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The energy budget in a valley nocturnal flow

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ABSTRACT

Calculations of radiative transfer within a V-shaped valley show that the radiative cooling of the valley air is greater than the cooling over a flat surface. The measured cooling of a drainage flow in a deep, steep-walled valley is compared to calculations of radiative transfer within the same valley. It is found that cooling throughout the full watershed of the valley, instead of only within the steep walled part of the valley, must be considered to account for the energy loss of air passing through the valley. Some 10% to 20% of this energy loss occurs as a result of direct radiative cooling of the air.

1. Introduction

Many mountainous valleys regularly develop nocturnal down valley flows that are fed by subsidence of air into the valley and by slope flows down the walls of the valley (Defant, 1951). Model computations have shown the flow will develop even if the floor of the valley has zero slope (McNider and Pielke, 1984). Previous research has also found that the flow is sensitive to the wind regime above the valley (Orgill et al., 1981).

Such nocturnal flows offer an opportunity to study the relative importance of direct radiative and turbulent transfer of energy between the air and the ground and the effect of altered area-height on this transfer. The area-height distribution has been found to be important in determining the difference in diurnal temperature cycles between valleys and nearby plains (Steinacker, 1985).

Determining the energy budget of a nocturnal valley flow is simplified because the flow evolves and continues over a period of hours (Whiteman, 1981), permitting the energy transfer to be considered as a near steady state process.

By selecting a case with winds above the valley light enough to be neglected and with insignificant latent heat changes, it is possible to assemble a relatively simple energy budget for the drainage flow. The significant components in this budget are the energy losses by the surface and the changes in the thermal and kinetic energy of the air between entering the valley and exiting as a flow down the valley. Radiative cooling of the air and turbulent transfer of heat to the radiatively cooled ground are the important means of heat loss.

Recent studies have suggested that radiative transfer is more important than previously thought in the cooling of the nocturnal boundary layer (Garratt and Brost, 1981; Andre and Mahrt, 1982). Drainage flow within the valleys has some similarities with as well as major differences from typical boundary layer studies that select situations having no complex terrain. The turbulence within the flow is greater than in a homogeneous boundary layer with the same Richardson number (Stone and Hoard, 1985), and radiative processes differ because the ground subtends a greater solid angle than flat terrain.

The increased turbulence as well as the increased surface-to-air volume within the valley enhances nonradiative transfer. The larger solid angle enhances the air-ground radiative transfer even though the net outgoing radiation at the valley top and at the same altitude above a plane surface is roughly the same. Both radiation and turbulence increase night-time cooling and are important in determining the character of the flow since the drainage comes about as a result of air within the valley cooling more rapidly than air outside the valley. The increased density of the cooler air within the valley creates the pressure gradient driving the outward flow as Nickus and Vergeiner (1984) have pointed out.

The importance of radiative cooling in valleys will be demonstrated by considering a simple V-shaped valley. Measurements of the energy budget in a steep walled mountain valley will then be discussed, and it will be shown that the energy budget of the entire drainage area of the valley must be considered instead of only the cooling within the prominent steep-walled portion of the valley. Computations of the radiative cooling of the valley surface and the air within the valley are then used to determine the relative importance of air cooling by radiative emission and by exchange with the surface.

2. Radiative transfer within a valley

The importance of radiative cooling of air is sometimes underestimated in importance because calculations at higher altitudes show radiative cooling of about a degree per day. Such slow cooling occurs when the air is exchanging radiation primarily with other air. However, the ground can cool more rapidly than the air because its high emissivity in the infra red window regions permits it to radiate to space. Air near the ground can then cool more rapidly by radiative interchange with the ground instead of only with nearby air.

This, as well as heat transfer to the ground, causes the heating and cooling of air within valleys to be greater because the ground surface to air volume ratio is larger. The ground is effectively wrapped partially around the air within the valley. There is some compensation because the ground cools more slowly due to the valley walls obscuring part of the sky, but computations show that this compensation is small. The decreased cooling rate of sloping ground has been previously estimated (Kondratyev, 1965), but little has been done with the more complex case of the double slopes that form valleys. The diurnal cycle is further complicated by the decreased sunlight reaching the valley floor and walls.

