Multidimensional Observation of Snow Temperature on Windy Days

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ABSTRACT

Three-dimensional field measurements of snow temperature in a shallow, seasonal snowpack were made during the winter of 1990–1991. The data show evidence of the thermal effects of windpumping down to depths of approximately 12 cm in a seasonal snow cover of 23-cm total depth. The air movement through the snow tends to decrease the local temperature gradient in the upper portion of the snowpack over the gradient that exists in windless conditions.

INTRODUCTION

The thermal response of snow to various meteorological conditions is important in remote sensing, infrared thermography, snow hydrology, and contaminant transport. In order to gain insight on the processes that occur in a seasonal snow cover, 3-dimensional field measurements of snow temperature were made during the winter of 1990–1991. The objective of the field test was to determine the thermal variability of a natural snow cover, to observe the effects of various meteorological conditions on snow temperature, and to observe naturally occurring thermal effects of air flow through snow. This paper is concerned with the flow of air through the snow due to effects of the wind, a phenomenon termed windpumping. Although it was an extremely mild winter characterized by a series of small snowstorms followed by warming and rain events, so that the shallow snowpack was often on the brink of extinction, some interesting data were collected near the end of January and in the early days of February that show evidence of the thermal effects of windpumping.

Several papers have been published that discuss field observations of windpumping. Reimer (1980) measured one-dimensional snow temperatures in a seasonal snow cover, and reported monthly averages of snow temperatures for various times of day. He used the data to determine effective thermal diffusivities of snow as a function of wind speed.

Field observations of windpumping effects have been reported by Clarke et al. (1987), who observed that upper-pack temperatures in glacial firn were warmer at a site that experienced more wind than at a nearby site that experienced low winds. They attribute the temperature change to viscous dissipation within the snow.

The purpose of this report is to make note of and discuss our field observations of multidimensional thermal effects of windpumping.

THE EXPERIMENT

In temperate climates like that of New England, the seasonal snow cover is almost always characterized by distinct layers of snow, with snow properties sometimes changing significantly between layers. In order to implement a three-dimensional snow temperature measurement in a manner that would preserve the integrity of the layers and possibly yield some insight into the behavior of the layered systems in nature, we planned that thermocouples would be laid in the snow in layers, with a layer of thermocouples being set down at the start of a snowstorm. Each layer was composed of 5 thermocouple rows, with 5 thermocouples per row. The first layer of 25 thermocouples was laid on a level sand surface at the start of winter. The next level of thermocouples was located in the snow approximately 12 cm above the sand/snow interface for the time period reported here, and approximately 11 cm of new snow covered the layer, so that the total snow depth was 23 cm. This was to be the deepest snowpack of the winter, for just after the period reported, a rain event and unseasonably warm weather eliminated almost the entire snowpack.

Although two layers of thermocouples do not constitute a definitive situation in terms of vertical temperature profiles, there is some evidence that the wind caused the temperatures midway down through the pack to deviate from their normal pattern. The nature of this disruption is discussed in more detail below.

THE OBSERVATIONS

The data discussed here came from the two layers of thermocouples (where there were 25 thermocouples arranged in a 10- × 10-cm grid spacing in each layer). Figure 1 depicts typical temperature reports for the layer of thermocouples on the ground and the layer midway through the pack, at a time when there was no wind. Note that the layer on the ground surface shows only minor temperature variations from the mean temperature at that location, while the mid-pack layer displays greater variations. The variation in temperature at the mid-pack location may be due in part to natural spatial variation in snow temperature, but in large part is most likely due to variations in thermocouple heights

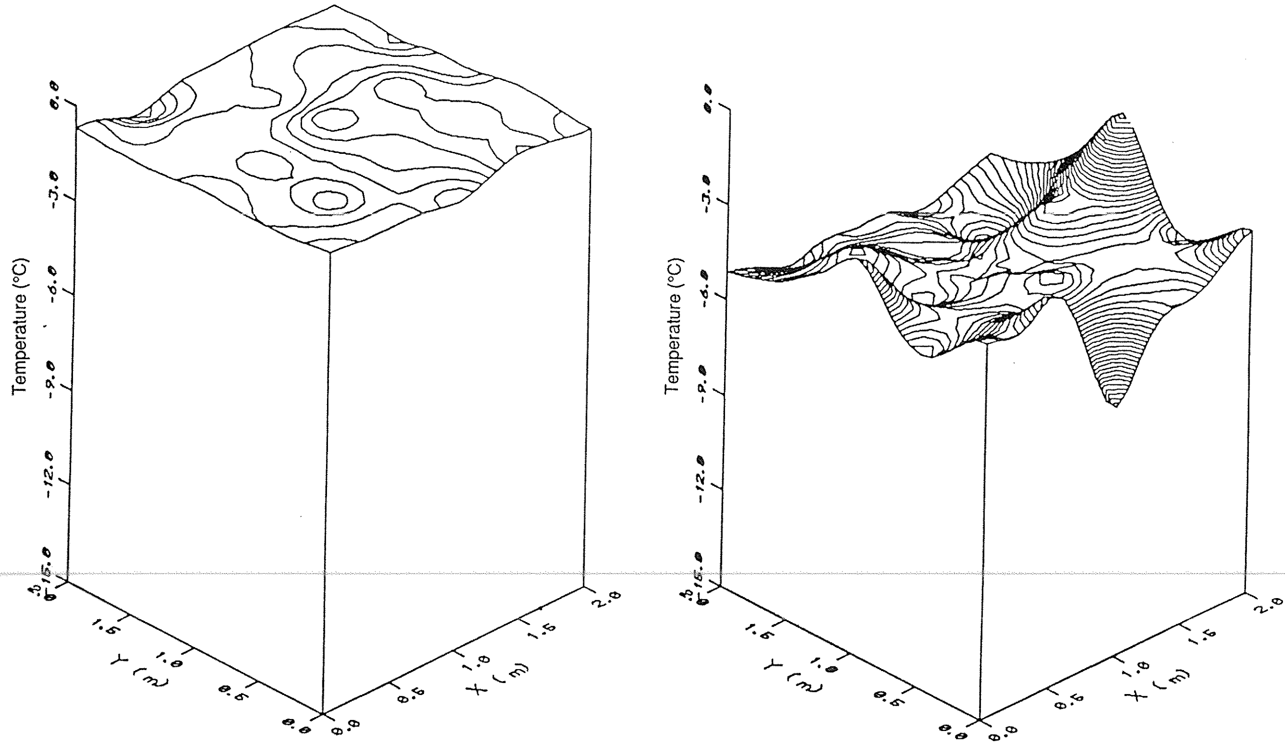

Figure 1. Temperature profiles at mid-pack and at the ground-snow interface for conditions "D" (see Fig. 7), 0600, 1 February 1991

