AUTOMATED SYSTEM FOR MEASURING SNOW SURFACE ENERGY BALANCE COMPONENTS IN MOUNTAINOUS TERRAIN

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ABSTRACT

The ability to continually monitor several meteorological parameters is needed to estimate snow surface energy balance components in mountainous terrain. In remote mountainous locations, limited accessibility and extreme weather conditions limit the use of delicate meteorological instrumentation. Robust instrumentation and radio telemetry are often needed to measure snow surface energy exchanges. This study examined the practicality and effectiveness of robust instrumentation in estimating radiative and turbulent exchanges in the forested Bear River Mountains of northern Utah. Measurement of reflected shortwave radiation was problematic due to possible selective absorption in the infra-red range. This resulted in overestimates of reflected shortwave radiation and decreased estimates of now surface albedo. During high snowfall, the pyranometer and net radiometer were occasionally covered with snow, resulting in inaccurate radiation measurements. Snow typically melted from instrument surfaces in less than one day under full sun. A relative humidity measurement accuracy of ±4% may have resulted in a possible error of 20% in the calculation of vapour pressure. Snow depth measurement with an acoustical sensor was affected by new or blowing snow, which resulted in inaccurate snow depth measurement 16·2% of the time. The longest period without a valid snow depth measurement was 19·5 hours. A new snow temperature thermocouple ladder was designed and constructed and provided accurate within-pack temperature measurements throughout the pre-melt and melt season.

INTRODUCTION

The estimation of snow energy balance components in mountainous regions requires the ability to continually monitor several meteorological parameters at remote locations. Limited accessibility inhibits the continuous maintenance of meteorological instrumentation. Subzero temperatures, high precipitation and strong winds prevent the unattended use of delicate instrumentation. Under extreme conditions, therefore, robust instrumentation and telemetry are needed to measure snow surface energy budget parameters. Increased durability may result in decreased instrumentation sensitivity, directly affecting the quality of collected data. The quality of snow surface energy information contributes significantly to the accuracy of estimating snow ablation rates in remote locations. Few studies have critically examined the effectiveness of robust meteorological instrumentation used to collect snow surface information. Thus the objective

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of this work was to examine the effectiveness of robust instrumentation and radiofrequency (RF) telemetry in providing information to estimate snow surface energy exchanges for use with the energy budget equation. Mention of manufacturer's brand names is to assist the reader and not to imply an endorsement of any kind.

SITE DESCRIPTION AND DATA RECORDING

The study was performed during the spring of 1991 in the Beaver Mountains of northern Utah. The study site is located near the Beaver Mountain ski resort (45°00′ N, 111°30′ W) 32·9 km north-east of Logan, Utah. Two test plots were constructed in a 30 × 40 m opening in mixed spruce–fir forest at an elevation of 2600 m, with a north-east aspect (Figure 1). The plots were located adjacent to one another 100 m downslope on the lee side of an open ridge on a 15° slope. One plot was lined with 1·0 mm plastic and channelled to a 10:1 V-notch weir (Mosley, 1979) to measure snowmelt at the soil surface. The second plot was unlined and trenched at the downslope end. Water emerging from the excavated face was also channelled into a 10:1 V-notch weir.

All measurements, except snow depth and temperature, were taken every 30 seconds and averaged over 30 minute periods. A 30 second measurement interval was considered adequate to provide meaningful input data. Measurement average intervals must be long enough to provide a realistic mean, but short enough not to reflect the influence of diurnal cycles. For this reason a 30 minute interval was considered adequate to provide representative values of the measured parameters.

