Observations of Vertical Atmospheric Structure in a Deep Mountain Valley

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ABSTRACT

A tethered balloon sounder was used to collect vertical temperature and wind structure data in the Gore River Valley of Western Colorado during December, 1975. Observations taken on a clear morning in which a deep inversion was initially present in the valley showed that the inversion top descended at a steady rate of $\sim$120 m hr^{-1}, reaching the valley bottom after approximately 4 hours. Weak down-valley winds were present within the inversion layer while stronger up-valley winds prevailed above. An hypothesis is presented to account for these observations. A case study is presented for afternoon and evening cooling in which a ground-based inversion developed to a depth of 175 m in less than 2 hours. Winds within the inversion became decoupled from the synoptic-scale winds and remained very weak during the night. The effect of cloud cover during a morning heating cycle was to make the temperature soundings approach isothermal while sensible heating continued throughout the valley volume.

1. Introduction

Evolution of atmospheric temperature structure in the free air within mountain valleys has rarely been studied over the years despite its obvious significance to valley air pollution dispersion problems (Scorer, 1973; Geiger, 1961). Hewson and Gill (1944) investigated temperature structure evolution by utilizing instrumented aircraft and a large tethered balloon to collect temperature data in the wide Columbia River Valley in connection with an investigation of air pollution from a lead and zinc smelter. The observations, concentrating on temperature structure changes leading to post-sunrise fumigations, were taken during 4 experimental periods during two days in 1939. Results indicated that inversion breakup could occur within a 3-hour period and that investigations of this phenomenon would require more frequent observations than could be attained with their experimental design.

In a recent study, Machalek (1973) took a 2-hourly series of temperature profile measurements on good weather days in the narrow Mürz Valley of Austria using a tethered balloon sounder. Several significant features of temperature structure evolution were observed during the experiment. These features were presented in the form of a case study (24-25 March, 1973) and include: 1) the initial development of a surface based inversion as early as 1400 local time (LT), 2) the gradual build-up of inversion depth through the night until it reached 500 m at 0600 LT and had attained a temperature difference of almost 7°C, and, 3) the dissipation of the inversion in the hours between sunrise and noon accomplished by two processes--the heating of the ground by insolation and the lowering of the upper boundary of the inversion.

Valley wind structure and evolution, in contrast to temperature structure and evolution, have been extensively studied by numerous investigators. The initial impetus for these studies was to gain a better understanding of the local wind circulations that are such a prominent feature of the climatology of valley sites. Investigations include those of Wagner (1938), Hewson and Gill (1944), Defant (1951), Davidson and Rao (1958 and 1963), Buettner and Thyer (1966), Tyson and Preston-Whyte (1972), and others.

An investigation in which simultaneous temperature and wind observations were made was reported by Thompson (1967). Thompson attempted to obtain detailed information on the 3-dimensional development and structure of temperature inversions near the mouth of Red Butte Canyon in northern Utah by taking summer observations from a network of five instrumented towers. The towers were of insufficient height to allow observation of the complete inversion structure except during a brief period in late afternoon when the inversion was just beginning to form, but provided important information on the structure in the lowest levels of the canyon. His summary of the significant features observed included: 1) the formation of a thin layer of downslope winds an hour or two before astronomical sunset, 2) a definite windshift to down-valley winds during a ten minute period near sunset, followed by a period of rapid cooling and increase in windspeed, and, 3) quasi-steady wind and little cooling within the first hour after the windshift, while moderate cooling occurred outside the canyon for several hours.

In this paper a series of simultaneous observations of temperature and wind structure are presented for the free air within a deep mountain valley in the Western Colorado Rocky Mountains. A case study, conducted over a 1½ day period, illustrates the evolution of, and interrelationships between wind and temperature structures observed during a clear, light wind period. Such periods occur frequently in many mountain areas of the world and are of concern because they frequently lead to the buildup of deep temperature inversions, poor mixing conditions, and high air pollution potential.

2. Data

An experiment was conducted in the Gore River Valley of Western Colorado during the period December 3-18, 1975. During this experiment, observations of vertical atmospheric structure within the valley were taken during frequent (∿1-hour) intervals during clear, light-wind weather periods using a tethered balloon profiler which has been described by Morris, et al. (1975). The profiler telemetered dry and wet (or ice) bulb temperature, wind speed, wind direction, and pressure data to a ground-based receiving station where the data were recorded.

