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Examining the Influence of Snow Cover on Morning Air Temperature

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ABSTRACT

There are large differences in mean minimum winter air temperature among very proximate New England stations. Daily differences are even greater when research sites are compared. We conducted a series of experiments, in morning twilight during the winter months, to examine the influence of topography and snow cover on early morning air temperature. We have proposed the hypothesis that the impoundment of the Connecticut River extending above the Wilder dam provides a temperature reference plane, allowing evaluation of physical factors modifying air temperatures adjacent to the reference plane. Analyses of surface air temperature with respect to elevation and distance along the Connecticut River valley show consistent vertical temperature structures that are related to snow cover. We present analyses of temperature structure and the relation of surface air temperature to vertical temperature structure in the vicinity of the reference plane.

INTRODUCTION

Hogan and Ferrick (1990) measured the warming of adjacent air by the latent heat released as ice cover thickened on the Connecticut River. Transects and cross sections of Connecticut River valley air temperatures obtained during these experiments included temperature differences as great as 12°C, with respect to elevation differences of tens of meters, and horizontal distances of hundreds of meters.

There are many winter-specific problems in atmospheric dispersion, hazardous waste remediation, hydrology, sanitary engineering, construction operations, and transportation that require knowledge of local air temperature, and/or vertical temperature structure. Meteorological observatories are sparse, relative to the area served by them, and the 12°C temperature difference observed is significant with respect to these problems.

A "river plane hypothesis" has been proposed by Hogan and Ferrick (1990, 1991, 1992) to establish a space, time and temperature coordinate system that will allow us to examine the physical mechanisms related to winter temperature differences along this valley. We assume that the air near the surface of the Connecticut River above the Wilder (Vermont–New Hampshire) dam equilibrates at a uniform overnight temperature. We then compare near surface air temperatures above other terrain along the Connecticut River valley to the river plane temperature, to examine terrain-induced temperature differences. Experimental verification of this hypothesis required measurement of air temperature above and adjacent to the river (Fig. 1). This paper describes an experimental test of the hypothesis, and applies the result to examine the variation of nearby air temperatures with respect to terrain and snow cover.

INSTRUMENTATION AND EXPERIMENTAL METHOD

These experiments examined techniques to extrapolate winter morning air temperatures through a defined region, based upon meteorological analysis of observations in that region. They also examined the physical cause of the large spatial variation in mean minimum and mean monthly temperatures reported (NOAA 1985), for winter months in areas of complex, snow-covered terrain.

There are numerous problems associated with measurement of air temperature near a snow surface, according to Andreas (1986). We measured air temperatures with a partially shielded thermistor, attached at a height