The family of curves in Fig. 1 shows the rate of energy loss by air within a valley relative to the loss by the same layer over flat ground. The layer thickness over the flat ground is equal to the valley depth. The curves relate to an idealized valley formed by two flat walls intersecting to form a V-shaped valley of depth D. These curves were generated using an emissivity of 1.0 for the walls and a wall temperature 1 K cooler than the air within the valley. The radiative model is described in the next section. It assumed a uniform temperature for air in the valley with a pressure of 800 mb at the valley floor. This pressure and the water vapor burden of the atmosphere were selected to correspond to the high altitude and dry air of Brush Creek.

The greatest cooling of the air occurs when the walls are steepest. In actual valleys the temperature will vary due to vegetation, airflow, and solar heating. The latter depends on the latitude and orientation of the valley with respect to the sun.

The top of a V-shaped valley and a uniform layer of equal depth and top area radiate at approximately the same rate, but the volume of air in the valley is only half the volume of an equally deep layer over a plane. This accounts for the curves in Fig. 1 approaching 2 for the larger

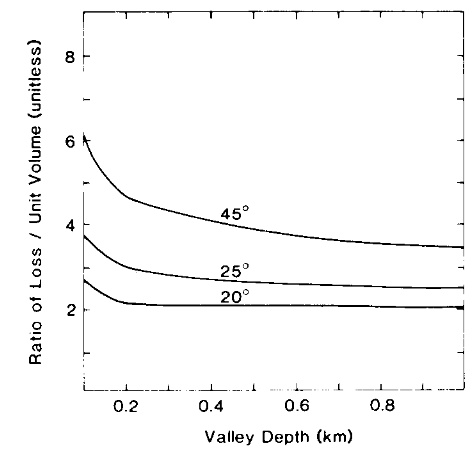

Fig. 1. The rate of energy loss from a valley relative to the loss from a plane layer of the same thickness and roof area is shown. The volume ratio of a V-shaped valley to the corresponding plane layer is 2 and the curves approach this value for large depths. The ratio of losses is always greater than 2, and considerably greater for shallow valleys. The curves are labeled with the angle the walls make with the horizontal.

valley depths. The thermal structure assumed for the atmosphere also contributes to the slope and curvature of the curves in Fig. 1, but the thermal structure used was not unrealistic for a night-time valley situation.

The roof area of a valley per unit valley length is the product of the valley depth, D, and the cotangent of the angular slope of the valley wall.

Fig. 2 shows that the net radiative loss from a V-shaped valley is approximately proportional to its roof area. If the values in Fig. 2 had been plotted against $D \cot \phi$, where D is the valley depth and ϕ the angular slope, the curves would have been almost coincident. There would have been some separation due to the absorption by the atmosphere resulting in emission at a different temperature than the soil temperature. The proportionality of the radiative loss to the roof area allows the rate of radiative loss, which is proportional to $D \cot \phi$, per unit volume to be approximated by

$$\frac{\text{area of valley top}}{\text{volume of valley}} = \frac{2D \cot \phi}{D^2 \cot \phi} = \frac{2}{D}. \tag{1}$$

This indicates that smaller valleys have more enhancement of radiative loss than larger valleys and is consistent with Fig. 1, which shows greater losses at small valley depths.

