Inferring Dynamic Winter Variables

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ABSTRACT

A majority of winter environmental data is measured or observed at meteorological or hydrological stations that coexist with other activities. It is often necessary to infer the air, snow, or ground temperature in a natural setting from the observations available at these stations. There are dynamic exchanges of heat, chemicals and water substances in natural settings that are quite complex. There is exchange near treetop level, at the air/snow interface, and at the snow/ground interface. These exchanges interact on differing time scales, making it difficult to synthesize the overall response to a dynamic change in the troposphere above. Air, snow, and soil temperatures have been measured at the margin of a regenerating forest for several winters. This paper examines spatial, temporal, and dimensionless scaling of winter temperatures. An interesting preliminary result is the response of the environment to some statistical "outliers" in the temperature of the air above the snow. The use of the proposed scaling methods to examine the sudden loss of New England snow coincident with heavy Pennsylvania rains described by the keynote speakers has been added to the paper.

INTRODUCTION

The northeastern United States is mostly covered by native forest, second growth forest, or abandoned farm land in some stage of regaining forest cover. Almost all available meteorological information in this area is obtained at airports, on college campuses, or at other well-manicured locations quite different from the prevalent environment. Airports, in particular, were selectively sited, often with the advice of meteorologists (Cassedy 1965)*, in places with less fog, fewer strong winds, and less frequent snowfall than typical of the surrounding area. The well-known Pasquill stability categories were derived over treeless, level terrain, and cannot be applied (Pasquill 1962) to this type of setting.

Smoke plumes from local chimneys are frequently used to estimate near-surface inversion height and the time of inversion break up over snow-covered ground. Hanna et al. (1982) illustrate how smoke plumes describe three-dimensional air motion, and were employed to establish the well-known Pasquill dispersion categories over relatively flat terrain. I have employed observations of a chimney plume, exiting just below treetop height, in conjunction with temperature measurements to examine stability and exchange in this quasi-natural complex setting.

Anderson and Larson (1996) indicated that the dynamic exchange of tropospheric heat and latent heat is a dominating factor influencing the winter surface in this area, especially during midwinter thaws. This paper explores the near-surface temperature structure in a quasi-natural setting, presents data on an experimental logarithmic scale and examines some unusual conditions accompanying the midwinter thaw of 1996.

Midlatitude winter is a period of radiation deficit, with the surface and boundary layer warmed by advected, rather than radiated, heat. Snow cover interacts with advection as well as incident radiation to reduce the surface temperature. It is apparent that the coupled effect of snow and tree cover diminishes surface wind as well. I have measured multilevel air, snow, and soil temperatures at a small opening in a regenerating forest for several winters. I have found it convenient to use a merged logarithmic scale to record and analyze this data. This scale is used to provide preliminary analysis of the modification of the near-surface boundary layer by snow and forest.

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* Cassedy, James A., Chief, WSO, Albany, New York, personal communication, 1965.

SITE DESCRIPTION

The experiment site is a T-like opening in a young regenerating forest at an elevation of 250 m, about 3 km east of the Connecticut River, at 44 °N latitude. The site lies along a slope of about 12°, facing west to northwest. There are hills or low mountains of 1000 m nearby. The top of the T is aligned roughly south–north along the slope and cleared for about 75 m. The leg of the T is of similar length lying along the contour. The clear area is 25 to 40 m wide, surrounded by mixed hardwoods and conifers of height 12–18 m. Poplar, maple, birch, and cherry dominate, covering more than two-thirds of the area, but white pines are the highest trees. A house 8 ×14 m, 8 m high, is in the intersection of the T.

A cylindrically shielded thermistor is suspended 8 m above ground in a sparse cherry tree within the cleared area. Similarly shielded thermistors are suspended on rods at 4 and 2 m about 10 m west of the cherry tree. The 8-, 4-, and 2-m temperatures are fixed, but a cantilevered thermistor can be adjusted to 1 m above ambient snow, and a urethane foam float suspends another thermistor 1 cm above the ambient surface. Snow temperature probes are pre-placed below the air temperature probes and below large pines 50 m southeast of them. Soil temperature thermistors are pre-placed below the air temperature probes, at the margin of the leg of the T and at the margin of the T top. All temperatures are measured in morning twilight each day, using the same digital meter. Snow depth, sky cover, and other related variables are also noted at this time. Irregular observations are made at other times of day.

