Breakup of a Nocturnal Temperature Inversion in the Dischma Valley during DISKUS

HANS MÜLLER

Fraunhofer Institut für Atmosphärische Umweltforschung, Garmisch-Partenkirchen, FRG

C. DAVID WHITEMAN*

Meteorologisches Institut der Universität München, FRG

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ABSTRACT

The nocturnal potential temperature inversion in Switzerland's Dischma Valley on 11 August 1980 was destroyed during a 4½-h period following sunrise. The temperature inversion breakup was accomplished primarily by descent of the inversion top rather than upward growth of a convective boundary layer from the valley floor. The thermodynamic model of Whiteman and McKee, as extended with Steinacker's concept of valley area-height relationships, simulated inversion breakup well when sensible heat flux was assumed to be about 6% of the extraterrestrial solar flux. Observations in the valley support this value of sensible heat flux, which is lower than values observed in the drier Colorado valleys where the model was initially tested.

1. Introduction

In deep mountain valleys the destruction of the nocturnal temperature inversion frequently differs from the well-known inversion breakup over the plains. Over flat terrain the inversion is destroyed predominantly by the upward growth of a convective boundary layer from the ground through the process of penetrative convection. In the valley, however, the destruction is often accomplished as the top of the temperature inversion descends and the valley atmosphere warms. This lowering of the upper inversion boundary, which has been observed at different valley sites—e.g., in the Mürz Valley (Machalek, 1974), in the Inn Valley (Brehm and Freytag, 1982), and in several western Colorado valleys (Whiteman, 1982), is caused by locally developed circulations in the valley. Specifically, after sunrise, mass is removed from the valley via upslope motions that develop over the heated sidewalls, and this removal requires a compensatory subsidence in the remaining part of the valley atmosphere (Whiteman and McKee, 1977; Brehm and Freytag, 1982).

In order to explain the gross features of inversion destruction in a mountain valley, Whiteman and McKee (1982) developed a bulk thermodynamic model in which sensible heat flux is the driving force. The model has, as its basis, a simplified energy budget equation for the valley atmosphere. Three patterns of potential temperature inversion breakup may be simulated depending on whether the sensible heat flux is used primarily 1) to cause convective boundary layers to grow over the valley floor and sidewalls (pattern 1); 2) to remove mass from the inversion layer via the upslope flows (pattern 2); or 3) to accomplish both (pattern 3). The primary inputs to the model are the valley configuration (floor width, sidewall inclination angles), characteristics of the valley inversion at sunrise, and an estimate of sensible heat flux obtained from solar radiation calculations. Bader and McKee (1985) concluded from dynamical model simulations of valley temperature inversion breakup that the bulk thermodynamic model accounts for the dominant mechanisms of inversion destruction.

In this contribution the thermodynamic model is applied to observations of temperature inversion breakup in the Dischma Valley near Davos, Switzerland, obtained during the DISKUS mountain wind experiment. (For details concerning DISKUS see Freytag and Hennemuth 1981, 1982; Hennemuth and Köhler 1984; or Hennemuth 1985). Steinacker's (1984) "area-height" concept is incorporated into the original version of the model to better account for actual valley topography. The results are described in terms of the valley's energy budget, and comparisons are made with inversion breakup in the Rocky Mountains.

2. Area-volume relationships for idealized valleys

It is well known from the first law of thermodynamics that a given input (or extraction) of thermal energy

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Corresponding author address: Dr. C. David Whiteman, Atmosphere Sciences Department, Battelle Pacific Northwest Laboratory, P.O. Box 999, Richland, WA 99352.

