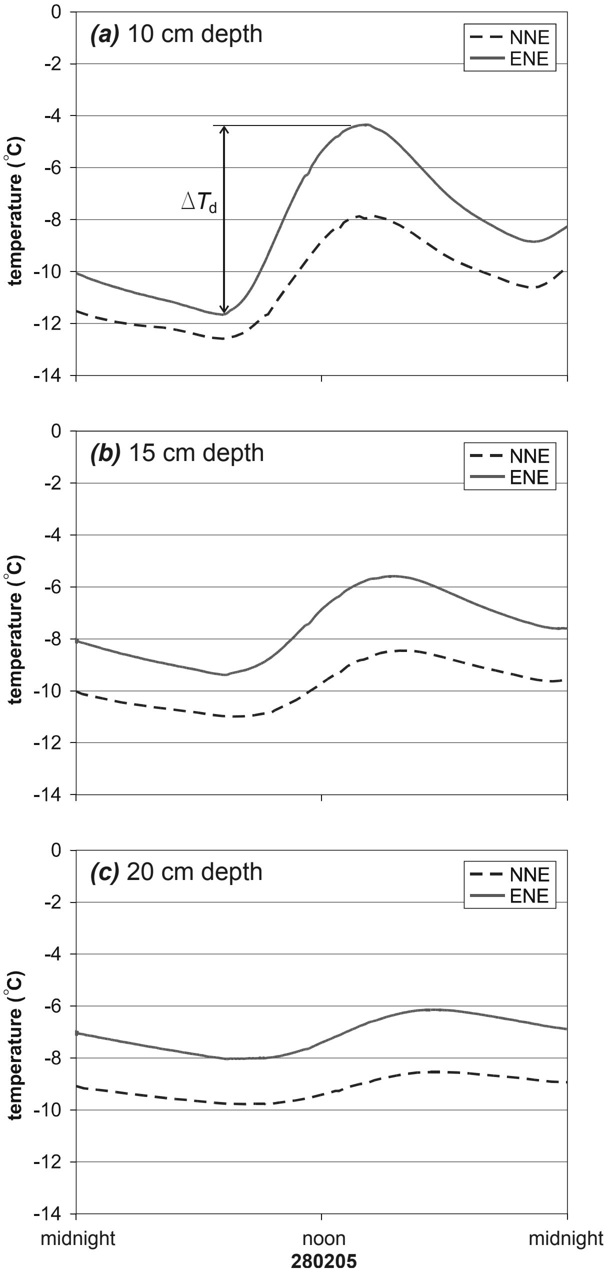

Figure 5: Temperature measurements made on 28 February 2005 at (a) 10 cm, (b) 15 cm, and (c) 20 cm depth. Daytime warming at 10 cm depth (ΔT_d) for the ENE array is shown.

Table 1: Daytime warming at ENE and NNE array sites on 28 February 2005.

Depth (cm)	**Daytime warming (°C)** *ENE*	**Daytime warming (°C)** *NNE*
10	7.3	4.7
15	3.8	2.5
20	1.9	1.2

While slightly warmer temperatures on a more easterly facing aspect are not surprising, the magnitude of the temperature difference, considering the relatively small change in aspect, is worth noting. An estimate based on solar position calculations outlined by Walraven (1978) and Robinson (1966, chapter 2) shows that, in late February under clear skies, the NNE array location would receive approximately 80% of the short wave radiation incident on the ENE slope.

A secondary factor which may have contributed to the temperature differences is related to the snowpack structure at each site. Manual snow profiles completed on the morning of 28 February 2005 show surface hoar crystals on the surface and a combination of decomposing fragments and mixed forms to a depth of 20 cm at both array locations. The main difference between the two profiles was in the hand hardness, as shown in Figure 6. Slightly higher hand hardness values in the top 10 cm of the snowpack on the

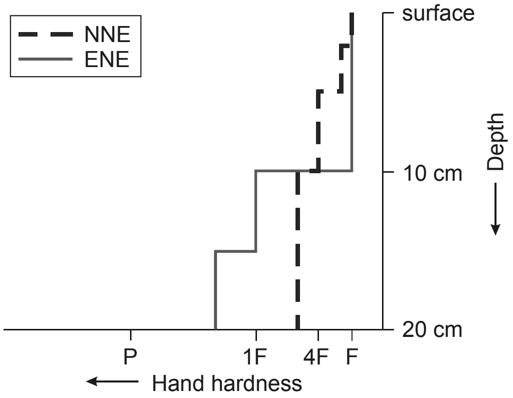

Figure 6: Hand hardness observations made the morning of 28 February 2005 at the two array locations.