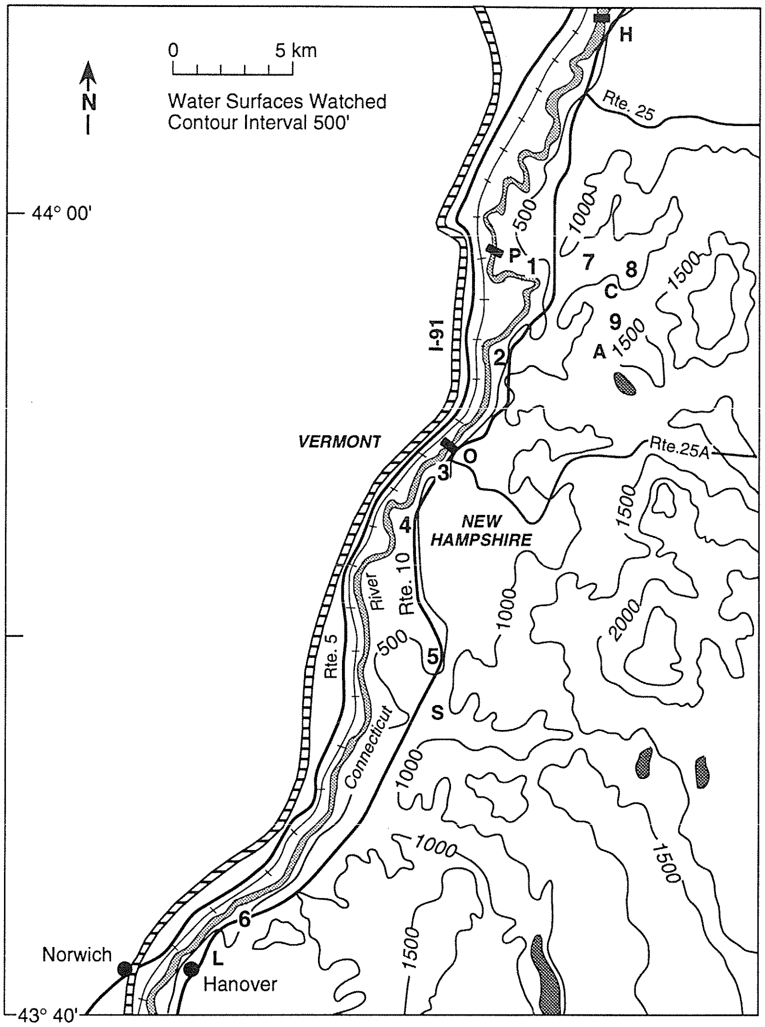

Figure 1. Connecticut River valley experiment area. Three bridges where over river temperatures were obtained are designated by H, P, *and* O. *Basins of essentially equal elevation along the river are designated by 1, 2, 3, 4, 5, and 6. A narrow* V*-shaped valley along a brook is at 7, and two basins lie at 8 and 9, well above river level. The measuring point of greatest elevation is at* A, *and* C *designates the location of quantitative daily snow depth measurements. Other designated points are defined in the text.*

of 1.5 m, on a moving vehicle. Experiments to estimate the time and space response of this measuring system, and the method of extraction of vertical temperature structure from the observations, were described in Hogan and Ferrick (1991). The thermistor responds to a change in air temperature integrated over a path of 60 to 300 m at typical rural road speeds. We assumed that a continuum of air temperature is present over the 5- to 15-m width between snowbanks of a rural road, and that the thermistor was bathed in undisturbed air. These assumptions were found valid in the initial experiments. We chose this technique because it provides comparable air temperature measurements at numerous sites in a minimum of time, eliminates installing instruments on private land, and does not require daily verification of all thermistor heights during the snow season.

The experiment area is shown in Figure 1; the locations of individual measurement points were given in Hogan and Ferrick (1990, 1991). The measuring point of highest elevation at the apex of a ridge is noted by A, and fixed site temperature measurements are available at an affiliated experiment site C and at CRREL, noted by L. Three bridges where air temperatures were measured a few meters above the river are denoted by H (Haverhill), P (Piermont), and O (Orford). A special series of observations, along A–H–P–O, were made during January and February 1992 to examine air temperatures directly above the river. Air temperatures were regularly measured along the path A–P–O–L on working days and along A–P–O on weekends and holidays.

The measuring points were chosen to include several "cold air drains" and locations similar to those representative of microclimates given by Geiger (1965), but more specific recent studies dominated the experiment plan. Measuring points reflecting hamlets (Landsberg 1981), basins (Maki et al. 1986), slopes (Maki and Harimaya 1988), barriers (Baines 1979), forest edges (Li et al. 1990), and forest/field boundaries (Rayner

1971) were selected to examine these influences, with respect to the river plane and the other features.

We limited the experiment to the time of morning twilight, and prior to local sunrise, constraining the observations to a 70- to 90-minute period each day. This is most frequently the period of minimum surface air temperature, the time of minimum rate of air temperature change, and a time at which minimal radiational heating of temperature sensors will occur. These measurements are part of an in-situ, real-time experiment, and not an attempt at climatology. No data were rejected after collection but measurements were discontinued on several days when liquid precipitation or supercooled fog caused instrument icing. The data include temperature and snow depth observations completed during the months of December, January and February, beginning December 1990 and ending February 1993.

Nakamura and Magono (1982) quite successfully modeled the horizontal distribution of winter temperatures in Hokkaido, but were not able to model the extremely cold air found in small basins and narrow valleys. They conducted an additional field experiment in the Moshiri Basin, the coldest in Hokkaido, and found an inversion to form more rapidly in the basin, decoupling it from the down-valley winds that continued to circulate heat much longer through the night along the slopes. Our study included six basins near river level, and two basins and a V valley (Yasudo and Sato 1986) 100 to 200 m above river level, defined in Figure 1. These basins contain multiple measuring points to experimentally examine the Nakamura and Magono (1982), and Magono et al. (1982) theories of winter basin cooling.