The location of the field site where profiler observations were taken is shown in Fig. 1. The topographic map shows the general E-W orientation of the valley, its origin in the high peaks (∿3950 m) of the Gore Range, and its confluence with the Eagle River Valley below the internationally-known ski resort of Vail, Colorado. The valley enters a relatively constricted canyon just above this confluence.

The observation site was located at West Vail, 18 m above the valley bottom on a SE-facing slope at an elevation of 2426 m MSL. A topographic cross-section normal to the valley at the profiler site is presented in Fig. 2 and a summary of the topographic characteristics of the valley in the vicinity of the profiler site is given in Table 1. During the period of the experiment the south-facing valley walls had a patchy cover of snow. The upper reaches of the south-facing slopes were covered with evergreen and aspen forests while the lower reaches were scattered with shrubs and the draws were filled with aspen stands. The north-facing slopes had more snow cover and contained mixed evergreen and aspen forests.

A period of fine weather occurred on 9 and 10 December and a series of observations were taken to document the evolution of free air temperature structure. During this period a Great Basin high associated with a ridge aloft was slowly weakening. Central pressures dropped from 1029 mb on the 9th at 1200 GMT to 1017 mb on the 11th at 0000 GMT. The 500 mb winds at the beginning of the period were from 325° at 18 m sec^{-1} and shifted gradually to 285° at 19 m sec^{-1} at the end of the period with the approach of a short wave trough. Winds at 700 mb were 335° at 11 m sec^{-1} shifting to 225° at 6 m sec^{-1} at the end of the period. Temperatures at 500 and 700 mb rose less than 3°C during the 36-hour period, indicating only weak warm air advection.

Figs. 3-5 present tethered balloon temperature and wind profiles for the Gore River Valley site during this period. The profiles presented, with the exception of the dotted profile in Fig. 5, are profiles taken during balloon ascent. Ascent rates averaged $\sim$.4 m/sec but usually decreased markedly near the top of the sounding as the balloon was required to lift more line. Temperature data is plotted with .25°C resolution; wind speed data is plotted to the nearest .5 m/sec using the convention that one barb corresponds to wind speeds of 1 m/sec. Wind direction data, plotted to the nearest 5° relative to true north, was obtained instrumentally from the orientation of the long, cigar shaped balloon which carries the instrument package. Winds are plotted at irregular intervals on the profiles corresponding to points where wind speed or direction trends change appreciably.

3. Data Analysis and Discussion

Three separate periods of evolution of atmospheric structure were observed in the valley during the case study. The three periods, presented in the following sections, include a morning warming with cloud cover, an evening cooling leading to a strong temperature inversion, and a morning warming under clear skies with a strong temperature inversion in the valley.

a. Warming Cycle of 9 December

Fig. 3 presents data for the warming cycle of 9 December. In early morning the sky was overcast with altocumulus. Breaks in the overcast appeared and the deck broke up rapidly between 1000 and 1100 MST. Clear skies then prevailed for the remainder of the case study period. During the cloudy period, warming occurred within the valley volume while the individual soundings remained essentially isothermal. Weak down-valley winds occurred during this period through most of the lowest 350 m of the soundings, with wind speeds near the threshold speed of the 3-cup anemometer ($\sim$.5 m/sec). Wind directions were up-valley in a shallow layer near the valley bottom. Weak westerly winds were observed near the tops of the profiles of the mid morning soundings, indicating a wind direction transition to up-valley or gradient level winds.

A 180-degree wind reversal occurred throughout the depth of the sounding in the period between 1126 and 1207 MST and stronger winds appeared to descend into the valley from aloft. The temperature profile became dry adiabatic in the upper levels (above $\sim$300 m) of the 1207 MST sounding, but retained an isothermal shape below. As the heating cycle continued, soundings became more nearly dry adiabatic and stronger winds were observed deeper in the valley.

Wind direction near the valley floor is influenced by weak slope wind circulations and the effect of friction and obstacles to the flow. The wind reversal in the main valley air mass is thus best observed at some distance above the valley bottom.

b. Cooling Cycle of 9 December

Fig. 4 shows the cooling cycle of 9 December. Cooling within the valley began before 1500 MST. The 1500 MST profile shows a 100 m deep isothermal layer surmounted by a layer of near-neutral stability. By 1600 MST the neutral layer had cooled by 1°C and a 1.5°C ground-based inversion was present in the lowest 100 meters of the valley. By 1600 MST winds within the inversion layer had decreased in strength relative to the 1500 MST sounding, although maintaining the up-valley direction prevalent in the neutral stability layer above. The 1640 MST observation shows a 175 m deep surface-based inversion surmounted by an isothermal layer which extends to 375 m with an unstable layer above. Winds within the surface-based inversion layer had become effectively decoupled from the upper level flow by this time.

