Cold Regions Science and Technology 59 (2009) 133–142

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

SWarm: A simple regression model to estimate near-surface snowpack warming for back-country avalanche forecasting

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ARTICLE INFO

Article history:
Received 1 November 2008
Accepted 12 June 2009

Keywords:
Avalanche forecasting
Near-surface warming
Diurnal warming
Snowpack temperatures
Solar radiation
Surface energy balance

ABSTRACT

Daytime warming in near-surface snowpack layers occurs as a result of short wave radiation penetrating the top portion of the snowpack. While there is some understanding of diurnal temperature fluctuations and their effects on snowpack stability, quantified estimates of their magnitude are not readily available to avalanche forecasters in western Canada. During the winters of 2005 and 2006, near-surface temperatures were measured on a knoll located in the Columbia Mountains of British Columbia. The field dataset was used to develop a near-surface warming model, based on linear regression analysis of predictor variables derived from surface energy flux terms. To facilitate use in large forecast areas where representative meteorological data are typically scarce, consideration was given to the availability of input data. In this dataset, a variable based on daily maximum incoming short wave radiation proved to be the only significant predictor of near-surface daytime warming. Based on slope, aspect, expected cloud cover and number of days since snowfall, the model predicts the magnitude of daytime warming, in a below freezing snowpack, 10 cm below the snow surface with an estimated root mean square error of 1.6 °C.

1. Introduction

Daytime warming in the upper snowpack, which occurs as a result of short wave radiation penetrating the top portion of the snowpack, can have important effects with respect to skier-triggered avalanches. These include changes in the mechanical properties of slabs (e.g. McClung and Schweizer, 1999; McClung, 1996) and the creation of conditions favourable for the formation of weak snow layers (e.g. Birkeland, 1998). Although additional research is required to fully understand the relationship between near-surface warming and avalanches (e.g. Exner and Jamieson, 2008a), experienced avalanche practitioners usually consider near-surface warming, among many other factors, when evaluating snow instability. Like most other Class II (snowpack) and Class III (meteorological) factors considered by forecasters when evaluating snow instability, daytime warming is not important in every instance.

Recent research regarding the absorption of short wave radiation in snow includes sophisticated measurement techniques and complex numerical modelling (e.g. Kaempfer et al., 2007; Warren et al., 2006; Meirold-Mautner, 2004). Taking a different approach from these physically-based models, which are invaluable in developing an understanding of the process behind near-surface warming, this paper outlines the development of an empirical model intended to provide avalanche practitioners in North America with quantitative information about the expected magnitude and spatial variation of near-surface daytime warming.

1.1. Current observations

Currently, of the many observations typically considered during the evaluation of snow instability in North America, snow temperature and solar (short wave) radiation are the two that relate best to near-surface warming. The temperature at 10 cm depth below the snow surface (T_{10}) is a standard study plot measurement outlined in the Canadian Avalanche Association (CAA) *Observation Guidelines and Recording Standards for Weather, Snowpack and Avalanches* (CAA, 2002, p.4). Surface temperature and sub-surface temperatures at 10 cm increments are also standard measurements at profile sites (CAA, 2002, p. 15). Similarly, the American Avalanche Association (AAA) *Snow, Weather, and Avalanches: Observational Guidelines for Avalanche Programs in the United States* (Greene et al., 2004, p.12, p. 28) describes the temperature at 20 cm depth below the snow surface (T_{20}) and temperatures at 10 cm increments as standard study plot and snow profile observations, respectively. While these data give some indication of near-surface snow temperatures, they are not typically taken at sufficient spatial and temporal resolution to identify daytime changes in the near-surface temperature (i.e. warming), or to illustrate how near-surface temperatures vary over terrain. Radiometers can be used to measure incoming solar radiation, but they are

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doi:10.1016/j.coldregions.2009.06.003

not common due to cost and maintenance issues (McClung and Schaerer, 2006, p. 206). Instead, qualitative assessments of cloud cover, surface melting and the intensity of insolation (e.g. felt on bare skin) typically provide the only available information about solar radiation to avalanche forecasting programs in North America.

1.2. Physically based models

CROCUS (Durand et al., 1999; Brun et al., 1992) and SNOWPACK (Bartelt and Lehning, 2002; Lehning et al., 2002a,b) are two physically-based computer models that simulate the layered structure of the snowpack and the metamorphism of snow crystals once deposited. Because detailed surface energy balance calculations are undertaken in order to model snowpack processes correctly, these models can provide quantitative information about near-surface warming. Operational use in North American avalanche forecasting programs is limited, however, because both models require high quality meteorological input data (including radiation data).

Although some professional avalanche forecasting operations in Canada (e.g. for mountain highways) have access to automated meteorological data, many (e.g. commercial guiding operations) rely primarily on extensive manual field observations. Based on the forecast areas for which the Canadian Avalanche Centre issues public bulletins and advisories, the extent of avalanche terrain in western Canada is greater than 300,000 km^2. Within this area, about 435 weather stations provide data potentially accessible to avalanche forecasting operations. It is estimated that less than 10% of these are automated weather stations located at or above treeline, and fewer than 2% include radiometers.