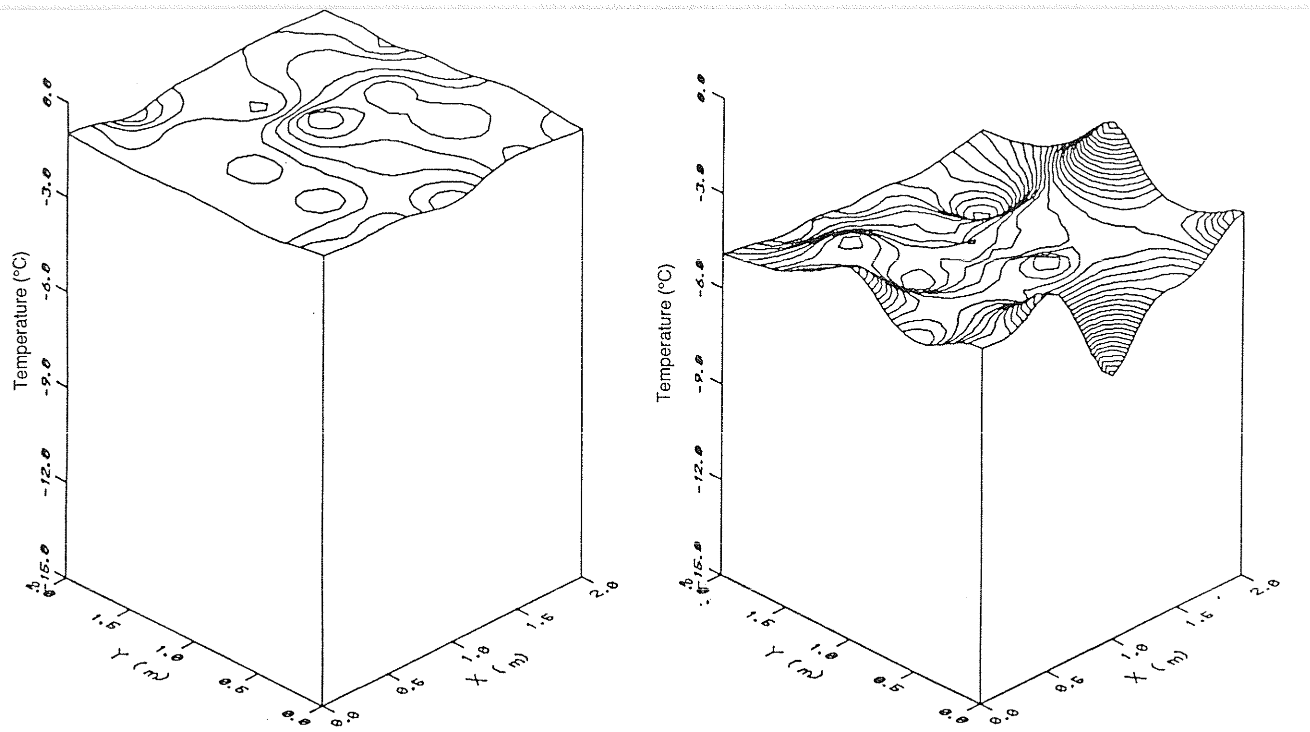

Figure 2. Temperature profiles at mid-pack and at the ground-snow interface for conditions "F," 1000 1 February 1991.

above the ground surface. The variations in temperature persist through meteorological changes, except for situations involving increased wind speed. In Figure 2, where the temperatures are plotted at a time 4 hours later, there is a noticeable decrease in the magnitude of the variations at the mid-pack level. During this time, the wind speed has increased from 0.2 to 3.2 m/s, but there has been no significant change in the air temperature or sand/snow interface temperature. We shall examine the data more closely in order to investigate this trend.

The meteorological data and snow temperature profiles cover a period of two days, starting at midnight on the last day of January, when there was no precipitation over this time period. For this period, the air temperature is shown in Figure 3, the solar radiation in Figure 4, long wave radiation in Figure 5, and the wind speed in Figure 6. The first thirty hours were characteristic of local weather following the passage of a cold front: a cold, windy, clear day, with the wind dying off near nightfall. A lesser wind blew on the second day, and around mid-morning on the second day, the air temperature warmed to above freezing. Figure 7 shows the average values, and high and low readings, for the layers of sensors on the ground surface and within the snow.

From Figure 7 we see that the mean temperatures of the snow/ground interface change less than 2.5°C over the 48-hour period, and we also note that the temperatures do not deviate much about the mean at that layer. This is not the case in the middle of the snowpack, where the mean temperature of the layer changes by 7°C, and the spread about the mean shows much greater variability in the center of the pack than at the bottom. The mean temperature at the center layer follows the trends in the air temperature over time.

We shall consider this variability in more detail. In Figure 8, the standard deviations of mean temperatures at mid-depth and at the bottom of the pack are shown. The standard deviation about the mean for the 25 readings at the snow/ground interface remains fairly constant, near 0.2°C, over the time period. However, the standard deviation about the mean temperature for the twenty-five sensors in the center of the pack ranges between 0.5° and 2.5°C in time. Such