Observations taken later in the evening show little change in the general features of the 1640 MST temperature sounding, although details of the upper portions of the valley could not be determined due to the limited range of the balloon sounder. By 2046 MST the inversion layer deepened slightly to 225 m and the winds reversed to down-valley throughout the entire sounding. Temperature soundings after 1640 MST are parallel in general form and show remarkably constant cooling rates through the entire depth of the sounding. It is interesting to note that Kuo (1968) has made the same observation for night-time cooling rates in the lowest several hundred meters of the atmosphere over O'Neill, Nebraska, where the terrain is flat.

c. Inversion Breakup

Fig. 5 illustrates the evolution of the wind and temperature structures through an entire daytime heating cycle in clear weather, and shows details of the breakup of the ground-based temperature inversion that built up within the valley during the night.

A comparison of the 0831 MST sounding of 10 December with the last sounding of the previous evening (2046 MST, 9 December, Fig. 4) reveals that marked cooling had occurred in the lowest levels of the sounding, while only weak cooling occurred above 175 m.

A 3°C inversion in 213 m (i.e., 1.41°C/100m) was present in the 2046 MST sounding. The 0831 MST sounding revealed an 11°C inversion in a depth of 444 m (i.e., 2.48°C/100m). Within this deeper stable layer was a more intense surface-based inversion of 7.75°C in 237 m (i.e., 3.27°C/100m). Light down-valley winds prevailed within the inversion layer on both soundings.

The most striking feature of temperature structure evolution in Fig. 5 is the steady descent of the top of the sharp inversion first noticed at a height of 425 m on the 0831 MST sounding. Sunrise at the balloon profiler site occurred at 0900 MST, although the southeastward facing slope above the site was sunlit earlier. The first profile taken after sunrise, at 0911, shows the sharp inversion (3°C in ∿20 m) at 325 m, and strong up-valley winds in a neutral stability layer above the inversion. Relatively strong speed-shear occurred across the top of the inversion. The 1000 MST sounding shows a superadiabatic layer has formed near the ground due to solar heating. Above the superadiabatic layer, a layer of cold air with weak down-valley winds is capped by the inversion at 250 m, and surmounted by a neutral layer containing stronger up-valley winds. The remaining soundings show the continuous descent of the sharp inversion with the strong up-valley winds following immediately behind. In the period from 1000 MST to 1058 MST the temperature structure is changed by the adiabatic heating of the descending air and by an additional 1°C to 1.5°C increase due to sensible heating, which is evident in Fig. 5 for the region above the inversion. The inversion reached the valley bottom in early afternoon and the 1545 MST sounding shows the well mixed nearly dry-adiabatic structure with up-valley wind speeds of 3 m sec^{-1} to 5 m sec^{-1}. Two thermographs, located in shelters northwest of the tethered balloon site at elevations of 49 m and 90 m above the site, were operational during the inversion descent. Passage of the inversion through the elevation of the thermographs was not evident from the temperature records.

Fig. 6, including both down- and up-sounding data, provides a clear picture of the descent of the inversion top into the valley. The average rate of descent is 121 m hr^{-1}. A similar rate of descent, ∿110 m hr^{-1}, can be obtained from Machalek's (1974) Fig. 2 for his case study of 25 March 1973 in the Mürz valley of Austria. Inversion descent there occurred over the period from 0800 to about 1100-1200 local time.

A number of investigators of valley wind structure have remarked on the downward transport into the valley of an up-valley wind system during the same time of day when we have observed inversion descent (Davidson and Rao, 1958, 1963; Ayer, 1961). Ayer hypothesized that the descent of up-valley winds was in response to the drainage of the cold air (or stable) layer out the end of the valley. Our wind observations in the stable layer, however, show that windspeeds were too low to turn the anemometer (threshold speed $\sim .5$ m sec^{-1}). Thus Ayer's hypothesis cannot be invoked to explain the Gore River Valley observations. Davidson and Rao (1958) suggested another hypothesis. They postulated that instability developed at ridgetop level and that the upper flow then descended into the valley. The more unstable the air at ridge level, the deeper does the prevailing flow penetrate into the valley. Presumably this mechanism would erode the top of the cold air layer from above. Our observations, however, show a formidable stable layer at the top of the cold air mass. Gradient Richardson number calculations for this layer show that turbulent mixing of the adjacent layers is strongly suppressed in this region.

