Meteorol. Atmos. Phys. 35, 220–226 (1986)

Meteorology
and Atmospheric
Physics

551.524.4

Pacific Northwest Laboratory, Richland, Washington, U.S.A.

Temperature Inversion Buildup in Colorado's Eagle Valley*

C. D. Whiteman

With 5 Figures

Received January 21, 1986
Revised April 9, 1986

Summary

The development of temperature inversion and wind structure in Colorado's Eagle Valley was investigated by means of tethered balloon ascents made during the late afternoon and evening of 15 October 1978. Strong cooling of the valley atmosphere began after 1630 MST. The mean rate of energy loss from a 1 m-thick cross section of the valley atmosphere during the 4 h period of observations was 1.23 MW. The zone of maximum rate of energy loss propagated upwards from the valley floor after 1630 MST and was accompanied by distinctive structures in both the temperature and wind fields. Transport of cold air in the downslope flows over the sidewalls is thought to play a major role in causing the rapid growth (250 m/h) in temperature inversion depth and the strong cooling of the atmosphere in the early stages of the evening transition period.

Zusammenfassung

Der Aufbau einer Temperaturinversion im Eagle Valley von Colorado

Die Entwicklung von Temperaturinversion und Windstruktur im Eagle Valley von Colorado wurde mittels Fesselballonaufstiegen untersucht. Diese Ballonaufstiege wurden am späten Nachmittag und Abend des 15. Oktober 1978 durchgeführt. Nach 1630 MST setzte eine starke Abkühlung der Talatmosphäre ein. Die mittlere Rate des Energieverlüstes während des vierstündigen Beobachtungszeitraumes von einem 1 m starken Querschnitt der Talatmosphäre war 1.23 MW. Die Zone der maximalen Energieverlustrate breitete sich nach 1630 MST vom Talboden nach oben aus, wobei sie von charakteristischen Temperatur- und Windfeldstrukturen begleitet wurde. Man nimmt an, daß der Transport von kalter Luft in den Abhangströmungen über die Seitenwände bei der Verursachung des raschen Anwachsens (250 m/h) der Mächtigkeit der Temperaturinversion und der starken Abkühlung der Atmosphäre in den frühen Stadien der abendlichen Übergangsperiode eine bedeutende Rolle spielt.

1. Introduction

The buildup of temperature inversions and the development of the nighttime local wind system is of increasing interest in studies of air pollution potential in complex terrain areas. In the Rocky Mountains of western Colorado, the high elevation and continentality of the climate result in strong diurnal changes in atmospheric structure during clear weather periods. Observations of these diurnal changes, which are well marked in this climate setting, allow the investigation of physical mechanisms by which mass and thermal energy are transferred in the valley atmosphere. In the present

---

* Contribution no. PNL-SA-13718. A slightly modified version of a paper presented at the American Meteorological Society's Second Conference on Mountain Meteorology at Steamboat Springs, Colorado, in November 1981.