SNOW DEPTH

Snow depth is measured each morning along a path through the cleared area, at three to five places about 1 m apart. Every few days, depending on the nature of the snow cover, one or more profiles of snow density are obtained in the adjacent area. There has been a tendency, during the last 10 winters, for this clearing and the adjacent woods to retain snow cover after early snows, or after midwinter thaws, when nearby and lower cleared land has little or no snow cover.

The number of days with specified snow cover during December, January, and February 1993–96 is plotted in Figure 1. Recent work by Hogan and Gow (1996) shows that annual snow accumulations are often log-normally distributed, and constant logarithmic intervals of snow depth were used to construct Figure 1. Realistically, 5 cm is about the limit of resolution of snow depth over terrain, and all observations of less than 5 cm are collected in a single discontinuous class, which constitutes more than one-fifth of winter days. Snow cover of 5 to 20 cm was least frequent, and more than 20 cm of cover was present on nearly one-half of the days. Cumulative frequency of snow cover was neither normally or log-normally distributed during these three winters.

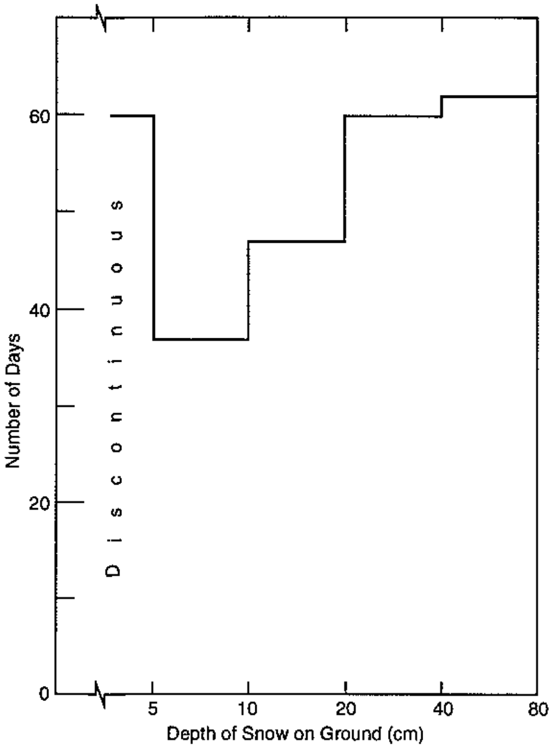

Figure 1. Number of mornings during winters 1993–96 with snow depths included in the stated class limits. Note that the 5-cm class is discontinuous, as its lower limit should be stated, but is in reality not observable.

AIR TEMPERATURE

Essenwanger (1986) indicates that air temperature and barometric pressure are normally distributed, with respect to the number of observations at many observing stations. Longley (1949) showed that snow on the ground suppressed the occurrence of air temperatures that were slightly above freezing, and Lettau (1971) showed that daily temperatures over snow in the polar regions significantly depart from normal distributions. The number of occurrences of 2-m air temperature, in 2°C class intervals, for the same days as snow depth in Figure 1 are shown in Figure 2. Temperature in the range –6° < T < 2°C occurred on 83 of the 270 days. Only 13 of these days had temperature –2° < T < 0°C, roughly one-half the frequency of the adjoining classes. This is apparently due to a similar modification of local air temperature by snow as reported by Longley.