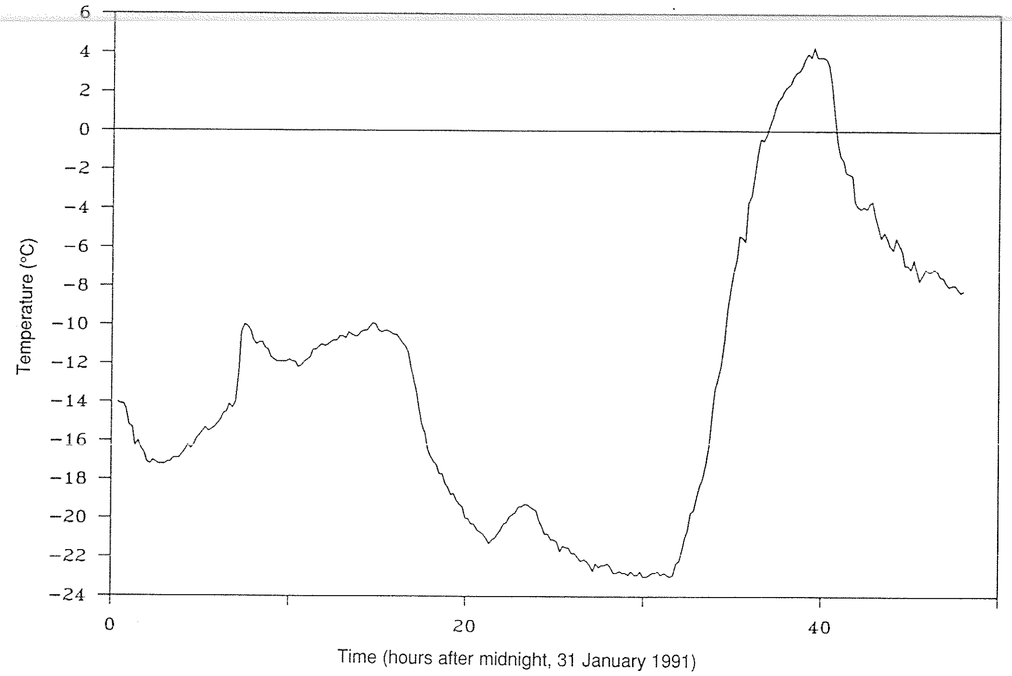

Figure 3. Air temperature (0.5 m) as a function of time.

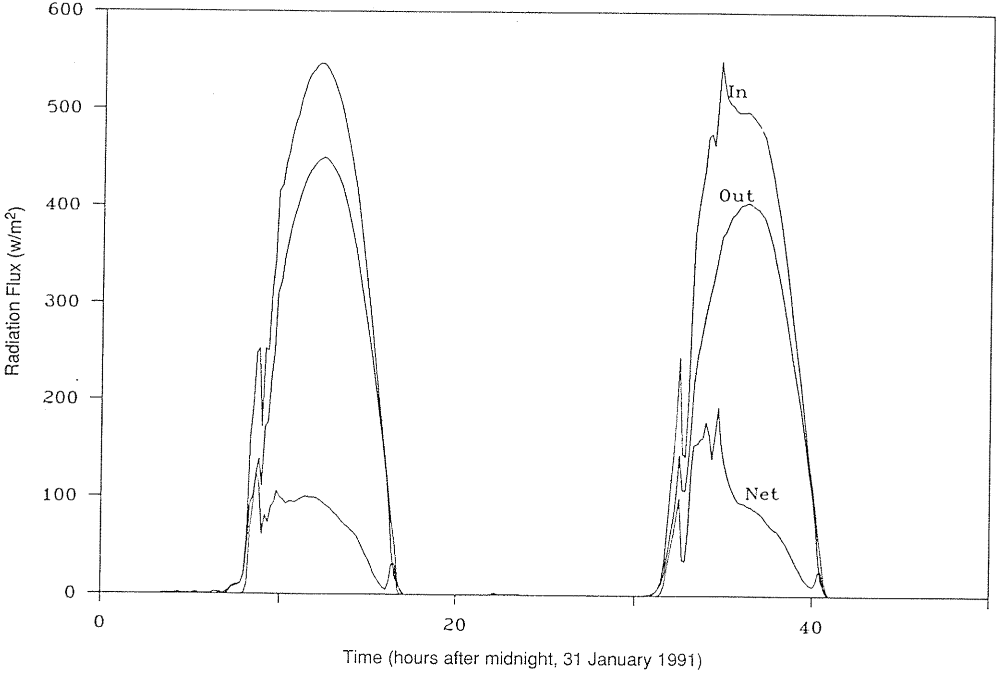

Figure 4. Solar radiation as a function of time.

variations at a single layer indicate a changing physics over time. At the center of the pack, the variation in temperature about the mean at a given time decreases substantially for periods of time when the wind is blowing, as is also evidenced in Figure 9 where the plot of the wind speed overlies the plot of the standard deviations.

Consider now the conditions between 0600 and 1600 on 1 February, conditions marked on Figure 7 as points "D" through "I." The half-meter air temperature during this time was approximately –12°C. The mean temperature for the center layer was near –4°C, but the difference between the high and low temperatures for that layer decreases over that

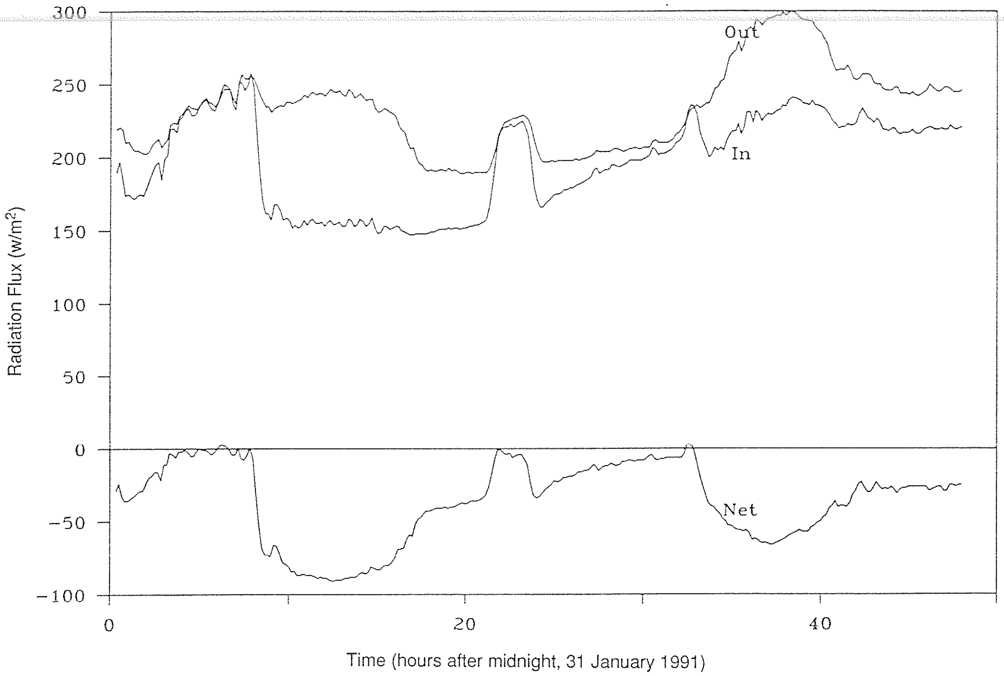

Figure 5. Long wave radiation as a function of time.

