Mass and Momentum Balance in the Brush Creek Drainage Flow Determined from Single-Profile Data

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(Manuscript received 17 February 1988, in final form 25 July 1988)

ABSTRACT

Fluxes and flux-divergences of mass and momentum in Brush Creek Valley, computed from measurements taken by Tethersondes and Doppler sodars in the 1984 ASCOT experiment, are presented. Estimates of mass influx from open sidewalls in Brush Creek, derived from concurrent tower measurements, are also given. Mass and momentum fluxes calculated from single-profile data were within a factor of 1.5 of those obtained by integrating Doppler lidar data. Flux-divergences for budget calculations should be derived from a Doppler lidar or equivalent remote sensor data, because single-profile measurements were found to have sampling errors which are too large for reliable flux divergence estimates. The mass influx from the sidewalls was insufficient to account for the mass flux-divergence in the main valley. This imbalance in the drainage flow mass budget is speculated to be due to the inflow from the small box-canyon tributaries, rather than from subsidence of air above the main valley.

1. Introduction

Assessment of air pollution dispersion in complex terrain suffers from large uncertainty in model predictions and in the representativeness of measurements. There is hope of reducing model uncertainty for nocturnal drainage flows in valleys through an understanding of the budgets of mass, momentum, and energy. In order to determine the representativeness of measurements in complex terrain, it is necessary to estimate the uncertainty in measurements taken with Tethersondes, Doppler sodars, and similar instruments which measure a single vertical profile per sampling period to characterize the distribution of winds over an area. Such single-profile measurements are currently the primary source of data for site surveys, impact assessments, and other routine applications.

In the autumn of 1984, the Atmospheric Studies in Complex Terrain (ASCOT) program of the U.S. Department of Energy conducted a major field experiment to study the nocturnal drainage flow in the Brush Creek valley of western Colorado. Clements et al. (1989a) describe this experiment, including technical objectives, measurements, and instrumentation. In this paper, we use the 1984 ASCOT data to investigate the budgets of mass and momentum in the Brush Creek drainage flow. We examine the suitability of single-profile measurements for estimating the mass and momentum fluxes and flux-divergences by comparing them with the corresponding results derived from Doppler lidar data. These latter data are considered to provide the most reliable estimates of the fluxes in Brush Creek, because the Doppler lidar (in each scan) could map the three-dimensional distribution of winds within the valley.

We briefly describe the measurement methods and accuracies of the various instruments, and discuss the errors and uncertainties in the 1984 ASCOT data used in this study. We summarize what is known about the source of the draining air in Brush Creek. We also compare our estimates of mass fluxes with the results of other studies, e.g., Whiteman and Barr (1986), who derived the mass fluxes from the Tethersonde data of the 1982 ASCOT experiment in the Brush Creek Valley.

2. The 1984 Brush Creek data and instrumentation

Brush Creek Valley is nearly straight and has steep sidewalls that lead to ridges of nearly constant height above sea level. The only tributaries are steep channels and short box canyons cut into the sidewalls. Clements et al. (1989a) describe the instruments deployed in the 1984 Brush Creek experiment. These included a Doppler lidar (Post and Neff 1986), and a dense net-

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work of Tethersondes, Doppler sodars and optical anemometers both in the main valley and in Pack Canyon, a major box-canyon tributary. Meteorological towers of 10 m to 20 m height were used to measure sidewall drainage. The shape of the valley and the deployment of the instruments of interest in this study are shown in Fig. 1. A full description of the measurement principles for each system used is beyond the scope of this paper, but a brief summary is given here of the kinds of data provided by the Tethersonde, Doppler sodar, and Doppler lidar, so that the reader may appreciate the disparate nature of the data from these different systems.

The Tethersonde is a commercially available variant of a tethered balloon sounding system. An aerodynamically shaped balloon supports a small instrument package; data are radio-telemetered to a ground station. An electric winch controls the tetherline. The system measures wind speed (rotating cup anemometer) and direction (the balloon acts as a highly damped wind vane), dry bulb temperature, and either wet bulb depression or wet bulb temperature (depending on model type). Altitude is obtained from a small pressure altimeter. The system has been documented by Morris et al. (1975), Whiteman (1980), and Call and Morris (1981); its performance has been evaluated in intercomparison studies (Kaimal et al. 1980) and described in previous ASCOT reports (Hosker 1983). The main difficulty in interpreting tethered balloon data is that the vertical profiles obtained are neither instantaneous snapshots nor true time-averages, but are instead a time sequence obtained in a nonstationary atmosphere.