Due to the failure of the two previous hypotheses to explain the observations, a third hypothesis, intended to apply to an inversion breakup, is proposed. Before sunrise it is supposed that a deep stable layer is present in the valley. After sunrise the slopes begin to be heated by solar insolation, and a thin superadiabatic sublayer forms along the sunlit slopes and over the sunlit valley floor. Convection begins in this layer and convective plumes penetrate into the stable cold air mass above. This penetrative convection results in entrainment of mass from the stable layer into the warm sublayer (Ball, 1960; Stull, 1973). An upslope component of motion in the convective sublayer carries the entrained mass up the slopes and out from under the cold air layer. The principle of mass continuity then requires that the inversion top descend. Later in the morning the inversion top continues to descend as mass is removed by the up-slope wind systems. As the stable layer shrinks, the up-valley winds progress deeper and deeper into the valley until the inversion layer is completely dissipated and up-valley winds prevail in the valley volume.

4. Summary

A field study was conducted during December 1975 to investigate vertical atmospheric structure in the deep Gore River Valley of Western Colorado. Using a tethered balloon sounder at ∿1 hr intervals during clear, light-wind weather periods, the evolution of temperature and wind structures within the valley was investigated. The following significant features of atmospheric structure were identified:

1. After sunrise, the nocturnal temperature inversion descended into the valley at a rate of about 120 m hr^{-1}. The wind field was characterized by up-valley winds in a nearly dry adiabatic layer above the inversion, light down-valley winds in the cold air below the inversion, and up-valley winds at the surface. The descent of the inversion was not evident in thermograph observations from the valley sides.
2. During late afternoon and early evening, the nocturnal ground-based temperature inversion developed rapidly to a depth of 175 m in less than two hours. The inversion continued to deepen

and was accompanied by a strong cooling of the air in the total depth of the sounding. Winds were very light in the valley during the night.

3. The effect of cloud cover was to make the vertical temperature structure nearly isothermal. Vertical soundings remained nearly isothermal during cloudy morning hours while heating continued to occur within the valley volume.

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Table 1

Gore River Valley Topographic Characteristics

Characteristics	Value
Width of valley floor	0.6 km
Distance between ridge lines	4.5 km
Length of valley	28.0 km
Height of ridge line above valley floor	0.6 km
Slope of valley floor	0.02