The number of temperature occurrences with respect to height for the 1995–96 winter is given in Figure 3, for 8 m, 2 m and 1 cm above the snow surface. There appears to be a diminution of the number of days –2° < T < 0°C at 8 m as well as at 2 m, indicating that temperature modification is not confined to a thin layer adjacent to the snow. A few very

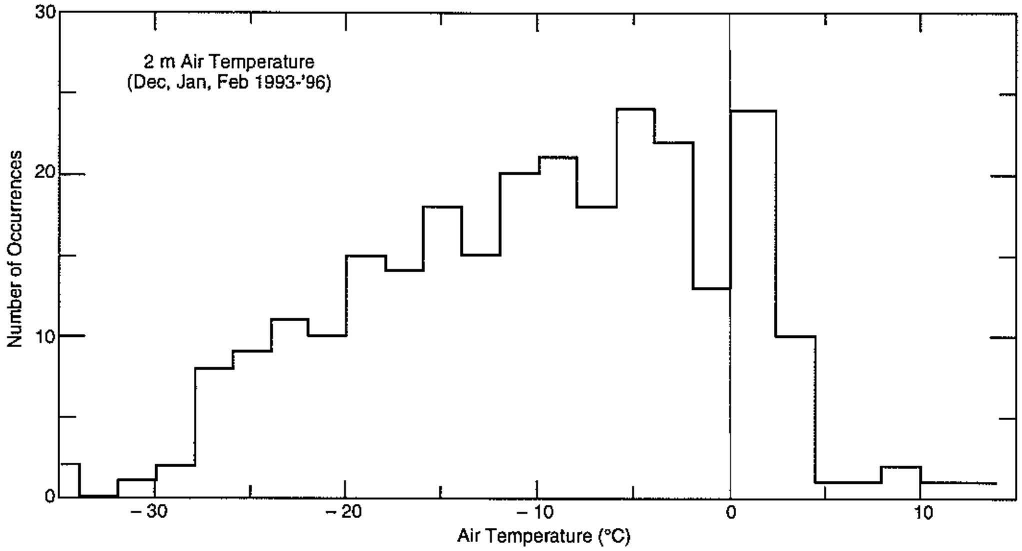

Figure 2. Distribution of the number of morning 2-m air temperatures over the same three winters. Note the relative sparsity of temperatures in the 0 to –2°C class, and the relative frequency of temperatures 0 to 2°C.

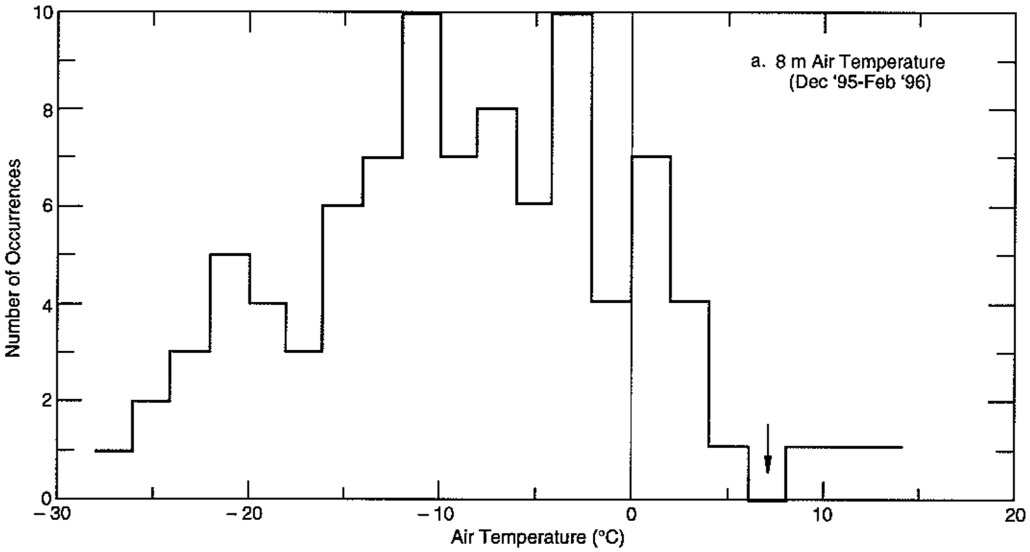

Figure 3. Morning air temperatures 8, 2, and 0.01 m above the surface on winter mornings 1995–96. Note again the sparsity of the 0 to –2°C class. There are 9 days missing from the 0.01 m distribution, as it is not possible to maintain the 0.01 m distance during snowfall.