There is considerable anecdotal evidence (e.g., Boshart 1980, Kebschull 1984) that forecasts of surface temperatures less than –18°C will be verified only if snow is present on the ground in the northeastern states. Lower air temperatures above snow-covered ground are a result of enhanced coupling of the lower atmospheric layers to the snow, as described by Miller (1956). A daily quantitative snow measurement was made at C in Figure 1. Qualitative snow observations were made at several other points each day by estimating snow depths with respect to fixed objects as done in Hokkaido, and by visually estimating the relative area of bare spots. Comparison of the quantitative and qualitative observations indicated that the observation at C numerically characterizes the snow cover along the Connecticut River valley as defined in Table 1.

Table 1. Definition of snow depth categories.

< 1 cm	This is reported for some early winter observations and some days following thaws when snow is absent from the basin.
< 3 cm	This is associated with sparse, or discontinuous remnant, snow cover in the Connecticut Valley
< 10 cm	This is associated with general snow cover, but bare or sparse spots occur in fields and on southern exposures.
< 30 cm	This is associated with nearly total and continuous snow cover.
> 30 cm	This is associated with total and continuous snow cover at all locations.

The snow depth and cover parameters, defined in Table 1, will be used with air temperature parameters to objectively examine temperature–snow cover dependence. The less-than-1-cm and less-than-3-cm snow depth categories are combined for some of the analyses, as bare ground is dominant in both cases. Most of the days with >30 cm of snow occurred in February. An additional 20- to 30-cm-depth category has been used in the analyses to examine the consistency of the data through the winter months.

RESULTS OF EXPERIMENTS

The initial analyses of these data indicated that the coldest morning air was consistently found at one of three places. These were at the apex of observations A; in basin 8; or at bridge P (Fig. 1). The least air temperatures measured on each of 158 mornings during three consecutive winters were categorized with respect to concurrent snow depth, and summarized in Table 2. The temperature difference between point A and basin 8 was used to determine if lapse or inversion conditions were present in the valley on each day. The number of occur-

Table 2. Air temperature with respect to snow cover, December 1990 to February 1993.

Snow cover (cm)	*N*	*> 0*	*0–5*	*5–10*	*10–15*	*15–20*	*20–25*	*25–30*	*30–35*
		No. of occurrences							
> 30	17	0	1	4	1	2	3	4	2
10–30	73	4	13	13	14	12	8	8	1
3–10	38	2	8	8	7	6	5	2	0
1–3	14	2	2	3	2	4	1	0	0
< 1	16	5	3	2	1	3	2	0	0
All	158	13	27	30	25	27	19	14	3

Temperature range (°C) applies to columns > 0 through 30–35.

Table 3. Occurrence of lapse and inversion events, winters 1990–1993.

Snow depth (cm)	No. of events Inversion	Lapse	Lapse while snowing
> 30	9	0	5
20–30	19	3	3
10–20	21	8	3
3–10	25	13	5
1–3	18	6	4
< 1	7	6	0

rences of lapse or inversion is given in Table 3; inversion is present on about two-thirds of mornings. There were three days in the lapse-while-snowing category when a complete temperature data set was not obtained. The categorized snow depth measurements at C have been used in conjunction with the presence of lapse or inversion to stratify the analyses of the temperatures that follow.

The mean temperature–elevation profiles for days with lapse are shown in Figure 2. The mean temperature difference at each elevation, with respect to the river level temperature at (P), is plotted for each snow category, and the number of occurrences in each category is given in the data block. The mean lapse rate in the valley on these days is about 6°C/km but there are many isothermal layers. The number and thickness of these isothermal layers increases with increasing snow cover, and the mean lapse rate below 330 m is about 2°C/km,when there is more than 30 cm of snow at C. The temperature inflection near 200 m on the trace representing <3 cm of snow may be related to cold air drainage in the V (valley) located at 7 in Figure 1; this

