SNOW-SURFACE TEMPERATURE ANALYSIS

ABSTRACT

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Measuring the snow/air interface temperature of an undisturbed snowpack is a difficult problem. The problem results because of the instrumentation, the logistics of setting up the equipment, the dynamic nature of the snow surface, and the ill-defined location of the surface. Instruments such as thermistors, thermocouples, dew-point/frost-point hygrometers, and infrared radiometers have been used to measure or calculate snow surface temperature. This paper gives a detailed analysis of near snow-surface temperature measurements gathered at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire, and at a National Guard facility located at Hollis, Maine. These data provided simultaneous hourly or half-hourly surface temperatures for intercomparison of the instrumentation noted above during three winters of field experiments.

Introduction

This paper examines a number of sensors used to measure or calculate snow surface temperature. Meteorological data were gathered by instrumentation installed at three different heights with respect to the snow surface: at the snow surface (or as close to the snow surface as possible), 15 cm above the snow surface, and 2 m above the snow surface. Thermistors and thermocouples obtained temperature data at the snow/air interface. The precision infrared radiometer (PIR) measured the apparent radiative temperature; this was assumed to be the best estimate of the true surface temperature.

The data analyzed for this study were measured over portions of three winters between 1986 and 1988. The specific dates for each measurement period were 2-9 February 1986 at Fort Hollis, Maine, and 24-28 February 1987 and 16-31 January 1988 at CRREL, Hanover, New Hampshire.

The data from Fort Hollis, Maine, gathered at various heights above the snow surface, included apparent temperature with an inverted infrared radiometer, air temperature at 2 m, dew point and air temperature at 15 cm and 2 m with a frost mirror system, and snow surface temperature with a thermocouple.

The data from CRREL, Hanover, New Hampshire, during 24-28 February 1987, included apparent temperature measured with an inverted Eppley pyrgeometer (inverted infrared radiometer), air temperature at 15 cm and 2 m, and dew point at 15 cm and 2 m. Also data gathered at CRREL, Hanover, New Hampshire, during 16-31 January 1988 were apparent temperature, air temperature at 2 m, dew point at 2 m and snow surface temperature (22-31 January only).

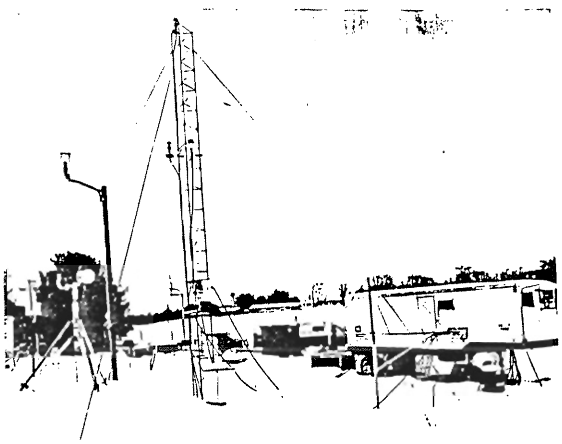
In order to determine the feasibility of using each measurement to estimate snow surface temperature, a linear regression analysis was performed. The analysis assumed that the apparent temperature measured with the radiometer was the actual snow surface temperature. A linear regression analysis was performed between the assumed true snow surface temperature and all other individual sensor measurements. This study was conducted using data collected hourly or half-hourly. This study initially addressed only near-surface air temperature. However, a report by Andreas (1) suggested a new method using the dew-point measuring snow-surface temperature, and, hence, dew-point temperature was included in the analysis.