NNE slope suggest slightly higher density snow, and therefore greater attenuation of short wave radiation (Bohren and Barkstrom, 1974) at this location. The effect of the hand hardness difference diminishes quickly as the short wave radiation flux decreases with depth. In addition to aspect-dependent differences in the major surface energy balance inputs, aspect may also influence near-surface temperatures through variability in snowpack characteristics (i.e. due to previous differences in wind exposure or surface energy balance).

3.2 7-12 February 2006

The longest field experiment, spanning six days in early February 2006, includes data collected under a variety of cloud cover conditions. Figure 7a illustrates the temperatures measured at 10 cm depth for arrays on the knoll top, north (N), east (E) and south (S) aspects. A representative sky condition observation is given for each day using symbols as defined in the Canadian Avalanche Association Observation Guidelines and Recording Standards (CAA, 2002, p. 2). Incoming short and long wave radiation data measured in the study plot are shown in Figure 7b. The average daytime air temperature, which was approximately -5 °C during most of the experiment, dropped to about -10 °C on the 9th and 10th.

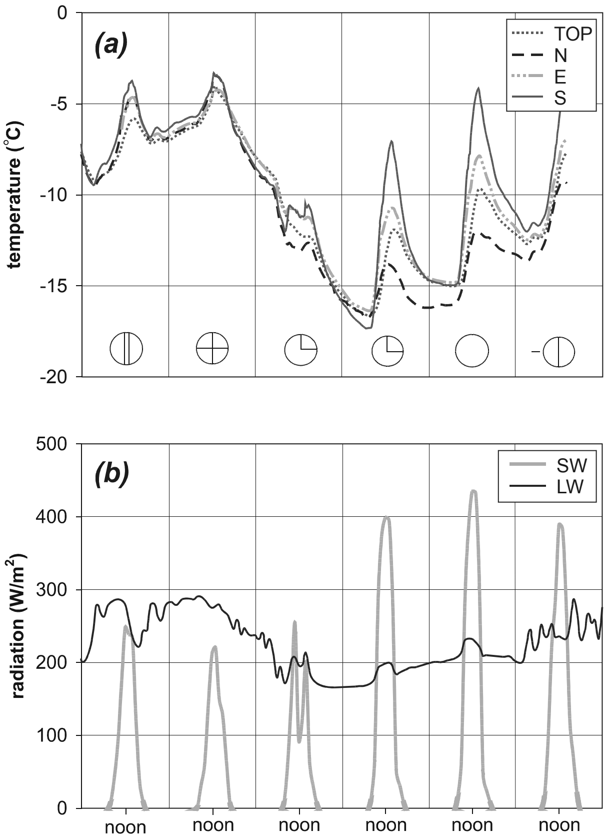

Figure 7: Measurements made on 7-12 February 2006: (a) temperature at 10 cm depth, (b) short wave (SW) and long wave (LW) radiation incident on a horizontal plane. A representative sky condition observation is given for each day (CAA, 2002, p. 2).

On an overcast day, 8 February, the measured snow temperatures did not vary much with aspect. At a depth of 10 cm, there was a difference of only one degree in the magnitude of daytime warming measured at each array location. In comparison, the aspect-dependent differences in near-surface temperature on a clear day, 11 February, were larger. Not only was there substantial variation in the peak afternoon temperature, but also in the magnitude of daytime warming. On 11 February, the maximum daytime warming at 10 cm was measured as 10.8 °C at the south-facing array site. This is almost 7 °C greater than the corresponding value measured on the north aspect. The difference in daytime warming between aspects decreased to approximately 2 °C at 20 cm depth. Table 2 presents a summary of the aspect-dependent differences in daytime warming measured on 8 and 11 February. On the overcast day (8 February) the maximum and minimum daytime warming values were measured on the north and east slopes, respectively.

Table 2: Maximum difference in daytime warming between aspects for an overcast day (8 February 2006) and a clear day (11 February 2006).

Depth (cm)	**Maximum difference in daytime warming between aspects (°C)**	
	080206 (OVC)	***110206 (CLR)***
10	1.0	6.9
15	0.4	3.0
20	0.3	1.8

With the exception of the temperature measurements made on 9 February, where a considerable drop in air temperature and a midday incoming short wave radiation 'blip' complicate the interpretation, a similar relationship between cloud cover and differences in daytime warming is observed throughout this measurement period. Days with broken or overcast cloud cover show less aspect-dependent differences in daytime warming than days with few clouds or clear skies. With little cloud cover, the proportion of direct short wave radiation is high and slopes facing the sun receive more short wave radiation than those with less exposure due to orientation or shading by surrounding terrain. Diffuse incoming short wave radiation is distributed more evenly over terrain, consistent with observations of less variation in daytime warming as scattering increases with cloud cover.