Three tripods supported a cross-member used to mount instrumentation and data recording equipment above the plots. Instrument deployment is illustrated in Figure 2. A white fibreglass environmental enclosure contained a data logger (Campbell Scientific, Model 21X), radio (Motorola, Model P50) and RF modem (Campbell Scientific, Model RF95). A separate tripod located on the ridge supported a Yagi RF antenna. Data were transmitted from the data logger to Logan every 24 hours via the RF
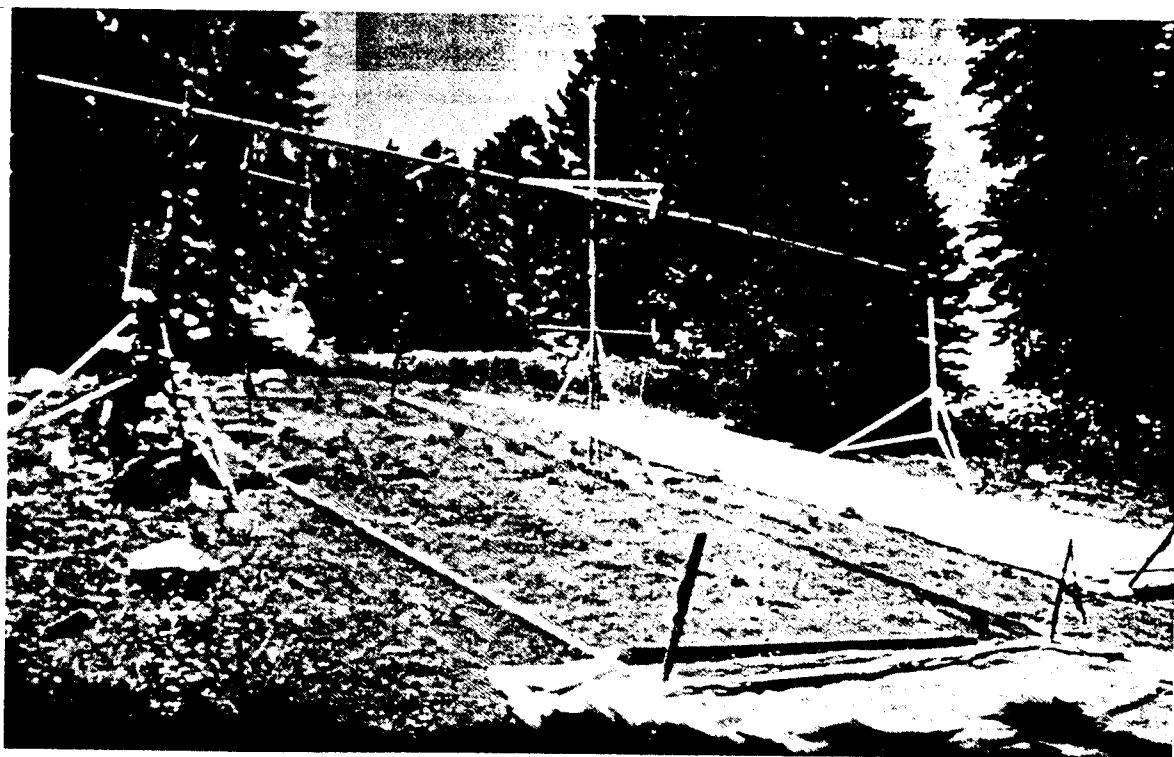