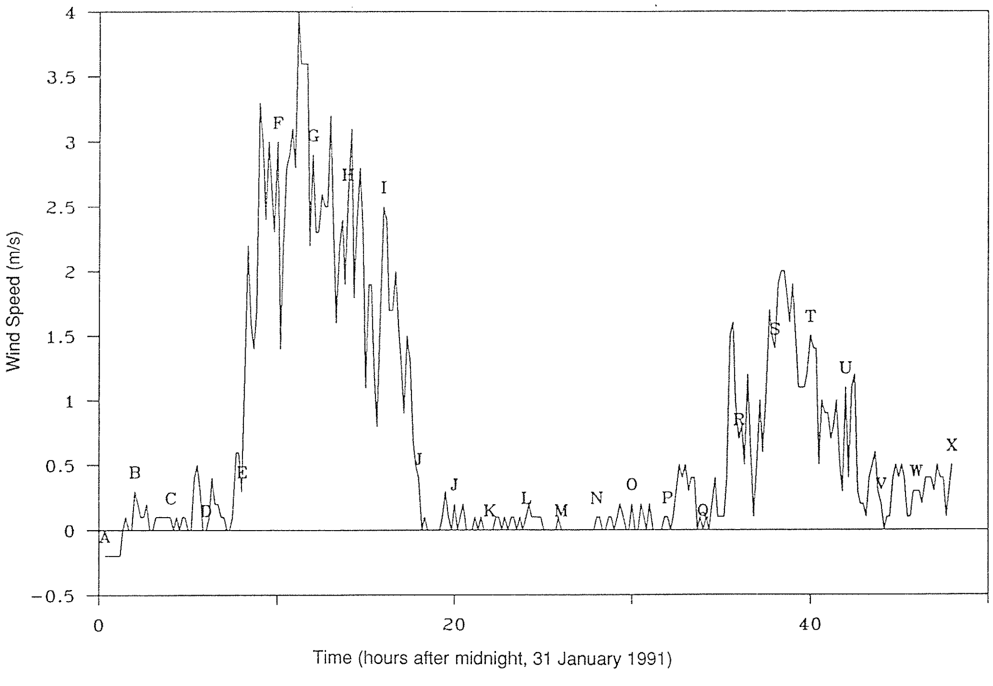

Figure 6. Wind speed (2 m) as a function of time.

time, while the standard deviation of the temperatures at that layer decreases from 1.3 to 0.6 °C. By inspection of the meteorological data, we see that the decrease in temperature variability reported at the middle layer follows a period where the two-meter wind speed was greater than 1 m/s. This decrease in variability of mid-pack temperatures is probably due to ventilation of the snow; the air movement through the snow tends to decrease the local temperature gradients in the snow for the ventilated areas of the upper part of the pack.

There is another, smaller wind event portrayed in this data set; this is the period of time between 0900 and 1500 on 2 February, times marked by symbols "S" through "V" in Figure 7 Again, the second layer shows a decrease in

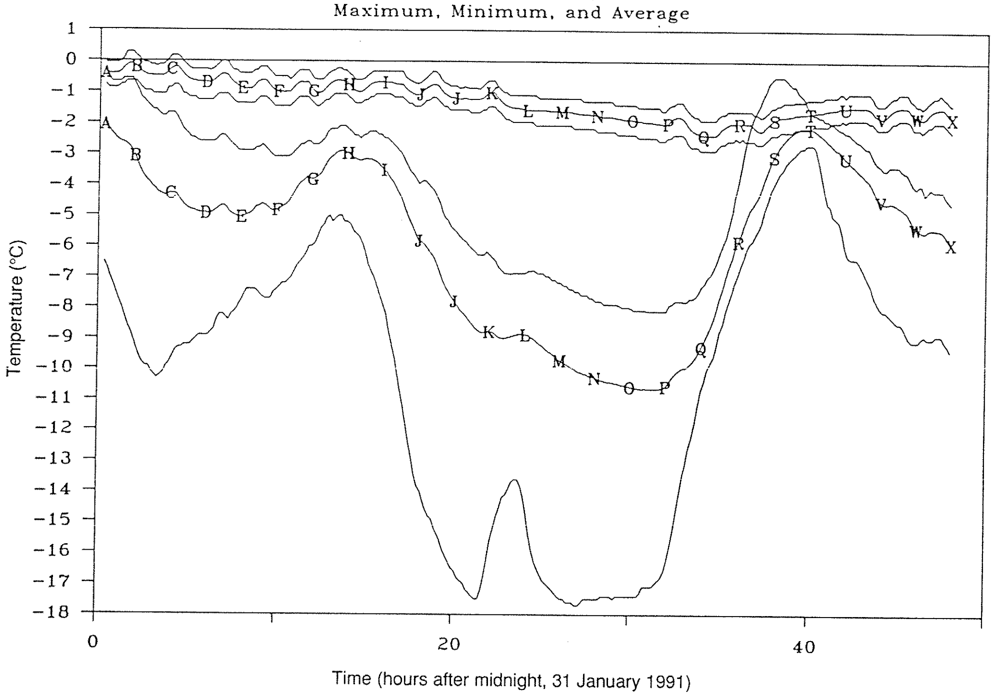

Figure 7. Snow temperatures at mid-pack and at the ground/snow interface, as a function of time. For each layer, the average of the 25 thermocouples, as well as the high and low temperatures recorded at that layer, are plotted.