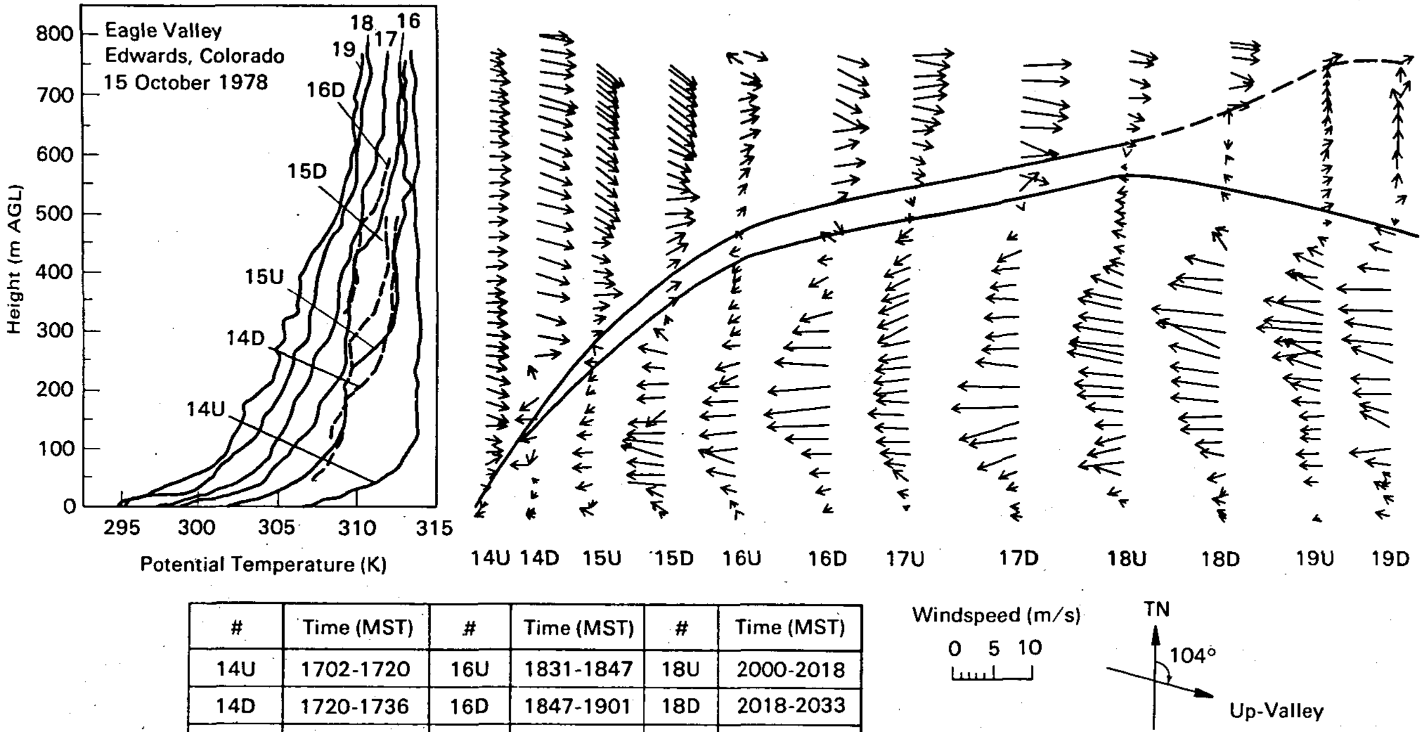
paper, we analyze the buildup of temperature inversions and the development of nocturnal drainage wind systems in Colorado's Eagle Valley using tethered balloon observations, and we draw some initial conclusions concerning the mass and thermal energy transfers in the valley atmosphere.

2. Case Study of 15 October 1978

Tethered balloon profiles taken in the 700 m-deep Eagle Valley during a 4 h period in the afternoon and evening of 15 October 1978 illustrate the normal evolution of valley temperature and wind structure during inversion formation (Fig. 1). Observations were taken from a valley floor site (38°38′23″N, 106°34′33″W, 2222 m elevation) near Edwards, Colorado, where the valley floor is 1450 m wide and the sidewall slopes are 10° (south-facing slope) and 21° (north-facing slope). Further details on the topography of the valley and the location of the site have been published by Whiteman (1982). Skies were clear and the atmosphere undisturbed, with a high-pressure cell over the western U.S. and weak upper-level winds. Late afternoon winds at the 700 mb level (i.e., at an elevation 955 m above the valley floor site) were from 265° at 7 m/s at Grand Junction, Colorado, the nearest National Weather Service upper-air sounding site, located 180 km west-southwest of Edwards, Colorado.

2.1 Winds and Potential Temperature Structure Evolution

In the afternoon a deep convective boundary layer is normally present over the western slope of the Colorado Rocky Mountains. Soundings from the floor of the Eagle Valley at this time usually show a deep adiabatic, or constant potential temperature, atmosphere containing up-valley winds with little variation in speed or direction with height. In the Eagle Valley on



#	Time (MST)	#	Time (MST)	#	Time (MST)
14U	1702-1720	16U	1831-1847	18U	2000-2018
14D	1720-1736	16D	1847-1901	18D	2018-2033
15U	1746-1803	17U	1914-1931	19U	2043-2102
15D	1803-1822	17D	1931-1945	19D	2102-2116