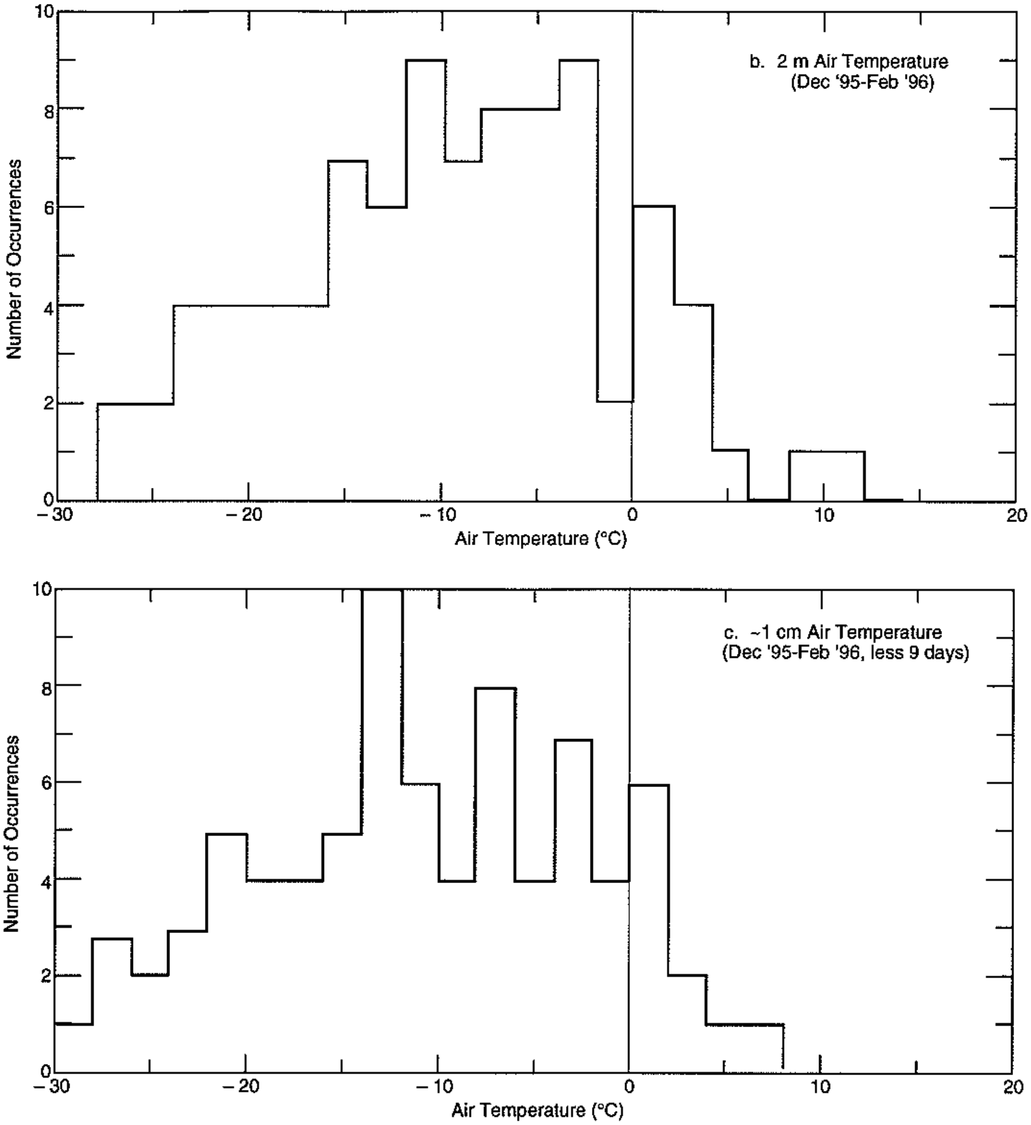

Figure 3 (cont'd). Morning air temperatures 8, 2, and 0.01 m above the surface on winter mornings 1995–96. Note again the sparsity of the 0 to –2°C class. There are 9 days missing from the 0.01 m distribution, as it is not possible to maintain the 0.01 m distance during snowfall.

warm days of T > 8°C occur at both 2 m and 8 m, but no air warmer than 8°C was observed at 1 cm.