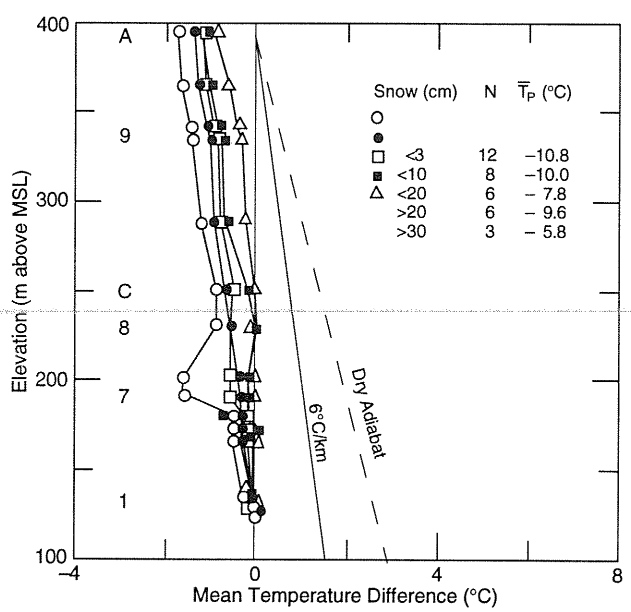

Figure 2. Mean temperature structure in the Connecticut River valley stratified by snow depth, for days with lapse above 230-m elevation. This is not the full data set given in Table 1; it includes only the days corresponding to Table 3 and Figure 4 to allow direct comparison.

layer corresponds to that occupied by fog in the fall. The data in Figure 2 verify that a diminution of temperature difference between the apex of observations and river level does occur in response to deepening of snow at C, and more continuous snow cover through the valley.

The mean temperature difference profiles for days with inversion above 230 m are given for the same snow depth categories in Figure 3. Inversion strength increases in proportion to snow cover at C and comparison of data blocks in Figures 2 and 3 shows a greater number of inversions coincide with greater snow depth at C. The temperature inflections corresponding to basins 1 (140 m); 8 (230 m); 9 (330 m) and the base of the V valley (180 m) indicate additional inversions at these places.

The formulation of mean lapse rates and inversion parameters, with respect to the influence of snow cover described above, allows objective, mathematical analysis of the surface temperatures along the river. The analysis was enhanced by dedicated experiments measuring the temperatures on the bridges denoted by H, P, and O, in Figure 1, with a minimum time difference separating the measurements. The bridges vary by only a few meters in elevation, and are radially separated by 10 (H–P) and 8 (P–O) km. Although only 15 days of data were obtained in the dedicated experiments, the frequency of lapse and the distribution of temperatures approximates the full data set. Only snow depth, which did not exceed 30 cm, differs from the longer record.

The temperature differences observed on these 15 days are stratified according to the snow cover and stability parameters coincident with the observations in Table 4. The mean temperature differences are less than one degree, but point to point differences exceed one degree on 8 of 45 opportunities. Only one observation of temperature difference exceeding one degree occurred

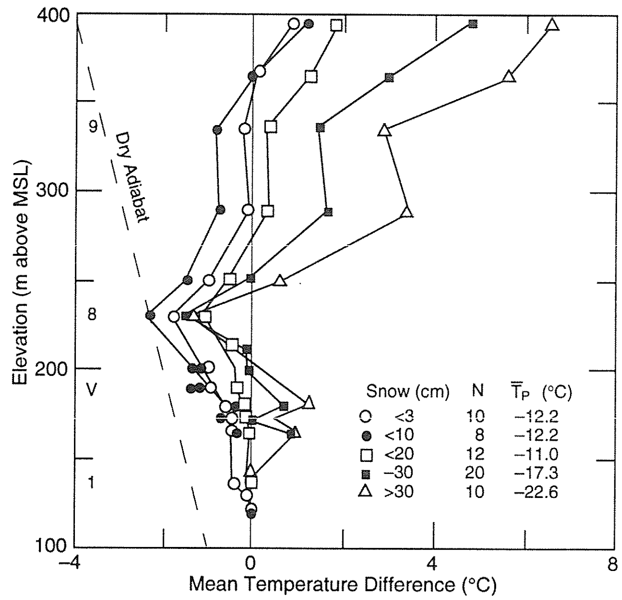

Figure 3. Mean temperature structure in the Connecticut River valley stratified by snow depth, for days with inversion above 230-m elevation. Again, the data corresponds to that of Table 3 and Figure 4.

with lapse conditions. Table 4 indicates that point-to-point temperature differences may increase under inversions. We previously (Hogan and Ferrick 1992) applied empirical dimensional considerations, like those given in Stull (1988), but not stability, to compare the temperature variation along the river. We now have a sufficient number of data points to examine the influence of stability and snow cover on temperature differences along a 30 km section of the Connecticut River.