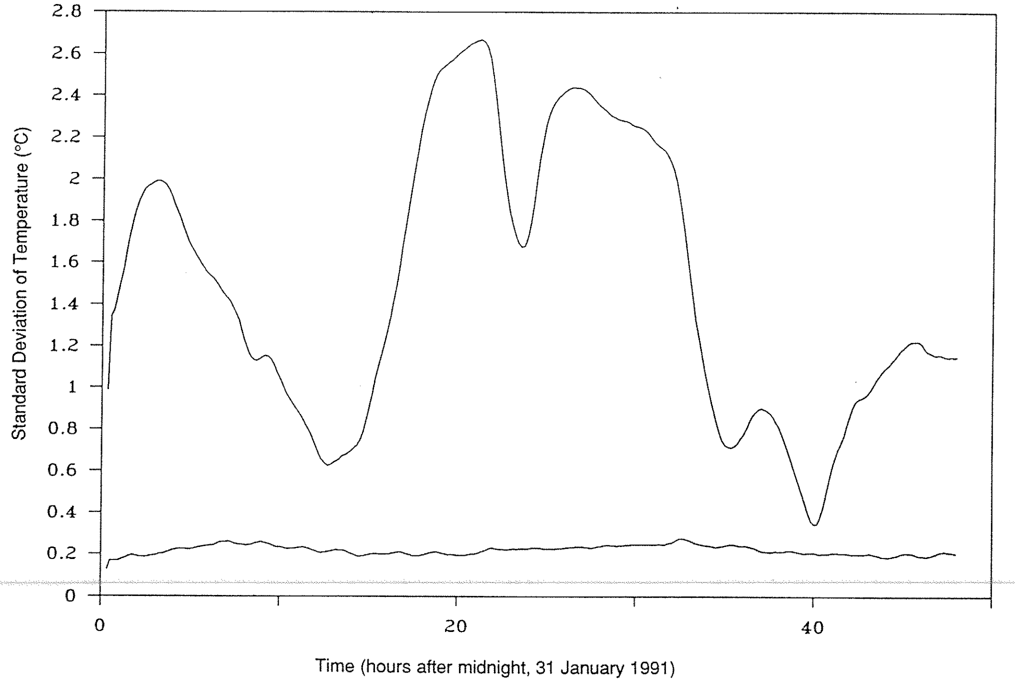

Figure 8. Standard deviation of snow temperature at mid-pack and at the snow/ground interface, as a function of time.

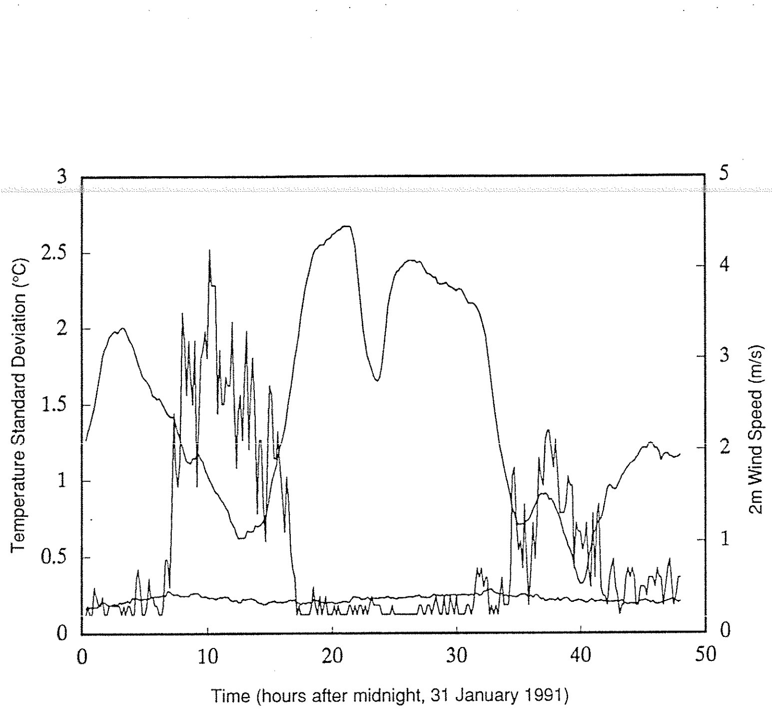

Figure 9. Standard deviation of snow temperature at mid-pack and at the snow/ground interface, plotted with wind speed, as a function of time.

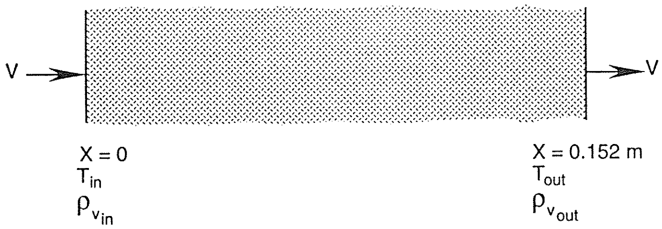

Figure 10. Schematic of one-dimensional snow ventilation investigation.

variability of readings during that time. It is, however, accompanied by a significant warming in the mean temperature of the snow layer over temperatures that the layer experienced several hours earlier. The snow warming is brought on by air temperatures rising at a rate of approximately 15°C per hour.

The hypothesis that forced air flow through snow can be a dominant purveyor of heat was explored in Albert and McGilvary (1991). That work documents a theoretical investigation of forced air flow through snow in a one-dimensional pattern, as depicted in Figure 10. We found that the resulting temperature profiles, depicted in Figure 11, arose mainly from the balance between the heat transported by convection of dry air and heat conduction driven by the temperature boundary conditions. In Figure 11, the solid lines represent the numerical solution, and the symbols represent published laboratory data (Yen 1962). It is evident that the effect of the air flow through the sample caused the temperature profile near the inlet to be more uniform than the profile that would exist from heat conduction alone. Although the temperature reports from the field data do not represent one-dimensional air flow paths, it is likely that pressure variations induced at the snow surface by the winds could provide the driving force necessary for air movement within the pack, especially in the upper portions of the pack. As in the one-dimensional case, the air movement could act as a mixing mechanism for heat transfer, and would tend to decrease the thermal gradients in the upper portion of the pack.