As mentioned above, the ground cools more slowly because of radiative interchange between

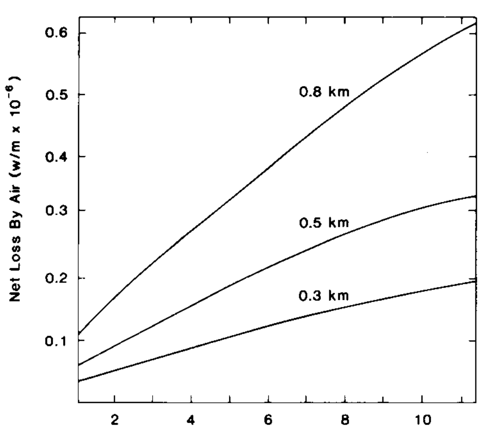

Fig. 2. The net radiative loss by air in a V-shaped valley is almost proportional to the cotangent of the wall slope. The loss is given in W/m of valley length. The different curves represent the labeled valley depths.

walls, but solar heating of the two walls will generally be different because the sun will strike the walls differently. The soil type and vegetative cover will also affect the wall temperature (Deardorff, 1978). The complex problems associated with the ground cooling rate and the wall temperatures will be avoided by taking the ground temperature to be uniform.

3. Computations for Brush Creek

The present observations were obtained in Brush Creek, a mountainous area on the Western Slope of the Colorado Rocky Mountains on the night of 17 September 1984 as a part of Project ASCOT. A number of investigators were observing the flow with surface instruments, sodar, Doppler lidar, and tethersondes during this evening. The other investigators plan to independently publish their results, but informal comparisons indicate the present results are consistent with the other measurements.

The valley is flanked by other valleys with relatively flat but still sloping ground on the ridges separating the valleys. The lack of suitable terrain for forming a nocturnal inversion and the drainage of air down the slopes mean the air at the top of the valley and at the ridge tops will be at comparable temperatures. Air entering the top of the valley to feed the drainage flow must either subside or flow down the slopes. In either case, it starts at approximately the ridge height air temperature.

The night selected for study had almost no wind near the valley roof. The lack of wind avoids coupling effects between the drainage flow and external winds.

Measurements of the temperature, wind speed, and direction obtained with a tethersonde between 01.00 and 01.30 on the selected night are shown in Fig. 3. Similar conditions existed at the next tethersonde ascent 1.5 h later. The drainage flow is in the down-valley direction. It almost fills the valley, and the inversion extends nearly to valley roof.

The valley extended 13.6 km above the tethersonde site, which was well above the mouth of the valley. At the tethersonde site, the valley floor was 579 m below the ridge defining the valley.

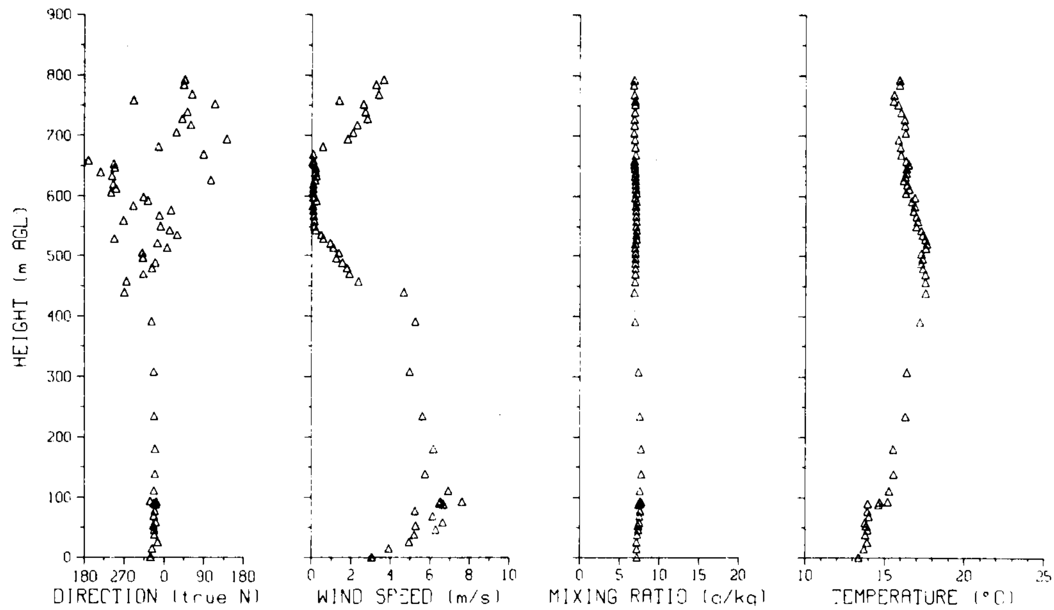

Fig. 3. The wind speed, direction and temperature were measured by a tethersonde ascent at a location where the valley was 570 m deep. At this time, there was no wind at the valley roof and the down valley flow almost filled the valley.