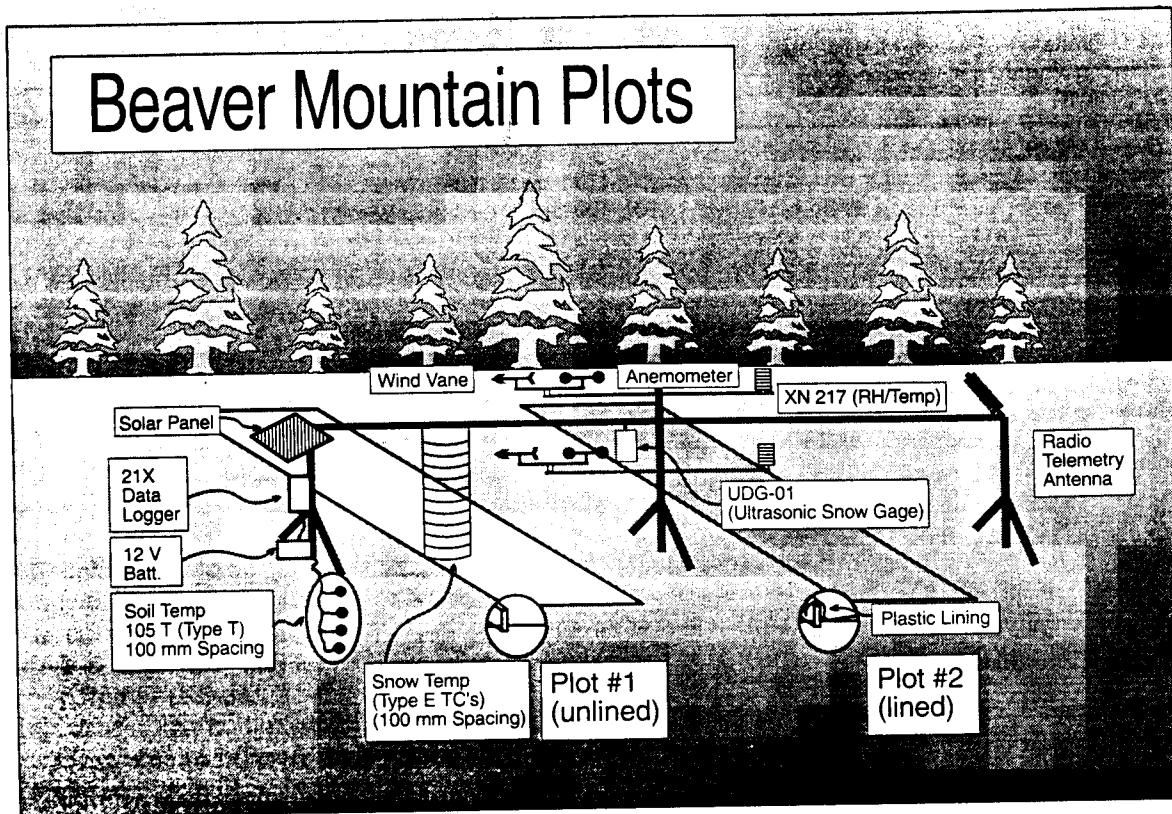Figure 1. Photograph of the experimental site and surrounding terrain

Figure 2. Graphical illustration of instrument deployment at the Beaver Mountain study site

communication link. The system was powered by a deep cycle marine battery continually trickle-charged by a 10 W solar panel. An analogue multiplexer (Campbell Scientific, Model AM416) was used to allow the measurement of 20 thermocouples (TCs) for snowpack temperature profiles.

The site was instrumented to measure the following: net radiation, incoming and reflected shortwave radiation, wind speed gradients, precipitation, relative humidity gradients, air temperature gradients, snowpack profile temperatures and snow depth. Snow ablation rates were determined by using these measured parameters to calculate the individual components of the energy budget equation. Instrumentation type, accuracy and measurement height are summarized in Table I. Resolution was a function of the data logger and sensor accuracy. No problems were encountered with the data recording and RF telemetry equipment after the initial setup period. The solar panel and deep cycle marine battery successfully powered the system during the whole study period.

Radiation measurement

The radiation balance at a snow surface is described by the following:

$$Q^* = (1 - \alpha)K_i + L_i - L_o \tag{1}$$

where Q^* is net radiation, α is the snow surface albedo, K_i and L_i are incoming shortwave and longwave radiation and L_o is the thermal radiation emitted by a snow surface.

Incoming radiation is composed of direct and diffuse shortwave radiation with a wavelength between 0·3 and 2·8 μm and emitted longwave radiation from the earth/atmosphere with a wavelength between 6·8 and 100 μm. The range between 2·8 and 6·8 μm includes both shortwave and longwave radiation, but is less than 5% of total incoming radiation (Geiger, 1966).

