Atmospheric Mass Transport by Along-Valley Wind Systems in a Deep Colorado Valley

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ABSTRACT

Hourly tethered-balloon wind soundings from the 650-m deep, narrow, Brush Creek Valley of Colorado are analyzed to determine the nocturnal atmospheric mass (or volume) budget of the valley. Under the assumption that the volume flux on an entire valley cross section can be approximated from balloon soundings over the valley center, volume fluxes are calculated from tethered balloon profiles taken on 30–31 July 1982 at several points along the valley's longitudinal axis in a 7-km long segment of the valley.

Down-valley volume fluxes increased in the 3 h following sunset to levels that were basically maintained through the night. Down-valley volume fluxes increased with distance down the valley axis from 0.9 million $m^3 s^{-1}$ at the upper end of the segment to 2.8 million $m^3 s^{-1}$ at the lower end, producing an average volume flux divergence of 271 $m^2 s^{-1}$. If we assume that the volume flux divergence is supported entirely by subsidence of air into the valley, a peak sinking rate of 0.10 $m s^{-1}$ is obtained at the level of the valley's rim. Mean vertical velocity profiles through the valley's depth are calculated, and an error analysis is performed.

1. Introduction

In the summer of 1982, the U.S. Department of Energy's (DOE) Atmospheric Studies in Complex Terrain (ASCOT) Program conducted a series of meteorological experiments in the Brush Creek Valley of western Colorado. The experiments included a variety of measurement systems that contributed to the project goals of documenting the structure and mechanics of the locally driven nocturnal circulation in the valley. One particularly useful series of measurements was from an along-valley array of tethered balloon sounding systems. The down-valley nocturnal drainage wind occupied a significant portion of the valley's 650-m depth, and the tethered balloon soundings had the potential of providing wind and temperature data to the top of the drainage layer. In this paper the tethersonde winds have been used as a basis for estimating the mass budget of the drainage flow for the night of 30–31 July 1982. The mass budget is a valuable diagnostic tool for intercomparing valleys with differing sizes, drainage areas, and depth/width aspect ratios. It also aids the intercomparison of different meteorological conditions in a single valley and offers a framework for analyzing the mechanisms of exchange between the valley and surrounding environments (e.g., mesa tops or confluent valleys). Previous research on this topic has been reported in conference proceedings by Whiteman and Barr (1984) and, independently, by Bernhofer and McKee (1984).

2. Experimental design

a. Location

The Brush Creek Valley of Colorado (Fig. 1) is a 25-km long side-valley that flows into the Roan Creek Valley, 55 km north-northeast of Grand Junction, Colorado. The Brush Creek Valley drains the Roan Plateau area south of the Piceance Basin. The valley runs from northwest to southeast, is 650 m deep at its lower end, has sidewalls with slopes of 30 to 40°, and a valley floor which falls 14 $m km^{-1}$. Except for a succession of short box canyons (especially on the valley's east side), the valley has no major tributaries.

b. Synoptic conditions

On 30 July, a high pressure ridge aloft had become established in western Utah and Idaho, producing northwesterly flow over the Brush Creek Valley region. At the surface, a large but weak high pressure cell covered the intermountain area. Cloud cover was about 50% in the late afternoon, with clearing shortly after sunset. Winds in the valley in the late afternoon were influenced by the synoptic flows and were blowing down the valley (i.e., from the northwest). They decreased in speed as the valley flows became decoupled from the upper air, but increased again as the local down-valley flows became established. The night of 30–31 July was clear, and observations showed that the local wind systems developed well during the night. A