A photo of Brush Creek during the winter when there is little foliage is shown in Fig. 4. The valley cross section consists of a fairly flat bottom with a small stream and scattered patches of trees and meadows. The walls rise from the valley floor at angles sometimes greater than 30° with slopes having a mixture of mountain mahogany, other bushes, and sizable regions of unvegetated shale. The walls then become almost vertical cliffs that change abruptly into slopes rising at some 7° and then sloping down into other similar mountain valleys.

The combined area of the valley and the sloping regions between valleys draining into Brush Creek above the measurement site is 3.5 times as large as the area of the valley within steep cliffs. The ratio is this large because a considerable drainage area is located at the head of the valley. The sloping terrain on each side of the cliffs and the width between cliffs are, for the most part, comparable.

Computations of radiation within a valley requires that a full three dimensional integration be carried out even if the valley has a uniform cross section. This is because the optical path length to the wall varies as a function of both azimuth and elevation. The computer code can be complex and the computational time can be long because additional integrations along the path and over the wavelength of the Planck function are required resulting in a multiple integral requiring 5 integrations.

A reduction in computer time required for multiple integrals can sometimes be achieved by using Monte Carlo techniques that allow the multiple integrals to be replaced by a computation involving a single set of randomly selected values of the integration variables. The integrand is evaluated with enough sets of random values to reliably determine the mean value of the integrand and the mean value theorem invoked to determine the value of the integral. This technique allows multiple integrals to be evaluated in roughly the same number of operations as a single integral.

The calculations of the radiative cooling of both the air and the surface in a valley have been carried out by such a Monte Carlo computational model (Kyle, 1986) that uses band model parameters (Garand, 1983) to determine the