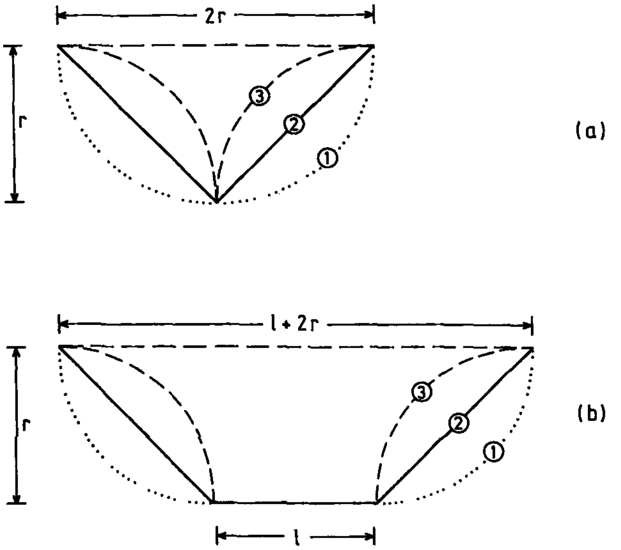


FIG. 1. Idealized valley cross sections. (a) 1 is U-shaped with radius r, 2 is V-shaped, 3 is convex sidewalls with radius r. (b) Same as (a), but for a flat-bottomed valley floor of width l.

to (or from) a volume of air will change its temperature—the smaller the volume, the larger the temperature change for a fixed energy increment. This means that the valley geometry, e.g., expressed by the ratio of the area at the top of the valley to the volume of the valley, is a key factor in any thermal energy budget consideration.

To illustrate this, let us consider in Fig. 1a three idealized valley cross sections where we choose, for convenience, valleys that are twice as wide as they are deep. The valley cross sections are assumed to be 1 m thick. The energy input to the valleys during daytime comes from solar radiation that streams into the top of the valley through area $A = 2r$ [m^2]. Some of this energy, when it reaches the ground, is converted to sensible heat flux, the source of heat to the valley atmosphere. All three of the valleys are assumed to have the same energy input, since they have the same width at ridgetop level and, thus, the same exposure to solar radiation. In the case of a U-shaped valley (valley 1) this energy is used to heat a larger volume than for a V-shaped valley (valley 2) or for a valley with convex sidewalls (valley 3). Accordingly, the temperature change in the convex-sidewall valley will be larger than that for a V-shaped or U-shaped valley. The volume of air over the plain below height r (i.e., $2r^2$) would be larger than for any of the valleys and the temperature changes would be appropriately smaller.

The more general case of flat-bottomed valleys with floor width l is shown in Fig. 1b. Table 1, as a reference, provides calculations of area-to-volume ratios for the individual valleys, and compares these ratios with that for a plain by defining a "topographic amplification factor," α. This amplification factor is an integral part of Whiteman and McKee's (1982) inversion breakup model, as we will see in section 4. In the case of $l \to \infty$, the valleys have amplification factors that approach 1, as for flat plains. For $l \to 0$, the upper limits of the U-shaped ($\alpha = 1.27$), V-shaped ($\alpha = 2$) or pure convex ($\alpha = 4.66$) valleys are attained. Thus, the amplification factors for the flat-bottomed valleys in Fig. 1b are lower than for the valleys pictured in Fig. 1a. The maximum range for all the particular valleys considered is $1 < \alpha \leqslant 4.66$.

Actual valleys typically have convex sidewalls in the upper elevations of the valley drainage areas, so that

TABLE 1. Area-volume relationships for different idealized valleys (i = 1, 2, 3) with the unit cross-sectional area, $A = (l + 2r)$ (see Fig. 1b).

Index (i)	A/V_i	α_i*	α_i $(l \to \infty)$	α_i $(l \to 0)$†	Comments
1	$\dfrac{l+2r}{lr+\frac{\pi}{2}r^2}$	$\dfrac{2(l+2r)}{2l+\pi r}$	1	$\dfrac{4}{\pi} \approx 1.27$	"U"-shaped valley
2	$\dfrac{l+2r}{lr+r^2}$	$\dfrac{l+2r}{l+r}$	1	2	"V"-shaped valley
3	$\dfrac{l+2r}{lr+\left(2-\frac{\pi}{2}\right)r^2}$	$\dfrac{2(l+2r)}{2l+(4-\pi)r}$	1	$\dfrac{4}{4-\pi} \approx 4.66$	convex valley
4	$\dfrac{1}{r}$	1	1	1	plains

* Topographic amplification factors for the valleys relative to the plain (i = 4) are defined by

$$\alpha_i = \frac{A/V_i}{A/V_4} = \frac{A}{V_i}\,r.$$

† Note that for $l \to 0$, the flat-bottomed valleys in Fig. 1b reduce to those pictured in Fig. 1a.

amplification factors greater than 2 are the rule. Steinacker (1984) has calculated an amplification factor of 2.1 for Austria's deep Inn Valley. In his analysis a segment of valley was chosen to include the effects of major tributaries in the calculations. His work extends that of Wagner (1938), who apparently made the first such calculations, but only for idealized cross sections.

