Tributary, Valley and Sidewall Air Flow Interactions in a Deep Valley

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ABSTRACT

Field experiments measuring nocturnal tributary flows have shown complex internal structure. Variations in the flow range from short-term (8–16 min) oscillations (related to tributary/valley flow interactions) to long-term flow changes throughout the night (related to upper ridge slope and tributary sidewall cooling rate changes). The mean vertical structure in the tributary flow shows a three layer structure. Outflow winds are observed near the surface and in an elevated jet up to several hundred meters height. A flow minimum or counterflow exists at about the height of the drainage flow maximum in the main valley. Comparisons of flow volumes and variations from a single large tributary show that 5%–15% of the nocturnal flow in the main valley may be contributed through one tributary. This implies that tributaries may dominate main valley sidewall and midvalley subsidence contributions to valley drainage flows.

1. Introduction

In 1984, a single tributary in Brush Creek Valley was chosen for concentrated measurements. Brush Creek Valley is a valley about 20 km in length cut to a depth of about 600 m and width of about 3 km at ridge top at the valley mouth. The valley walls have an average slope of about 40° and the valley runs from the north-northwest at the source to south-southeast at the mouth. The tributary chosen for study was on the east side of the valley about 5 km north of the valley mouth. The tributary is about 1 km wide and about 1 km deep at ridge top with similar slope angles to the main valley. Two ridge slope valleys contribute to this tributary giving it a box canyon appearance and two small waterfalls during spring.

The rationale for measuring valley wind structure in a deep valley (Brush Creek, Colorado) has been described by others in this volume (e.g., Clements et al. 1989). Interest in deep valley wind structure led to a preliminary experiment in 1982 described by Whiteman and Barr (1986). One of the unexpected results of this study was that wind speeds and drainage layer depths were almost the same at locations with a difference of over a factor of 2 in valley cross-sectional area. The divergence in horizontal flow characteristic of nocturnal drainage might imply a vertical subsidence in the center of the valley of about 0.10 ms s^{-1}. This large a subsidence is difficult to explain (Nappo and Rao 1987; Dobosy 1989) based on the small slope of the valley floor (14 m km^{-1}). Another possibility would be some topographic difference in this lower part of the valley allowing extra flow from the valley sides. Since the ridge slope collecting area is about the same all along the valley (Neff and King 1985), it was natural to suspect the larger size of the tributaries as well as the more corrugated nature of the sidewalls in this lower region of the valley.

A measurement array of optical cross-path wind sensors, conventional meteorological towers, a Doppler acoustic sounder and an instrumented tethered balloon were deployed along the sides of Brush Creek Valley and within Pack Canyon, one of the major tributaries during the 1984 experiment. These instruments were deployed to test the hypothesis that tributaries and corrugated sidewalls contribute a disproportionate share

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of cold air to the valley flow during drainage conditions. Limited supporting measurements were also made in two other smaller tributaries. All the tributaries investigated were on the northeastern side of Brush Creek Valley. Pack Canyon was also supplied in 1984 with a perfluorocarbon tracer release and oil fog generator at one of the three ridge slope collecting regions at the tributary rim as well as a sampling balloon within the tributary. The oil fog was photographed from sites across the valley and up-valley from the tributary.

Comparison of flux estimates using the tracer data or the meteorological data indicate that under weak synoptic wind conditions, the flow out of Pack Canyon alone can be 5%–15% of the flow down Brush Creek near the mouth of Brush Creek. There are 4 to 8 similarly sized tributaries as well as 10 to 20 much smaller tributaries along Brush Creek. Measurements in the tributary north of Pack Canyon using a mini-Doppler acoustic sounder on one night in 1984 and a tethered balloon in 1986 indicated flows close to 5% of the main valley flow. No measurements were made in the tributaries on the west side of the valley. The number of these tributaries and the flow magnitudes in the selected tributaries indicate that most of the flow divergence in Brush Creek Valley could be supplied through the tributaries. The exposed Brush Creek Valley sidewall flows were found to be very shallow and weak (Stone and Hoard 1989). Detailed analysis of flows within the tributary and comparison with flow contributions from the ridge slope flows above the tributary indicate that most of the outflow is generated within the tributary (Coulter et al. 1989). Comparison of wind flow showed an unexpected 2 to 4 times larger flow out of the mouth of Pack Canyon than measured only 300 m up canyon from the mouth. Also, the acoustic sounder data showed a very regular oscillation of about 16 minutes in the tributary flow. These observations caused us to return to Pack Canyon in 1985, 1986, and 1987 to validate and test these observations.