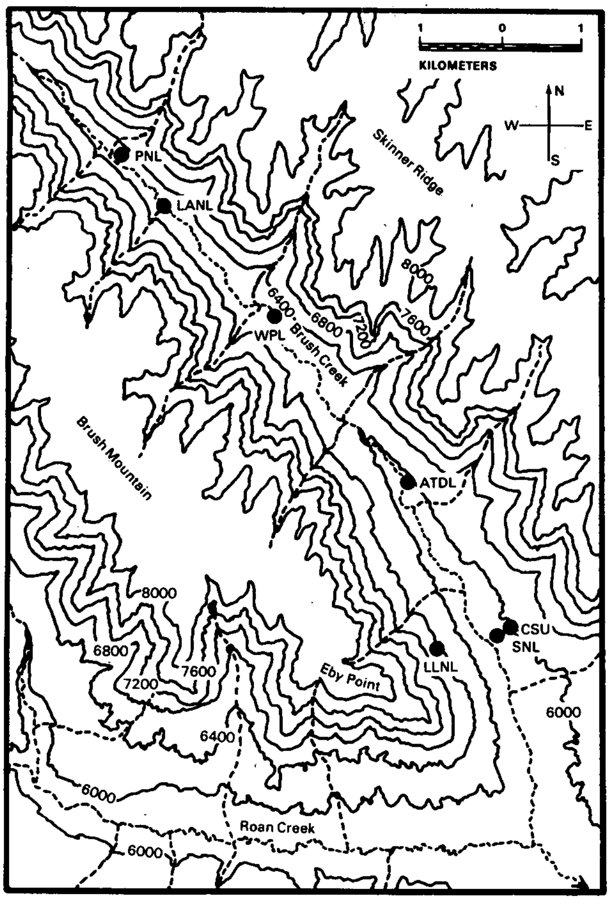

FIG. 1. Topographic map of the Brush Creek Valley, with tethered balloons sites indicated. Contour interval is 122 m (400 ft).

smaller number of observations taken in the valley on 4 and 6 August 1982 showed that the wind systems that developed on the night of 30–31 July were rather typical for that time of year. Observations on the cloudy night of 28–29 July 1982 showed weaker drainage flows than observed in the 30–31 July experiment, while observations on 11 June 1982 showed somewhat stronger drainage flows than were observed in the 30–31 July experiment.

c. *Equipment and sites*

Tethered balloon soundings were conducted in the lowest 10 km of the 25-km long valley from as many as seven sites to investigate wind and temperature structure evolution during the experimental period. Hourly soundings were taken from 1700 MST on 30 July to 0900 MST on 31 July. Tethered balloon data acquisition systems[1] of the type described by Morris et al. (1975) were used for hourly soundings of the valley atmosphere. The sites were located primarily near the center of the valley floor at different distances along the axis of the valley (Fig. 1). Three sites were located on a cross section of the valley at its lower end. Topographic characteristics of the sites are listed in Table 1. The LANL, WPL, ATDL, CSU, and LLNL sites were operated on an hourly schedule. The PNL and SNL sites, operated as part of a tracer release experiment, conducted soundings successfully only after 0600 MST. The up-soundings from the tethered balloons, to be analyzed in this paper, were generally completed in 15 to 40 min. Due to strong nocturnal winds, tethered balloons were frequently unable to profile through the full valley depth. The depth of the soundings varied from sounding to sounding and from site to site, depending on the wind speeds encountered.

3. Analyses

The goal of the analysis was to estimate how atmospheric mass or volume fluxes through valley cross sections would change with distance down the valley. For this purpose, volume fluxes were calculated at each of the tethersonde observation sites for each observation time. Calculations were made for 25-m deep layers on the cross section using the formula

$$\dot{V}_i = \bar{A}_i \bar{U}_i \qquad (1)$$

where $\dot{V}_i$ is the volume flux [m^3 s^{-1}] for the ith layer, $\bar{A}_i$ is the cross-sectional area [m^2] of the layer, and $\bar{U}_i$ is the mean down-valley component of wind speed [m s^{-1}] in the layer.

The value of $\bar{A}_i$ was calculated from topographic cross sections obtained from a 1:24 000-scale topographic map of the experimental area. The valley cross sections at individual sites were drawn roughly per-

TABLE 1. Brush Creek Valley sounding sites.

Site*	Elevation (m MSL)	Distance** (km)	Drainage area (km^2)	Up-valley direction (deg true)
PNL	1922	0.0	61.9	318
LANL	1908	0.7	62.8	320
WPL	1871	2.8	75.0	321
ATDL	1820	5.4	84.9	323
LLNL	1922	7.7	95.3	331
SNL	1780	7.7	95.3	327
CSU	1798	7.7	95.3	324

* Site names refer to organizations that collected the data. U.S. DOE laboratories include Pacific Northwest Laboratory (PNL), Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), and Sandia National Laboratory (SNL). U.S. National Oceanic and Atmospheric Administration laboratories include the Wave Propagation Laboratory (WPL) and the Atmospheric Turbulence and Diffusion Laboratory (ATDL). The remaining site was operated by Colorado State University (CSU).

** Down-valley distance from PNL site.

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[1] Tethersonde Systems, Atmospheric Instrumentation Research, Inc., Boulder, Colorado.

pendicular to the valley at each site, but were drawn up the fall line of the main sidewalls of the valley. Thus, the tributary canyons to Brush Creek have been excluded from the cross-sectional area calculations, since the wind soundings in Brush Creek are not expected to be representative of the tributaries.

The value of $\bar{U}_i$ was calculated under the assumption that the tethersonde wind sounding was representative of the entire cross section. The average down-valley wind speed for each 25-m deep layer was calculated as a weighted average wind speed, taking account of the increase in cross-sectional area with height. The calculation involved interpolation of the wind soundings and topographic cross sections at 1-m intervals. The down-valley component of wind speed was calculated at each site using the local orientation of the valley (Table 1).