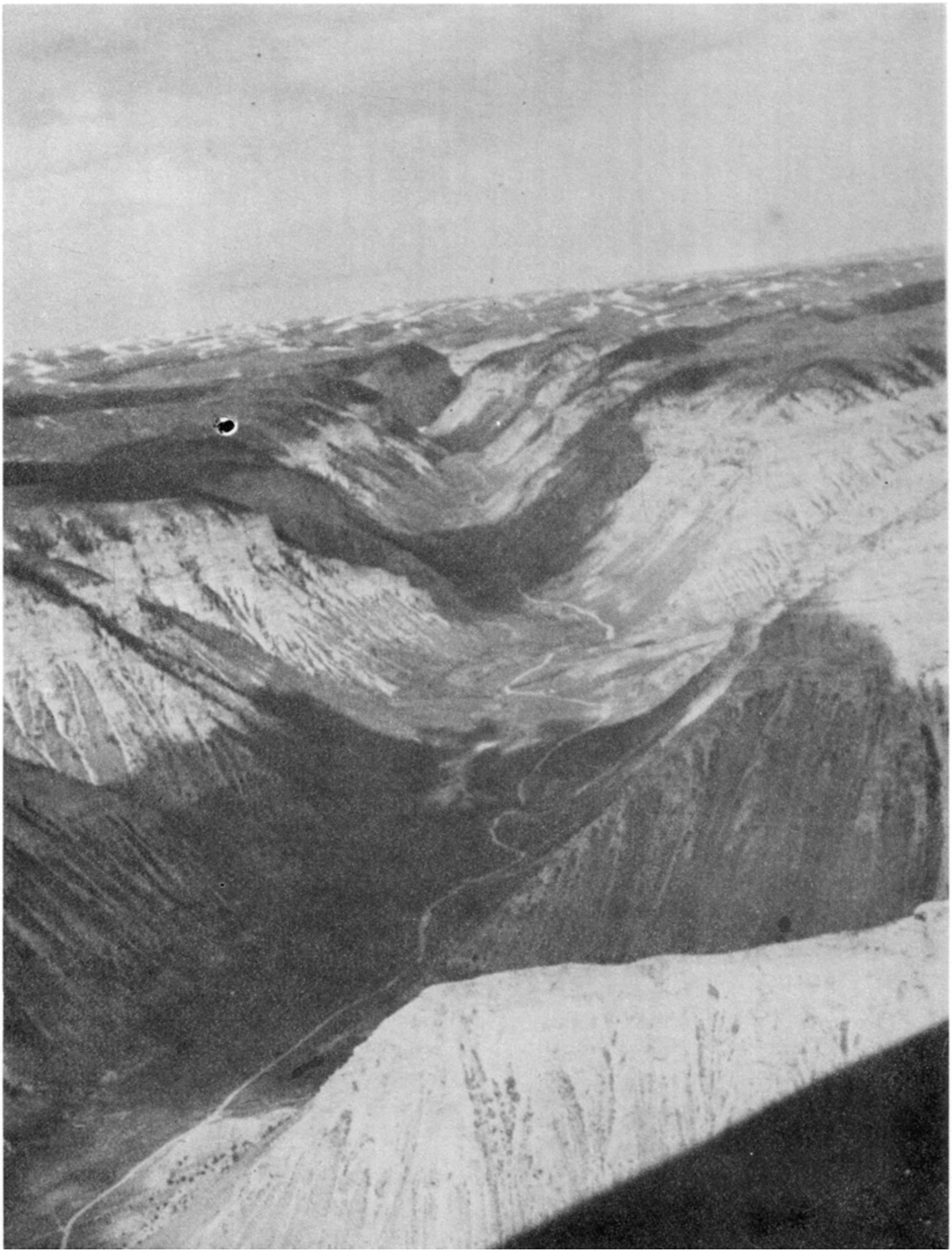

Fig. 4. This is a view looking up Brush Creek. The photo was taken during winter when there was little vegetative foliage. A road can be seen along the bottom of the valley.

radiative flux at the top and at the walls of a long straight valley. The flux through the valley roof determines the radiative budget for the valley. The budget can be partitioned into soil and air components by using the differences in the flux from the walls and through the valley roof.

The parameters required, in addition to the geometry, are the temperature structure of the atmosphere and the valley walls, the wall emissivity, and distribution of water vapor and ozone in the atmosphere. The other atmospheric absorbers are considered to be uniformly mixed at all altitudes.

The model considers the geometry of an infinitely long valley of uniform cross section and determines the net radiative flux per unit length of the valley. The walls of the valley are composed of planar segments as illustrated in Fig. 5.

The depth and cross section of Brush Creek varies slowly enough for the valley to be represented as if made from 7 different cross sections. The length of valley represented by the different cross sections varies from 0.7 to 2.3 km. Each cross section is uniform and represented by up to 20 straight line segments.

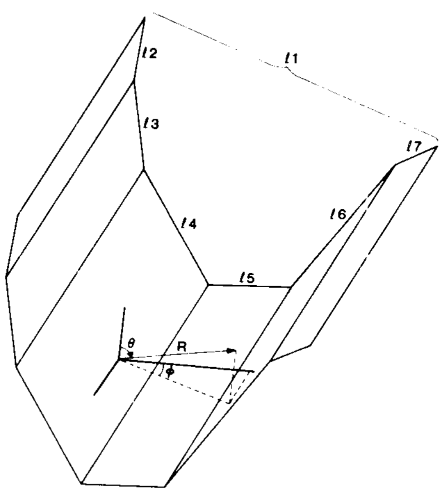

Fig. 5. The radiative model considers the valley as infinitely long and of uniform cross section with walls formed by plane sections. The value of the integrand is evaluated at random locations and viewing directions until the mean value of the integrand is determined, then the mean value theorem used to evaluate the integral.