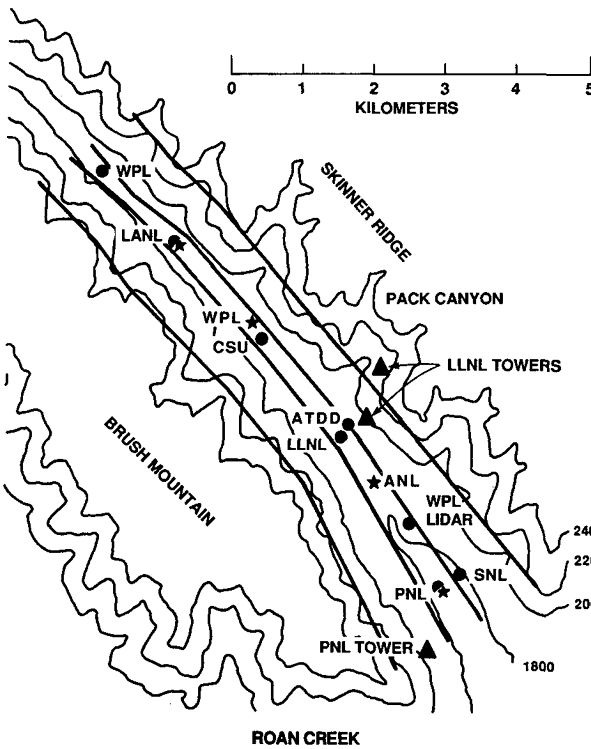

FIG. 1. Topographic map of Brush Creek Valley with height contours in meters ASL. Heavy lines indicate the edges of the budget volume. The center pair of heavy lines delineates the valley floor. Tethersonde sites (●), sidewall towers (▲), and Doppler sodar sites (★) are indicated. The LANL and PNL sites have Tethersonde and Doppler sodar collocated.

Doppler acoustic sounders (Doppler sodars) detect fluctuations of the acoustic refractive index of the atmosphere. Such fluctuations are themselves caused by fluctuations in temperature, wind, and (to a minor extent) humidity. A pulse of acoustic energy is back-scattered toward a receiving antenna by these acoustic refractive index fluctuations. If the fluctuations are moving, the received signal exhibits a velocity-dependent Doppler shift in its frequency. The elapsed time between a transmitted pulse and a received echo indicates the height of the scattering region; hence "range gates" corresponding to specific elevations can be prescribed, and the wind component can be determined within these "gates". Estimates from individual echoes will generally be subject to wide variations, so typically an average value will be calculated within each gate or atmospheric layer from a sequence of echoes. The use of multiple transmitters and receivers allows measurement of wind vector components with user-selectable averaging times, typically on the order of 10–15 min.

For the 1984 Brush Creek main valley study, the Doppler sodars were set to provide 15 min averages through 30 m deep layers, beginning about 30 m AGL. The data from the ASCOT Doppler sodars included echo return strength (for estimating signal-to-noise ratio—important for determining the reliability of the velocity estimate), horizontal wind speed and direction, the standard deviation of the horizontal wind direction, vertical wind speed, and its standard deviation. The results from sodars are known to be sensitive to site-specific "nonwhite" noise (e.g., machinery, or aeolian noise), inversions (which can scatter noise from distant sources to the receiver), and echoes from stationary objects (e.g., equipment trailers, or nearby cliffs).

Doppler sodars have been described in numerous articles (e.g., Neff and Coulter 1986, and McCready 1980, among others), including their use within the ASCOT program (Coulter and Martin 1983; Hosker 1983; and others). Extensive intercomparisons of Doppler sodar performance to other systems such as fixed meteorological towers have been and will be performed (Chintawongvanich and Olsen 1988; Gaynor 1988 private communication; Kaimal et al. 1980, 1984). Schwiesow (1986a) suggests that one can typically expect horizontal velocity component accuracies of ±10 percent, and vertical velocity accuracy of about ± 0.2 m s^{-1}.

Lidar systems have been reviewed by Schwiesow (1986b). The Doppler lidar and experimental procedures used in the 1984 Brush Creek valley study have been described by Post and Neff (1986). The system transmits brief pulses from an infrared laser ten times per second. The energy in these pulses is scattered by ambient aerosols, and its frequency is Doppler shifted according to the velocity of the scattering particles. The energy that is backscattered to the lidar is frequency-shifted by an amount proportional to the wind component along the lidar beam; within the narrow Brush Creek valley, this component is within a few percent of the along-valley wind (see Fig. 1). Special electronics process the signal to determine this radial wind component within each of a series of range gates; the wind component is thus representative of an approximately cylindrical volume of 300 m length and about 0.5 m diameter. Data are collected from about 1.5 km to 20 km distance from the lidar unit.

A programmed sequence of elevation and azimuth angle changes (a "raster scan") was used to sweep the lidar beam through the Brush Creek valley cross section, providing a cross-sectional view of the along-valley flow component. Scans were made both up- and down-valley. Data were collected about every 30 min. Up to eight minutes were needed to perform a scan, so rapidly varying flow features were probably not detected. Other scanning modes (PPI and RHI) were also used for other purposes, but are not discussed here. Post and Neff (1986) suggest that the velocity component accuracy is about ± 0.5 m s^{-1} for a reasonable signal-to-noise ratio.

Neff (1987 private communication) used these Doppler lidar data to calculate the mass and momentum fluxes in Brush Creek Valley. At each of the lidar's 300-m range intervals, he spatially integrated the measurements of u and u^2 over the valley's cross-sectional area. He excluded negative (up-valley) values of u from the integrations, under the assumption that these measurements were outside of the drainage flow.

3. Calculation of mass and momentum fluxes in Brush Creek

We assume that the time-averaged flow is steady and incompressible. The latter assumption permits the average air density to be treated as a constant, and the mass budget to be expressed in terms of volume fluxes. The steady state mass budget for a draining valley balances the flux divergence down the valley with the mass added or removed through the sides and the top. Changes in the mass of the drainage flow can come from sidewall drainage, from tributaries, and from subsidence or entrainment through the top of the flow. The steady state momentum budget for a draining valley balances the divergence of down-valley momentum flux with the gain or loss of momentum due to buoyancy forces and surface drag, and momentum transfer due to the addition or removal of mass through the top and the sides of the valley. Mahrt (1982) described a scale analysis of the momentum equations to determine the relative contributions of these factors for various drainage flow conditions.