Fig. 1. Sequential tethered balloon profiles of potential temperature and winds during the evening of 15 October 1978 in the Eagle Valley. Vector winds are plotted as a function of height; vector lengths correspond to wind speeds (see wind speed legend). The up-valley direction is given for reference. The time intervals over which the up (U) and down (D) soundings were conducted are given in the table. The solid lines in the wind profiles delineate the boundaries of the wind transition layer

15 October a convective boundary layer was present and warmed during the afternoon to a maximum potential temperature of 314 K at about 1630 MST (the time of maximum heating was determined from a thermograph and is not shown in Fig. 1). Winds in the valley were up-valley at about 3 m/s. The cooling that began at the valley floor at 1630 MST occurred near the time when valley surfaces first became shaded, or when the surface sensible heat flux became negative. At this time, near-surface air in the valley begins to cool and cold air begins to flow down the sidewalls. Thus, by the first soudning, at 1702 MST, an appreciable depth (125 m) of cold air was already present over the valley floor when it was still illuminated by sunlight. The energy budget at the surface had evidently reversed by this time, since the ground was cooler than the atmosphere immediately adjacent to it. Thus, in addition to the cold air drainage onto the valley floor, the air over the valley floor is cooled by turbulent heat transport from the atmospheric surface layer to the ground.

The surface energy balance at this time would be characterized by a net loss of all-wave radiation balanced by sensible heat transfer towards the surface and upward ground heat flux. Latent heat flux is assumed to be negligible under the dry surface conditions observed. The valley atmosphere is also cooled by radiative flux divergence. The first indication in the wind profiles of inversion buildup was a decrease in up-valley wind speeds near the ground followed by weak cross-valley breezes. Further cooling and an increase in the depth of the surface-based inversion are apparent in subsequent soundings, taken after the valley floor became shaded at 1715 MST. The rapid buildup occurs as down-valley winds are initiated within the inversion layer. The inversion and down-valley flow layers propagate upwards at speeds of 250 m/h over the first 1–1/2 h of observation, but then the rate of propagation slows.

Winds in the down-valley flow regime are quite strong in the center of the layer (up to 8 or 9 m/s) but decrease as the ground or the top of the layer are approached. At the top of the down-valley flow a 50 m-deep transition layer separates the down-valley flow from the up-valley flows that persist aloft. The wind transition layer contains weak winds with appreciable cross-valley components and corresponds closely to an intense stable layer in the temperature profiles. This thin, intense stable layer is called the "inversion cap" in subsequent paragraphs. By 2100 MST the up-valley winds are no longer present in the upper levels of the valley, having been replaced by light winds of variable direction. At this time the valley winds are completely decoupled from the prevailing flows above the valley ridge tops.

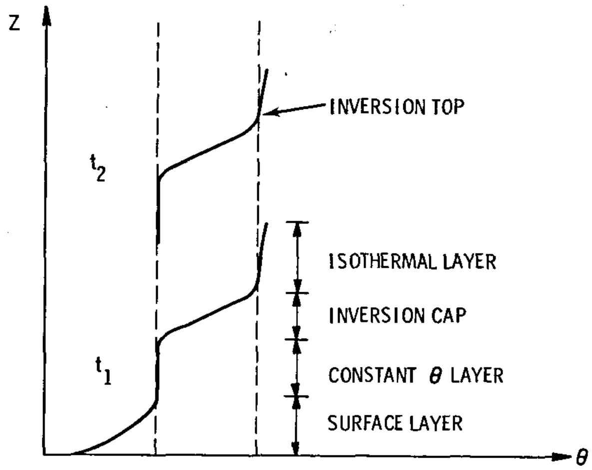


Fig. 2. Schematic diagram showing persistent layers and features in the evening potential temperature profiles