Though the question of how much cold air is supplied to the main valley through the tributaries may appear academic, it could be very important for air pollutant source siting and receptor determination. If tributary outflow is as large a proportion of the valley flow as our measurements suggest, this implies that the tributaries represent regions of substantial subsidence and would be regions where stack plumes above ridge top could enter the valley regions. Surprisingly, there is little in the scientific literature about nocturnal tributary/valley flow interactions. Steinacker (1984) describes the difficulty of describing the valley cross section where tributaries intersect the main valley. Freytag (1987) describes mass budget estimates from the MERKUR experiment in the Inn Valley, but the tributary flows were not measured, only estimated based on the respective cross-sectional areas of the tributary and the main valley. Fluid dynamic interactions of transverse jets and water flows have been studied by Broadwell and Breidenthal (1984). But, analogous laboratory studies in air or water simulating interacting drainage flows have not been performed. The benefit of the field experiments described below is an improved understanding of how tributaries contribute to valley flows and how numerical models, which cannot resolve the tributaries, can begin to parameterize their effects.

2. Experiment design

One of the unique aspects of the Atmospheric Studies in Complex Terrain (ASCOT) experimental program in Brush Creek Valley in September–October 1984 was the diverse use of remote sensing instrumentation. Doppler lidar (King 1987) provided the down-valley flow structure in Brush Creek Valley but could not determine the contribution from sidewalls and tributaries. Doppler acoustic sounders provided vertical structure of horizontal winds in the main valley and in Pack Canyon (Coulter et al. 1988). Cross-path optical anemometers were used to measure spatially averaged flow components down the valley and valley sides.

Cross-path optical anemometers use the horizontal movement of optical turbulence across an optical path to deduce the spatially averaged wind (Lawrence et al. 1972). The advantage these instruments have is that they provide spatially averaged values that are more compatible with the resolution of numerical models and can measure very light winds common in drainage

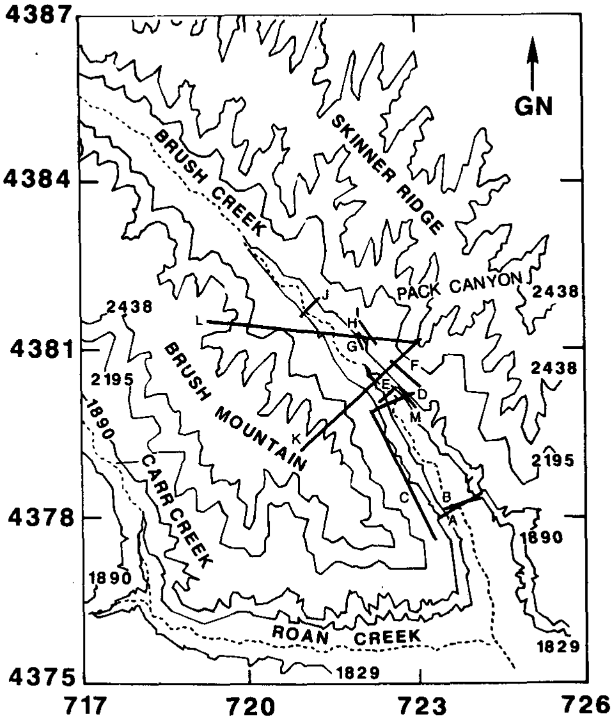

FIG. 1. Thirteen optical cross-path wind sensor paths for the September–October 1984 ASCOT field experiment.

flow conditions (Porch 1982a). The major disadvantage of these instruments is that they only measure the cross-path component at the elevation of the beam. This means that either a large number of stacked paths must be used to measure the vertical distribution of the flow or the data must be supplemented with temporally averaged balloon or tower data.