In order to calculate mass and momentum fluxes from the single-profile (Tethersonde and Doppler sodar) data, we had to create a simple budget volume that contains the bulk of the Brush Creek drainage flow. Because of the simplicity of the valley geometry and the near-uniform slopes of the sidewalls, we assumed a trough-shaped budget volume with a trapezoidal cross section. The sides of this trough are a series of straight sections extending down the valley from one promontory to another; sideslope and tributary flows are therefore external sources of mass and momentum. At each of the promontories, the dimensions of the trapezoidal cross section represent a best fit by eye to the actual valley cross section. The bottom of the budget volume is at the valley floor, and its height is 425 m, which is the average observed depth of the drainage flow. Figure 1 shows the shape and location of the budget volume.

The along-valley wind component u was assumed to vary in the y and z directions according to the equation

$$u(y, z) = u_m(z)\left\{1 - \left[\frac{y}{y_m(z)}\right]^2\right\}, \qquad (1)$$

where $y_m(z)$ is the half width of the budget volume at height z, and $u_m(z)$ is the velocity component measured by the single-profile instrument. The parabolic distribution in Eq. (1) is consistent with the wind measurements in Brush Creek (Clements et al. 1989b; King 1989). At the WPL Doppler sodar site there were two sodars at opposite sides of the valley floor, about 164 m apart. The vertical profile utilized for this site was a composite, using the larger of the two down-valley wind components at each elevation.

After determining the wind distribution $u(y, z)$ at a single-profile instrument site from Eq. (1), the volume flux, V, and the momentum flux, M, of the flow through the valley cross section at that site are calculated as follows:

$$V = \sum_{j=1}^{N}\left[\int_{y_W(z)}^{y_E(z)} u(y, z)dy\right]_j \Delta z_j \qquad (2)$$

$$M = \sum_{j=1}^{N}\left[\int_{y_W(z)}^{y_E(z)} u^2(y, z)dy\right]_j \Delta z_j. \qquad (3)$$

Here, $y_E(z)$ and $y_W(z)$ are the crosswind distances to the eastern and western sidewalls, respectively, from the instrument site, Δz_j is the thickness of the vertical layer centered on the jth observation level, and N is the total number of vertical layers in the budget volume. In our analyses, we used a uniform thickness for all vertical layers—15 m for the Tethersonde data, and 30 m for the Doppler sodar data. The volume flux V in Eq. (2) has units of m^3 s^{-1}, and the momentum flux M in Eq. (3) has units of m^4 s^{-2}.

The averaging time for the single-profile wind data used in Eqs. (2) and (3) was 2330–0730 MST; this period was chosen to allow as large a sample as possible (up to six soundings per site) in the Tethersonde data. The averaging time of the Doppler lidar fluxes varied from day to day; the typical averaging period was from 2300 to 0330 MST. The effect of this difference in averaging times was tested with the Doppler sodar data. The differences between fluxes derived from the Doppler sodar with the two different averaging times are 0.34×10^5 m^3 s^{-1} for the volume flux, and 0.16×10^6 m^4 s^{-2} for the momentum flux. These values, which are about 5 to 12 percent of the fluxes, are within the range of scatter of the single-profile data.

4. Down-valley fluxes

The down-valley fluxes of mass and momentum, defined in Eqs. (2) and (3), are the best-determined components of the mass and momentum budgets in the Brush Creek drainage flow. In the budget calculations, we determined the divergences of these fluxes as the slopes of the best-fit straight lines through the flux data. Fluxes and flux-divergences obtained by the Doppler lidar are taken as the standard, because they were derived from winds directly measured over the whole valley cross section. In the following subsections, these lidar-derived fluxes are compared with those obtained from the Tethersondes and the Doppler sodars to illustrate the kind of accuracy that can be expected from the use of the single-profile data. The Brush Creek drainage was particularly suited to single-profile data analysis, because of the regular shape of the valley and the relatively slow variation of the mean flow with time.

a. Comparison of Doppler lidar and single-profile measurements

Figures 2, 3, and 4 compare the fluxes derived from the lidar, the Tethersondes, and the two up-valley Doppler sodars for 20, 26, and 30 September 1984, respectively; the integrated lidar fluxes in Brush Creek were available only for these three nights. The two straight lines in the figures represent best-fits to the single-profile data and the lidar data. Tables 1 and 2 summarize the comparison between the average down-valley fluxes determined from the single-profile measurements and the lidar data. Percent differences are given relative to the lidar data. The slopes are derived from the best-fit straight lines. The mass and momentum fluxes in Tables 1 and 2 were computed only from measurements in the upper part of the valley where lidar data were available. Though the fluxes derived from the Doppler sodar at the ANL site are shown in Figures 2, 3, and 4, these fluxes were not considered for determining the best-fit lines, because of incompatibility problems which will be discussed later.

The fluxes derived from the single-profile measurements differ from those derived from lidar data by about ±25 percent on the average. These results are obtained under particularly favorable conditions: the data were taken primarily in the upper part of Brush Creek, where the valley is narrower and straighter, and the drainage flow is unaffected by the confluence with Roan Creek flow at the valley mouth.