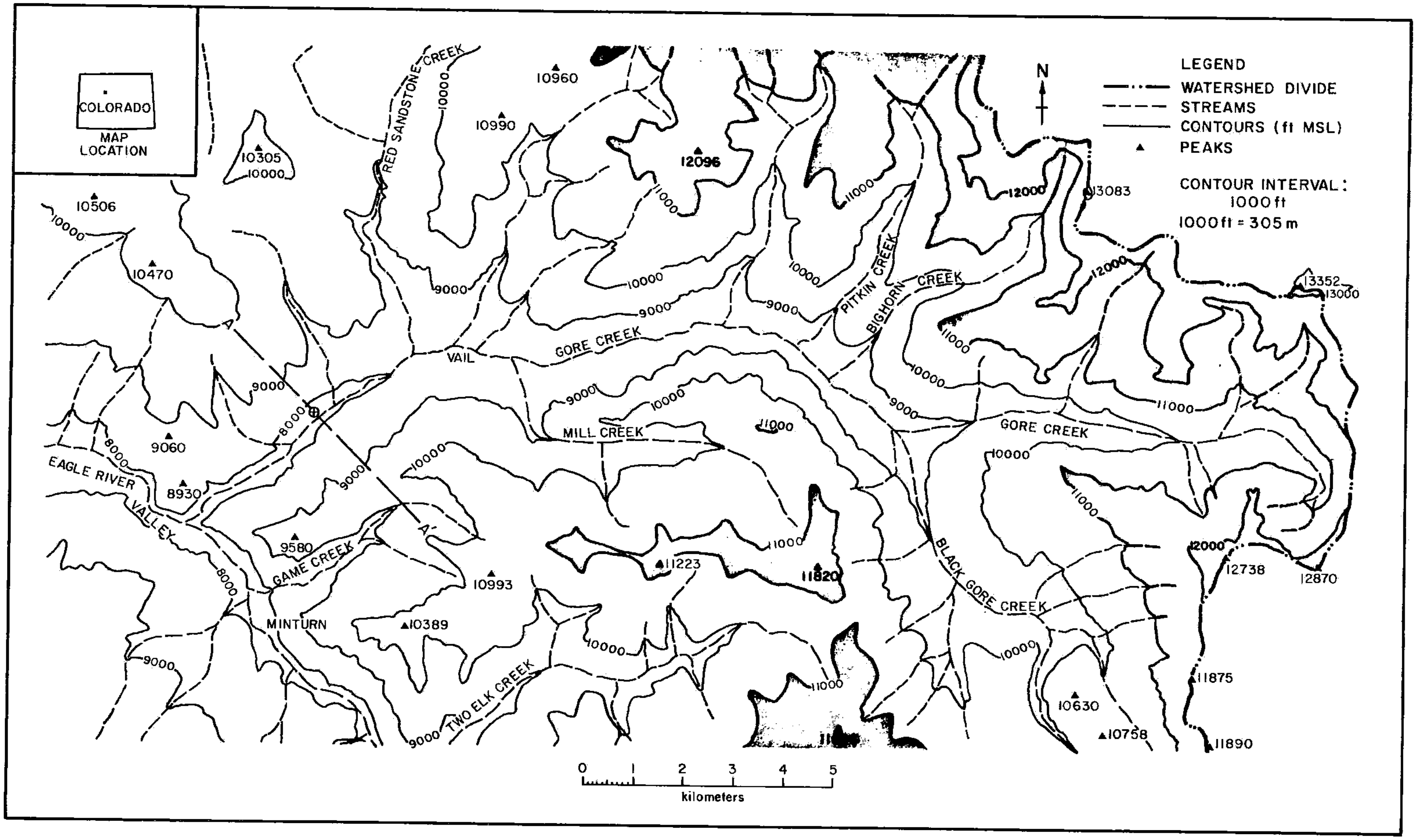

Fig. 1. Topographic map of Gore Creek region, Colorado. Location of tethered balloon profiler site is shown as a circled cross. Topographic cross-section AA' is shown in Fig. 2.

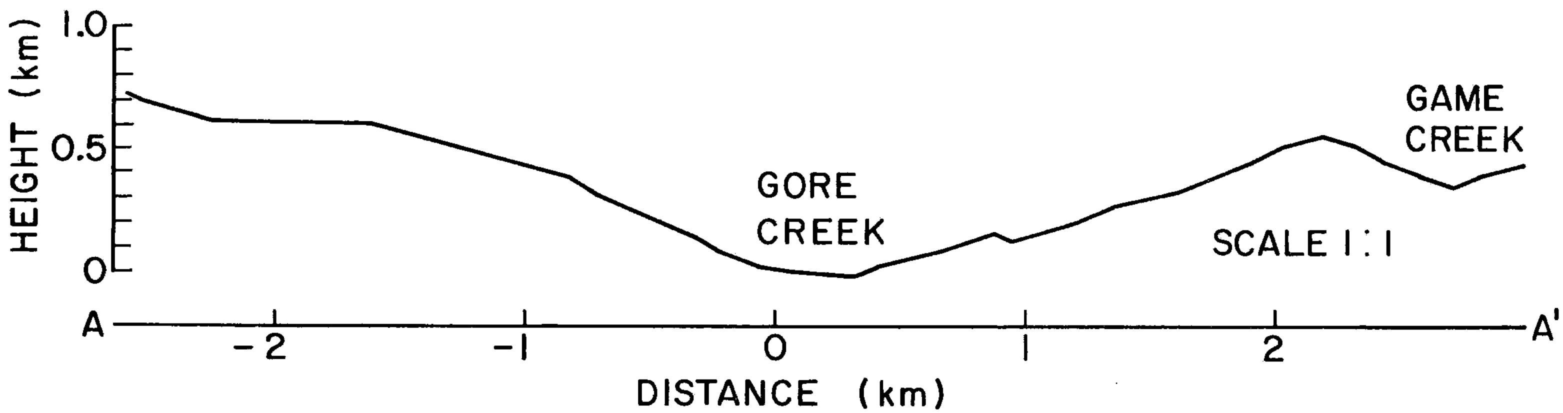

Fig. 2. Topographic cross-section AA' through the balloon profiler site normal to the valley axis.