Equation (1) calculates the volume flux for individual layers, and the volume fluxes of the individual layers could be summed to determine fluxes over desired height intervals. The corresponding mass fluxes can be determined using the formula

$$\dot{M}_i = \bar{\rho}_i \dot{V}_i \qquad (2)$$

where $\bar{\rho}_i$ is the mean air density of the layer. In this paper the discussion will proceed in terms of volume fluxes, but the results can be converted to approximate mass fluxes by multiplying the volume fluxes by $\bar{\rho} = 0.96$ kg m^{-3}, the average air density in the midvalley atmosphere during the night of 30–31 July. The air density varies only 5% from this value through the valley depth.

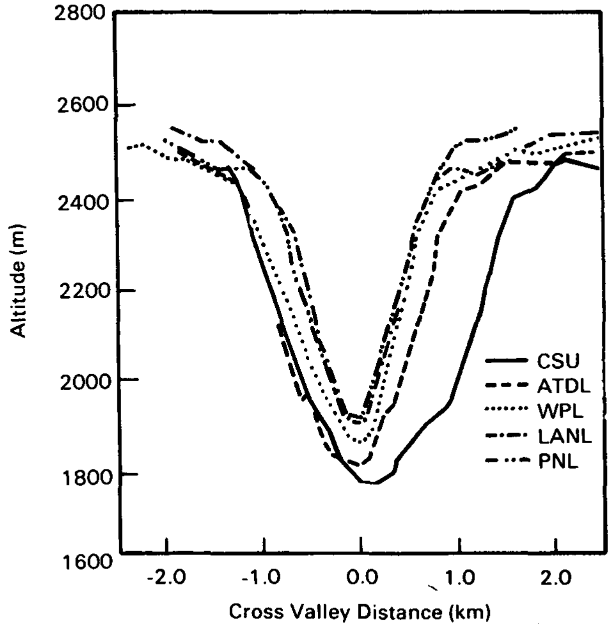

FIG. 2. Topographic cross sections of the Brush Creek Valley at individual tethered balloon sites. The cross sections were drawn to exclude the influence of box canyons.

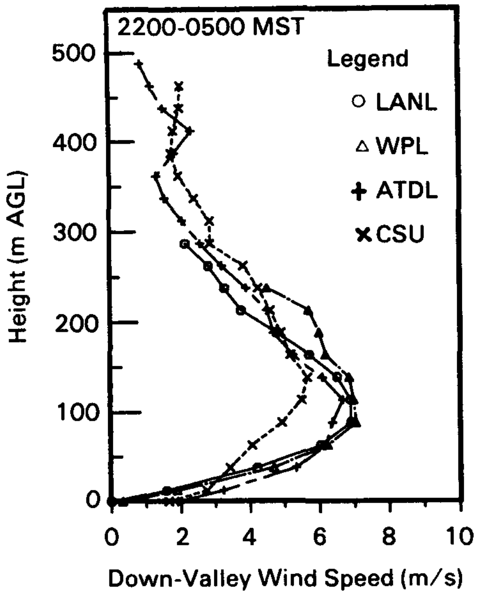

FIG. 3. Average down-valley wind speed as a function of height for four tethered balloon sites.

The focus of the analysis will be on changes in the down-valley volume flux $\dot{V}$ occurring as a function of down-valley distance x. When $\partial\dot{V}/\partial x$ is positive, a volume flux divergence is said to occur between the two cross sections.

a. Topographic cross sections

Figure 2 presents topographic cross sections through each of the sites. The sites nearer the valley mouth have significantly more cross-sectional area than those farther up the valley. For example, the cross-sectional area at the CSU site is 2½ times the cross-sectional area at the PNL site. The plateau into which Brush Creek is cut is clearly seen in the cross sections by noting the near-constant MSL ridge-top height at all sites. The valley is thus seen to be a nearly straight drainage path from a plateau area. No topographic constrictions are present along the valley's course, and the valley widens significantly with down-valley distance. Air flowing out of the valley flows into the large, open drainage areas of the Roan and Colorado valleys.

b. Wind observations

A plot of the down-valley wind component as a function of height is presented in Fig. 3 for the LANL, WPL, ATDL, and CSU sites. The curves are averages of the hourly wind soundings taken from 2200 to 0500 MST, a period when nocturnal wind profiles varied little from sounding to sounding at individual sites. The characteristics of the nocturnal winds in the deep valley are clearly seen in these profiles. A "jet" occurred in the profiles with maximum wind speeds of 5 to 8 m

s^{-1} at heights of 100 to 150 m. Down-valley winds increased rapidly from the surface to the peak of the jet, with winds decreasing more slowly above the jet to near-zero at about ridge-top level. The jet winds decreased somewhat in strength and rose in AGL height with down-valley distance.