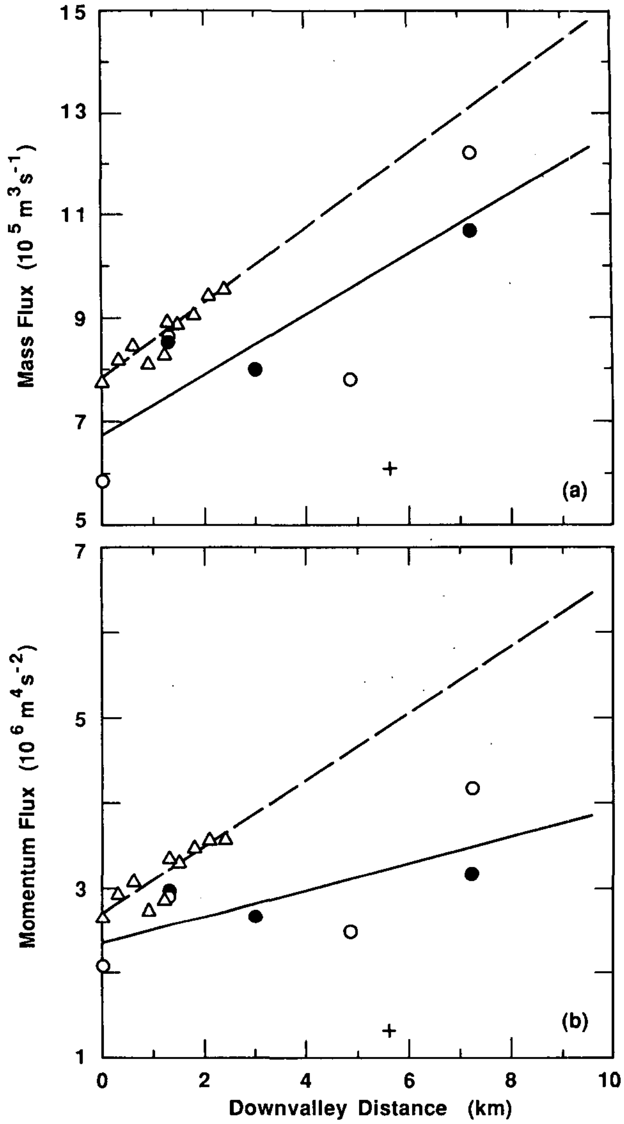

FIG. 2. Comparison for 20 September 1984, between cross-valley-integrated fluxes of (a) mass, and (b) momentum derived from single-profile measurements and from Doppler lidar data in Brush Creek Valley. The fluxes are presented as functions of distance down-valley from the WPL Tethersonde site (shown in Fig. 1). Data points are from Doppler lidar (△), Doppler sodar (●), and Tethersonde (○). Fluxes computed from the ANL sodar are shown by (+) for comparison, but are not used in the analysis. The linear regression best-fit lines to the flux data (excluding the ANL sodar) are also shown (solid line: single-profile data, dashed line: lidar data).

The flux divergences, which are given by the slopes in Tables 1 and 2, give a mixed result. Mass-flux divergences derived from Tethersonde and Doppler lidar measurements taken on 20 and 30 September match

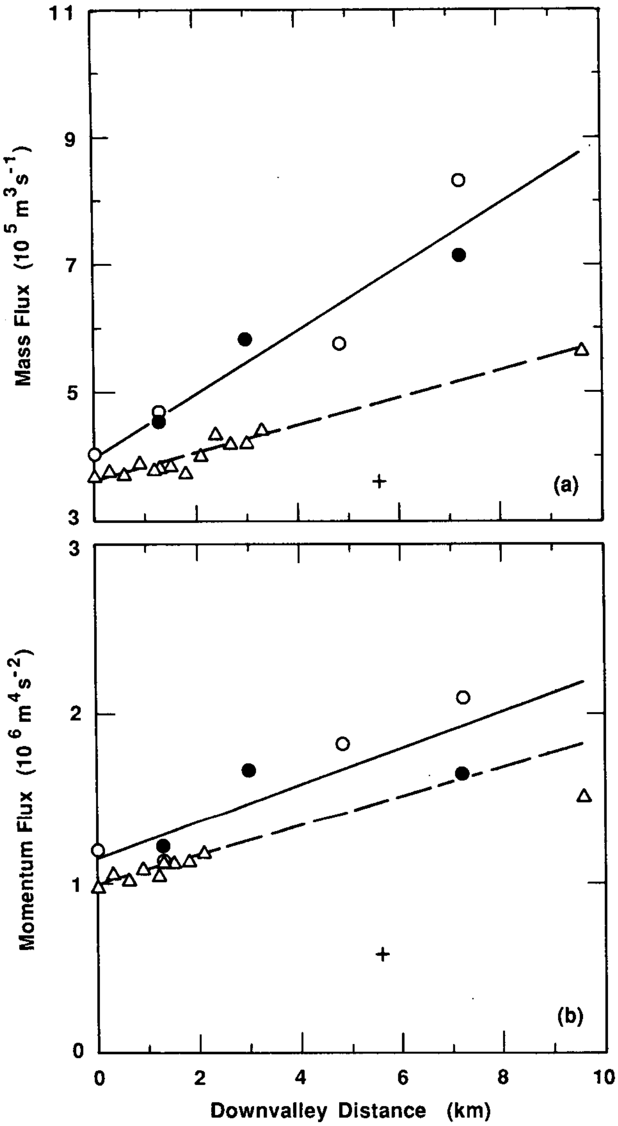

FIG. 3. Same as Fig. 2 except for 26 September 1984. Lidar fluxes plotted at 9.6 km down-valley are not used in the linear regression fit.

to within 20 percent but the slope derived from single-profile data is much too steep on 26 September (see Table 1 and Fig. 3a). Some of this discrepancy may be traced to the mass flux computed from the PNL Tethersonde data collected near the valley mouth. King (1989) computed Doppler lidar mass fluxes at several cross sections in Brush Creek Valley by assuming that the wind was uniform in the y-direction. He compared these hypothetical single-profile fluxes with the mass fluxes derived from integration of the actual Doppler-lidar winds over the cross section. At the up-valley locations, the assumption of uniform wind across the valley overestimated the mass flux by a factor of 1.5. Our assumption of a parabolic wind distribution corrects this overestimate. Near the valley mouth, however, the uniform wind assumption overestimated the mass flux by a factor of two. Therefore, our parabolic wind profile will also overestimate the mass flux near the valley mouth. This overestimation may have been particularly prominent at the PNL site on 26 September.