Table I. Summary of meteorological instrumentation on study site

Instrument	Model	Range	Resolution	Accuracy	Height	Linearity
Radiation (K_i, K_o, Q^*)						
Pyranometer (K_i, K_o)	Li–Cor LI2005	400–1100 nm	±0.22 W m^{-2}	$\pm3\%$[†]	3.0 m	—
Net radiometer	REBS Q–5	400–800 nm	±0.0129 W m^{-2}	$\pm5\%$[†]	3.0 m	—
Air Temperature (T_a)						
Thermistor	Fenwall UUT51J1	−35 to +50°C	—	±0.3°C[†]	0.5 m 2.0 m[‡]	≤0.5°C
Relative humidity (R_h)						
Inert cellulose crystal	Hygrometrix XN 217	0–100%	—	$\pm4.0\%$[†]	0.5 m 2.0 m[‡]	$\pm 2.0\%$
Wind speed and direction (u_z, 0–360°C)						
Three-cup anemometer[§]	RM Young 03001–5	0–50 m s^{-1}	—	—	0.5 m 2.0 m[‡]	—
Wind vane	RM Young 03001–5	0–350°C	—	—	0.5 m 2.0 m[‡]	—
Snow temperature (T_s)						
Type E TC (0.25 mm)[¶]	—	−40 to +40°	±0.005°C (59 μV °C^{-1})	±0.05°C (100 mm apart)	0–2000 mm	—
Snow depth (D_{snow})						
Ultrasonic transducer	CSC UDG–01	0–10 m	5 mm	±4 mm	3.0 m	—

[†] Information determined from manufacturer's specifications.
[‡] Instrument height adjusted periodically during the study.
[§] Distance constant, 2.3 m; threshold, 0.5 m s^{-1}.
[¶] Reference temperature, thermistor UUT51J1.

Incoming (K_i) and reflected (K_o) shortwave radiation was measured by silicone photodiode pyranometers (LI-COR, Model LI200S) developed from the work of Kerr et al. (1967). The photodiode sensor is insensitive to the near infra-red range with a spectral response of 400–1100 nm (Flowers, 1978). The manufacturer compensates for the near infra-red region insensitivity by adjusting the pyranometer calibration factor. Snow surface albedo varies with the wavelength of solar radiation; short wavelengths result in high reflectivity, reflectivity values decreasing to very low values in the near infra-red range (Male and Granger, 1981; Oke, 1987). Owing to the selective absorption in the near infra-red, the LI-COR pyranometer could possibly overestimate the reflected radiation. Albedos calculated in this study are substantially lower than those postulated by Sellers (1965), or the values reported by Choudhury (1981), Choudhury and Chang (1981a, 1981b), Choudhury et al. (1981) and Warren (1982). This has the effect of significantly increasing the net solar radiation, even after new snow has fallen. In short, unattended measurement of the albedo was problematic because of shadowing by the instrument. The use of a higher quality hemispherical sensor is recommended for future studies of this type.

Net radiation was measured with a high output 62 junction thermopile net radiometer (Radiation Energy Balance Systems, Model Q-5). The sensor consisted of a black and white sensing surface protected by a 0.25 mm polyethylene inner and an outer dome encased in a white enamelled body. The net radiometer mounting arm contained a desiccant which prevented condensation from forming inside the dome.

Precipitation occasionally covered the pyranometer resulting in inaccurate measurements of K_i. Snow typically melted from the small black coloured pyranometer in less than one day under full sun. Measurement of net radiation was minimally affected by snow; the smooth polyethylene dome and narrow sensor body minimized snow accumulation on the sensor. Figure 3 shows an example of the effects of snow on radiation measurements on 10 May 1991.

Air temperature and relative humidity

Air temperature and relative humidity were measured at two heights (0.5 and 2 m) using a single sensor at each height (Hygrometrix, Model XN217). A thermistor, incorporated in the sensor was used to measure air temperature (T_a). The sensors were shielded from direct and reflected radiation by a passive, white
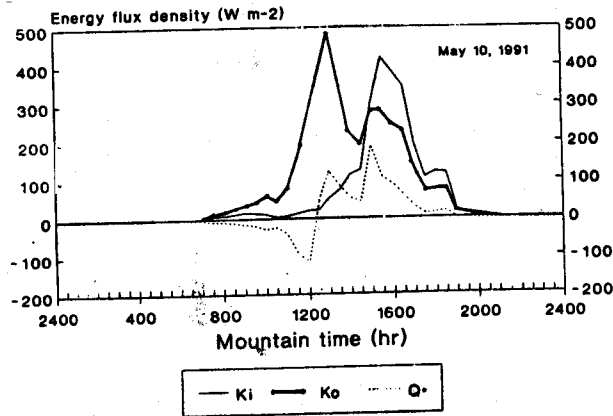
Figure 3. Effect of snow accumulation on measurement of diurnal radiation balance on 10 May 1991