MODIFICATION OF AIR TEMPERATURE

I observed, on several occasions prior to the 1995–96 winter, that the air near the snow was 1° to 2°C colder than the air at 2 m, on days when strong winds were audible aloft and upper tree limbs were in motion. The house chimney reaches 8 m and is about 20 m west of the 8-m temperature probe. I observed the smoke at the chimney each morning in 1995–96 and used the methods described in Slade (1968) to determine the stability of the air in the vicinity of the chimney. I simplified this to three classes after a few observations.

a. Solid vertical, leaning, or rotating smoke plume; inversion, 1-m s^{-1} wind speed at 8 m, extremely stable.

b. Streaming or ventilating smoke plume at chimney level; lapse, but stable at 8 m.

c. Fumigating and/or looping smoke plume at chimney level, smoke reaching 2-m level within clearing; lapse, unstable.

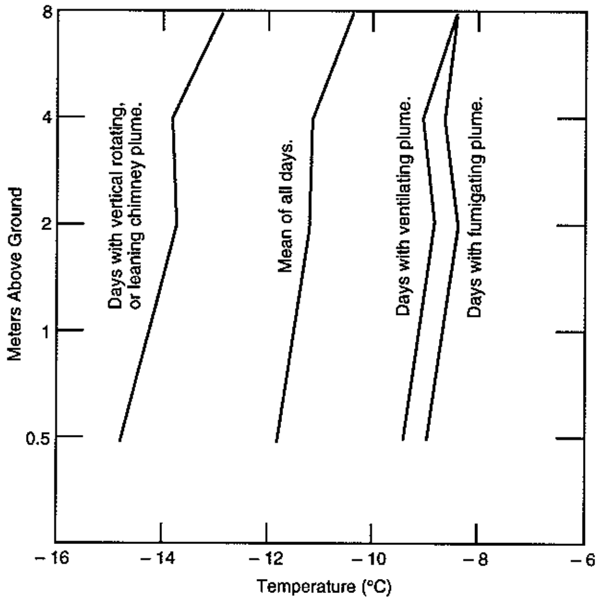

Figure 4. Mean morning air temperature over snow as a function of stability, determined by observation of a smoke plume. An inversion was maintained over snow, even during instability accompanying fumigation and looping.

The vertical temperature measurements indicated that there was a temperature inversion greater than 0.3°C below 8 m on 60 days, and a potential temperature inversion approximating an isothermal structure with less than 0.2°C temperature difference below 8 m on 10 days. There was temperature lapse greater than 0.3°C below 8 m on 5 days. The snowfall rate was sufficient to interfere with surface temperature measurement on 11 days; there were five occurrences of inversion, five occurrences of isothermal, and one occurrence of lapse between 8 and 2 m on these days. The remaining four days had fog or drizzle that prevented air temperature measurement above 2-m elevation.

The mean of the 8-m, 4-m, 2-m, and 1-cm temperatures observed in each stability class are plotted in Figure 4. About two-thirds of the mornings of the 1995-96 winter were in the solid (a) plume class, including many days when clouds moved rapidly above and some when motion of uppermost tree branches was evident. Inversion was frequently apparent in temperature profile below 8 m, when the smoke indicated (a) or (b) were present at 8-m level. The inversion was essentially confined to the layer below 2 m when the smoke indicated (c) was present.

Interpretation of the mean temperature and inversion values in Figure 4 again pose a question. The 8-m, 4-m, and 2-m temperatures are measured at a fixed separation distance, but the distance separating the 2-m temperature and the 1-cm temperature varies with snow depth. The real value of inversion strength below 2-m increases with increasing snow depth and cannot be inferred from the slope plotted in Figure 4.