c. *Volume fluxes*

Volume fluxes were calculated at each site for 25-m height intervals using wind and cross-sectional area data. To estimate the mass budget for the entire valley depth, it was necessary to extend some of the wind soundings vertically. This was done for the CSU, ATDL, and LANL soundings by choosing a function that fit the existing, deep wind speed soundings and by using this function to extend soundings that had attained heights above the level of the jet but below the ridge top. The volume flux corrections obtained by estimating wind speeds in the upper part of the valley atmosphere are small, since wind speeds tend to be light, and decrease with height near the top of the observed soundings. We estimate that the average correction obtained by extrapolating the observed soundings to the ridge top represents only 7 to 15% of the total volume fluxes at the three sites. The function used is a modification of Prandtl's (1942) slope wind formula. Prandtl's original formula characterized the main elements of the velocity profiles, except that the observed profiles decreased more rapidly with height above the wind speed maximum than the Prandtl formula predicted. By enhancing the damping factor we were able to achieve good fits over the entire altitude range, although we were interested primarily in the upper 200 m of the valley. The modified Prandtl formula is given as follows:

$$U(z) = A \sin \frac{z}{D} \exp\left[-\left(\frac{z}{D}\right)^{B}\right] \tag{3}$$

where U is the (total) wind speed, A a parameter to fit the maximum speed of the jet, D a parameter to fit the height of the jet maximum, and B a parameter to decrease the speed to near-zero at ridge-top height. Here B is a fixed value for each site, while A and D vary from sounding to sounding. The formula fit the deep observations well and is thought to have estimated wind speeds well in the upper levels of the valley atmosphere for the shorter soundings. Since nocturnal winds blew predominantly along the valley axis, Eq. (3) was used directly to estimate the along-valley wind component.

It is interesting that Eq. (3) fits the observed wind speed profiles. Prandtl originally derived his damped sine function for the wind speed profile over a slope, by locally balancing a buoyant driving force with vertical momentum diffusion. He developed a similar balance between advection and diffusion for the temperature field above the slope. The down-valley wind is an accumulation of flow contributions from the available upstream air-shed and is, therefore, fundamentally three-dimensional. The physical processes governing the down-valley wind structure go well beyond the simple balances assumed in the original Prandtl model. At this point it is a fortuitous empirical observation that the damped Prandtl function is successful in fitting the observed wind profiles.

4. Results

Results of the volume flux computations for the LANL, WPL, ATDL, and CSU sites are presented in Figs. 4 a–d, where a time–height analysis of 25-m average volume fluxes is shown. Several features of the valley volume flux field are apparent in the figures. First, winds in the valley in the late afternoon were down-valley because of synoptic conditions. Down-valley volume fluxes decreased in the late afternoon, a weak up-valley flow produced short-lived negative volume fluxes in the upper levels of the valley after sunset (1922 MST), and local down-valley flows developed rapidly during the 2000 to 2200 MST period. Strong, positive down-valley volume fluxes persisted in the valley through the rest of the night. Volume fluxes decreased rapidly after sunrise (0504 MST), reversing to up-valley after 0700 MST.

During the period from 2200 to 0500 MST, down-valley volume fluxes were fairly steady at all sites except the CSU site. Peak volume fluxes occurred at about the 150- to 200-m levels at all sites, with numerical values increasing from 10×10^4 m^3 s^{-1} at the uppermost site (LANL) to 26×10^4 m^3 s^{-1} at the lowermost site (CSU). At the CSU site, located just above the confluence of the Roan and Brush Creek Valleys, there was a large hourly variation in volume flux during the night at the level of the jet (~200 m). This variation may have been caused by side-to-side oscillations of the jet core at this site (Neff, personal communication, 1984) or by some as yet unspecified influence of the Roan Valley wind system in the zone near the confluence of the two valleys.

The total volume flux (extended to ridge-top level) for the CSU, ATDL, and LANL sites is plotted in Fig. 5 as a function of time. The average nocturnal flux at the LANL site is about 0.9×10^6 m^3 s^{-1}, at the ATDL site 1.7×10^6 m^3 s^{-1}, and at the CSU site 3.0×10^6 m^3 s^{-1}. Total volume fluxes at the LANL and ATDL sites are steady throughout the night, while significant oscillations occur in the total volume flux at the CSU site. (Note that 2300 and 0400 MST soundings were not taken at the CSU site.)