What else, apart from convection, could cause the variation in reported temperatures at a level to decrease? A decrease in the overall temperature gradient across the pack would accomplish this, although from Figure 3 it is evident

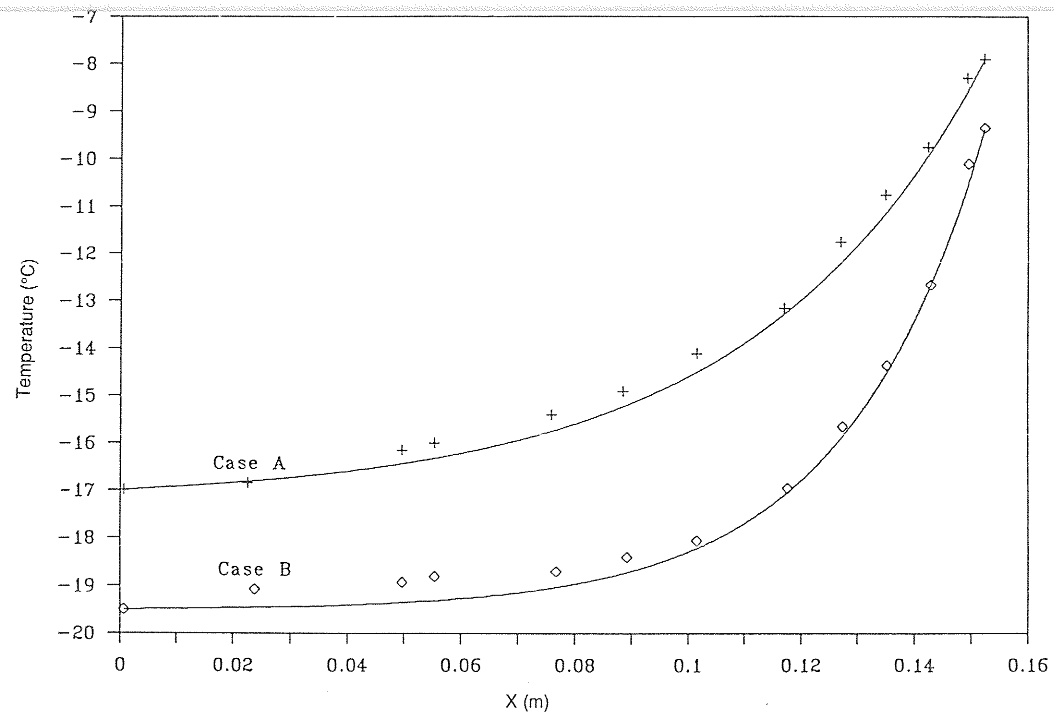

Figure 11. Temperature profiles resulting from the snow ventilation investigation. Solid lines are numerical results, and symbols represent laboratory data.

that the half-meter air temperature was −12°C or lower for that time period, while the temperatures at the soil surface remained near −1°C. Thus the reduction in variability near the mid-pack is not due to a reduction in the overall gradient. By inspection of Figure 4 we note that this wind event occurred during the daytime, so that the effects of radiation must be considered. In order to accomplish this, we pursue two ideas. First, we consider the variability of the temperatures correlated to wind speed and that correlated to radiation effects. Secondly, we present a simple theoretical analysis that shows that the radiation effects will not induce a large reduction in thermal variability at a depth of 10 cm.

DECREASED VARIABILITY AT 10 CM: RADIATION OR WINDPUMPING?

Statistical evidence

We first investigate some of the statistics associated with this data set. Recall that variability in reported snow temperatures of a layer is believed to be primarily caused by variations in vertical placement of the thermocouples in the snowpack. This being the case, for thermal conditions involving only heat conduction in the snow, the standard deviation of the mean temperature of a layer at a particular time would depend on the temperature difference over the snowpack. For example, if heat conduction rules the physics of the situation, the standard deviation of the mean temperature would be larger when there is a greater temperature difference over the pack, but should diminish when the overall temperature difference diminishes. The observation reported above shows that the standard deviation diminishes when the temperature difference over the pack stays approximately the same, and we think that this is due to forced convection effects in the snow induced by the pressure differences at the snow surface, which are brought about by the wind. In order to show that radiation effects do not have the same effect on the temperature variability, we will now examine several graphs in which the standard deviation of the mean temperature of a layer is plotted against the temperature difference between the air temperature and the mean temperature of the snow/ground interface. For these plots, the data portrayed in Figures 3 through 7 are sorted according to the conditions discussed below.

In Figures 12 and 13 the data for the thermocouple layer at the center of the pack is first sorted according to the wind speed. The standard deviation at the snow/ground interface is also depicted. For the conditions reported here, we observed that the snow temperature variability at mid-pack displayed a different trend when the wind speed was less than 0.6 m/s than for greater wind speeds, and now discuss this difference. The data points in Figure 12 correspond

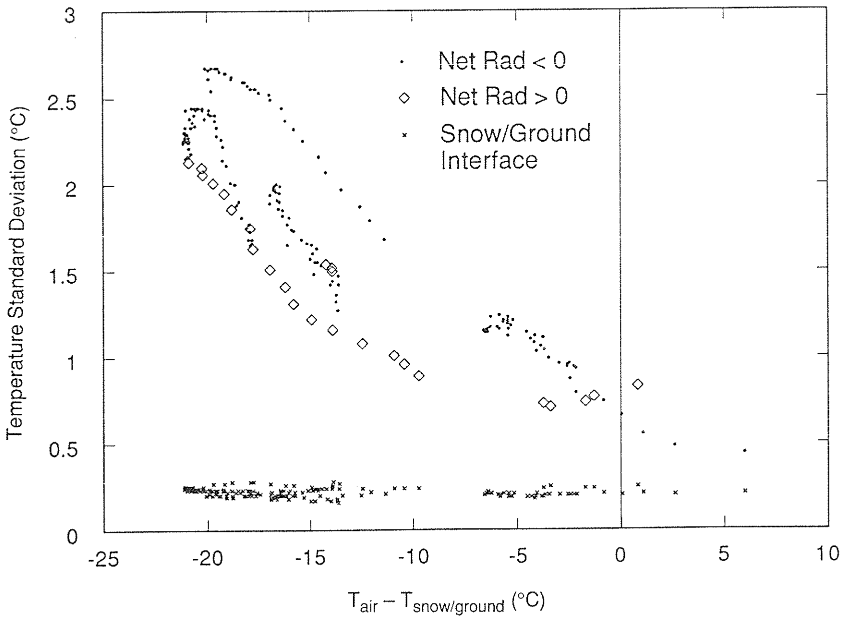

Figure 12. Standard deviation of snow temperature at mid-pack as a function of temperature difference over the entire pack, for wind speeds less than 0.6 m/s. Solid dots represent data when the incoming radiation was less than the outgoing radiation (net rad < 0), and diamonds represent data when the incoming radiation was greater than the outgoing radiation (net rad > 0). Crosses represent data from the snow/ground interface, for comparison.