APPLICATION OF MEASUREMENTS

It was shown in Figures 1, 2, and 3 that neither snow depth, nor temperature over snow, was normally distributed at this site during these three winters. It is especially important to note that when 2-m to 8-m air temperature was near, or exceeded, the melting point of ice, snow cover modified the temperature structure near the surface even when ventilation or fumigation was present at 8 m. As many of the dynamic meteorological events of winter, including thaws or freezing rain, occur when the surface temperature is near freezing but the lower troposphere is not, understanding and interpretation of the near-surface layer become quite important. The preceding sections have provided temperature profiles that support a hypothesis that near surface temperature inversion is prevalent in a quasi-natural winter setting, even when strong winds are present at treetop level. A period of dynamic change in air temperature, wind, and snow depth occurred in January 1996, which appears to exhibit the turbulent transfer of heat to snow described by Anderson and Larson (1996). Some innovative scaling is used in Figures 5, 6, and 7 to examine this dynamic period of change.

The "surface" is a dynamic variable, rather than a fixed reference, in a natural setting. Air circulates within grass, forest litter, and the upper millimeters of snow. The ground interacts exhaling moisture, latent heat, and sensible heat into the base of the grass, litter, and snowpack. I call this shared volume the "thatch," with an effective thickness of about 3 cm. This allows establishment of two logarithmic coordinate systems, one increasing upwards and one increasing downwards, which share 3 cm of thatch and have no zero level. Snow accumulates along the upward coordinates, and water percolates into the downward coordinates.

The temperature profile from 8 m above the thatch to 2 m below the thatch on the morning of 15 January 1996 is shown in Figure 5. There were 60 cm of snow on the ground, with no evidence of drifting or melt crusts. The snow temperatures were obtained from another set of probes 10 m west of the clearing,

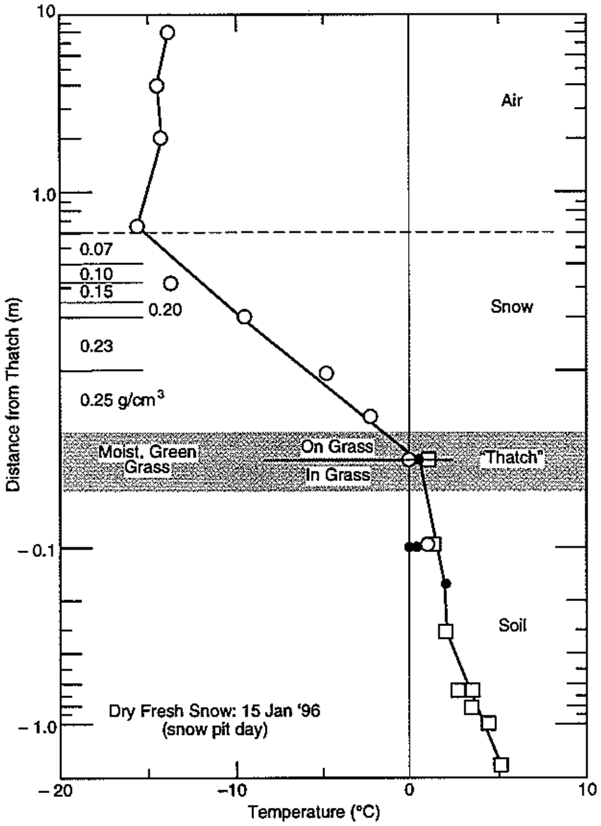

Figure 5. Vertical profile of air, snow, and soil temperatures on 15 January 1996. There was 60 cm of snow on the ground, and the density of each layer is noted at its level. Air temperatures and snow temperatures are designated by open circles. Soil temperatures are noted by open squares, and soil temperatures in roots or mulch are noted by solid circles. All three media may coexist in the "thatch."