There are 70 days of data available to analyze air temperatures measured along A–P–O–L with respect to stability and snow depth. This has been done by defining contiguous basins of nearly equal elevation (Fig. 1), and calculating the mean air temperature in the basin coincident with the snow depth categories. A north–south cross section of elevation of these basins is given in Figure 4. The cross section A–P is projected to an imaginary extension of the N–S axis, repeating basin 1 in both sectors.

When lapse is present the air temperatures in basins 1, 2, 3, 4, 5, and at the elevated points from basin 5 to S vary less than 1.1°C with respect to the air temperature at P. These air temperatures are quite precisely related to that at P through elevation and lapse rate.

The mean basin air temperatures coincident with snow depth category under inversion conditions are plotted in Figure 4b. When snow is sparse, several basins within 20 km south of P are systematically cooler than P, and many inflections correspond to elevation changes. This may reflect cold air drainage, as these are foggy basins in autumn. Increases in snow cover are accompanied by relatively greater air temperature in basins 2, 3, 4, 5, and on the higher ground surrounding S. The basin temperatures, including basin 6, 30 km distant from P, are less than 1°C in excess of the temperature at P under most conditions, and 2°C in excess when snow depth exceeds 30 cm.

The air temperature at S systematically exceeds the air temperature at basin 8 by an increasing amount as snow depth increases. The mean difference at these two points of similar elevation is 6°C over 30 cm of snow and 3°C over other lesser snow covers. Basins of similar distance separation at lower elevation differ in temperature by less than 1°C except at times of 30-cm snow cover. It appears that the inversion based at 230 m is not uniform over the Connecticut River segment

Table 4. Temperature differences among three bridges (O–Orford, H–Haverhill, P–Piermont).

Snow depth (cm)	*Temp diff (°C)* O/P	H/P	O/H
Days with lapse			
> 10	0.2	0.0	0.2
3–10	0.1	0.1	0.2
	0.5	1.3	0.8
< 3	0.1	0.5	0.4
	0.7	0.3	1.0
	0.4	0.4	0.0
Days with inversion			
>10	0.5	0.0	0.5
	2.3	0.3	2.6
	0.5	0.0	0.5
3–10	1.8	0.6	1.2
	0.3	0.1	0.2
<3	0.8	1.0	0.2
	0.0	1.2	1.2
	0.5	0.3	0.2
	0.8	1.0	0.2