3. Dischma valley topographic amplification factors

The Dischma valley—the experimental area of DISKUS in August 1980—is a small Alpine end valley of simple structure (Fig. 2). It is about 15 km long, 4–5 km wide from crest to crest, and 1 km deep. It runs almost linearly from SSE to NNW and enters the main Landwasser Valley near Davos. The valley floor elevations range between 1600 and 2000 m MSL.

Dischma valley drainage area was determined as a function of height above the measuring site "Hof" by planimeter from a topographic map on the scale of 1:25 000 using 100-m contour intervals. The results are plotted in nondimensional form in Fig. 3. The topographic amplification factor is also plotted as a function of nondimensional height in Fig. 3. The valley volumes required to determine the factors were obtained from the drainage area data by treating the layers as trapezoids. The average value of the amplification factor over the valley depth is about 2.67, and this value varies only slightly with height. The factor of 2.67 illustrates the predominantly convex shape of the valley sidewalls when considered to extend to the ridgetop elevations.

4. Temperature inversion breakup in the Dischma valley

Tethered balloon potential temperature profiles in the Dischma valley at the "Uf den Chaiseren" site (CH, Fig. 2) during the inversion breakup period of 11 August 1980 are shown in Fig. 4. The corresponding analyzed field of along-valley wind components is presented in a time–height section in Fig. 5. In this case, inversion breakup follows pattern 2 and is accomplished primarily through descent of the inversion top rather than through the upward growth from the surface of a convective boundary layer. A comparison with Fig. 5 shows that the down-valley winds persist in the remnants of the inversion during the inversion breakup period, and up-valley winds descend into the valley as the temperature inversion top descends.

Since the temperature profiles are quite well fit by a simple two layer structure with constant gradients (Fig. 4) Whiteman and McKee's (1982) thermodynamic model can be applied to simulate this inversion breakup. For this purpose we may use their Eq. (18) for a pattern 2 inversion destruction in which the rate of change of inversion depth h is given as

$$\frac{dh}{dt} = -\frac{\theta}{T}\frac{\alpha}{\rho c_p \gamma h} A_0 S_F(t), \qquad (1)$$