thermoplastic, six-plate gill radiation shield. Over snow surfaces, large errors are possible due to radiant heating of passive radiation shields when wind speeds are less than $3-4\,\mathrm{m\,s^{-1}}$ (Tanner, 1990).

An error in the measurement of T_a affects sensible and latent heat flux calculations. In northern Utah, periods of high turbulent exchange are accompanied by high winds and overcast skies, occurring mainly during frontal passages. High winds and low values of direct radiation should minimize air temperature measurement errors, but an expectation of errors less than $1\cdot0°C$ is unrealistic when passive radiation shields are used to measure air temperatures.

Bulk aerodynamic methods require only air temperature gradient measurements, not absolute values. The effects of solar heating due to the passive radiation shields are common to both air temperature measurements and cancel each other. A more accurate and less expensive air temperature measurement could have been achieved by using 30-gauge ($0\cdot25\,\mathrm{mm}$) chromel–constantan (Type E) TC wire configured for a temperature gradient measurement during this study. The effects of solar heating are common to both junctions and cancel each other. Wind speeds of $0\cdot2-0\cdot3\,\mathrm{m\,s^{-1}}$ would be adequate to prevent any significant radiant heating (Tanner, 1990).

Accurate measurement of relative humidity is required to calculate latent heat fluxes at the snow surface. In the mountainous terrain of northern Utah, winter temperatures can be lower than $-40°C$; any sensor used to provide a continuous measurement of relative humidity must be capable of operating under extreme conditions. Several methods exist to measure the water vapour content of air, such as thermodynamic, hygromechanical, condensation, pressure or optical methods (Platt and Griffiths, 1972). In remote alpine studies hygromechanical sensors are the most practical method because of subzero conditions, limited power and minimal sensor maintenance. Continuous relative humidity values were recorded throughout the study period with hygromechanical sensors.

Each sensor consisted of a silicone, piezoresistive, thermally-matched strain gauge. The sensing element was composed of a combination organic and inorganic cellulose crystal. The crystal senses moisture, which results in hygromechanical stress being induced on a pair of silicone strain gauges bonded in a half-bridge configuration (Fenner, 1973). Humidity was measured continually during the winter to calculate vapour pressure gradients above the snow surface.

Saturated vapour pressure was computed in the data logger by the following equation (Lowe, 1977):