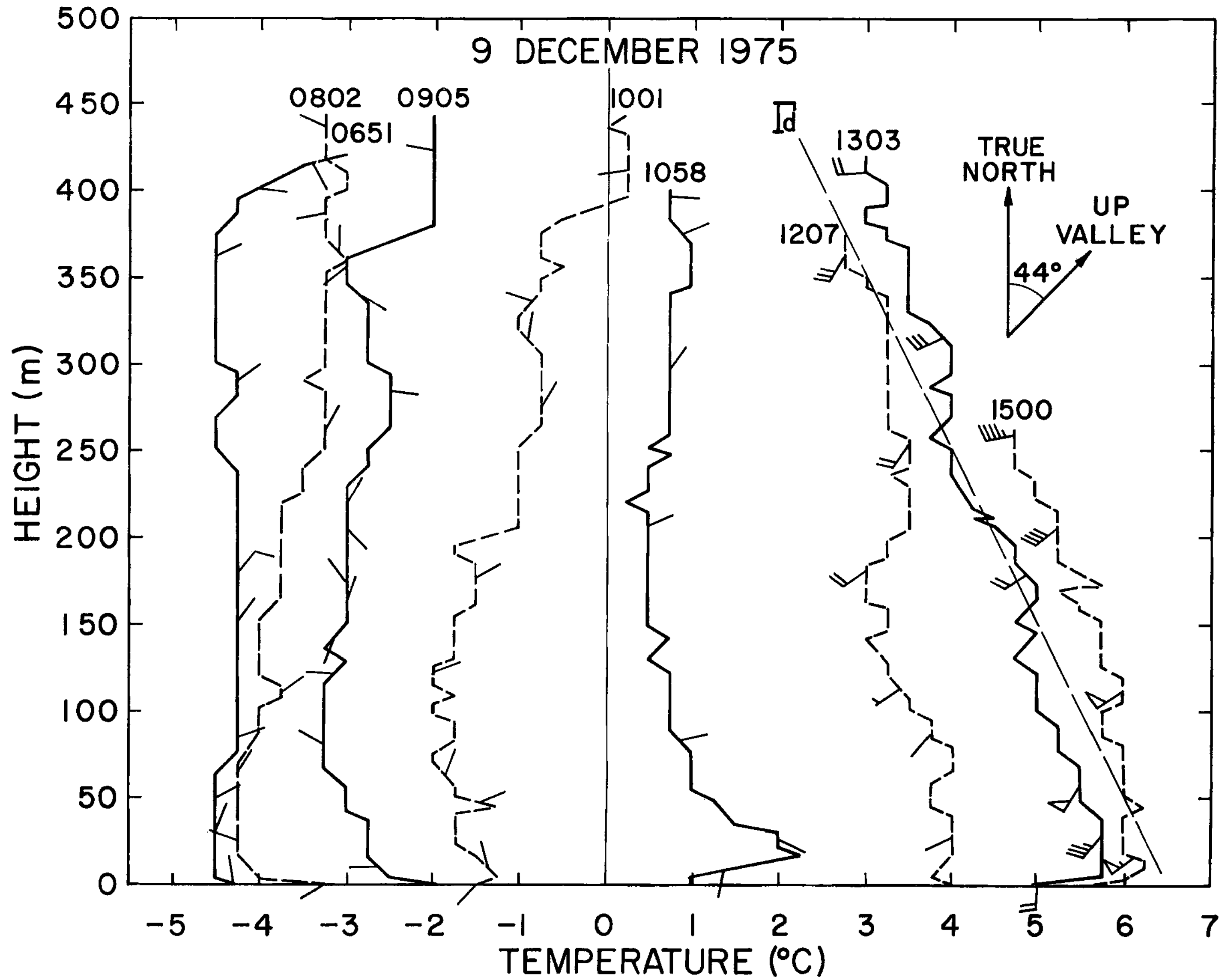

Fig. 3. Tethered balloon soundings, 9 December 1975. Temperature soundings are shown for the times (MST) indicated. Wind directions and speeds are superimposed on the temperature soundings. A single barb indicates 1 m/sec. Triangle indicates 5 m/sec. The dry adiabatic lapse rate (Γ_d) is given for reference.