Data Measurements and Site Discussion

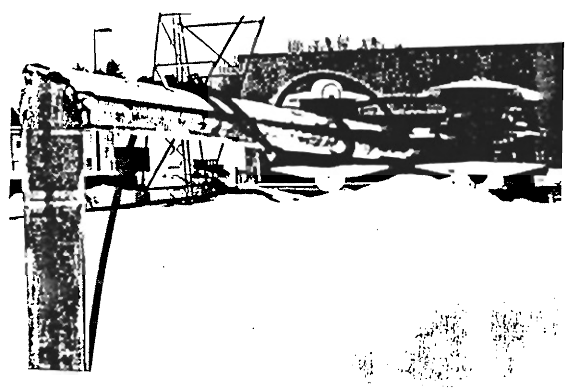
The instrumentation setup was generally the same for all three winters. The individual measurements were taken within a few meters of each other. Care was taken in collocating sensors so that the sensors did not physically interfere with each other.

Figure 1 shows a typical instrument setup for gathering and recording the necessary radiation temperature and dew-point data. The instruments used included an Eppley radiometer for measurement of reflected infrared apparent temperature data. A General Eastern 1200 MPS cooled-mirror dew-point hygrometer was mounted 8 cm above the surface for dew-point and air temperature measurements. A General Eastern Model 650/612A was also used to obtain air temperature data. Both the thermistors and thermocouples were mounted on snow stakes every 5 cm from the ground surface to above the snow surface to obtain the snow temperature profile and near-surface temperature as the snow accumulated.

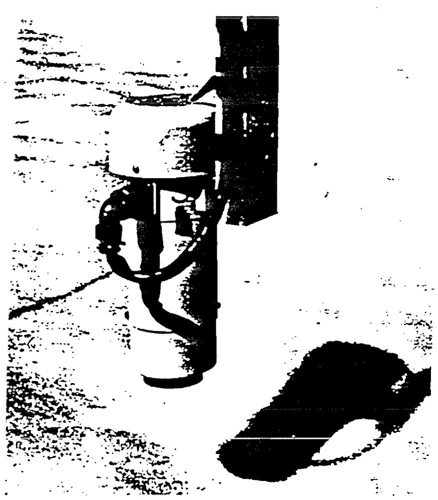
The hourly temperature data gathered at the two sites during three winters of measurement were analyzed. For the 1987 winter and four days of the 1988 winter, data taken



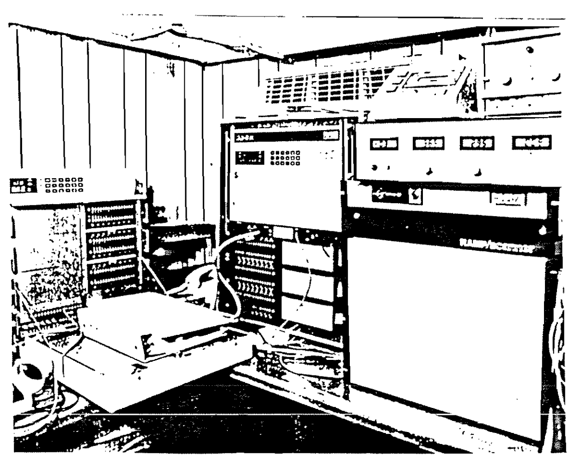
a. Typical instrument array.



b. Precision infrared and visible radiometers.



c. Cooled mirror with dew point and temperature sensors.



d. Data recording setup and supporting interfaces.

Figure 1. CRREL meteorological instrumentation.

Table 1. Hourly temperature comparisons for Fort Hollis, Maine (2-9 February 1986).

Date	No. data points (n)	Mean infrared temp.(°C)	Mean air temp. (15 cm)	Correlation* coefficient (r)	Mean dew-point temp. (°C) (15 cm)	Correlation* coefficient (r)	Mean air temp. (2 m)	Correlation* coefficient (r)	Mean thermo temp.	Correlation* coefficient (r)
Feb 1986										
2	24	-5.9	-3.6	0.72	-6.0	0.86	-2.0	0.65	-4.3	0.96
3	24	-15.0	-9.8	0.94	-13.8	0.65	-6.8	0.91	-11.1	0.99
4	24	-14.3	-12.6	0.99	-15.6	0.92	-11.1	0.97	-12.1	0.99
5	24	-5.8	-4.0	0.84	-5.8	0.82	-2.2	0.64	-3.5	0.73
6	24	-15.9	-11.9	0.96	-14.7	0.30	-8.9	0.95	-9.7	0.95
7	24	-15.6	-14.1	0.99	-20.6	0.79	-12.1	0.97	-11.6	0.98
8	24	-11.1	-8.1	0.96	-15.1	0.54	-6.0	0.90	-6.9	0.96
9	24	-15.7	-11.5	0.97	-18.9	0.60	-8.4	0.95	-10.2	0.99
Overall	192	-12.4	-9.4	0.99	-12.7	0.69	-7.2	0.91	-8.7	0.96