Figure 1 shows the deployment geometry of 13 optical cross-wind sensors in and across Brush Creek Valley during the 1984 experiment. Each instrument was calibrated and compared against each other on a test range in Boulder, Colorado, before being used in the 1984 experiment. The test system consisted of a linear array of single component propellor anemometers connected to a data analysis system. Table 1 shows the location, orientation, and effective path heights of the paths shown in Fig. 1. The effective height of the optical path is defined as the convolution of the underlying topography with the optical weighting function. These paths were chosen to study the variation of drainage flow in the main valley, the flow down the main valley sidewalls, flow out of Pack Canyon and the intrusion of synoptic wind into the top of the valley. The path characteristics are described in Clements et al. (1987). The raw data consist of 10 minute averages at all locations except paths A and B (1 minute resolution) in 1984.

Path F was chosen to study the sidewall flow above the height of the drainage wind maximum in the valley center from a fairly uniform part of the exposed northeast side. Path C includes several tributaries along a corrugated portion of the southwest side of the valley. The heights of the three cross-tributary paths were chosen based on an oil fog and smoke tracer release experiment conducted in June 1984 (Porch et al. 1984). Tethersonde data and smoke pictures showed a three level structure to the tributary outflow with a flow minimum at about 70 m above the tributary floor.

TABLE 1. Features of optical paths.

	Coordinates of path center				
Path	*X*-UTM (km)	*Y*-UTM (km)	Path from north (°)	Path length (m)	Effective path height (m)
A	723.72	4378.21	54	860	61
B	723.72	4378.21	65	640	42
C	722.75	4378.77	334	2550	47
D	722.57	4380.07	66	850	110
E	722.49	4380.21	47	410	24
F	722.80	4380.58	312	725	13
G	721.98	4381.15	336	340	20
H	722.06	4381.20	333	350	67
I	722.13	4381.32	324	550	110
J	721.12	4381.77	45	475	65
K	722.01	4380.21	47	2940	363
L	721.17	4381.31	276	3795	417
M	722.82	4380.17	321	505	8

Figure 2 shows a schematic of the general layout of the tributary measurements in 1984 (Clements et al. 1988). The vertical profile of the wind and temperature was measured about 300 m farther into the tributary. These measurements were supplemented by perfluorocarbon and smoke tracer releases on the ridge slopes and tower measurements on one of the tributary sidewalls. On one night during the experiment doppler acoustic sounder data were obtained in the tributary north of Pack Canyon (Neff and King 1987).

In June 1985, the three optical paths across the tributary from the 1984 experiment were replicated, only with the tethered balloon moved down the tributary to the former location of the tracer sampling balloon. Also, the optical cross-wind sensor data were recorded at 1-minute averages. The sampling of 10 minute averages in 1984 yields a Nyquist period of 20 minutes which is too low to resolve the observed oscillations. The presence of very thin cirrus clouds on this night caused an overall weaker drainage flow than the strongest drainage nights in 1984.

In September 1986, a different design was used incorporating two tethered balloons and a triangular array of cross-path wind sensors (Fig. 3). This arrangement of tethersondes allowed an actual measurement of the flux difference between the two locations in the tributary. The triangular array of cross-wind sensors allowed a measurement of convergence at the height of the highest optical wind sensor. Also, in September 1987 a small smoke release experiment was performed where smoke was released in the other ridge slope valley feeding Pack Canyon to the north, on a ridge slope away from this collecting valley and from the southern side of Pack Canyon.

3. Results

a. 1984 experiment

Analysis of the data from the 1984 experiment showed that the optical anemometer measured winds at the highest level (~110 m above the lowest point in the tributary below the optical path) were much higher than would be expected if the air flow were the same at the tributary mouth as measured 300 m into the tributary. The estimated air flow was corrected for height and assumed a parabolic decrease in wind speed at the tributary sides to 20% of the value at the center. This implies that the measured flow was much greater at the mouth than 300 m farther into the tributary. Also, strip chart recordings from the optical cross-wind sensors and high frequency data from the Doppler acoustic sounder showed regular 15–20 minute oscillations in the flow out of the tributary up to 100 m. Stone and Hoard (1989) found a broad low frequency oscillation in the main valley flow of a similar period.