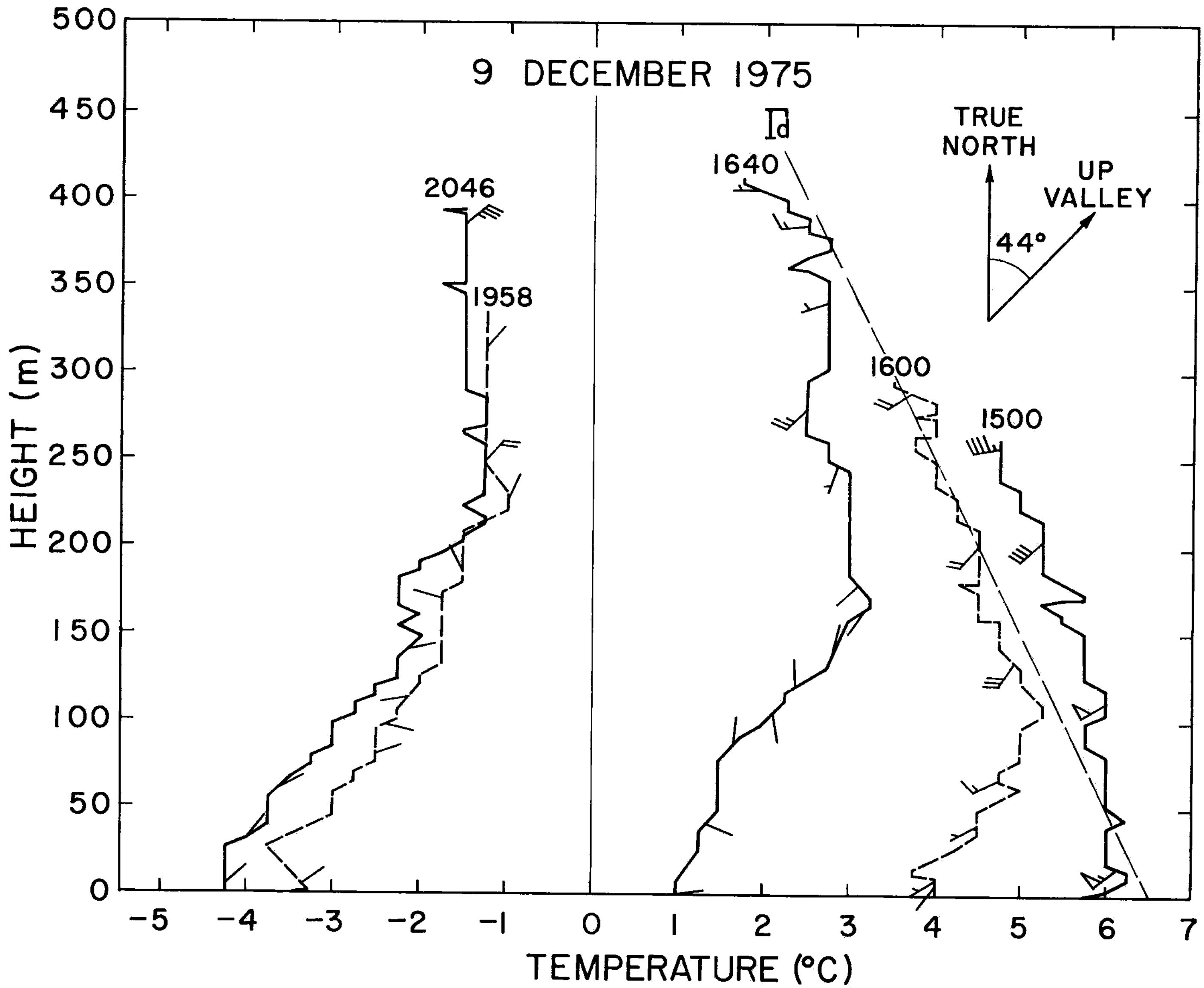

Fig. 4. Same as Fig. 3.