* Correlation of individual hourly temperature readings with infrared temperature (°C).

on a frequency of 30 min were analyzed. All other data were hourly temperature readings for each day. The radiometer readings were converted to temperature using the Stefan-Boltzmann law shown below:

$$w = \epsilon \sigma T_k^4$$

where w is the total radiant emittance, ϵ is the emissivity, σ is the Stefan-Boltzmann constant (5.6698×10^{-12} W cm^{-2} K^{-4}) and T_k is the absolute temperature. The emissivity for snow $\epsilon = 0.98$ was used to conduct the analyses. However, comparisons were made using emissivities of 0.95 and 1.00, and the results were not significantly different. The equation was used to solve for T_k, the absolute temperature. The absolute temperature was then converted to temperature in degrees Celsius. The analyses were performed assuming that the apparent surface temperature converted from the reflected infrared radiometer data was the dependent variable. Regression analyses were also performed for the hourly/half-hourly readings for each winter and finally for the combined data for all three winters.

Table 1 provides a summary of the data gathered at Fort Hollis, Maine, during the 1986 winter. From Table 1 it is quite apparent that, of the temperature sensors, overall thermocouples provide the best approximation of snow surface temperature. The correlation coefficients for all the days range from 0.73 to 0.99. The air temperature measurements taken at 15 cm and 2 m provide slightly less reliable estimates of snow surface temperature. The range of correlation coefficients was 0.72 to 0.99 for 15-cm and 0.65 to 0.97 for 2-m air temperature. Figure 2 presents 6 February data analysis results for the 2-m air temperature. Dew point temperature provides the least reliable estimates of snow surface temperature. Dew point temperature, however, is in the acceptable range for all days except 6 February (Fig. 3). It should be noted that it snowed on 5 February and that this may have had some impact on the poor correlation of the dew-point temperature with the PIR temperature measurements. This is probably due to the ingestion of snow by the dew-point aspirator.

The 1987 winter CRREL measurements are shown in Table 2. These data are 30-minute measurements taken on 24-28 February. For these five days, air temperature measurements at 15 cm and 2 m both correlated closely to the snow surface temperature as measured with the radiometer. The correlation coefficients ranged from 0.74 to 0.98 for 15 cm, compared to 0.85 to 0.98 for 2 m. The overall correlation coefficient for 2 m was 0.94. The correlation of snow surface temperature with the 2-m and 15-cm dew-point ranged from 0.74 to 0.85 and 0.77 to 0.91, respectively. This is considered to be quite acceptable. The overall correlation for all days combined was 0.75 for 2 m and 0.92 for 15 cm. Figure 4 presents the best fit results and the dew-point half-hourly measurements at 15 cm. Figure 5 presents similar results for air temperature at 2 m. Figures 6 and 7 show analyzed