The interrelationships between layers in the wind and temperature profiles are to be emphasized, since they are a regular feature in the Eagle Valley. Down-valley winds typically prevail within the surface-based inversion, while winds in the neutral layer above the growing valley inversion typically maintain their late afternoon up-valley flow and decrease in speed during the period of inversion buildup. Especially noteworthy in the Eagle Valley soundings are the presence of special structural features in the temperature profiles, some of which correspond to features in the wind profiles. These features can be followed from sounding to sounding in Fig. 1. The nomenclature used to refer to these features is given in the schematic diagram of Fig. 2. An intriguing feature of consecutive potential temperature profiles on 15 October (a feature observed on other nights in this valley and in other valleys as well) is the upward propagation of the *inversion cap*. The cap, which corresponds in height to the transition layer observed in the wind profiles, retains its characteristic shape and potential temperature from profile to profile, until attaining an elevation of 500 to 600 m above the valley floor. One possible explanation for the vertical propagation of the inversion cap is its upwards transport by rising motions over the valley center. Following this explanation, potential temperatures above the inversion cap change with time due to adiabatic vertical advection. The change in temperature structure caused by this mechanism alone is indicated in Fig. 2 by the two curves labeled t_1 and t_2. Such ascending motions have been predicted by previous investigators (Wagner 1938; Defant 1949) but have never been directly measured. If this is the explanation for the inversion cap's ascent, it is necessary to postulate a mechanism for mass convergence below the inversion cap. Downslope flows from the valley sidewalls (Fig. 3) can provide the required mass convergence mechanism, if parcels in these flows have temperature deficits larger than the temperature jump across the inversion cap and if their volume flux is sufficient to provide enough mass convergence below the inversion cap to account for the rise of the inversion cap at the observed rate. For the geometry of the Eagle Valley, the required volume flux from the downslope flows, if this were the only mechanism operating, would be about 160 m^3/s. This volume flux could be met, for example, by 80 m-deep slope flows on each sidewall having downslope velocities of 1 m/s. Other mechanisms operating in the valley atmosphere, such as radiative flux divergence and turbulent heat transport towards the ground, would decrease the slope flow volume flux requirements, since these processes act independently to produce a growing inversion layer. It is difficult, on the basis of the data at hand, to determine the relative importance of individual physical processes in causing inversion growth, but the observations seem to support the conclusion that transport of cold air in the downslope flows plays a major role.

The *constant-θ layer*, which corresponds to the top portion of the down-valley flow regime in the wind profiles, tends to increase in depth with successive soundings. Wind speed shear is characteristic of this layer, and wind directions are decidedly cross-valley, indicating flow off the extensive, non wooded, south-facing sidewall. This cross-valley flow persists until about 1900 MST, and its decay corresponds in time to the decay of the constant-θ layer and the disappearance of the inversion cap. A tentative conclusion from the observations is that downslope flows from the valley sidewalls above the level of the inversion top are mixed into the valley inversion below the inversion cap in the constant-θ layer.

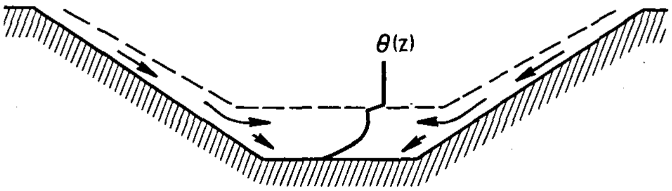


Fig. 3. Mass convergence below the inversion cap from the slope flow layers

The *surface layer* undergoes an extremely rapid cooling initially, but its cooling rate slows with time and its depth increases with time until, near the end of the 4 h period of observations, it makes up nearly the entire depth of the valley atmosphere. Cooling rates in this and other layers prove interesting and will be discussed in the next subsection.

2.2 *The Cooling of the Valley Atmosphere*

Cooling of an air mass, no matter how it is accomplished, represents an energy loss from the mass. The energy loss from a height layer, z_1 to z_2, over a time interval δt can be calculated from consecutive vertical temperature profiles by observing the temperature change between profiles as a function of height, $\delta T(z)$, through the depth of the layer. Calculations can be made assuming 1) that the vertical profiles are representative of a vertical column extending above the observation site (Fig. 4a), or 2) that the vertical profiles are representative of the full width of the valley (Fig. 4b).