The momentum-flux divergences computed from single-profile data compare poorly with those from the Doppler lidar. The match of divergences on 26 September for the momentum flux, however, is much improved over that for the mass flux. For this night, the vertical profiles in Fig. 5 show a significant relative contribution from winds above 200 m AGL to the mass flux computed from the PNL Tethersonde. By contrast, the relative contribution from upper level winds to the momentum flux at the PNL site is much less, because

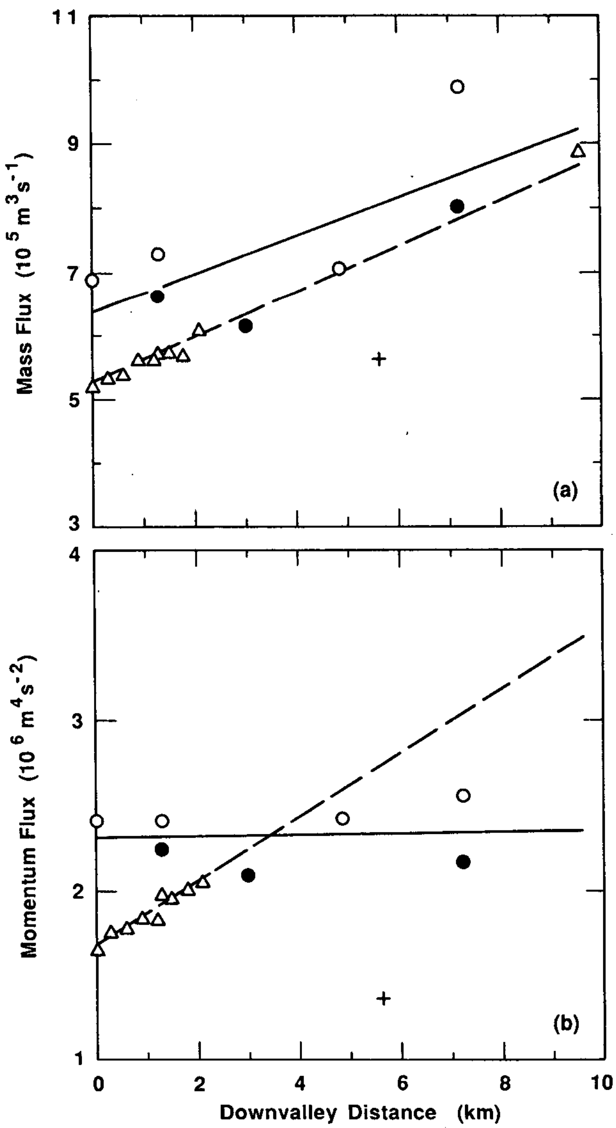

FIG. 4. Same as Fig. 2 except for 30 September 1984.

TABLE 1. Volume fluxes in Brush Creek calculated from single-profile data and lidar data. The slopes of the best-fit lines represent the flux divergences. Percentage differences are given relative to the lidar data.

Night	System	Average flux [$\times 10^5$ ($m^3 s^{-1}$)]	Flux difference	Slope ($m^2 s^{-1}$)	Slope difference
20 Sept	Single profile	7.5		58.4	
	Lidar	8.7	−14.6%	72.8	−19.8%
26 Sept	Single profile	4.8		49.9	
	Lidar	4.0	20.0%	21.4	133.0%
30 Sept	Single profile	6.7		29.7	
	Lidar	5.6	18.5%	34.5	−13.9%

the small relative wind component is squared. The reasons for the poor agreement between momentum flux-divergences derived from the lidar and the single-profile methods on 30 September (see Table 2 and Fig. 4b) are not yet clear. Since both Doppler sodar and Tethersonde data give consistent results on this night (Fig. 4a and b), sample errors due to infrequent Tethersonde launches cannot be the explanation.

Single-profile flux divergences exhibit at least two sources of error. First, the influence of winds above the drainage jet is amplified, because the flux integrals are weighted by the valley width, which increases with height. Uncertainties in the measurement of the light-and-variable winds above the jet level are thus magnified, especially in the calculation of mass flux. Second, Doppler lidar observations show that the drainage jet undergoes fairly strong meander and other temporal changes on short time scales. Furthermore, the jet's average position varies significantly from night to night (King 1989). This nonstationarity was most pronounced between Pack Canyon and the valley mouth, accounting for the greater tendency for error in the fluxes computed from the LLNL and PNL Tethersonde sites and the ANL Doppler sodar site.

Reducing the averaging time of the single-profile measurements to be same as that of the Doppler lidar measurements (0000–0400 MST) does not materially alter the flux-divergence results. Although the momentum flux divergences for 20 and 26 September match more closely those from the Doppler lidar (±20 percent), the worst cases in Tables 1 and 2 are not improved significantly.

b. Comparison of Doppler sodar and tethersonde measurements

Tethersonde profiles in Brush Creek were taken infrequently (every 90 min) and slowly (about 45 min per ascent). In view of the short-term fluctuations and the meandering of the jet, sampling errors were very likely. Doppler sodar has the advantage of taking profiles rapidly and much more frequently.