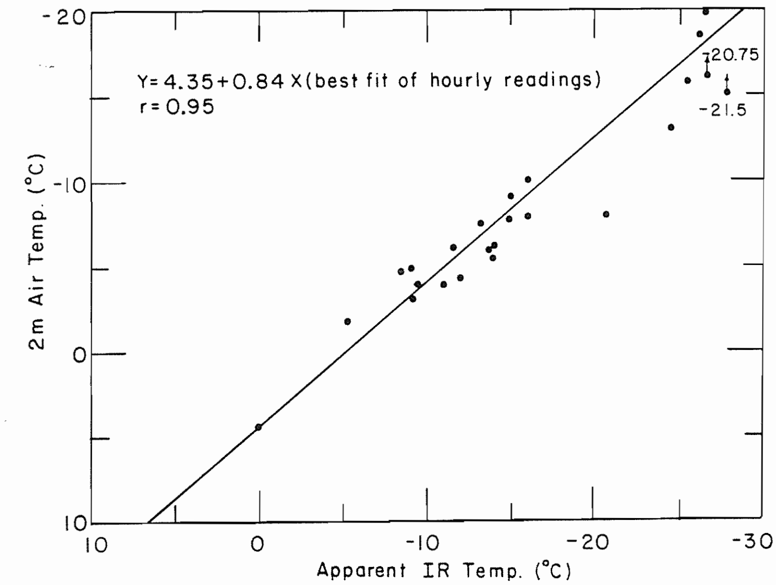


Figure 2. Dew point vs infrared temperature, Fort Hollis, Maine, 6 February 1986.

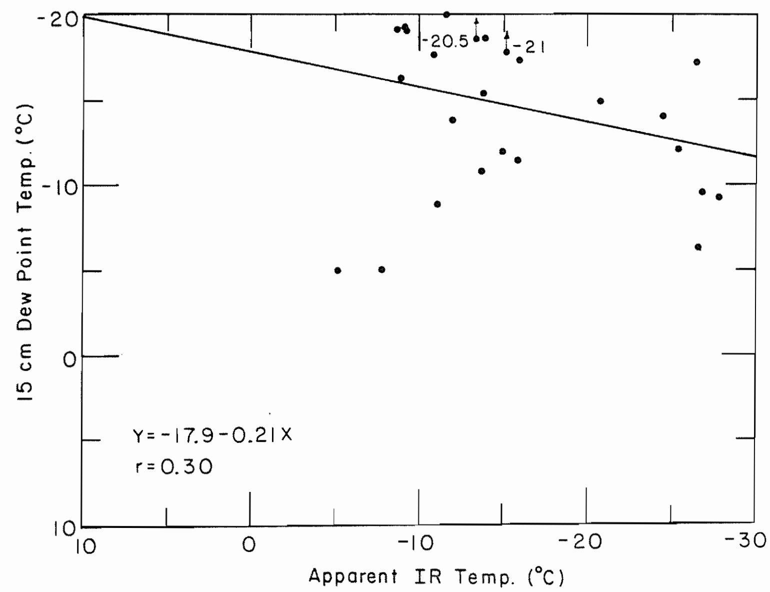


Figure 3. Air temperature vs infrared temperature, Fort Hollis, Maine, 6 February 1986.

results for dew point at 15 cm and air temperature at 2 m for the entire time period of 24-28 February 1987. It is evident from these two figures that air temperature and dew point can provide estimates of snow surface temperature.

The 1988 winter CRREL measurements are summarized in Table 3. Data measured from 16-27 January are hourly readings and the 21-31 January data are half-hourly measurements. Averages of the surface thermistor data also approximated the snow radiative surface temperature. The correlation coefficients ranged between 0.76 and 0.99. The 2-m air temperature measurements also correlated well with snow surface temperature. The correlation coefficients ranged between 0.59 and 0.97. Dew-point measurements also correlated well with snow surface temperature except for 27 February 1987. The correlation coefficient for that day was 0.30. Similar to the results obtained on 6 February 1986 at Fort Hollis, it snowed on 25 and 26 February at CRREL. Although snowfall occurred on only two days, it appears that using dew-point temperature to estimate snow-surface temperature may not be acceptable under these conditions. The range of the other days was 0.58 to 0.94.

Table 2. Half-hourly temperature comparisons - CRREL, Hanover, NH (24-28 February 1987).