Figure 4 shows a comparison of the main down-valley winds and the valley sidewall winds during the

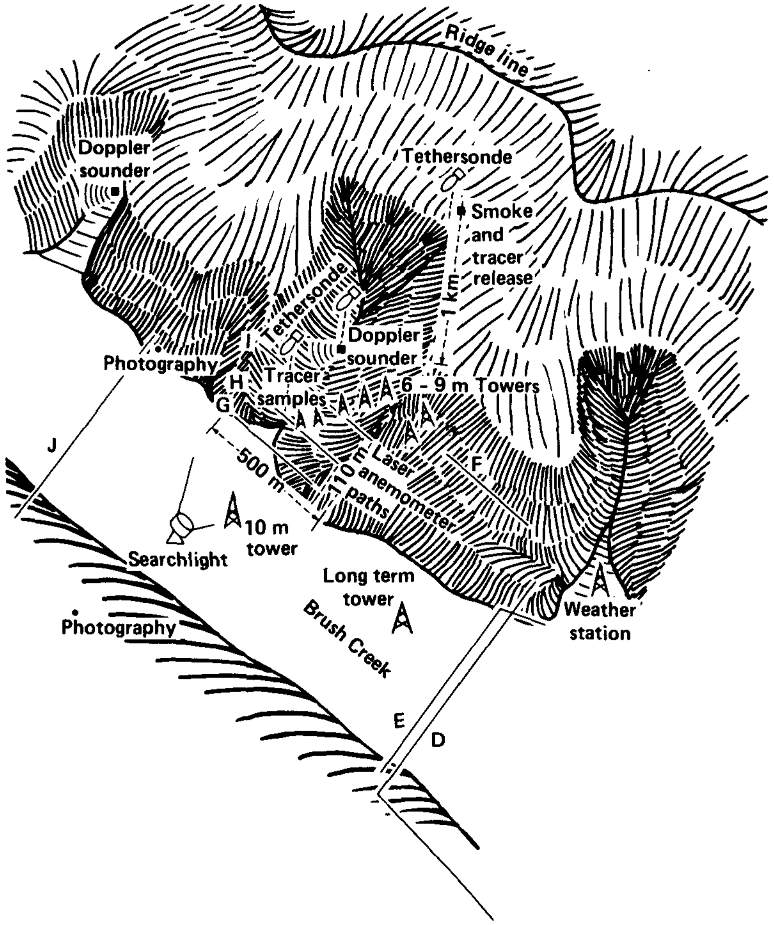

FIG. 2. Design of the September–October 1984 tributary experiment showing the placement of optical cross-path wind sensors both across the tributary and along the main valley sides as well as the locations of meteorological towers, Doppler acoustic sounders, tethersondes and smoke and perfluorocarbon tracer release and sampling sites.

night in 1984 with the least synoptic wind influence and when tracers were released. The most interesting features observed on this night include the following:

1) The onset of strong downslope flow on the western side of the valley early in the afternoon (~1500 MST) as this side is shaded.

2) Subsequent decrease in this sidewall flow as the main valley drainage flows increase.

3) An earlier transition to drainage flows after sunset in the lower paths than the higher paths.

4) Generally light sidewall flows anticorrelated with the strength of the main valley drainage.

These features imply an inhibiting effect on the sidewall contribution to the cold air mass flux by the main valley drainage flow itself. Also, though the magnitude of the wind speeds are comparable on the east and west side path, the much greater effective height of the west than the east side path (47 m and 13 m, respectively) implies a much greater flow contribution from a side including gullies than from one without (assuming a decreasing side flow with height).

b. Comparison of 1984 and 1985 results

The results of three cross-path optical wind sensors across Pack Canyon on the same night are shown in Fig. 5. Also shown in Fig. 5 are data from a night in June 1985 when tethersonde data from a location near the optical paths were available. These data as well as tethered balloon and smoke release measurements (Porch et al. 1984) show a three layer structure. A small volume outflow is observed near the bottom of the tributary up to about 40 m. A flow minimum or counterflow occurs at about the height of the drainage flow maximum in the main valley. Most of the flow volume exits the tributary from a deep layer (100–200 m) above this flow minimum. The lengths of the paths were 300 m to 600 m and the dimension shown in Fig. 5 is the weighted (both optical and topographic) mean height