The model calculates the radiative fluxes by selecting enough random positions and viewing directions to determine the mean value of the kernel of the integrals over directions and the surface. A random number generator provides values for the triangular coordinates, the wavelength and a position on either the valley wall or the valley roof. The radiative flux per unit area is calculated by summing the contribution from each increment of the optical path. The lower angle viewing directions terminate at the valley wall but the higher angles pass through the full depth of the atmosphere.

About 30,000 sets of random positions and directions were required to satisfy the specified accuracy of the integration. The program selected new sets of random integration variables until the variance in the sequence of mean values of the integrand was less than 3%.

The radiative computations modeled the atmosphere with 2 km thick isothermal layers at altitudes from the top of the valley to 16 km and an additional layer to represent the atmosphere above 16 km. The air within the valley was treated as an additional isothermal layer with a temperature determined by the lapse rate in the layer just above the valley.

Instead of adopting one of the considerable range of values of emissivity available in the literature, the wall temperature was treated as a radiative rather than actual temperature. Calculations carried out for the full valley indicate that a 1% decrease in emissivity corresponds to a 1 K decrease in surface temperature. The approach was to treat the surface temperature as unknown and to determine its value by balancing the radiative losses of the air and the surface with the sensible heat transport by air flowing through the valley.

The radiative flux through the walls and the roof were calculated independently. The resulting values could be used to determine the net energy emitted by the air within the valley.

In considering the energy balance, the energy transfers due to the cooling of the soil were accounted for by taking the temperature of the ground as a sinusoidal function with a 24-h period and an amplitude of T_0. When the surface temperature is given by

$$T(t) = T_0 \cos \omega t. \tag{2a}$$

The temperature at depth x below the surface can be shown to be

$$T(x, t) = T_0 \exp\left(-\frac{x}{\alpha}\sqrt{\frac{\omega}{2}}\right)\cos\left(\omega t - \frac{x}{\alpha}\sqrt{\frac{\omega}{2}}\right), \tag{2b}$$

where ω is the angular frequency corresponding to a 24-h cycle and α is the thermal diffusivity.

Multiplying (2b) by the density, ρ, and the specific heat of the soil, c_s, then integrating through all depths at times from 0 to 12 h gives the change in the thermal energy stored in the soil between these times. This value can be converted to the average rate of heat loss per unit area of the soil, P, required to provide the assumed daily surface temperature cycle. In such differing terrain, it was felt preferable to use the average rate of heat loss than to use the instantaneous values. The result for a 12-h average (the period of increase or decrease) is

$$P = \beta T_0, \tag{3}$$

where

$$\beta = \rho c_s \sqrt{(\alpha^2/\omega)}.$$

Using appropriate values for the clay soil found in Brush Creek gives a value of 3.95 for β.

As the night proceeds, the temperature inversion in the valley grows, but conditions change slowly enough for the energy exchanges to be considered a steady state process.

Measurements of vertical velocities by a sodar sounder at the tethersonde site indicated the air feeding the valley flow was entering the valley primarily by subsidence at the valley top. The valley top, or ridge height, was taken to always be an altitude, h, of 579 m above the tethersonde site. The air started with no significant horizontal velocity and with potential temperature θ_0. Air passing the tethersonde site at altitude z, where the valley has width $b(z)$, had potential temperature $\theta(z)$ and a down valley velocity $v(z)$. The energy loss per second or rate of sensible heat transport is given by

$$P' = \int_0^h c_p(\theta(z) - (\theta(h))\,\rho(z)\,v(z)\,b(z)\,\mathrm{d}z - \frac{1}{2}\int_0^h \rho(z)\,v(z)^3\,b(z)\,\mathrm{d}z. \tag{4}$$

The tethersonde measurements of temperature and wind speed permits sensible heat transport by the air to be calculated. Lidar measured velocity profiles indicate the average cross valley wind is 0.8 of the tethersonde measured wind. This factor was taken into account in the computations.