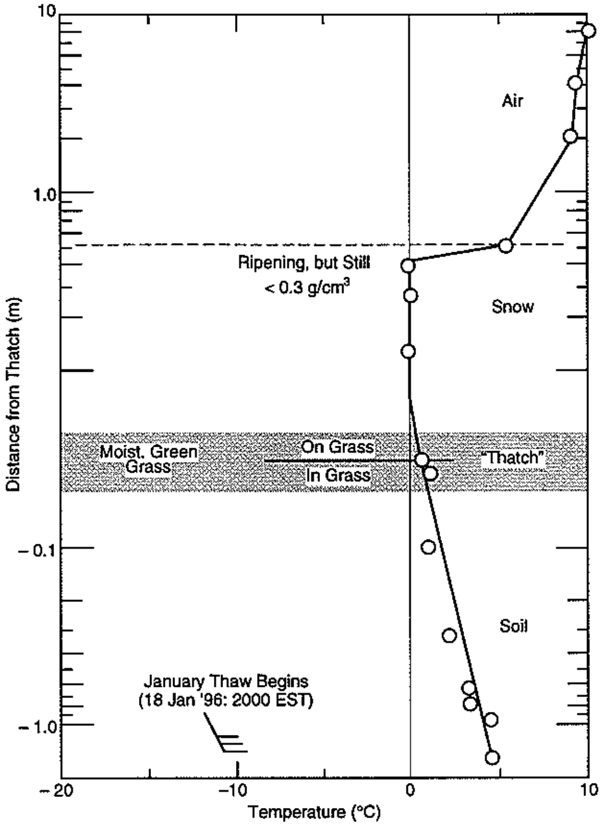

Figure 6. Profile of air, snow, and soil temperatures on the evening of 18 January 1996, as snow achieved a uniform 0°C temperature through the pack. Note that the air temperature is 5°C at 1 cm above the pack at the elevation shown by the dashed line, and that there is an additional 5°C of inversion below 2 m, even though treetop winds exceed 15 m s^{-1}.

beneath large white pine trees. The snow densities were obtained with the LaChappelle method near the southern edge of the cleared T.

The coldest layer was near the snow/air interface, as is typical, and there was 2°C of inversion from 1 cm above the snow to 8 m, with most of the inversion occurring below 2 m. The temperature at the top of the thatch, within the thatch, and at the bottom of the thatch was very near the melting point of ice. The thatch temperatures were nearly the same beneath the air temperature array within the cleared T, and at the other site beneath the pines. Moist green grass was observed at the base of the snow upon opening the snow pit, which contained the snow that had fallen during the last 46 days. No air temperature above 0°C had occurred during these 46 days. All temperatures beneath the thatch were above freezing, and increased with downward distance.

Warm advection began on 16 January and the depth of snow diminished through the morning of 18 January, but no melting occurred. Very strong warm advection occurred as a southeast wind (downslope at this site) of 15 m s^{-1}, with stronger gusts, during daylight on 18 January. The temperature profile obtained with 40 cm of ripe snowpack during the evening of 18 January is shown in Figure 6, when water drops were observed condensed on the surface of the snow. Although fumigating was occurring below chimney level, in company with gusty winds indicative of instability in the boundary layer, an inversion of 5°C was maintained just above the snow. All snow temperatures were 0°C, and thatch temperatures were slightly above the melting point. No melt was observed, but some water apparently percolated through the soil, slightly modifying the soil temperature profile.