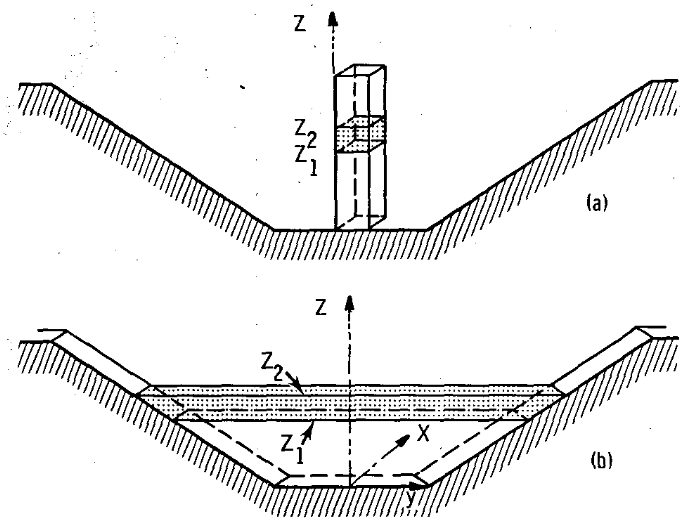


Fig. 4. Geometric scheme used in the calculation of valley energy loss. In (a), observations are considered to be representative of energy loss in a unit vertical column; in (b), observations are considered to be representative of the entire valley width at the height level considered

The rate of loss of energy, F, can then be calculated from the First Law of Thermodynamics as follows

$$F_1 = -\frac{c_p\bar{\rho}}{\delta t}\int_{z_1}^{z_2}\int_0^1\int_0^1 \delta T(z)\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\ [\mathrm{J/s}] \qquad (1)$$

or

$$F_2 = -\frac{c_p\bar{\rho}}{\delta t}\int_{z_1}^{z_2}\int_{y_L}^{y_R}\int_0^1 \delta T(z)\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\ [\mathrm{J/s}]\,, \qquad (2)$$

where $y_L = -\frac{l}{2} - \frac{z}{\tan\alpha_1}$ $\quad y_R = \frac{l}{2} + \frac{z}{\tan\alpha_2}$,

c_p is the specific heat of dry air, $\bar{\rho}$ is the average density in the layer, l is the valley floor width, and α_1 and α_2 are the slope angles of the sidewalls. F_1 and F_2 for 15 October, calculated numerically from temperature profile data, are presented for 50 m height intervals in Fig. 5.