An additional point to note is the difference between incoming long wave radiation on 10 February, a day with few clouds, and 12 February, a day with thin scattered cloud. Increased cloud cover corresponded with an increase in incoming long wave radiation. At the same time, however, there was very little decrease in incoming short wave radiation, as much of it was able to penetrate the thin cloud occurring on 12 February. Under these thin cloud conditions, near-surface warming received relatively strong contributions from both short and long wave radiation fluxes.

3.3 <u>10 February 2006; 14 March 2005</u>

To look at the effect of timing on near-surface warming, data from 10 February 2006 and 14 March 2005 were examined. For both of these days, arrays were set up on north, east and south aspects as well as the knoll top. Corresponding array sites were within 7° in slope angle and 16° in azimuth. The sky conditions differed slightly, with few thin clouds present throughout 10 February and few clouds increasing to scattered clouds on the afternoon of 14 March. Differences in terrain characteristics and cloud cover are considered in the calculations done to project the study plot measurements of incoming short wave radiation from a horizontal plane to each array slope (Walraven ,1978; Robinson, 1966, chapter 2). The average daytime air temperatures were -10 °C and -1 °C for 10 February and 14 March, respectively.

Figure 8 shows measured temperatures at 10 cm depth and projected incoming short wave radiation for each array location. On both days, maximum daytime temperatures occurred on the south aspect, with successively cooler temperatures on the east-facing slope, knoll top and north-facing slope. Incoming short wave radiation values for each array site show similar trends.

In comparing daytime warming at each array site, we note an increase of 2.5-3 °C from February to March for the knoll top, north, and east arrays. On the south-facing slope, however, the magnitude of daytime warming actually decreases by approximately 2 °C (Table 3). The data from 14 March also show slightly more daytime warming at 10 cm depth on the east-facing slope than on the south. The midday temperature values remain higher on the south-facing slope because the early morning temperatures are approximately 1 °C warmer than those measured at the east array location.

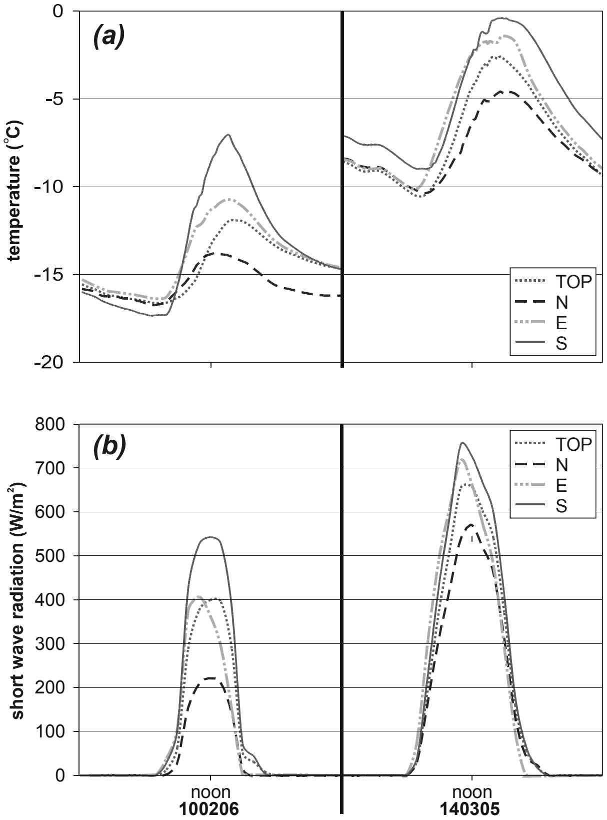

Figure 8: Measurements made on 10 February 2006 and 14 March 2005: (a) temperature at 10 cm depth, (b) incident short wave radiation on each array slope estimated from horizontal study plot data (Walraven,1978; Robinson, 1966, chapter 2).

Table 3: Daytime warming at 10 cm depth measured on 10 February 2006 and 14 March 2005.

Aspect	**Daytime warming (°C)**	
	100206	***140305***
TOP	4.7	7.7
N	2.9	5.4
E	5.7	8.6
S	10.3	8.3

These results are not consistent with the incoming short wave radiation trends noted above. Variability in the characteristics of the surface snowpack layers, which has not yet been considered in this discussion, is one explanation for the apparent contradiction. Differences in albedo and extinction coefficient may have altered the amount of short wave radiation reaching 10 cm below the snow surface and thus the magnitude of daytime warming at depth.

Figure 9 presents the data in a different format. Measured values of daytime warming at 10 cm depth and peak incoming short wave radiation (projected to each array location) are shown relative to the corresponding knoll top measurement. Estimated values of short wave radiation at 10 cm depth for each array location are also given. These estimates, based on manual snow profile observations made at each array location, are approximate.