The kinetic energy of the outflow is considerably greater than that of the inflow, but it is of the order of a percent of the sensible heat transport. This permits the kinetic energy of the inflow to be neglected. Using the tethersonde measurements shown in Figs. 3, 4 gives the rate of sensible heat transport by the valley wind as 3.99×10^9 W.

4. Comparison of calculations and observations

The watershed of the valley is 6.2×10^7 m^2 while the area that includes the steep cliff-like walls is 1.7×10^7 m^2. Neglecting the cooling of the soil, a radiative loss of almost 240 W/m^2 would be required if the cooling all took place within the area defined by the steep walls. It is clear that the energy losses from the area within steep walled portion are insufficient to account for the cooled outflow from the valley. Even from the complete watershed the air must cool at a rate P' of 64 W/m^2.

The total radiative flux through the valley walls divided by the area of the valley watershed, P_w, and the rate of radiative cooling per unit area of the air within the valley, P_a, are known from the radiative transfer computations. The computations were carried out for ground radiative temperatures of 2° and 5° less than the air temperature, T_a, within the valley. As mentioned above, the rate of energy loss by the surface depends upon the difference in the daily minimum and maximum soil surface temperatures, $2T_0$. The sum of the soil energy flux, P, and the sensible heat transport, P', by the valley wind must be balanced by the radiative losses of the air and the walls. That is,

$$P' + P = P_a - P_w.$$

The calculated radiative values are given in Table 1. Considering likely values for the emissivity of the ground, the radiative ground

Table 1. *The total radiative loss by the valley above the tethersonde site; the components of the radiative loss are given for two computational conditions; the conditions are for the walls 2 and 5 K cooler than the valley air*

Radiative temperature of ground (K)	Total radiative loss (W/m^2)	Direct radiative loss by air (W/m^2)	Radiative loss by ground (W/m^2)
$T_a - 2$	125.0	17.1	108.9
$T_a - 5$	109.7	23.6	86.1

temperature cannot be expected to be greater than $T_a - 2$. That temperature would result in the daily temperature cycle, according to (5), of $2T_0$ or 30.6 K. This seems a bit large since the surface air temperature in the valley was observed to have a daily range of 20 K. The surface temperature being the driving source of the diurnal variation suggests that the diurnal cycle of the ground should be larger than that of the air, but probably not 50% greater.

Using (5) and the radiative fluxes calculated when the radiative temperature of the ground is $T_a - 5.0$ temperature of the air within the valley gives a daily temperature cycle at the ground of $2T_0$ equal to 22.5 K. In this case 21.5% of the energy loss by the air occurs by direct radiative transfer. It would seem that this cooler radiative surface temperature is more reasonable than the 2 K used above. The effective temperature would seem to lie somewhere within the limits of these two radiative calculations.

The necessity of using the full watershed area to account for the radiative cooling explains the sensitivity to ambient winds that has been observed in valley winds (Orgill et al., 1981). Particularly in the present case, where a group of valleys are separated by fairly small mesas, a small wind at the mesa level could keep the mesas swept with ambient air that has not been cooled by the night-time inversion. This would deprive the air entering the valley of the cooling that occurs on the mesas because the wind would be continually replacing the mesa air with ambient air.

It is interesting that the direct radiative cooling of the air is so significant even though the turbulence along the walls is considerably greater than would be expected in homogeneous turbulence on the basis of the Richardson numbers. If the direct radiative cooling of air is neglected, the values determined for the soil surface temperature range, $2T_0$, would drop from 30.6 and 22.5 K to 9.8 and 4.0 K, respectively.

Computations were carried out to determine if the conclusions would be the same if there were a higher humidity in the valley or if cirrus clouds were affecting the radiative cooling. The conclusion that the full watershed of the valley is needed to account for the flow was unaltered. There was only a minor change in the ratio of turbulent and radiative cooling of the air.

5. Acknowledgements

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