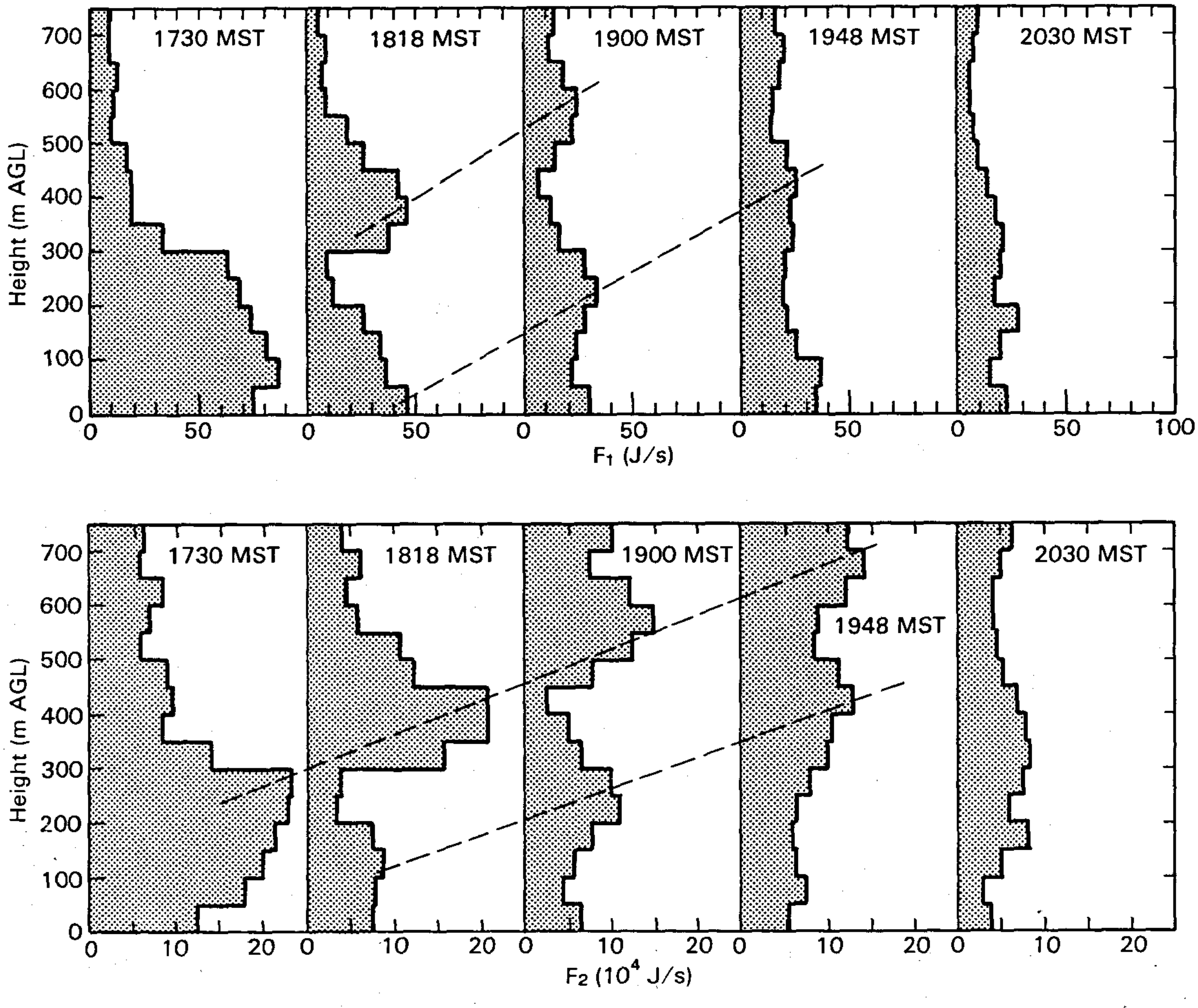


Fig. 5. Valley energy losses F_1 and F_2 calculated according to Eqs. (1) and (2) for 15 October

For reference, a 50 m-deep layer in a unit column cooling by 1 C in 1 h has an energy loss rate, F_1, of 14 J/s or 14 W.

The greatest rate of loss of energy from the valley atmosphere occurs early in the inversion formation cycle in the layer nearest the valley floor. The zone of rapid energy loss subsequently propagates upwards from the surface, producing the greatest energy losses just below the inversion cap as it ascends. The full significance of this cooling relative to the volume of the valley atmosphere is most clearly seen in F_2 calculations in Fig. 5. A smaller secondary maximum in the rate of energy loss occurs near the top of the growing surface layer.

Calculations of energy loss for the complete cross section made over the 4 h period of observations through a depth of 750 m reveal that the average rate of energy loss in the 1 m-thick cross section was 1.23 MJ/s. The corresponding number for the unit column was 323 J/s. Some interesting observations of valley energy loss from the time of inversion formation to sunrise (not shown here) indicate that the total energy loss from the upper levels of the valley atmosphere is actually greater than the loss from the surface layers. This greater loss is possible despite the greater cooling near the ground, because of the larger mass of air in the upper levels.

3. Discussion and Conclusions

A case study of temperature inversion buildup and down-valley wind system development was conducted for the Eagle Valley using observations taken during the afternoon and evening period of 15 October 1978. Temperature inversion buildup began about 45 min before astronomical sunset (i.e., at 1630 MST). The depth of the inversion increased rapidly, with average growth rates of 250 m/h during the first 1–1/2 h of the inversion buildup period. The inversion extended through the entire valley depth by 2000 to 2100 MST, and the mean rate of energy loss from a 1 m-thick cross section of the valley atmosphere during the 4 h inversion buildup period was 1.23 MW. The energy loss can be due to a number of physical processes including sensible heat flux, radiative flux divergence, and cold air advection by the down-valley and down-slope flows. Redistribution of the cooling within the valley may also be accomplished by vertical motions (Hennemuth 1986).