1.3. Objective

Our objective was to develop a practical model that would predict near-surface daytime warming for the many North American back-country avalanche forecasting operations without access to automated meteorological data representative of relevant avalanche starting zones. The model had to be practical for forecasters and guides used to considering the contributions of various factors when evaluating instability (e.g. McClung and Schaerer, 2006, pp. 166–172), and had to work using input data available in the morning before a day of work or travel in avalanche terrain. Because field workers and guides do not typically access numerical data during the field day, the model output (predicted near-surface warming for the day) also needed to be in a format that could be easily summarized. It was, therefore, deemed acceptable to simply predict warming by aspect and slope angle, ignoring the effects of the surrounding terrain.

2. Background

Armstrong and Brun (2008, Chapter 3) provide a detailed description of energy fluxes which influence accumulation, layering, melting, sublimation and evaporation of the snowpack. They present the snowpack energy balance as a volume balance of the following energy fluxes:

$$-dH/dt = Q_{sw}{\downarrow} + Q_{sw}{\uparrow} + Q_{lw}{\downarrow} + Q_{lw}{\uparrow} + Q_s + Q_l + Q_P + Q_G \quad (1)$$

where

dH/dt net change rate of snowpack's internal energy per unit area
$Q_{sw}{\downarrow}$ incoming short wave radiation flux
$Q_{sw}{\uparrow}$ reflected short wave radiation flux
$Q_{lw}{\downarrow}$ incoming long wave radiation flux
$Q_{lw}{\uparrow}$ outgoing long wave radiation flux
Q_s sensible turbulent heat flux
Q_l latent turbulent heat flux
Q_P sensible or latent energy flux due to precipitation
Q_G ground heat flux

The relative importance of each of these energy fluxes varies due to differences in location, terrain, snowpack characteristics, meteorological conditions, day of year and time of day. Many discussions regarding the surface energy balance suggest that net radiation is often the largest component (e.g. Armstrong and Brun, 2008; Plüss, 1997; Male and Granger, 1981; Obled and Harder, 1978). Unlike the other energy flux terms included in Eq. (1), incoming short wave radiation penetrates and warms the near-surface snowpack layers directly, eliminating any delay resulting from heat transfer via thermal conduction. We expect, therefore, that incoming short wave radiation will be an important parameter in modelling daytime warming in the near-surface snowpack layers.

3. Field methods

Field data were collected on Gopher Butte (51°14′17″ N, 117°42′10″ W, 1940 m), a treeline knoll near the Mount Fidelity research station and study plot (1905 m) in Glacier National Park (Figs. 1 and 2). The field site is located within the Columbia Mountains of British Columbia, Canada, which Hägeli and McClung (2003) describe as having a transitional snow climate with a strong maritime influence.

For each of the eleven different measurement periods undertaken during the winters of 2005 and 2006, thermocouple arrays were set up at a flat location on the knoll top and at three undisturbed locations on the knoll side slopes to measure near-surface temperatures (Fig. 3). For each measurement period, which ranged in length from one to six days, the side slope arrays were positioned on different aspects. To maintain measurement depths close to the snow surface, the field equipment was only set up during periods for which precipitation was not forecasted.

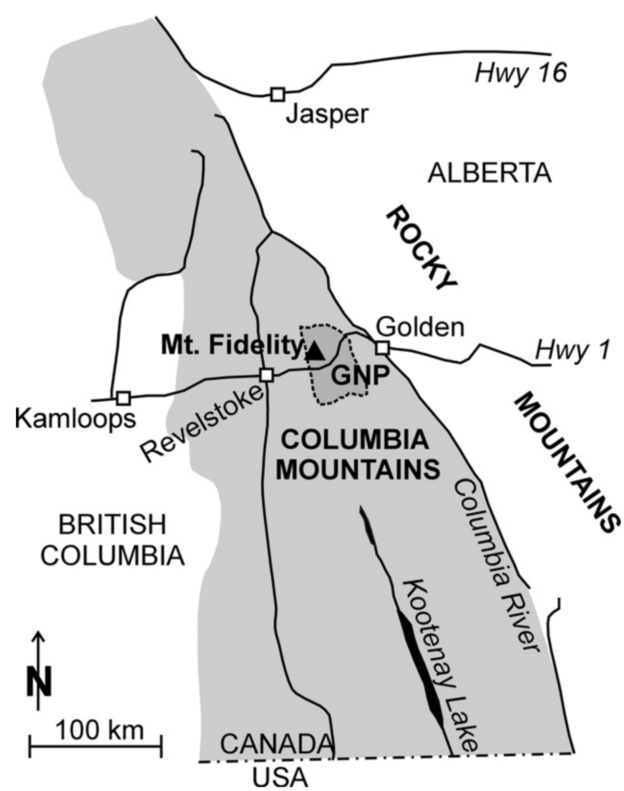

Fig. 1. The location of the study site at Mount Fidelity in Glacier National Park (GNP).