$$E_s = a_0 + T[a_1 + T(a_2 + T\{a_3 + T[a_4 + T(a_5 + a_6T)]\})] \qquad (2)$$

where $a_0 = 6\cdot109177956$, $a_1 = 5\cdot03469897 \times 10^{-1}$, $a_2 = 1\cdot886013408 \times 10^{-2}$, $a_3 = 4\cdot176223716 \times 10^{-4}$, $a_4 = 5\cdot824720208 \times 10^{-6}$, $a_5 = 4\cdot838803174 \times 10^{-8}$, $a_6 = 1\cdot838826904 \times 10^{-10}$ and T is the air temperature (°C). Vapour pressure was determined using this value and the measured relative humidity. This method provided a reliable estimation of vapour pressure. A concern with this approach is the sensitivity of vapour pressure calculations to errors in humidity measurements.
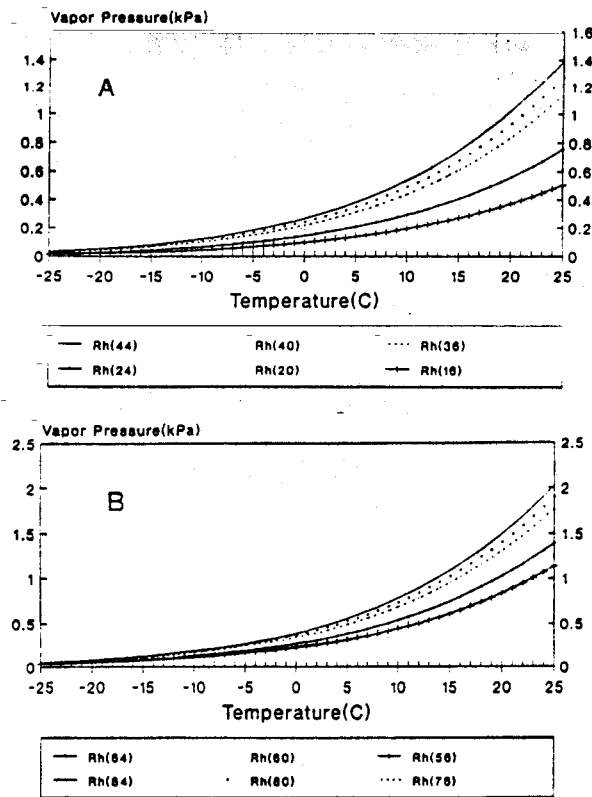
Figure 4. Effects of relative humidity measurement errors on vapour pressure calculations from −25 to 25°C at relative humidity values of (A) 20 and 40% and (B) 60 and 80%

Humidity sensors were accurate to ±4% absolute over the 0–100% range. A two point salt solution calibration was conducted before installing the sensors to verify the manufacturer's calibration and specifications. Results from the calibration indicated that sensor accuracy was within the ±4% specification. Figure 4A shows the possible errors for relative humidity values of 20 and 40% and Figure 4B those for 60 and 80%. A 20% error is possible in the calculated value of vapour pressure at relative humidity values less than 20%, but as relative humidity approaches 100%, the error is reduced to less than 5%. The cellulose sensing element used had a response time of three minutes for a 63% change in humidity. This slow response time limits the ability to detect the rapid upward or downward transport of vapour fluxes, possibly resulting in underestimation of latent heat fluxes.

Early in the study, blowing and drifting snow filled the radiation shield and sensor cavity resulting in inaccurate readings until cleaned. White nylon stockings were stretched over the radiation shields and prevented the reoccurrence of this problem for the remainder of the study. During active melt, the stockings were removed to prevent any measurement error due to radiant heating or reduced passive aspiration.

Wind speed and direction

Wind speed and direction were measured at 0·5 and 2 m heights above the snow surface (RM Young Wind Sentry, Model 03001-5). Sensors were mounted on a vertically adjusted cross-arm. Cross-arm heights were adjusted periodically during snow accumulation and melt periods to maintain the 0·5 and 2 m measurement height above the snow surface. Wind speed was measured by an anemometer consisting
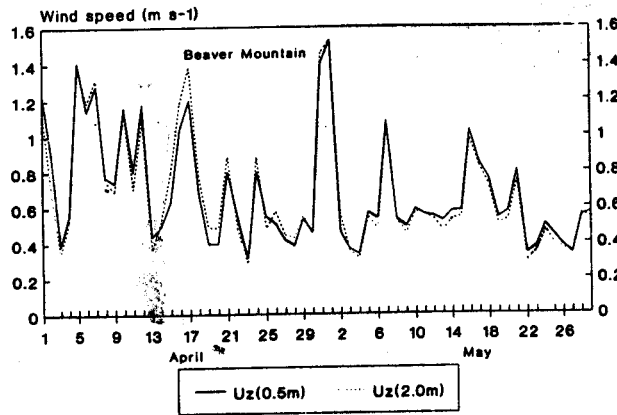
Figure 5. Comparison of daily average wind speeds measured at 0·5 and 2·0 m above the snow surface at Beaver Mountain from 1 April to 28 May 1991

of three 120 mm plastic cups, which produce an AC sine wave voltage signal. The frequency produced is directly proportional to wind speed ($0.75\,\mathrm{m\,s^{-1}\,Hz^{-1}}$). The AC signal is induced in a stationary coil by a two-pole magnet mounted in the cup wheel assembly. Wind direction was measured using a wind vane assembly with a potentiometer to indicate position. A resistance value was measured by the data logger to indicate wind direction.