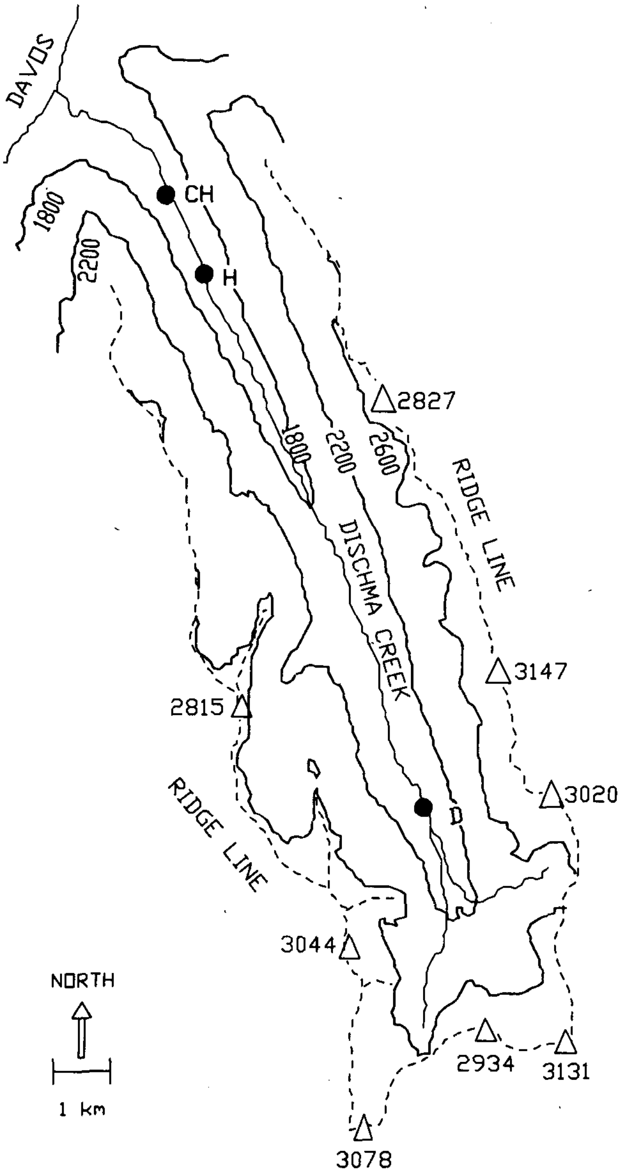


FIG. 2. Topographic map of the Dischma Valley with elevations in m MSL. Sites mentioned in the text are located at CH ("Uf den Chaiseren": 1590 m), H ("Hof": 1650 m) and D ("Dürrboden": 1970 m). Contour interval: 400 m. Dotted: ridge line. △: mountain peak.

where S_F, the extraterrestrial solar flux, is approximated by

$$S_F = A_1 \sin\left[\frac{\pi}{\tau}(t - t_i)\right].$$

The parameters in the equation are defined in Table 2.

Integrating Eq. (1) under the assumption that α is independent of height, we obtain an equation for predicting inversion depth as a function of time,

$$h = \left[h_i^2 + 2\frac{\theta}{T}\frac{\alpha}{\rho c_p \gamma} A_0 A_1 \frac{\tau}{\pi}\left\{\cos\frac{\pi}{\tau}(t - t_i) - 1\right\}\right]^{1/2}. \qquad (2)$$

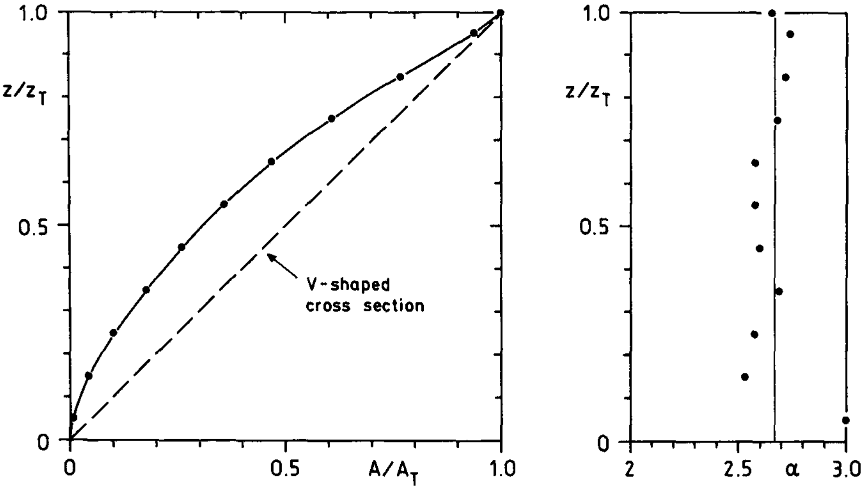
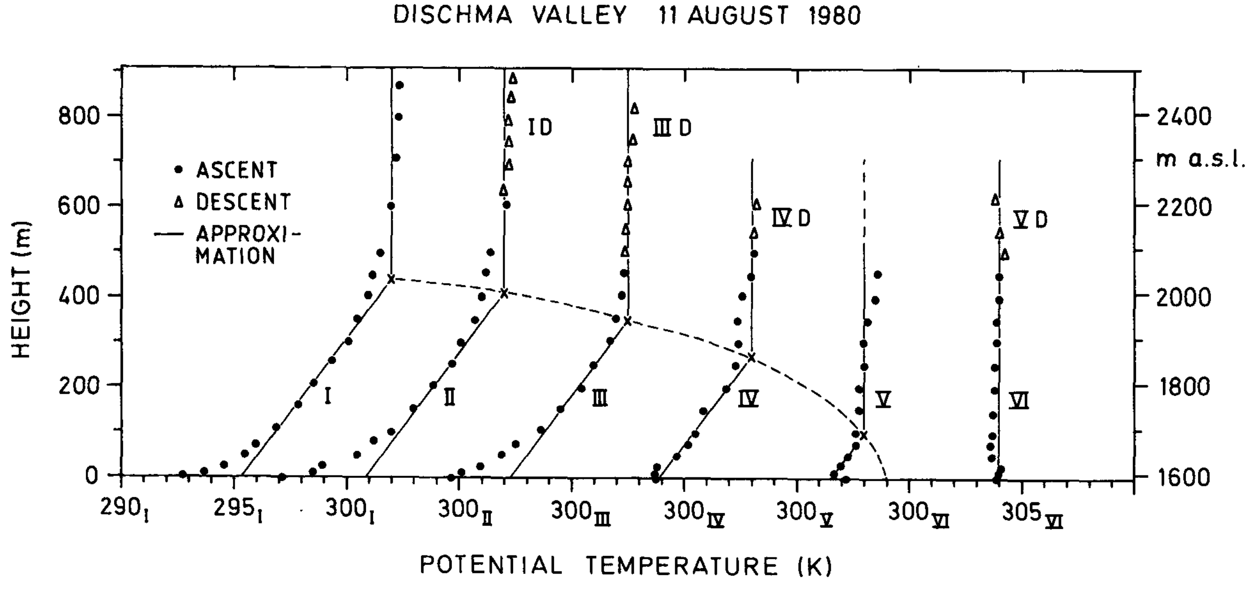