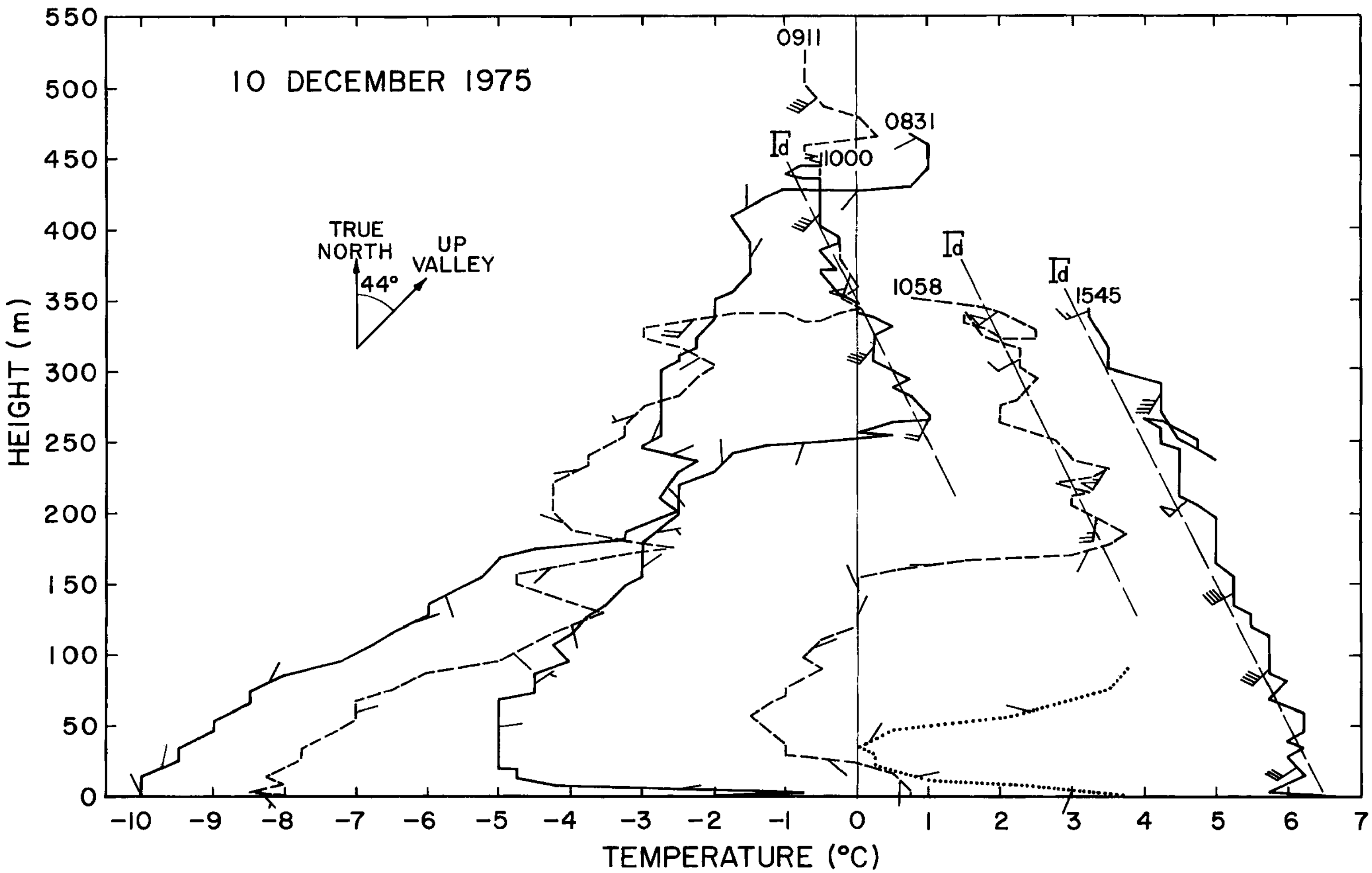

Fig. 5. Same as Fig. 3., except for 10 December 1975.

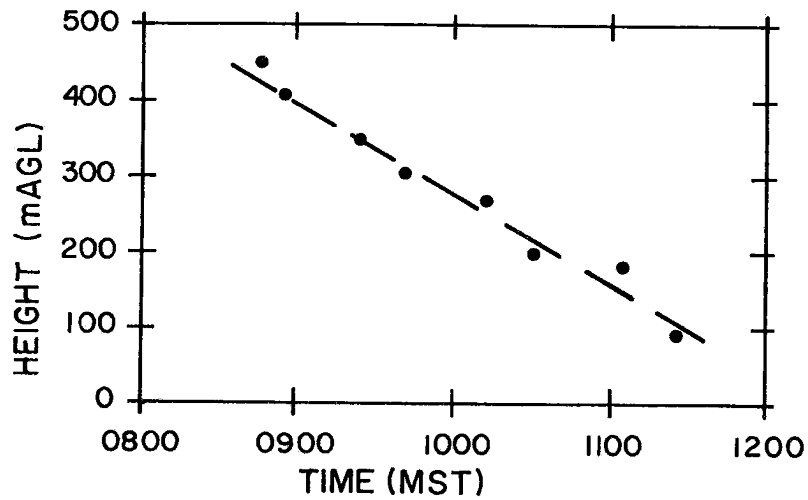

Fig. 6. Inversion top height versus time,
10 December 1975.

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15. Supplementary Notes

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16. Abstracts

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17. Key Words and Document Analysis. 17a. Descriptors

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Valley Meteorology

Vertical Temperature and Wind Structure

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

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