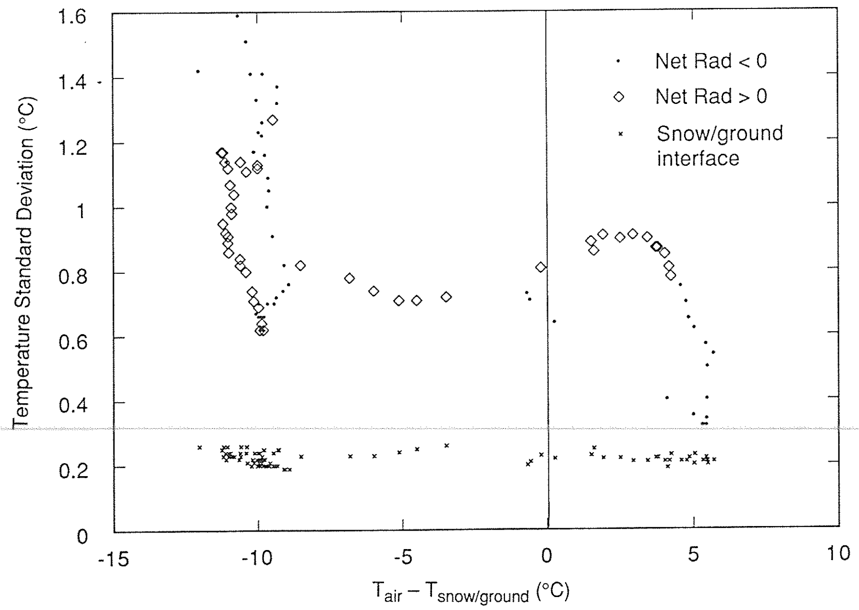

Figure 13. Standard deviation of snow temperature at mid-pack as a function of temperature difference over the entire pack, for wind speeds greater than 0.6 m/s.

to conditions when the wind speed is less than 0.6 m/s. We note first that the standard deviation of temperature decreases as the temperature difference between the air and the snow/ground interface decreases; as discussed above, this trend can be expected when the governing phenomenon is heat conduction. Also evident in the figure is that the variability (standard deviation) is slightly decreased when the incoming radiation is greater than outgoing radiation ("Net Rad > 0" on the graph). Thus solar effects can decrease variability slightly, but not enough to disrupt the temperature patterns significantly over those expected from heat conduction. In Figure 13, the standard deviation of the mean temperature is plotted for wind speeds greater than 0.6 m/s. The linear decrease in standard deviation per decrease in overall temperature difference is gone; there is no longer a correlation between the thermal variability within the pack and temperature difference over the entire pack. This indicates that in periods where the wind was in excess of 0.6 m/s, the temperature gradients in the upper portion of the pack were decreased. That is, the effect of windpumping is to make the temperatures in the upper portion of the pack more uniform than they would otherwise be.

Now for comparison, in Figures 14 and 15 the same data are sorted according to whether there is or is not solar radiation. Both plots still display the linear decrease in variability characteristic of the heat conduction, except for times when the wind velocity is greater than 0.6 m/s. It is evident from the trends portrayed in Figures 12–15 that windpumping effects have greater potential to diminish temperature gradients in the upper portions of the pack than do radiation effects.

Theoretical evidence

In order to provide a simple analysis that can be used to estimate the effect of solar radiation to disrupt the thermal regime from a linear heat conduction profile, we solve the heat conduction equation including the possibility of absorption of solar energy by the snow. The governing equation is

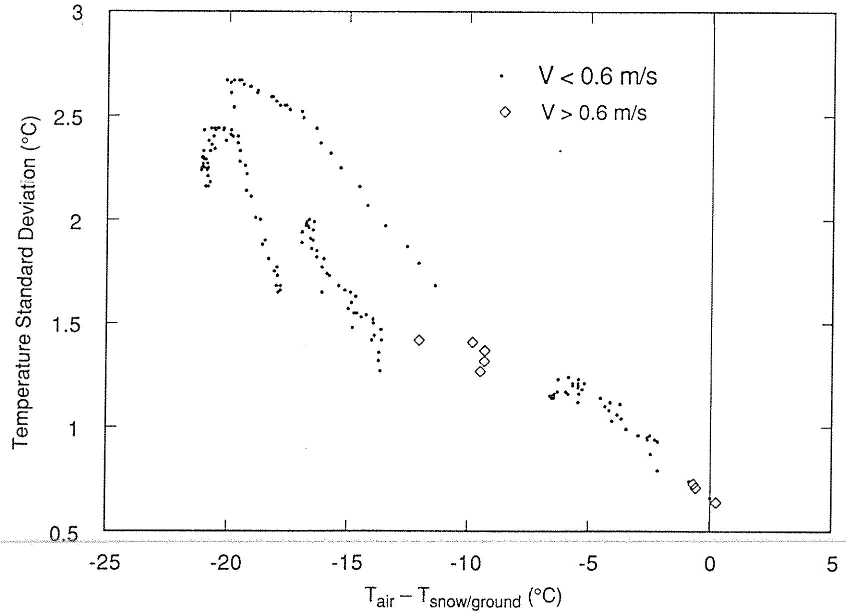

Figure 14. Standard deviation of snow temperature at mid-pack as a function of temperature difference over the entire pack, for data when there was no solar radiation. Solid dots represent data when the wind velocity V was less than 0.6 m/s, and diamonds represent data when the wind speed was greater than 0.6 m/s.

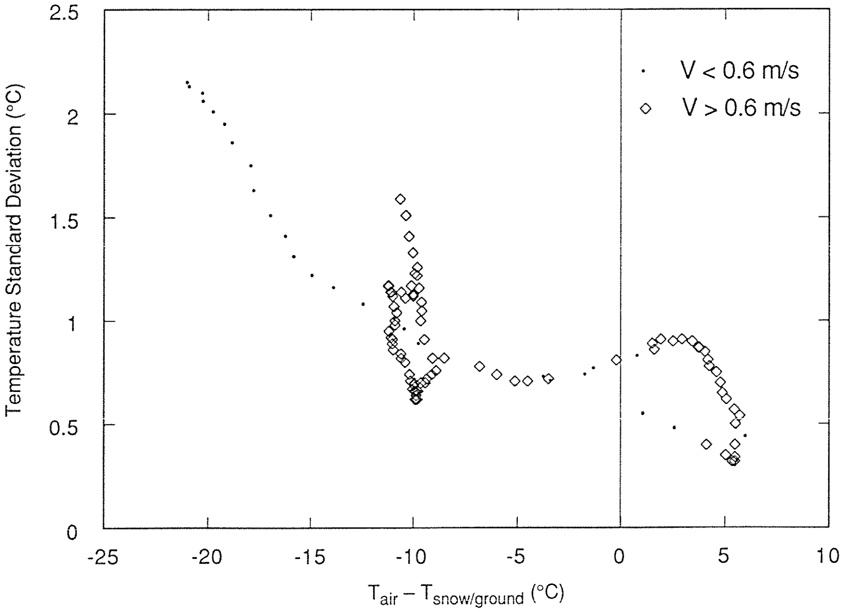

Figure 15. Standard deviation of snow temperature at mid-pack as a function of temperature difference over the entire pack, for data when solar radiation was present.