FIG. 3. Normalized area-height distribution (Z_T = 1000 m, A_T = 38.7 km^2) for the Dischma Valley above the measuring site "Hof."

This model equation fits the data well when A_0, the only unspecified parameter (Table 2), is set to 0.056. This value is obtained by a best fit of the model curve to the data in Fig. 6. If we use the amplification factor for an idealized V-shaped valley (α = 2) we obtain A_0 = 0.075.

This fit of the model to the data implies that the energy budget of the Dischma Valley is such that only about 6% of the extraterrestrial solar radiation is converted to sensible heat flux within the valley during the 4½-h inversion breakup period. This energy is used to accomplish the descent of the inversion top mainly via



	TIME (CET)
I	0438 - 0511
ID	0514 - 0519
II	0554 - 0621
III	0732 - 0756
IIID	0806 - 0812

	TIME (CET)
IV	0840 - 0905
IVD	0908 - 0910
V	0928 - 0950
VD	0957 - 0959
VI	1018 - 1041

THEORETICAL SUNRISE SR : 0516 CET

FIG. 4. Potential temperature profiles on 11 August 1980 illustrating inversion breakup at the measuring site "Uf den Chaiseren" (1590 m MSL) according to Aepli's (1981) tethered balloon soundings (I–VI). Profile data are fit using a two-layer model. Inversion depths are indicated by X's.