Beaver Mountain wind speeds during the months of April and May (Figure 5) indicate that speeds measured at 0·5 m were periodically greater than the 2·0 m values. Visual observation confirmed this occurrence on several occasions during the study. The sensors and data logger were checked to verify correct operation. Average daily wind speeds were only $0.6\,\mathrm{m\,s^{-1}}$ at the forested Beaver Mountain site. With low wind speeds, the anemometer accuracy is questionable, possibly contributing to the observed decrease with height. Wind direction data commonly indicated different and highly variable air flow patterns between the 0·5 and 2·0 m height. These swirling wind patterns within the forest opening may have contributed to decreased wind speed with height. Considering the low wind speeds in forested terrain, a more sensitive anemometer could have been used to provide increased accuracy in wind gradient measurements.

Snow temperature

A new 20 junction TC ladder was designed and constructed to provide continuous monitoring of snowpack temperatures. Chromel–constatan (Type E) TCs were supported by a mono-filament ladder structure on 100 mm spacings in the snowpack. The TCs were connected to an analogue multiplexer (Campbell Scientific, Model AM416) stored in a picnic cooler buried in the snowpack. The low thermal conductivity of the snowpack minimized diurnal temperature fluctuations and created an isothermal environment in the cooler, which minimized temperature gradients between the thermistor and TC reference junctions. Each hour, the data logger measured each TC junction 10 times and calculated an average temperature for each TC junction. Multiple measurements were intended to minimize the effect of signal noise on snow temperature averages.

Chromel–constatan (Type E) TC wire was used instead of copper–constatan (Type T) because chromel has a thermal conductivity approximately 20 times lower than copper (Tanner and Gaza, 1990). Thirty-gauge (0·25 mm) wire was used to minimize the mass exposed to radient heating and subsequent thermal conduction to each TC junction. The TC wire was routed from the ground surface, up the ladder sides and then horizontally across the mono-filament ladder rungs to further minimize heat transfer from the surface to the TC junctions.

A thermistor, taped to the multiplexer, provided a reference temperature for TC measurements. A single point ice-bath calibration was conducted to determine the thermistor's offset of 0·126°C. The reference
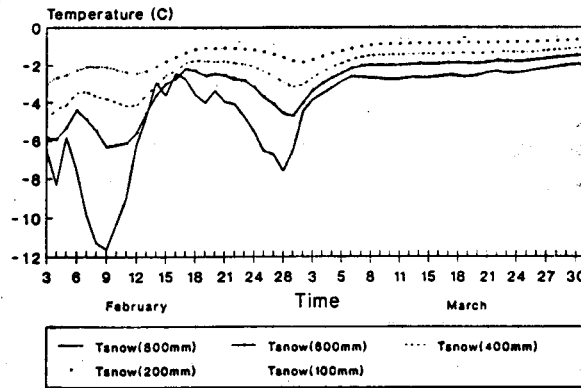
Figure 6. Five daily average snow temperatures (distances from soil surface) from 3 February to 30 March 1991 at Beaver Mountain

temperature offset was corrected in the computer, but could have been corrected using a −0·126 offset value in the data logger.

During active melt, maximum cavitation of 10 mm in diameter and 20 mm in depth was observed around the mono-filament support structure. Daily average snow temperatures at 10, 20, 40, 60 and 80 cm in the snowpack are shown in Figure 6 for February and March. Snow temperature data indicated that the upper snowpack became isothermal ($T_{snow} = 0°C$) around 30 April. Examination of hourly snow temperature data indicates that the entire snowpack became isothermal on 5 May.