A zone of maximum rate of energy loss propagated upwards from the valley floor after 1630 MST and was accompanied by distinctive structures in both the temperature and wind fields. A persistent zone of intense stability was observed at the top of the growing inversion layer. This inversion cap corresponded in height to a wind reversal zone. The zone itself was characterized by weak winds of variable direction. Below this ascending zone were strong (up to 7 m/s) down-valley winds, while above it up-valley winds persisted. The temperature jump at the inversion cap weakened as the cap ascended. A zone of strong cooling under the inversion cap appears to be best explained by ascent of the cap itself (i.e., temperatures change because of vertical advection). The rising of the cap requires that there be mass convergence below the cap. This mass convergence could be caused by convergence of the downslope flows from the two sidewalls below the level of the inversion cap. A well-developed cross-valley flow occurred in a constant potential temperature layer just below the inversion cap, suggesting that the mass convergence required for inversion cap ascent occurs here. This observation suggests that downslope flows separate from the two sidewalls and produce horizontal mass flux convergence just below the rising inversion top. This process should be thought of as discontinuous or stochastic, since the slope flows would not be expected to flow out into the valley center as a steady stream. Thus, we tentatively conclude that, during the inversion buildup period, downslope flows are not continuous. That is, parcels of air carried in the downslope flows high on the sidewalls are typically not carried all the way down the slope to the valley floor to converge near the center of the valley floor. Rather, parcels in the downslope flow layers are mixed into the inversion layer from the valley slope flows when they attain their level of buoyancy equilibrium. This mixing occurs just below the inversion cap because the parcels encounter a sudden temperature jump (decrease) when descending through the level of the rising inversion cap.

The limited amount of data available for the Eagle Valley case study does not allow us to investigate along-valley atmospheric structure, nor can we be confident that the slope flows are performing as postulated. The hypothesis developed above seems plausible and is consistent with the data but will have to be tested using a more complete data set or numerical models. The implications of the hypothesis for air pollution dispersion in valleys during the inversion buildup period seem significant. If the hypothesis is correct, pollutants emitted in the downslope flows will be mixed effectively through the valley volume rather than being carried down the slopes to the valley floor. Thus, we suggest that further and more complete observational programs be conducted and that simulations be performed with numerical models that include the appropriate physics.

Acknowledgements

Research was supported by the U.S. Environmental Protection Agency and the U.S. Department of Energy under related services agreement DE-AC06-76RLO-1830. Data collection was supported under Grant ATM76-84405 from the Atmospheric Sciences Section, National Science Foundation (NSF) while the author was at the Department of Atmopheric Sciences, Colorado State University. The Field Observing Facility of the National Center for Atmospheric Research (NCAR) provided a tethered balloon system and an experienced technician who helped collect much of the field data. The NCAR is supported by the NSF. Dr. T. B. McKee's support in the early stages of this research is greatly appreciated. Discussions with Dr. T. W. Horst aided the author in interpretation of the data.

References

Defant F (1949) Zur Theorie der Hangwinde, nebst Bemerkungen zur Theorie der Berg- und Talwinde (a theory of slope winds, along with remarks on the theory of mountain winds and valley winds). Arch Met Geoph Biokl A1: 421–450 (English translation: Whiteman CD, Dreiseitl E (eds) (1984) Alpine meteorology – translations of classic contributions by A. Wagner, E. Ekhart and F. Defant. PNL-5141/ ASCOT-84-3, Pacific Northwest Laboratory, Richland, WA 99352)

Hennemuth B (1986) Temperature field and energy budget of a small Alpine valley. Contr Atm Phys 58(4): 545–559

Wagner A (1938) Theorie und Beobachtung der periodischen Gebirgswinde (theory and observation of periodic mountain winds). Gerlands Beitr Geophys (Leipzig) 52: 408–449 (English translation: Whiteman CD, Dreiseitl E (eds) (1984) Alpine meteorology – translations of classic contributions by A. Wagner, E. Ekhart and F. Defant. PNL-5141/ ASCOT-84-3, Pacific Northwest Laboratory, Richland, WA 99352)

Whiteman CD (1982) Breakup of temperature inversions in deep mountain valley, part I: Observations. J Appl Met 21(3): 270–289

Author's address: Dr. C. David Whiteman, Senior Research Scientist, Battelle Pacific Northwest Laboratories, P.O. Box 999, Richland, WA 99352, U.S.A.