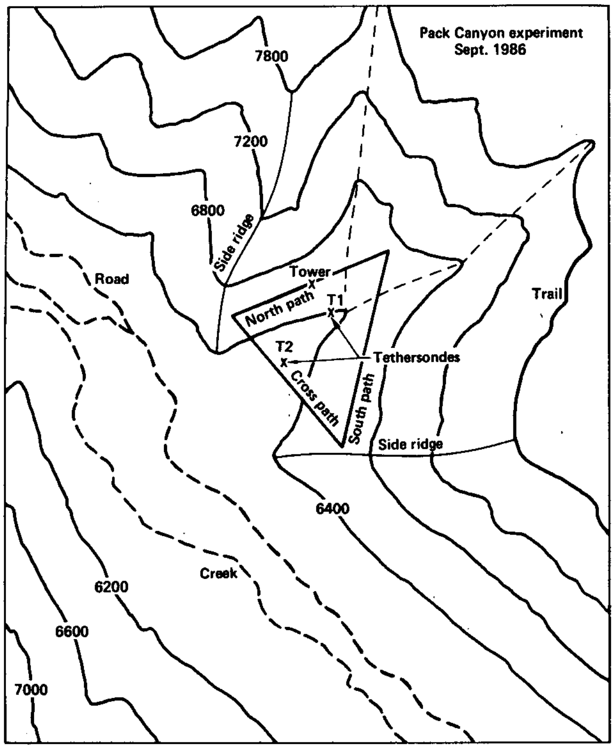

FIG. 3. Design of the September 1986 tributary experiment using two tethersondes and a triangular array of optical cross-path wind sensors.

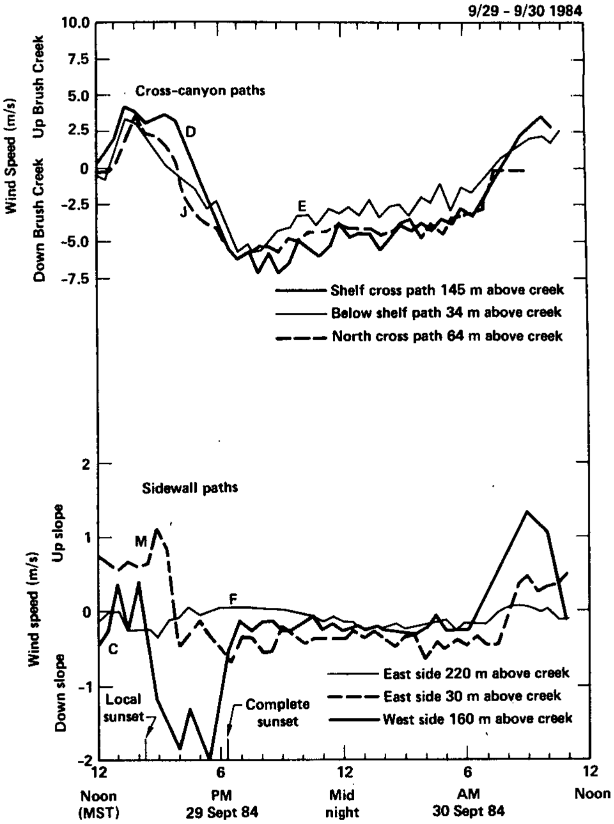

FIG. 4. Valley sidewall and cross-valley spatially averaged wind speeds measured on the night of 29/30 September 1984. Negative values refer to down-valley or down-slope flow direction component.

above the tributary floor. The features from these data show the following:

1) The drainage flow was much stronger during the September night than during the June night at the I path.

2) The middle path showed very weak drainage to counter drainage flow during the two experiments with counterflow predominating during the weaker drainage.

3) The data in Fig. 5 and other experiments showed a tendency toward a later transition from (and earlier transition to) drainage flow at the lowest path than at the upper path.

Comparison of the data in Fig. 5 with Fig. 4 shows that this east side tributary outflow peaks after the main valley flow peaks. If the tributaries are as important a cold air source to the main valley flow as outflow estimates from Pack Canyon imply, then there should be an earlier peak in the outflow of the west side tributaries where the sun first sets. This is supported but not proven by the timing of the flow on the west side path (C).