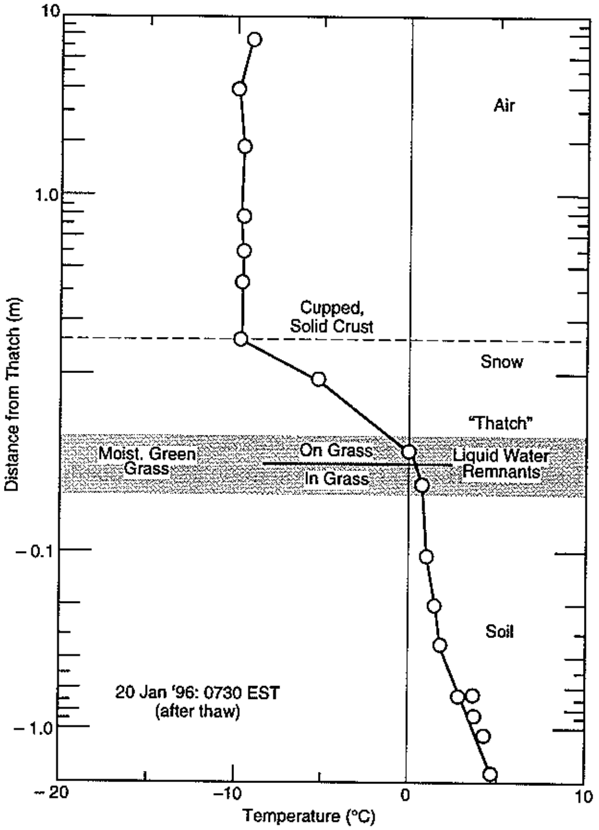

Figure 7. Temperature profile on 20 January 1996, after passage of a cold front ended a midwinter thaw. Liquid water was observed at the base of the snow and in the thatch. The additional air temperatures below 1 m were obtained from former snow temperature probes which were exposed by the recent thaw. I attribute the rare absence of inversion to the release of latent heat by water freezing at the base of the remnant snowpack.

This warm advection continued through 19 January, and several hours of 16°C surface temperatures were observed during daylight on that day, prior to onset of rain. The pack settled to 30 cm by 0700 EST that morning, and by noon all snow was gone from fields at river level. Much less rain fell here than reported by Anderson and Larson (1966) for this same system in Pennsylvania, and little flooding occurred. The temperature diminished to near 0°C overnight.

The temperature profile obtained on the morning of 20 January is shown in Figure 7. About 15 cm of snow with a very cupped and irregular surface remained in this small clearing, and in the surrounding woods, but snow remained only along the wooded margins of large fields. The snow had refrozen with sufficient strength to support walking on it, but liquid water was visible through old tracks lying at the base of the remaining pack. The thatch temperatures remained very near the melting point, and soil just below the thatch was cooling quite rapidly.

DISCUSSION

Figures 2 and 3 indicate that air temperatures warmer than 5°C are "unusual" or "outliers" relative to distribution of morning air temperatures observed at this site over a three-year period. Near-surface air temperatures exceeding 8°C persisted for nearly 48 hours on 17–19 January 1996. An isobaric analysis would indicate that this SE wind would have originated over the near 0°C Atlantic Ocean surface and passed over 100 km of snow-covered ground before reaching the thermometer. I propose that this air was conveyed from the mid-troposphere over the Susquehanna Valley, where 10 to 15 cm of rain fell during this period. This air was warmed by subsidence in addition to the warming by recovery of latent heat. This subsident warming and drying accounts for a lack of fog in the Connecticut Valley during rapid melt of 30 cm of snow that occurred during less than 6 hours on the morning of 19 January.

Figure 6 shows that 5°C of temperature inversion was maintained adjacent to the snow during this period of strong advection. Observation indicated that this inversion averaged about 0.3-m thickness, with a flow of 1 m/s in the layer. An air to snow heat exchange of 2.6 cal cm^{-2} min (a little more than the solar constant) would maintain this temperature differential. This heat flux could melt 1.9 cm of snow water per hour, which approximates the rate snow melted in the Connecticut Valley on 19 January 1996.

The frequency distributions of Figures 2 and 3 show that occurrences of air temperatures greater than −2°C depart from the number that would be predicted from a normal distribution, probably due to modification of the boundary layer by snow cover. Figure 4 provided insight that inversion persists over snow-covered ground, even when extremely unstable air is present a few meters above the surface. Figures 5, 6, and 7 showed the magnitude of coupling and exchange of heat flux from air to snow, and facilitated approximation of a numerical value of this flux.

CONCLUSION

Snow cover modifies near-surface air temperature beneath the forest canopy in quasi-natural settings. This modification is especially significant when tropospheric temperatures exceed the melting point of water, as the dynamics of the temperature modification may govern the magnitude of thaw or the occurrence of freezing rain. Frequency analysis shows that warmest midwinter air is an "outlier" when compared with the normal distribution of surface air temperatures. The source of the unusually warm air is latent heat released by precipitation which is conveyed to the surface by a subsident trajectory about a storm southwest of the observation point.

A near-surface temperature inversion is a characteristic of snow-covered ground in quasi-natural settings. Some inversion is present in the lowest layer, even when snow is sparse or cover intermittent. Inversion persists below 2 m on days when extreme instability is indicated by fumigation in the layers a few meters higher above the surface.

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