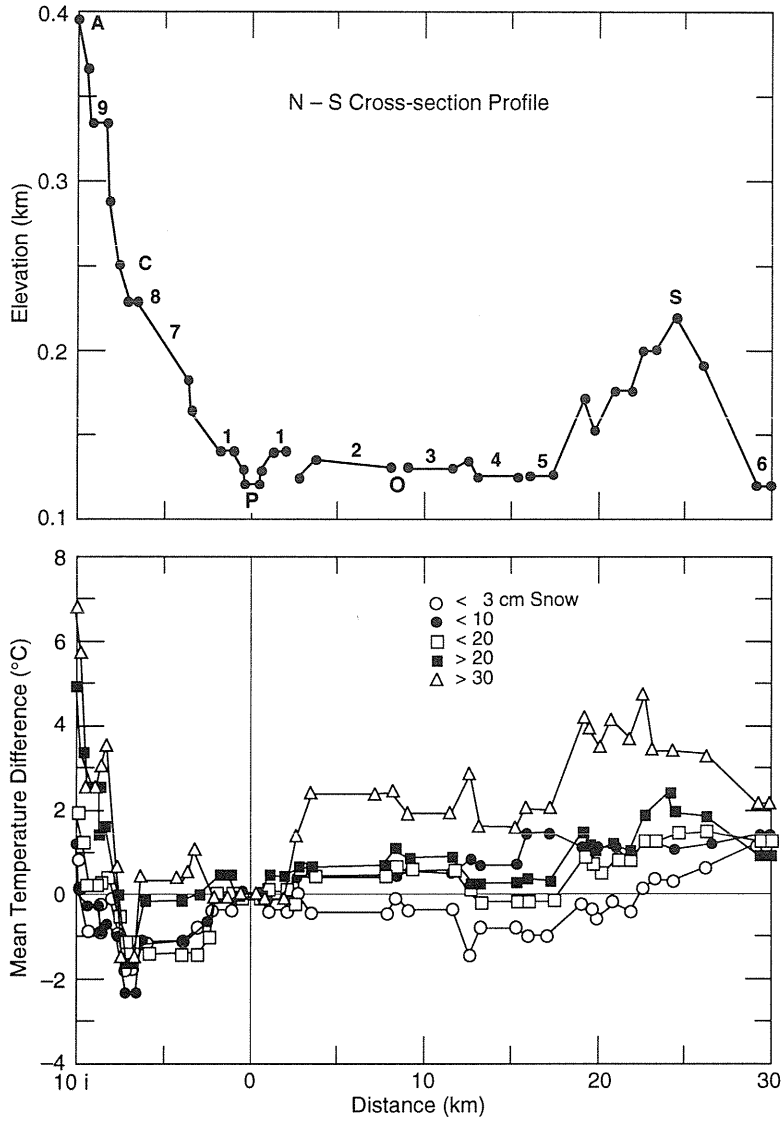

Figure 4. Transect temperature analyses along the Connecticut River valley, stratified by snow depth, for days with inversion above 230-m elevation. The elevation cross section is shown in the upper panel, with the basin identifiers from Figure 1 noted. Note that basin temperatures near river level are quite comparable but that basin 8 is consistently cooler than ridge S *although they are at similar elevation.*

studied, but that several discontinuous inversions prevent advection of the warm air observed at A to points along the valley of less than 250-m elevation.

DISCUSSION AND CONCLUSION

Very repeatable temperature structures formed within the Connecticut River valley during three winters, which responded in the mean to the depth and continuity of snow cover. Surface air temperatures above the river, in basins adjacent to the river, and on the slopes within a few kilometers of the valley were isentropically related on mornings when lapse structure was present. The frequency of occurrence of lapse diminished as snow depth increased. It appears that only well-organized systems with relatively great pressure gradients maintained lapse near the surface when that surface was covered by snow.

On two-thirds of the days, air cooled through contact with the snow surface and accelerated the diminution of lapse rate, which decoupled the surface from tropospheric heat input. One or more inversions formed between river level and the apex of observations on these days, and further decoupled the surfaces beneath from heat input.

The surface air temperatures above the river, and in basins adjacent to the river, equilibrated on most of these inversion days. This is in agreement with Nakimura and Magono (1982), who experimentally verified model prediction of temperatures in snow-covered valleys in Hokkaido. The temperatures along slopes and in small valleys and basins above river level were not analytically predictable, also similar to the Hokkaido results. Magono et al. (1982) later proposed that elevated basins experienced earlier formation of inversions, which provided a longer decoupling from tropospheric heat input, and resulted in lower surface temperatures in these basins than in valleys below or on the ridges above.

The orderliness of surface air temperatures near the river, and in basins adjacent to the river, supports the river plane hypothesis as a viable analytical tool. Hamlets near bridges H, P and O did not produce heat islands of sufficient magnitude to be differentiated from temperatures in the same basin or along the same slope. The influence of barriers, forest edges, and forest field/boundaries could not be isolated along slopes, but may be found in more sophisticated analysis of basin data. Cold air drains were found in the mean temperature structure of sparse snow days, but were not found with complete snow cover.

The disorderliness of surface air temperatures along slopes and in small basins embedded in slopes is apparent, and this disorderliness increases with snow cover and inversion strength. This disorderliness may account for some of the large variation in mean winter temperatures reported in the eastern U.S., but requires further analysis of local slope and basin influences.

These results represent a single locale and three winters. They seem internally consistent, and approximate those of Magono and his coworkers in Hokkaido, warranting similar experiments in another locale. A more sophisticated and lengthy program might isolate additional terrain-induced temperature structure, and determine the basin aspects influencing early inversion formation.

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