The results of the analysis (see Table 2) clearly show that the nocturnal volume flux across Brush Creek Valley cross sections increases with down-valley distance. The divergence of volume flux between valley cross sections was 170 m^3 s^{-1} per meter of distance along the valley axis in the ATDL–LANL valley seg-

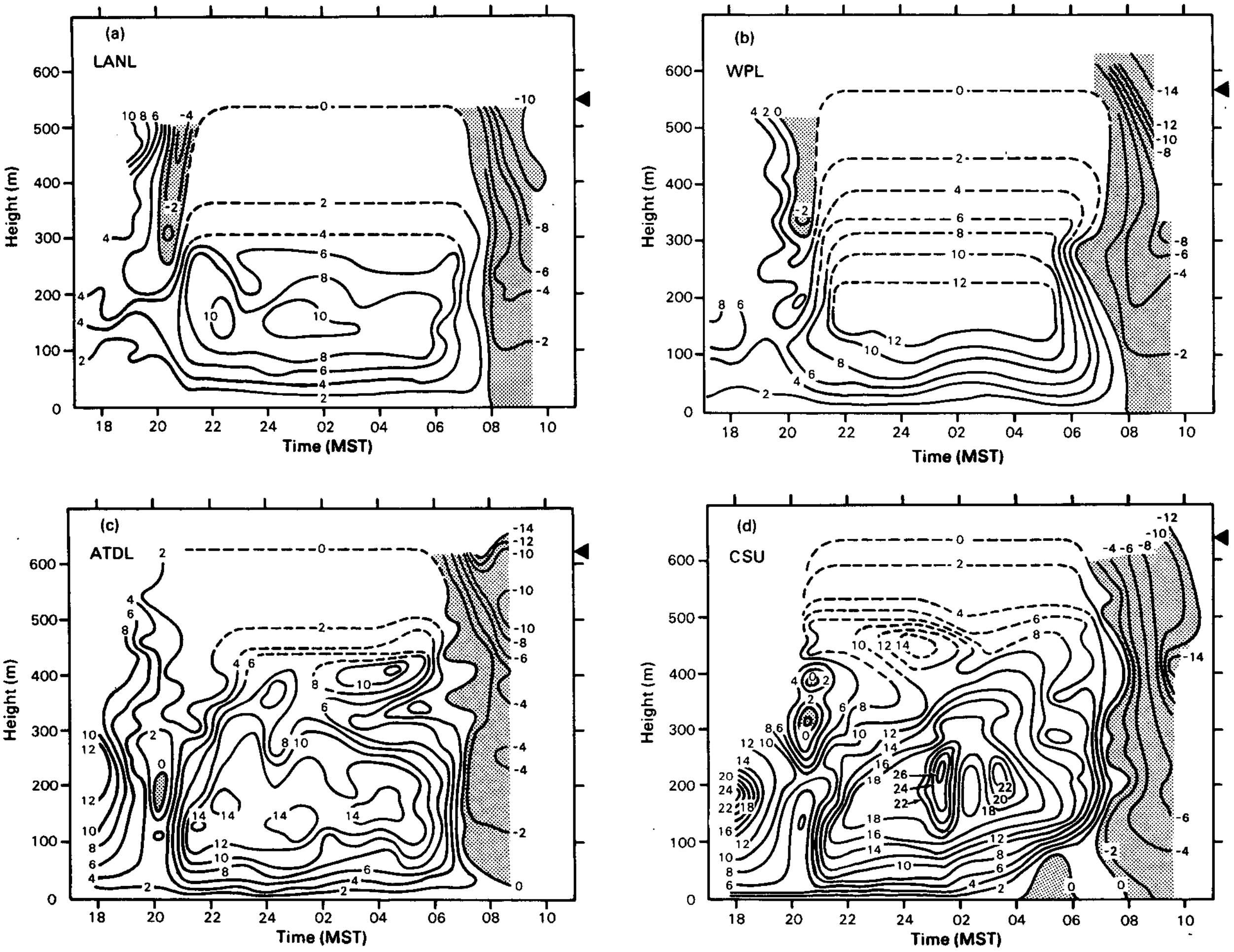

FIG. 4. Down-valley volume flux (10^4 m^3 s^{-1}) computed over 25-m deep layers as a function of time and height for the (a) LANL, (b) WPL, (c) ATDL, and (d) CSU sites. Dashed lines indicate missing data regions where Eq. (3) was used to extrapolate the wind soundings. Darkened triangles indicate ridge-top heights.

ment and 478 m^2 s^{-1} in the CSU-ATDL segment. Volume flux divergence between the CSU and LANL cross sections was 271 m^2 s^{-1}. Rao (1970), in his studies of three Vermont valleys varying in depth from 300 to 800 m, found nocturnal volume flux divergences from 100 to 300 m^2 s^{-1}—a finding consistent with our results, except for the higher value observed on the CSU–ATDL valley segment.