Differences in the results obtained by the two instruments are particularly evident at the PNL site on 26 September, 1984. For this site, Fig. 5 compares the profiles of mass and momentum flux contributions from successive vertical layers of 30 m thickness, derived from the Tethersonde and the Doppler sodar data. The areas under the curves are proportional to the total integrated mass and momentum fluxes, respectively. The PNL Tethersonde and Doppler sodar were within 40 m of each other, and the same valley cross section was assumed in computing all fluxes. There were only four Tethersonde ascents during the time period covered, while there were many Doppler sodar profiles (nominally every 20 s) over the same period, greatly reducing the likelihood of sampling error in the Doppler-sodar measurements. Through the jet level, the Tethersonde fluxes in Fig. 5 are clearly stronger than those from the Doppler sodar.

TABLE 2. Momentum fluxes in Brush Creek calculated from single-profile data and lidar data. The slopes of the best-fit lines represent the flux divergences. Percentage differences are given relative to the lidar data.

Night	System	Average flux [$\times 10^6$ ($m^4 s^{-2}$)]	Flux difference	Slope ($m^3 s^{-2}$)	Slope difference
20 Sept	Single profile	2.6		156.0	
	Lidar	3.2	−19.8%	392.0	−60.2%
26 Sept	Single profile	1.3		108.0	
	Lidar	1.1	16.5%	86.0	25.7%
30 Sept	Single profile	2.3		4.0	
	Lidar	1.9	22.9%	188.0	−97.8%

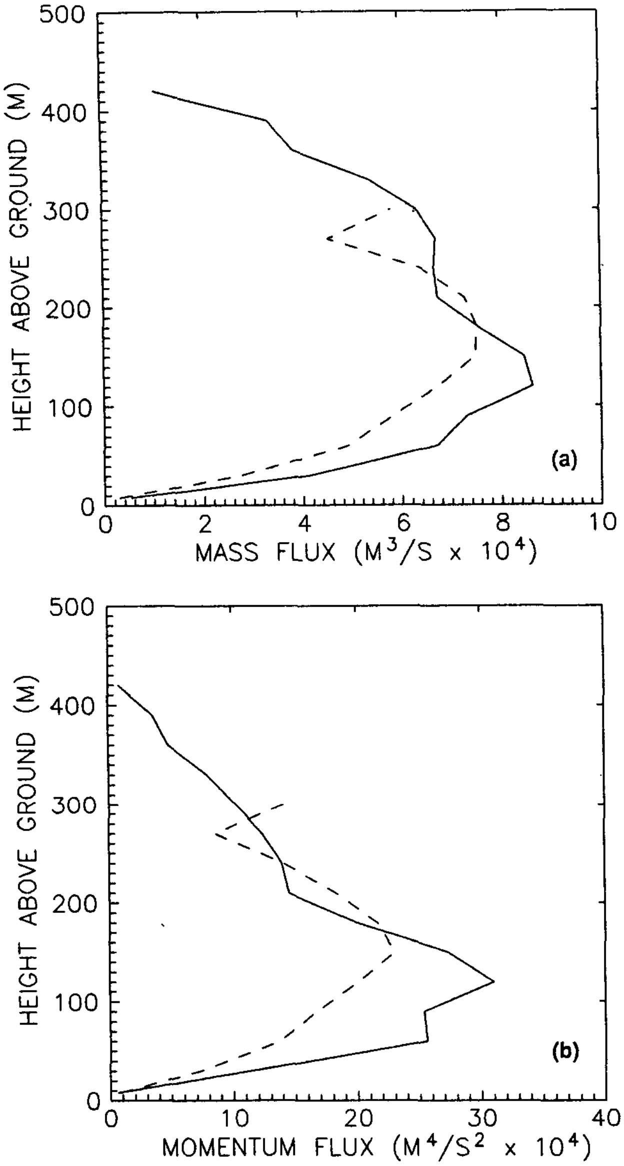

FIG. 5. Vertical profiles of the contribution of each 30-m layer to the (a) mass flux, and (b) momentum flux at the PNL site as measured by Tethersonde (solid line) and Doppler sodar (dashed line) on 26 September 1984. The total flux is proportional to the area under the appropriate curve.

Although the Doppler sodar almost certainly gave a better estimate of the time-average winds than the Tethersonde, both instruments probably underestimated the actual down-valley fluxes. The parabolic cross-valley wind profile in Eq. (1) assumes that the single-profile instruments measure the maximum $u_m(z)$; if the drainage flow meanders, or if an instrument is off to the side of the jet, then the measured winds will result in an underestimate of the actual fluxes.

The Doppler sodar data from the ANL site have been omitted from the previous discussion because of incompatibility problems. For the ANL site, the computed fluxes were about 30 to 60 percent below the best-fit line through the fluxes at other sites, as shown in Figs. 2, 3, and 4. Most likely, the ANL sodar missed the drainage jet. A similar situation is illustrated in Fig. 6 for the LLNL and ATDD Tethersonde locations, about 1 km up-valley from the ANL site. The mass fluxes computed from the LLNL Tethersonde data were unexpectedly small, similar to those from the ANL sodar, but to a lesser extent.