Date	No. data points (n)	Mean infrared temp.	Mean air temp. (2 m)	Correlation* coefficient (r)	Mean dew-point temp. (2 m)	Correlation* coefficient (r)	Mean air temp. (15 cm)	Correlation* coefficient (r)	Mean dew point (15 cm)	Correlation* coefficient (r)
Feb 1988										
24	25	-6.5	-1.7	0.96	-10.5	0.84	-4.5	0.97	-11.1	0.77
25	48	-10.4	-4.4	0.95	-11.2	0.77	-7.7	0.97	-11.5	0.85
26	47	-10.5	-3.3	0.85	-9.8	0.83	-7.6	0.92	-10.5	0.91
27	47	-8.3	-1.8	0.98	-8.4	0.74	-7.2	0.74	-9.5	0.89
28	47	-5.5	-0.4	0.96	-6.5	0.85	-5.1	0.98	-6.6	0.87
Overall	214	-8.4	-2.4	0.94	-9.1	0.75	-6.6	0.90	-9.7	0.92

* Correlation of individual temperature with infrared temperature (°C).

Table 3. Hourly and half-hourly temperature comparisons - CRREL, Hanover, NH (16-31 January 1988).

Date	No. data points (n)	Mean infrared temp.	Mean air temp. (2 m)	Correlation* coefficient (r)	Mean dew point (2 m)	Correlation* coefficient (r)	Thermistor surface temperature	Correlation* coefficient (r)
Jan 1988								
16	24	-16.1	-9.6	0.93	-15.4	0.69	-	-
17	23	-7.4	-1.6	0.96	-10.2	0.92	-	-
18	24	-0.2	+3.4	0.59	-2.8	0.68	-	-
19	23	-1.6	+4.1	0.86	-4.7	0.75	-	-
20	24	-1.9	+2.0	0.94	-5.5	0.82	-	-
21	24	-0.8	+3.4	0.65	-4.2	0.88	-	-
22	24	-10.4	-4.6	0.92	-14.5	0.79	-8.0	0.98
23	24	-14.2	-9.1	0.90	-16.7	0.83	-14.4	0.99
24	24	-8.4	-4.9	0.95	-12.6	0.04	-8.3	0.98
25	17	-4.9	+1.2	0.97	-6.0	0.92	-3.4	0.99
26	19	-6.7	-1.	0.97	-9.6	0.92	-4.7	0.99
27	24	-22.4	-11.5	0.91	-18.8	0.30	-17.4	0.98
28	48	-23.0	-11.9	0.74	-18.4	0.58	-22.8	0.96
29	44	-19.9	-10.0	0.83	-17.0	0.85	-16.7	0.95
30	48	-2.4	+1.7	0.86	-3.3	0.92	-1.7	0.93
31	46	+0.8	+6.7	0.89	-2.1	0.84	+2.8	0.76
Overall	460	-8.5	-2.8	0.95	-10.1	0.91	-9.3**	0.98

* Correlation of individual temperature with infrared temperature (C).

** There were 318 thermistor data points and the mean infrared temperature was -11.4

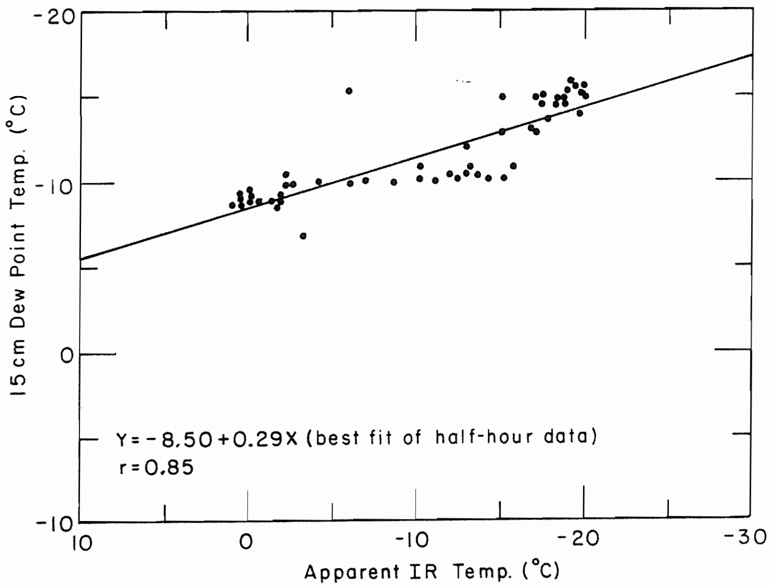


Figure 4. Dew point vs infrared temperature, Hanover, New Hampshire, 25 February 1987.