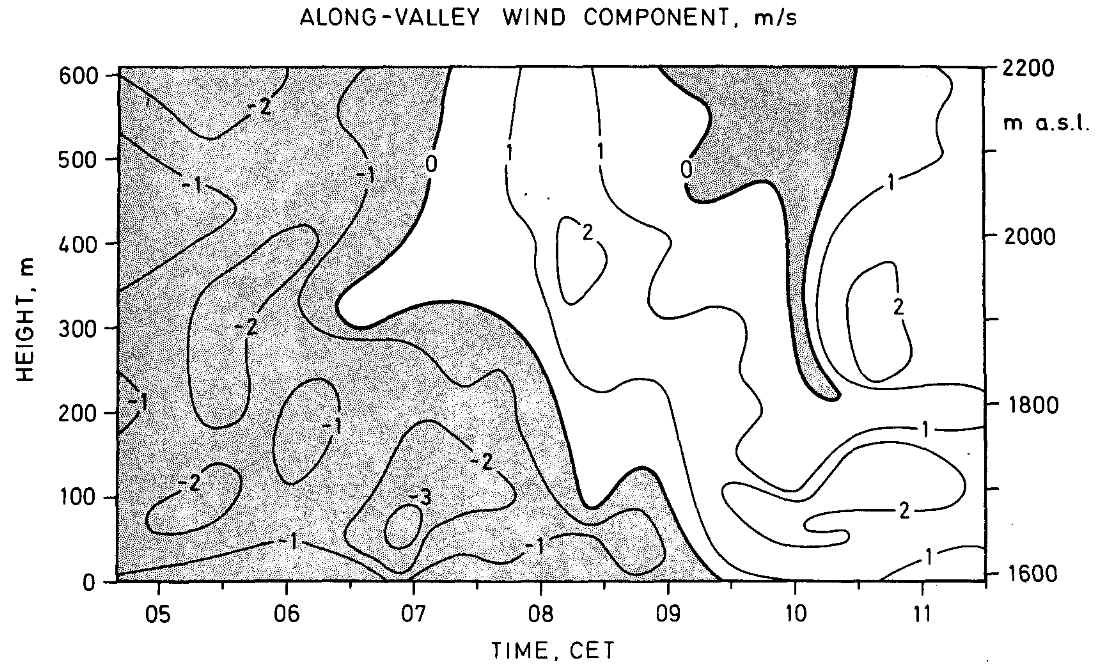


FIG. 5. Time-height analysis of along-valley wind components (m s^{-1}) on 11 August 1980 at the measuring site "Uf den Chaiseren", as measured by Aepli (1981) with a tethered balloon. Negative values blow down the valley.

the slope wind mechanism (pattern 2). Observations of the surface energy budget at the Dürrboden measurement site (D, Fig. 2) by Halbsguth et al. (1984) lend support to this estimate. Their figures indicate that between local sunrise (~0730 CET) and the time of inversion destruction (~0948 CET), the sensible heat flux total was about 0.4 to 0.5 MJm^{-2}. The total extraterrestrial solar flux on a horizontal surface above the Dischma Valley from astronomical sunrise (0516 CET) to 0948 CET, as calculated by a theoretical model, was 8.0 MJ m^{-2}. Thus, the observations at the Dürrboden site allow us to calculate a value for A_0 of 0.050 to 0.062, in good agreement with the model. This agreement between a valley-volume-integrated total and individual site measurements is somewhat fortuitous, however. Other sites would have different local sunrise times, soil moisture conditions, vegetation types, and other factors affecting the local surface energy budget. In fact, the surface cover of the Dischma valley is quite heterogeneous; extensive wood- and

TABLE 2. Model input parameters for Dischma Valley potential temperature inversion breakup on 11 August 1980.

Parameter	Definition
$t_i = 0$ *s*	theoretical sunrise (0516 CET)
t	time after sunrise (s)
$h_i = 435$ m	initial inversion height
$\gamma = 0.015$ K m^{-1}	potential temperature gradient
$\tau = 50400$ *s*	day length (14 h)
$A_1 = 1127$ W m^{-2}	extraterrestrial solar flux at solar noon
A_0 = unspecified	fraction of extraterrestrial solar flux converted to sensible heat flux in valley
$\alpha = 2.67$	amplification factor
$\theta/T = 1.1$	temperature ratio (θ = potential temperature)
$\rho = 1$ kg m^{-3}	air density
$c_p = 1000$ J kg^{-1} K^{-1}	specific heat at constant pressure

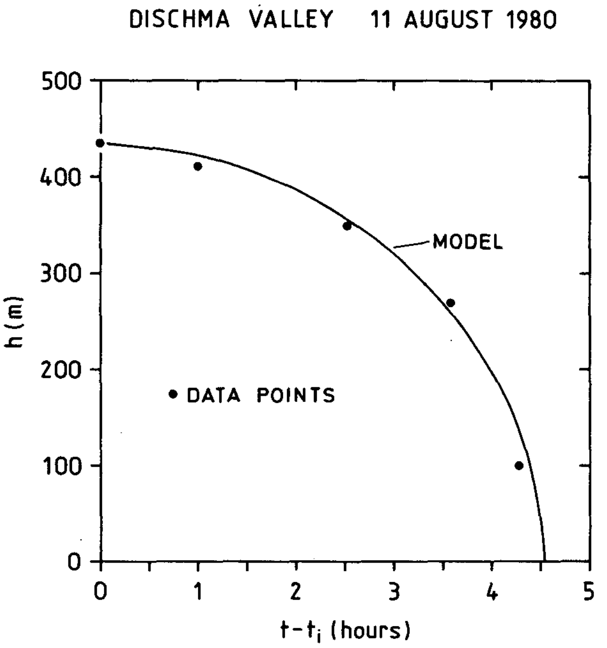


FIG. 6. Comparison of the model simulation of inversion height (h) with observations. Model input parameters are listed in Table 2. Data points are from Fig. 4.