Similiar calculations of volume flux and volume flux divergence were made on the cloudy night of 28–29 July 1982 for the CSU and LANL sites. On this night, which followed an afternoon rainstorm in the valley, down-valley winds were much weaker near the mouth of the valley. Nocturnal volume fluxes on the two valley cross sections averaged about 1.1 million m^3 s^{-1}, with hourly excursions ranging from 0.5 to 2.0 million m^3 s^{-1}. The volume flux divergence between the two sites averaged zero, with alternating periods of convergence and divergence through the night.

The source of the additional volume flux with down-valley distance on 30–31 July is of interest. If the source is assumed to be the slope flows and we use the 5% rule (Horst and Doran, 1985) that the depth of the downslope flow on a valley sidewall can be estimated as 5% of the height difference between the site of interest and the ridge top, we can estimate that 30-m deep slope flows would form on the two valley sidewalls. In order to explain the observed volume flux divergence, 5 m s^{-1} average downslope flow speeds would be necessary. These speeds are much higher than would be expected from slope flows and are much higher than speeds observed at the LLNL site on the west sidewall. Further, the full mass flux in a slope flow near the base of a slope cannot be considered as "new" mass in the volume flux divergence calculations for the valley volume between two cross sections. The volume flux in the downslope flow increases with distance down the slope because of entrainment of air adjacent to the slope and,

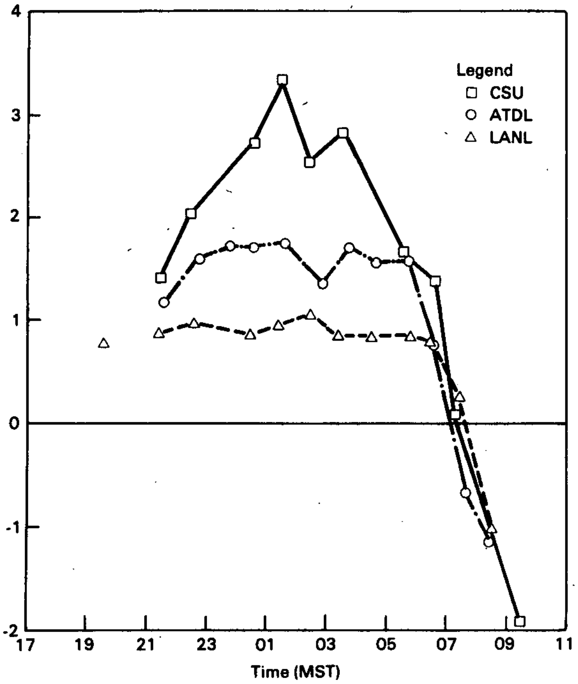

FIG. 5. Total volume flux across valley cross sections at the CSU, ATDL and LANL sites as a function of time.

hence, already within the valley (e.g., see Manins and Sawford, 1979).

A source of new mass, which could explain the volume flux divergence between two cross sections, is the mass flowing into the main valley from the tributary canyons. There are ten well-defined tributary canyons between the LANL and CSU sites (five on the east side of the valley and five on the west side) having an average drainage area of 2 km^2. If we assume that the drainage from these canyons occurs in the lowest 50 m of their outlet into the Brush Creek Valley over an outlet area (projected into a vertical plane) of typically 15 000 m^2 at a mean speed of 3 m s^{-1}, we can calculate a volume flux of 0.45×10^6 m^3 s^{-1} from the ten canyons. This should be compared to the 1.9×10^6 m^3 s^{-1} required (Table 2). A 120-m deep flow would be approximately sufficient to explain the observed along-valley volume flux divergence. It seems unlikely that such a strong flow would issue from the small tributary canyons. No observations of the tributary flow are available from the 1982 experiments, but further experiments conducted in the valley in the fall of 1984 should be sufficient to estimate the characteristics of these flows.

TABLE 2. Calculations of volume flux divergence.

Sites	Volume flux difference (10^6 m^{3}s^{-1})	Distance (km)	Volume flux divergence (m^{2}s^{-1})
ATDL-LANL	1.7–0.9	4.7	170
CSU-ATDL	2.8–1.7	2.3	478
CSU-LANL	2.8–0.9	7.0	271

A second source of new mass is the air directly above the valley. If we assume that the required mass comes entirely from above the valley, we can calculate vertical velocity profiles in the valley atmosphere. This is done using the formula

$$w = -\frac{1}{(y_R - y_L)_H}\frac{\partial}{\partial x}\int_0^H \int_{y_L(z)}^{y_R(z)} U dy dz \qquad (4)$$

where w is the upward velocity at height H in a coordinate frame in which x runs down the valley axis, z is perpendicular to the valley floor (i.e., not vertical), and y is the cross valley distance from the z-axis above the middle of the valley floor to the left (y_L) and right (y_R) sidewalls. The results of the calculations for three valley segments are shown in Fig. 6. Subsidence is seen to occur at all levels in the valley except for a shallow layer just above the valley floor in the ATDL–CSU segment. Peak subsidence velocities of 0.10 to 0.15 m s^{-1} occur at the level of the valley rim (ca. 450–500 m AGL). Subsidence rates decrease nearly linearly to zero as the valley floor is approached and decrease rapidly with height above the valley rim, where valley width increases rapidly. The calculated subsidence profiles look reasonable, although the quantitative values are somewhat overestimated because of assumptions made in the analysis (horizontal homogeneity,