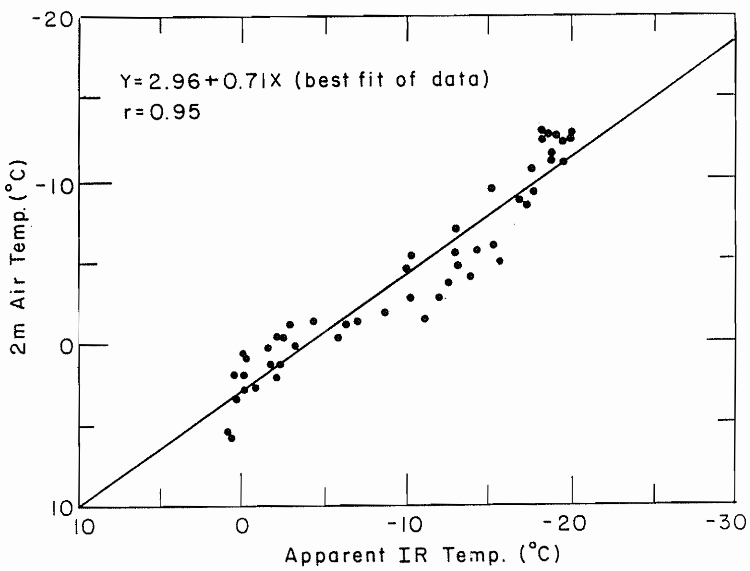


Figure 5. Air temperature vs infrared temperature, Hanover, New Hampshire, 25 February 1987.

Conclusions

It is evident that thermocouples and thermistors can be used effectively to measure snow surface temperature. However, they are not always practical in terms of manpower and maintaining proximity to the snow surface without disturbing the snow surface conditions. Air temperature measurements, which are much easier to obtain and are not dependent on undisturbed snow surface conditions, can be used to estimate snow surface temperature, but these measurements are not nearly as reliable as those from thermistor and thermocouple measurements. Table 4 summarizes the results of all three winters. These results show that air temperature can be used to estimate snow surface temperature regardless of the particular site or location of measurements. The best regression equations in Table 4 should be used to estimate snow surface temperature in any future tests. It is recommended that 2-m air temperature measurements be taken at various distances from the radiometer to obtain spacial determinations of surface temperature. These data could then be the basis for correlating snow surface temperature at various distances from routine

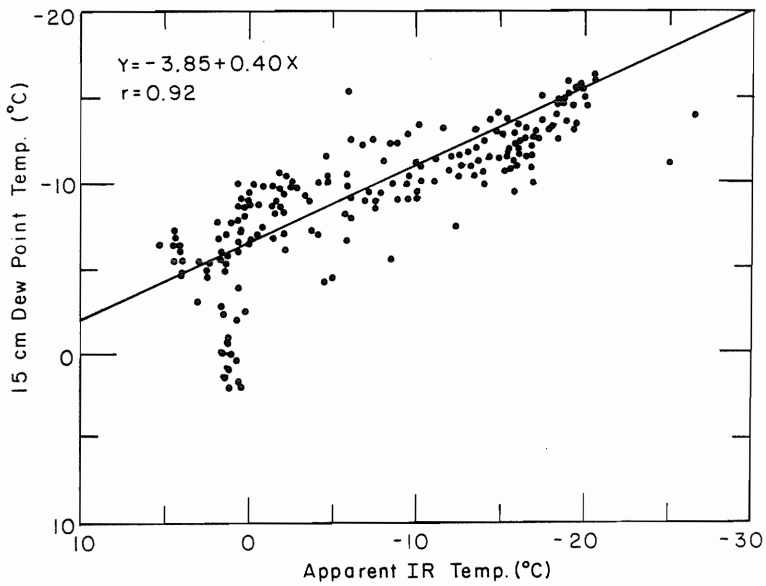


Figure 6. Dew point vs infrared temperature, Hanover, New Hampshire, 24-28 February 1987.