$$k\frac{\partial^2 T}{\partial x^2} - \lambda\, q_s\, e^{-\lambda x} = 0 \qquad (1)$$

where k = thermal conductivity
T = temperature
x = snow depth
q_s = heat flux due to solar radiation
λ = extinction coefficient.

The boundary conditions are $T = T_0$ at $x = 0$ (snow surface), and $T = T_L$ at $x = L$ (snow/soil interface). The analytic solution can be derived in a very straightforward manner from the homogeneous and particular solutions; the answer is

$$T = T_0 + \left[(T_L - T_0) + \frac{q}{k\lambda}\left(1 - e^{-\lambda L}\right)\right]\frac{x}{L} - \frac{q}{k\lambda}\left(1 - e^{-\lambda x}\right). \qquad (2)$$

This solution is plotted in Figure 16 for snow with total depth 25 cm, assuming that the incoming solar radiation is 100 W/m^2, snow surface temperature is –20°C, snow/soil interface temperature is –3°C, and that the thermal conductivity of the snow is 0.25 W/m K. The extinction coefficient, λ, varies from 7 to 10 cm “ in the plot. The straight line represents the heat conduction solution without the effects of solar radiation. It is evident that the effect of the radiation is to increase the temperature gradient near the surface of the pack, but for depths near 10 cm, which is approximately where the mid-depth thermocouple array discussed above was located, the solar radiation serves to warm the snow, but not to increase the local temperature gradient (e.g., the slopes of the two lines are approximately equal at depths between 8 and 12 cm). Thus this theoretical solution lends credence to the observation that the large reduction in temperature gradient, as evidenced by decreased variability at the mid-pack level in the shallow snow cover, must have been due to the wind. The effects of solar radiation could not have produced such an effect.

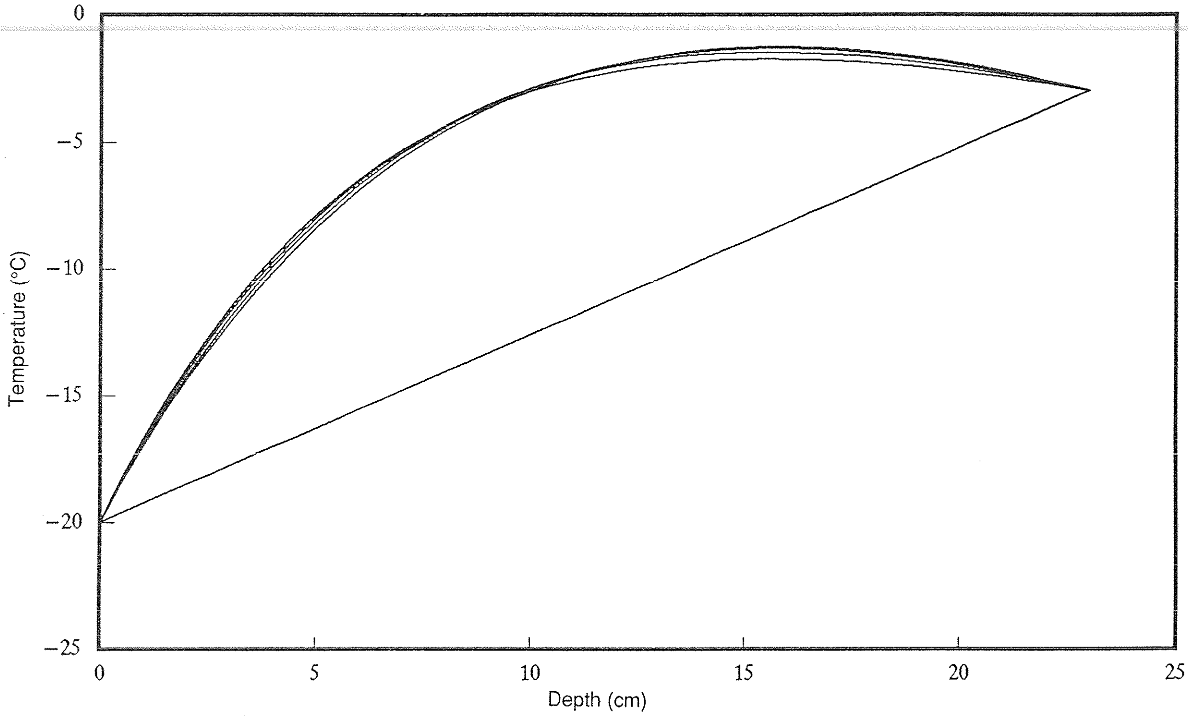

Figure 16. Effect of solar radiation on the theoretical temperature profiles for one-dimensional snow temperature. The curved lines represent the solution to the heat conduction equation with a source term for solar radiation, while the straight line is the solution to the heat conduction equation alone.

CONCLUSIONS

There is evidence in these data that even moderate winds can influence the temperature regime in the snow to change from the temperature regimes experienced in windless conditions. For the conditions reported here, the wind was shown to have a thermal effect at depths of approximately 10–12 cm in the snow. The nature of the effect is that the thermal variability near that depth is decreased.

The results presented above are convincing, but do not constitute a definitive study; more work is needed. Because the thermocouples were deployed in layers that moved with the snow, the precise location of the individual thermocouples is not known. Thus, while we speculate that most of the usual variability in temperature readings at a layer is due to a possible vertical displacement of the probes, this cannot be quantified at this time. In order to do more precise field observations of multidimensional profiles and to further isolate the effects, it will be necessary to devise a system whereby the sensors are fixed in space. Plans are underway to conduct such experiments during the 1991–1992 winter.

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