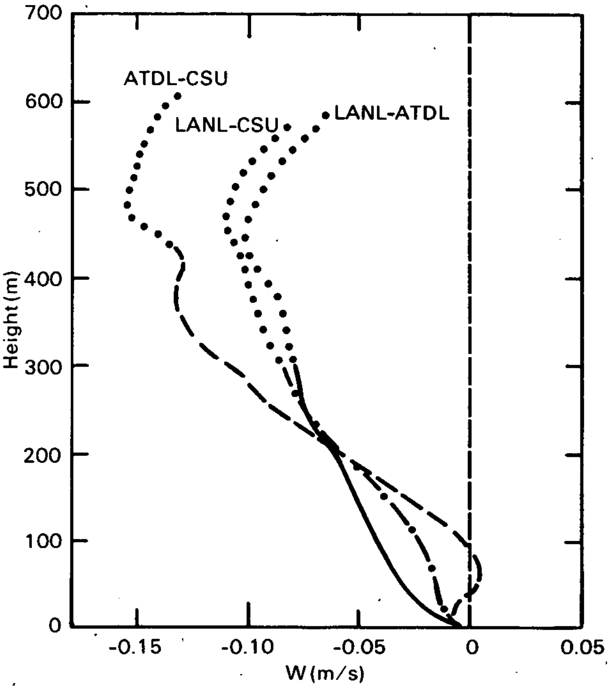

FIG. 6. Vertical velocity profiles for three valley segments. Dotted line segments indicate regions of missing data where Eq. (3) was used to extrapolate the wind soundings.

no valley tributaries, etc.). The existence of the subsidence field, as determined from mass budget considerations, raises some interesting questions concerning the valley momentum and thermal energy budgets. For example, subsidence in a stable atmosphere produces local warming [i.e., $\partial\theta/\partial t = -w(\partial\theta/\partial z)$]. This subsidence warming must be counteracted by cold air advection in down-valley winds or by diabatic or other processes, if the valley atmosphere is to continue to cool during the night.

The most likely scenario seems to be one in which the nocturnal volume flux divergence of the along-valley flows is maintained in a steady state primarily caused by subsidence at the top of the valley atmosphere, but with some contribution of volume flux from the tributaries. The sinking rates are probably not uniform across the valley top, but may vary depending on the wind direction in the air flowing above the valley and the availability and sources of cooled air on the mesa tops. The simple conceptual models of Wagner (1938) and Defant (1949), in which rising motions occur in the center of an ideal valley at night as a response to downslope flows over the valley sidewalls, do not seem to be supported by the Brush Creek Valley data.

5. Discussion of assumptions and analysis of errors

It is convenient, at this point, to consider the possible effects of measurement errors and analysis assumptions on the results obtained in the previous sections.

The principal measurement errors are associated with the wind data. In particular, wind observations collected with tethered balloon systems are known to contain experimental errors associated with the semi-Lagrangian nature of the balloon system (Whiteman, 1980). On the up-soundings, the balloons tend to drift downwind as they ascend because of the drag of the wind on the balloon and tetherline. This effect, especially pronounced in strong wind regimes, results in the airborne sensor reporting wind speeds that are too low during up-soundings. This will result in an underestimate of cross-valley volume fluxes. Since the balloon's position in space was not recorded (except for height) as a function of time during the Brush Valley soundings and down-soundings are not available for comparison with the up-soundings, it is difficult to estimate the magnitude of these wind speed errors from the Brush Valley data alone. Comparison of selected up- and down-soundings from other experiments (Whiteman, 1980) in other Colorado valleys where the winds were strong allows us to estimate the average difference in wind speeds as about 2 m s^{-1}. The magnitude of error in an up-sounding through a high wind layer of, say, 8 m s^{-1} might, therefore, be expected to be about half of this value or 1 m s^{-1}. In any case, the error would seem to be in the range of 10 to 20% in the high wind layer. Given the general shape of the wind profiles (Fig. 3), the balloon-borne wind sensors are expected to give such percentage errors in the jet layer, but to perform better above the jet layer as the balloon path becomes more nearly vertical.