meadow-areas are located near the valley's entrance, while rock and heath cover are predominant near the end of the valley (Hennemuth 1985). Nevertheless, the agreement gives us confidence that the model is performing as expected.

It is interesting to compare the Dischma Valley simulations to results obtained by Whiteman and McKee (1982) for valleys in the Rocky Mountains. The A_0 values can be much higher in the drier climates there. Model calculations on an October day in 1977 for Colorado's Eagle Valley produced an A_0 value of 0.45. This value is, no doubt, too high, since the topographic amplification factor was calculated on the basis of linear sidewalls and a flat-bottomed valley floor. Use of a larger amplification factor is justified by the actual topography and, as we have demonstrated, this larger factor will reduce the requirement on A_0. It is also interesting that no pure pattern 2 inversion destruction was observed in the Colorado series of experiments in summertime. This pattern of inversion destruction was observed only in the winter season when snow cover produced high albedos that reduced the energy available for sensible heat flux. The Dischma Valley simulation shows that pattern 2 inversion destruction can occur in summer in moist valleys when available energy is partitioned mainly into latent heat flux. Precipitation observations at Davos indicate that rain had fallen on each of the 3 days previous to 11 August with a total accumulation of 215 mm (Freytag and Hennemuth, 1982).

5. Discussion and conclusions

The nocturnal potential temperature inversion in the Dischma Valley on 11 August 1980 was destroyed within 4½ h following sunrise. Temperature structure evolution during this period followed Whiteman's (1982) description of a pattern 2 inversion destruction in which the primary process was the sinking of the top of the inversion, rather than the upward growth of a convective boundary layer from the surface. The inversion destruction was modeled using the bulk thermodynamic model of Whiteman and McKee (1982), as modified to more realistically account for the effects of actual topography on the valley atmosphere's thermal energy budget. The modification followed Steinacker's (1984) approach, in which the horizontally projected area of a drainage basin is compared to the actual volume of air within the drainage basin to determine the amplification of the diurnal thermal wave in the valley relative to a flat plain. Our calculations assumed that sensible heat flux convergence is the only term of the atmospheric energy budget equation which acts to increase atmospheric temperature—note that advective terms and radiative flux convergences may be important in some circumstances—and that sensible heat flux will produce energy gains only in the valley atmospheric volume described (i.e., no "leakage" from the volume). Finally, our calculations were made assuming a simplified initial thermal structure in the valley. Steinacker has demonstrated that the distribution of sensible heat flux convergence within a valley volume depends on temperature structure within the volume. Over the plains the normal processes of temperature inversion destruction by convective boundary layer growth and the buildup of temperature inversions takes place primarily in the layers immediately adjacent to the ground. In contrast, the topography of a valley allows heat to be produced over a range of altitudes within the valley, and the slope flows distribute the heat efficiently through the entire valley atmosphere through compensating vertical motions over the valley center.

The destruction of the potential temperature inversion in the Dischma Valley on 11 August 1980 occurred following the same pattern observed in Colorado valleys with winter snow cover. We hypothesize that this pattern of inversion destruction is preferred when the rate of input of sensible heat flux is low. In the winter case the energy available for sensible heat flux is reduced by the reflection of the incoming solar beam. In the moist Dischma Valley environment, on the other hand, the energy available for sensible heat flux is reduced by the strong partitioning of available energy into evaporative flux. Model calculations for the breakup of the Dischma Valley inversion indicate that only 6% of the extraterrestrial solar radiation flux is required to be converted to sensible heat within the valley to explain the observed rate of inversion destruction. The model-estimated values are supported by surface energy budget measurements made in the valley by Halbsguth et al. (1984).

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