For all three parameters, data from 10 February shows greater variability between aspects than the data from 14 March. This is consistent with the expectation that, as the sun becomes higher in the sky, differences in exposure to direct short wave radiation would tend to decrease. The measured daytime warming values on the east and south aspects, particularly, are very similar on 14 March, corresponding with short wave radiation values that are also very alike.

Despite their approximate nature, the estimates of short wave radiation flux at depth typically relate better to the variation in measured daytime warming values than the maximum short wave radiation values do. This suggests that, in some cases, variation in snowpack properties may have an effect on the distribution of near-surface warming over terrain.

4. MEASUREMENT CHALLENGES

The physical and optical properties of snow contribute to the difficulty in obtaining accurate measurements of near-surface temperature. The fragile snow structure is disturbed by placement and settlement of equipment within the snowpack. Measurement errors also occur because of differences in albedo and emissivity between the field measurement equipment and the snow. Most materials have lower albedo and emissivity than snow, absorbing more short wave and emitting less long wave radiation than the undisturbed snowpack. The resultant heating errors are difficult to eliminate and to quantify.

Several studies that included field measurements of near-surface temperature report equipment-related differences between measured and expected values. Andreas (1986) compared thermistor and thermocouple measurements to snow-surface measurements made with a dew-point hygrometer placed approximately 10 cm above the snow surface. The values showed reasonable agreement overnight, but both the thermistor and thermocouple measured noticeably warmer temperatures during times of peak incoming short wave radiation.

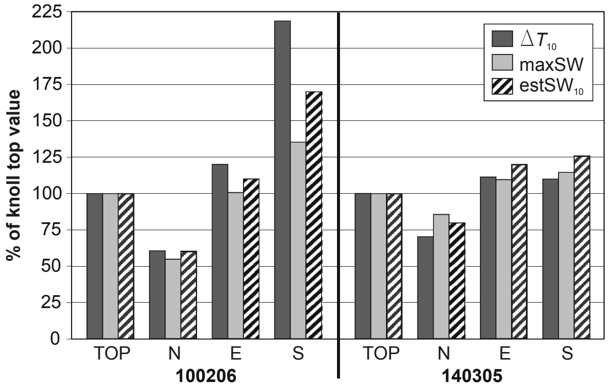

*Figure 9: Comparison of measured daytime warming at 10 cm (ΔT_{10}, dark solid bars), maximum incoming short wave radiation (*maxSW*, light solid bars) and estimated peak short wave radiation at 10 cm depth (*estSW$_{10}$*, striped bars). Values are relative to the corresponding knoll top measurement/estimate.*

When a near-surface thermocouple array was shaded from direct sunlight with a piece of plywood, Brandt and Warren (1993) observed initial cooling, attributed to elimination of short wave radiation absorbed by the thermocouples, followed by subsequent gradual cooling, thought to reflect cooling of the snowpack itself. Morstad (2004) measured similar temperature changes in an environmental chamber when the metal halide lamp used as a radiation source was turned off at the end of each experiment. In both of the above-noted studies, the magnitude of these temperature changes decreased with depth and was minimal below approximately 10 cm.

Near-surface snow temperatures greater than zero degrees Celsius were measured during the field experiments completed for this study. Despite steps taken to match the properties of the measurement equipment to the snow, differences in the absorption and emission characteristics of the equipment resulted in temperature measurement errors. Temperature data collected when near-surface snow conditions were isothermal and during experiments in which arrays were shaded from direct short wave radiation for brief periods helped to quantify these measurement errors. Estimates based on both groups of data indicate that, under non-melt conditions, the magnitude of measurement errors at 10 cm depth was less than 0.3 ºC (Bakermans, in prep.).

5. CONCLUSIONS

Based on field data collected over two winter seasons, the following conclusions regarding variability in near-surface warming can be made:

- The magnitude of daytime temperature fluctuations typically decreases with depth below the snow surface.
- Even small changes in aspect can result in substantial differences in near-surface warming.
- In addition to resultant differences in radiation input, aspect may influence near-surface warming through variation in snowpack properties that affect penetration of short wave radiation in the upper snowpack.
- As cloud cover increases, aspect-dependent differences in daytime warming may decrease.
- Because thin cloud can enhance incoming long wave radiation without substantially reducing incoming short wave radiation, the upper snowpack can undergo substantial daytime warming under thin cloud conditions.
- While the magnitude of daytime warming may increase with increased short wave radiation as the winter season progresses, variability over terrain may decrease.
- The distribution of near-surface temperature fluctuations over terrain may change as a result of variation in the properties of upper snowpack layers, both over time and over terrain.

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