At the PNL site, the down-valley wind component $u(z)$ measured by the Doppler sodar on each night attained questionably high values above about 300 m height; this is illustrated in Fig. 7. To extrapolate above this level, we used Whiteman and Barr's (1986) technique of fitting the damped sine function

$$u(z) = A \sin\left(\frac{z}{D}\right) \exp\left\{-\left(\frac{z}{D}\right)^B\right\} \qquad (4)$$

originally derived by Prandtl (1942). The parameters A and D were adjusted to fit the observed maximum wind speed and the height of its occurrence. Parameter B was adjusted to match the wind at the highest point judged to have credible data, based on comparison of sodar profiles with those from the Tethersonde. The measured Doppler sodar data were used up to the level where they became suspect, above which the extrapolation formula was used to obtain the winds.

c. Comparison with other work

Our mass fluxes from the autumn 1984 experiment can be compared with Whiteman and Barr's (1986) mass fluxes from the summer 1982 experiment in Brush Creek. At the LANL site, which was at about the same up-valley location in both experiments, the mass flux of $0.9 \times 10^6\ m^3\ s^{-1}$ estimated by Whiteman

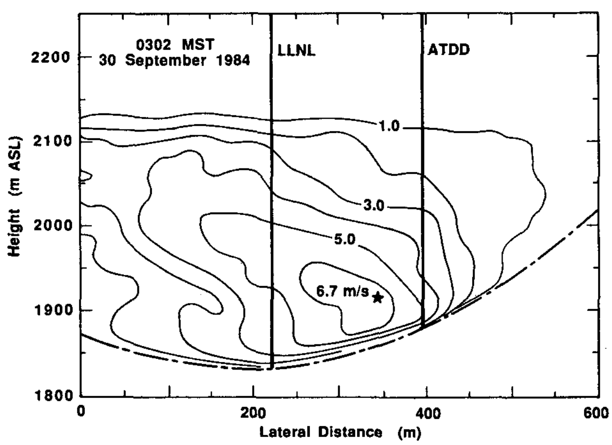

FIG. 6. A typical plot of isotachs of down-valley wind component measured by the Doppler lidar at the cross section through the LLNL and ATDD Tethersonde sites showing a time when the jet maximum was between the two Tethersondes.

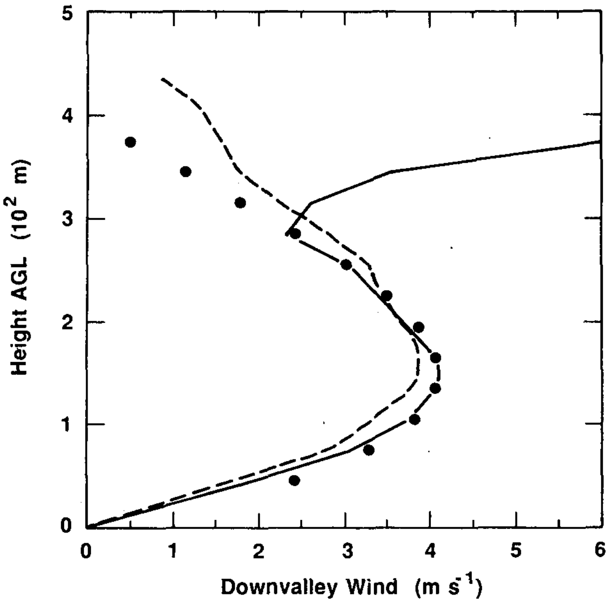

FIG. 7. Vertical profiles of down-valley mean wind component at the PNL site on 30 September 1984, showing typical structure. Doppler sodar data: solid line, Tethersonde data: dashed line. Sodar data above 285 m are suspect and are replaced by an extrapolation, indicated by (●). Although the extrapolation formula is not used below 285 m, its whole profile is displayed to illustrate its fit to the sodar data.

and Barr (1986) is nearly equal to our result of 0.86 $\times 10^6$ m^3 s^{-1} for 20 September 1984. The corresponding results at the down-valley end of the budget volume differ by more than a factor of two: 2.8 $\times 10^6$ m^3 s^{-1} versus 1.2 $\times 10^6$ m^3 s^{-1}. Furthermore, Whiteman and Barr's (1986) overall mass flux divergence of 271 m^2 s^{-1} is about five times larger than the single-profile mass flux-divergences shown in Table 1.

The vertical profiles of average down-valley wind speed on the night (30–31 July, 1982) examined by Whiteman and Barr (1986) show winds comparable to those measured in fall 1984. The fluxes computed in both studies should thus be comparable, apart from differences in assumptions. Whiteman and Barr (1986) assumed constant wind across the valley whereas we assumed a parabolic profile. Also, they integrated up to the valley rim at about 600 m while we stopped at 425 m, about where the wind speed approached zero. Such differences will have increasingly pronounced effect as the valley widens towards its mouth.

Gudiksen and Shearer (1989) used data from perfluorocarbon tracers, released near the WPL Tethersonde site during the 1984 ASCOT experiment, to estimate the mass flux down Brush Creek Valley. Their estimates apply at the PNL site, where we also have mass fluxes estimated from both sodar and Tethersonde data. Though one of the single-profile mass fluxes is smaller than the tracer-derived estimate by 40 percent, most of the other results are within ±20 percent. These results are comparable to the ±25 percent discrepancies we observed between single-profile and lidar estimates of mass flux.

5. Sources of draining air

It is important in air-quality planning to know the source of air which drains into a valley. There are three possibilities: (i) drainage down open sidewalls, (ii) supply through tributaries, and (iii) direct subsidence from above the valley.