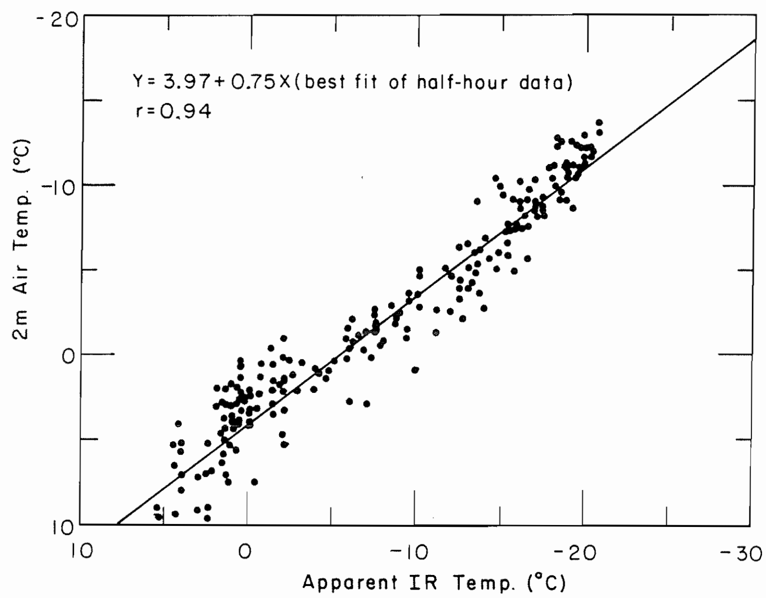


Figure 7. Air temperature vs infrared temperature, Hanover, New Hampshire, 24-28 February 1987.

air temperature point measurements. This method gives a better spatial distribution of surface snow temperature. Dew point measurement provides acceptable snow surface temperature estimates, but is not as practical as air temperature measurement from both manpower and cost considerations as well as being less accurate under cold, moist air mass conditions. In addition it appears that dew-point temperature may not be a good estimator of snow-surface temperature for 24 hours following a low water content snowstorm. Therefore, in terms of accuracy, the following sequence of instrumentation is recommended

1. Radiometer-apparent temperature
2. Thermistor/thermocouple
3. Air temperature
4. Dew point temperature

It should be noted that these analyses have been performed on hourly and half-hourly readings, and thus air temperature can be used effectively to estimate snow surface temperature at any instant in time. Certainly if the need is only to estimate average daily

Table 4. Comparisons of hourly temperature - data for 1986, 1987 and 1988 winters combined.

	No. of data points (n)	Mean air temp. (15 cm)	Mean IR temperature	Correlation coefficient (r)	Best fit* regression equation
Air temp. (15 cm) vs. IR	405	-8.0	-10.3	0.94	y = -0.2 + 0.75 x
DEW-point temp. (15 cm) vs IR	406	-11.1	-10.0	0.76	y = -6.1 + 0.5 x
Air temp. (2 m) vs. IR	866	-3.7	-9.3	0.94	y = 4.0 + 0.8 x
DEW point temp. (2 m) vs IR	532	-11.6	-9.5	0.90	y = -7.5 + 0.4 x

* Where y is the air or dew-point temperature and x is IR temperature.

or monthly temperatures, this report shows there are other possible alternatives for obtaining estimates or predictions of snow surface temperature than thermistors and/or thermocouples.

Acknowledgments

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