Snow depth and precipitation

Snow depth measurements were made with an ultrsonic sensor mounted 3 m above the snow surface (Campbell Scientific Canada, Model UDG-01). Readings were taken every 30 seconds and averaged hourly during the early part of the study, and then averaged every 30 minutes during the active melt season. A detailed description of the design and operation of the sensor is provided by Goodison et al. (1984; 1988) and Tanner and Gaza (1990). In general, the distance to the snow surface is measured by an acoustic signal produced by an ultrasonic transducer. The distance from the sensor to the snow surface is determined by recording the time required for an acoustic signal to be reflected by the snowpack to the sensor. This distance was used to calculate the snow depth in the data logger.

Several factors affect ultrasonic snow depth measurements and are discussed in detail by Goodison et al. (1988). During this study, measurement accuracy was affected by the snow surface density, periods of heavy snowfall, or blowing snow. In northern Utah, new snow density averages are between 5 and 10% of the density of water. After heavy snowfall, the acoustic signal can penetrate the low density surface before reflecting back to the sensor, resulting in inaccurate measurements. Snow depth measurement accuracy improves as the snow surface consolidates. Observation during the study reflected discrepancies of ±30 mm in the early season, improving to ±5 mm during the active melt period.

Heavy snowfall or blowing and drifting snow can result in scattering of the transmitted acoustic signal and subsequent failure to receive a reflected signal. Frequent measurements (30 second intervals) were taken to minimize the effects of reflected signals on 30 minute average calculations. During the study 4485 averages were recorded of which 725 (16·2%) were invalid according to post-measurement data analysis. At least one valid reading was obtained for each 24 hour period. The longest time without a valid reading was 19·5 hours.

Acoustic snow depth sensors must be mounted perpendicular to the surface being measured to prevent signal deflection away from the sensor. For this reason, the sensor was mounted on a 1 m mast extended from the cross-member and angled to be parallel with the sloped snow surface.

Precipitation was measured with an unshielded, propane heated, tipping bucket type precipitation gauge. The propane heating element was difficult to keep running at the 2600 m elevation, resulting in a

discontinuous precipitation record, but a continuous record of precipitation was obtained during the period of active melt.

Heated precipitation gauge measurement accuracy is a function of convective heat turbulence (Bergman, 1982), wind speed, particle buoyancy and gauge location (Goodison *et al.*, 1981). Convective heat turbulence and wind produce most of the error in precipitation measurement. Larson and Peck (1974) compared shielded and unshielded precipitation gauges. They determined that catch error increased non-linearly with wind speeds and that shielded gauges measured precipitation amounts more accurately than unshielded gauges. Bergman (1982) reported that convective turbulence from heated precipitation gauges prevented some snow from entering the orifice during cold conditions with low density snowfall, but decreased with increased snowfall intensities. During this study, the precipitation gauge was sheltered from the prevailing winds by conifers and was located in a forest opening. Wind speeds were less than $2\,m\,s^{-1}$, minimizing possible errors due to the lack of a wind shield.

Precipitation temperature, T_r, was determined by taking an average value of three exposed TC junctions during precipitation events. This value was used to determine the contributions of Q_P to the snowpack energy budget.

SUMMARY

Estimation of snow energy balance components in remote mountainous regions requires the ability to continually monitor several meteorological parameters. This paper reports the measurement of net radiation, incoming and reflected shortwave radiation, air temperature gradients, snow temperature, relative humidity, wind gradients and direction, snow depth and precipitation. Each measured parameter was examined for performance in the extreme conditions of a mountainous site in northern Utah during the 1991 melt season.

Unattended remote measurement of solar radiation. albedo, relative humidity and snow depth were most problematic during this study. Reflected solar radiation values were overestimated, possibly due to selective absorption in the near infra-red. As a result, the calculated albedo values were lower than those reported elsewhere. Periodically, snow accumulation affected solar radiation and net radiation measurement during the study. Continuous measurement of relative humidity was possible during the whole study using a hygromechanical type sensor. An accuracy of ±4% resulted in a possible error of 20% in vapour pressure calculations and the slow response time limited the ability to detect rapid vertical vapour transport. Overall. reliable relative humidity data were obtained throughout the study period. Snow depth measurements were affected by snow surface density and heavy snowfall or blowing snow. These problems resulted in invalid snow depth measurements 16·2% of the time. The longest period without a valid reading was 19·5 hours.

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