The flux down the sidewalls is relatively easy to measure. During the 1984 ASCOT experiment, towers of 10 m height were placed on the sidewalls by three groups: PNL, LANL and LLNL. Table 3 gives the average integrated sidewall flux from the PNL tower on the west sidewall of Brush Creek Valley, the LLNL towers on the east sidewall just below Pack Canyon, and the LLNL towers on a side slope in Pack Canyon. These sites are shown in Fig. 1. We did not analyze the data from the LANL towers, because a preliminary examination showed the sidewall fluxes there to be comparable to those at the other towers.

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TABLE 3. Estimates of mass fluxes from the sidewalls in Brush Creek and Pack Canyon.

			Average measured sidewall flux		
Night	System	Implied sidewall flux* (m^2 s^{-1})	Brush Creek PNL (m^2 s^{-1})	Brush Creek LLNL (m^2 s^{-1})	Pack Canyon LLNL (m^2 s^{-1})
20 Sept	Single profile	16.5	3.81	—	—
	Lidar	20.5			
26 Sept	Single profile	14.1	3.28	2.81	3.54
	Lidar	6.0			
30 Sept	Single profile	8.4	3.12	2.84	3.59
	Lidar	9.7			

* See text for details.

Table 3 gives the sidewall flux required to account for the derived mass-flux divergence. The units are mass flux per meter of sidewall length (i.e., $m^2 s^{-1}$). The implied sidewall flux is computed by taking the change in mass flux from WPL to PNL, derived from lidar or single-profile measurements, and dividing by the total ridgeline length over that segment of the valley, including tributaries. The total ridgeline length at about 2400 m MSL, approximated as the arc length of a sine wave (see Fig. 1), was estimated to be 25.6 km.

Clearly the measured sidewall drainage is smaller than the implied drainage by a factor of two or more. Thus, open sidewall drainage does not supply sufficient mass to account for the observed mass-flux divergence in the Brush Creek Valley. This result applies to a fully developed valley drainage flow. Initially, at local sunset, the sidewall drainage has been observed to be much stronger, weakening as the main-valley flow develops (Doran et al. 1987).

The two remaining sources of mass are much more difficult to measure and are not as well determined. Mass fluxes between 5 percent and 15 percent of the Brush Creek flux were calculated for the flow from Pack Canyon, using optical anemometer data (Porch et al. 1989) and tracer data (Gudiksen and Shearer 1989). Although Pack Canyon is one of the largest tributaries, this value was considered to be too high by many ASCOT participants. If all tributaries contributed comparable amounts there would be more mass added than indicated by the measured down-valley mass flux divergence.

The direct subsidence required to account for all of the observed mass flux divergence in the valley can be estimated by dividing the mass flux change over the budget volume by the surface area of the top of the budget volume. This gives an upper bound of 0.01 m s^{-1} to 0.04 m s^{-1} to the average subsidence rate in the 1984 experiment. These values are generally consistent with those estimated by Horst et al. (1987) from their evaluation of the thermal energy budget in the Brush Creek Valley drainage flow using the 1984 data. Whiteman and Barr (1986) obtained a somewhat higher value of 0.1 m s^{-1} from the 1982 data. Such small average vertical velocities are, however, almost impossible to measure to the required accuracy with currently available instrumentation. The Doppler sodar measurements made in Brush Creek Valley have vertical velocities of that order, but are not of consistent sign. Furthermore, the time-averaged vertical motion almost certainly varies from place to place requiring extensive spatial resolution to avoid sampling bias.

6. Conclusions

For the Brush Creek drainage flow, single-profile data provide integrated mass and momentum fluxes accurate to within a factor of about 1.5 under favorable conditions, but the measured flux divergences are not dependable. Even in a regular valley such as Brush Creek, nonsteady phenomena and irregular flow patterns introduce sampling errors into single-profile measurements. For estimating budgets, a Doppler lidar or an equivalent remote sensor is necessary. For an ordinary site survey characterizing a valley drainage within a factor of two, single-profile measurements are adequate. A Doppler sodar is the single-profile instrument preferred over the Tethersonde, because of the sodar's much higher sampling rate.

The Brush Creek data characterize the main-valley drainage flow fairly well. Although the source of imbalance in the mass budget of this flow is not yet satisfactorily resolved, we can speculate from our current understanding. Whiteman and Barr (1986) concluded that direct subsidence is the major source of mass into Brush Creek Valley. They postulated only small drainage flows from the tributary canyons, assuming these flows to emerge at the canyon floor where the canyon is the narrowest. Data taken during the 1984 experiment (Porch et al. 1989), however, demonstrated that most of the mass flux from Pack Canyon enters above 100 m AGL. There the canyon is much wider, providing larger mass fluxes with lighter winds. Estimates of Pack Canyon mass contribution as high as 5 percent–15 percent of Brush Creek mass flux were reported; difficulties in measuring the Pack Canyon flow currently limit our confidence in these numbers (Porch et al. 1989). It is reasonable to conclude, however, that the volume flux out of Pack Canyon probably represents a small percentage of the total flow within the Brush Creek Valley, in agreement with the results of Coulter et al. (1989). Further analysis of the Brush Creek data and additional field measurements in similar valleys will be necessary to better determine the source of mass in a valley drainage flow.

Acknowledgments. This work was performed under an agreement between the National Oceanic and Atmospheric Administration and the U.S. Department of Energy as part of the ASCOT program. Integrated Doppler lidar data were provided by W. D. Neff of NOAA's Wave Propagation Laboratory. The average measured sidewall fluxes from LLNL in Table 3 were integrated and provided by the group working under J. Shinn, who also made the measurements. R. T. McMillen of NOAA/ATDD arranged the digital terrain data and plotted the contours for Fig. 1.

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