An estimate of the errors introduced into the volume flux calculations by the wind speed underestimates was made as follows. First, the LANL wind profile in Fig. 3 was extended using Eq. (3) and total volume flux in the cross section was calculated using Eq. (1). Next, all wind speeds in the profile greater than 4 m s^{-1} were increased by 15%, and the total volume flux was calculated again. The calculated 8% difference in the two volume fluxes represents a reasonable estimate of volume flux errors caused by wind speed underestimates made with the tethersonde.

Another primary source of error in the calculations is the assumption that the profiles, taken from sites located on the valley floor, are representative of the entire valley cross section above the sites. This error will result in an overestimation of the volume flux on a cross section, since down-valley wind speeds will generally be strongest over the valley center and will decrease near the sidewalls because of friction. The assumption of a horizontally homogeneous atmosphere used in our calculations is supported, however, by Rao (1968, 1970), whose observations in a number of Vermont valleys indicated that, with the exception of a narrow region near the valley sidewalls, the velocity of the down-valley flows was horizontally homogeneous within cross-valley sections. Few other observations of the cross-valley structure of a down-valley wind regime are available in the literature. During the nighttime, strong buoyancy forces within the valley inversion are expected to tend to stratify the valley atmosphere, except for the above-mentioned effects of friction in the vicinity of the sidewalls. Significant asymmetries can occur, however, in the valley atmosphere during daytime, as shown by Reiter et al. (1983) for the topographically complicated Loisach Valley of southern Germany.

The limited number of coincident soundings in the Brush Creek Valley at the LLNL–SNL–CSU cross section after 0600 MST on 31 July 1982 support Rao's (1968) conclusions. Coincident soundings at the LLNL and CSU sites earlier in the night indicated that differences in the wind soundings occurred primarily in the lowest 150 m over the sidewall site. From this information we can estimate errors in the total volume flux calculations at the CSU site. We begin by assuming that the valley wind regime is horizontally homogeneous on the valley cross section except in a 150-m deep layer above the valley sidewalls. Down-valley wind speeds in this layer are assumed to be one-half the speed at the corresponding altitude over the valley center. Volume fluxes on the CSU cross section are then calculated using the mean wind speed sounding of Fig. 3 as extended using Eq. (3). Calculations show that the volume flux computed under the full horizontal homogeneity assumption (i.e., sidewall to sidewall) is overestimated by about 15%. Considering our 8% underestimate caused by wind speed measurement errors, we find that our total volume flux is overestimated by about 7%.

Volume flux divergences are calculated as the difference in volume fluxes calculated at the same time at different sites. It is of interest to estimate the errors involved in volume flux divergence calculations. Identical tethersonde systems were used at the different sites, and soundings were conducted at the same times during the experimental period. The vertical wind profiles varied little from site to site (Fig. 3), and calculated volume fluxes increased by a factor of 3 in the lowest 10 km of the valley. Except for the CSU site, volume fluxes at individual sites varied little with time through the night (Fig. 4). Calculations show that errors in volume flux divergences should be similar to those estimated for total volume fluxes; i.e., they appear to be slightly overestimated.

6. Conclusions

Tethered balloon wind observations were made in the Brush Creek Valley of western Colorado on a clear July night. Strong down-valley winds occurred in the deep, narrow, well-drained valley. These winds took the form of a "jet" with peak speeds of 5 to 8 m s^{-1} at heights of 100 to 150 m above the floor of the 650-m deep valley. The jet persisted in a relatively steady state throughout the night, except near the valley exit. The wind profiles above the valley center changed only slightly with down-valley distance in the lowest 10 km of the valley, while the cross-sectional area of the valley increased sharply. Since the along-valley wind is approximately horizontally homogeneous on a valley cross section, the result is an increase with down-valley distance of volume (or mass) flux through valley cross sections. This divergence of volume flux is approximately 270 m^3 s^{-1} per meter of distance down the valley. To conserve atmospheric mass, additional mass must be introduced into the valley between cross sections to support the along-valley mass flux divergence. Data and theoretical considerations show that this cannot be accomplished by downslope flows on the main sidewalls of the valley. It appears to be accomplished by subsidence at the top of the valley and, to a lesser extent, by inflow from the small tributaries to the valley. If all the additional mass were introduced into the valley by subsidence, the mean subsidence rate at the valley's rim would be 0.10 m s^{-1}.

A more extensive field experiment was conducted in the Brush Creek Valley in the fall of 1984 as part of the U.S. Department of Energy's ASCOT program. Future work will focus on the atmospheric mass and energy budgets within the valley to investigate the physics and air pollution implications of the locally developed valley circulations. The 1984 data, when available, should provide additional information on the role of the tributary canyons in the mass budget of the valley and may allow subsidence rates to be determined from acoustic doppler, lidar, and other data.

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