Figure 6 shows the average of eight hourly ascents and descents of the tethersonde at the mouth of Pack Canyon in June 1985. This profile was compared with the optical cross-path wind sensor data averaged over the same period. Though the averages were similar for

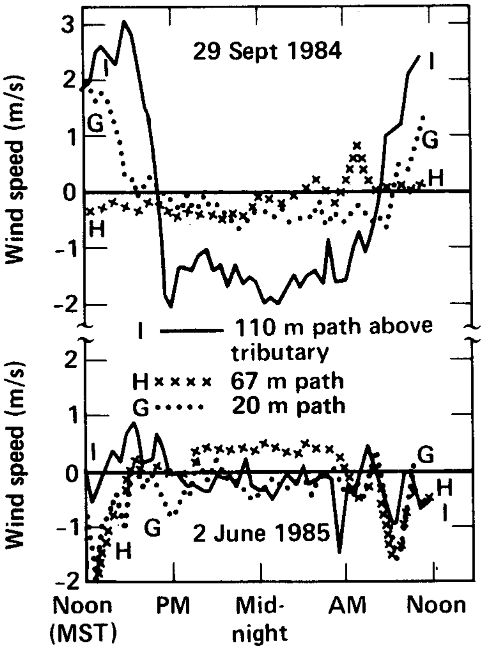

FIG. 5. Same as Fig. 4 for the three tributary paths for 29/30 September 1984 and 2/3 June 1985.

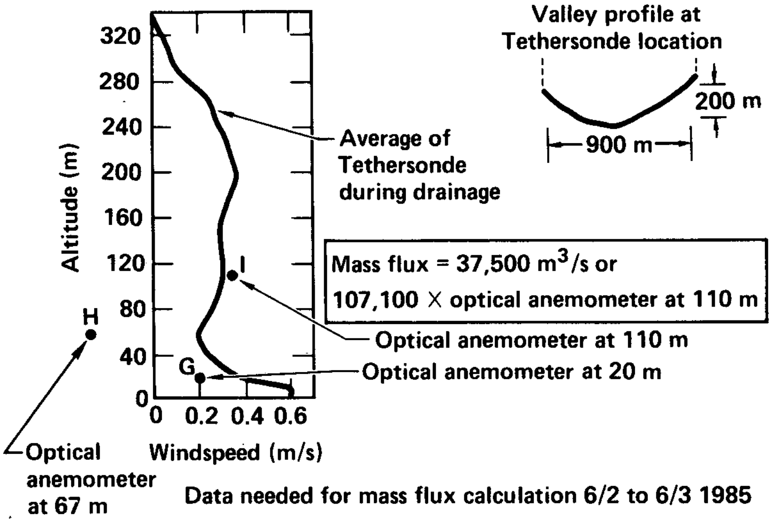

FIG. 6. Smoothed mean wind vertical profile determined from tethersonde data in June 1985, its relationship to averaged optical anemometer data for the total period of established drainage (i.e., not just the times simultaneous with the tethersonde observation at that height) and the valley cross section used to calculate the volume flow.

the highest path, the oscillations of flow in and out of the tributary caused a much greater difference at the other paths, especially at the middle path. This is because, even though the mean flow was into the tributary at the middle path height, at the particular times the tethersonde sampled at this height the flow happened to be out of the tributary. The standard deviation of the tethered balloon comparisons at the height of maximum flow was about 0.7 m s^{-1}. Using only the simultaneous data (24 ascent and descent values) the highest correlation between the tethersonde and optical anemometer data was found for heights 10–20 m lower than the maximum height of the beam above topography. This reflects the fact that the optically determined wind represents a convolution of the topography and optical weighting function of the instrument which peaks at the center of the path and goes to zero at the sides.

If we assume that the mean shape of the tethered balloon measured along tributary wind speed profile from 2300 to 0600 at the location of the cross-wind sensors in 1984 is the same as the measured profile at this location in 1985, we can use the measured optical anemometer data at the most representative location (Path I) to scale the flux. This would imply that, if the flow is linearly related to the wind at the highest path, the wind flow is about 100 000 m^2 multiplied by the optical anemometer value. When this is done for the night with the least synoptic influence in which tracers were released (29/30 September), one would calculate a value of about 150 000 m^3 s^{-1} out of the tributary. The assumption that the flow relationship was similar in 1985 to 1984 leads to a higher flux estimate than derived in Coulter et al. (1989) where a linear decrease was assumed above the upper path. A similar flow relationship was found in 1986 (scaling factor of 130 000 compared to 107 000 m^2). Also, the flow derived for 29/30 September 1984 using the flow relation assumption agrees with tracer estimates. In the absence of measurements at the mouth of Pack Canyon, however, it is impossible to otherwise rate the relative merit of the flow profile assumptions in 1984. The flow determined with this assumption corresponds well with volume flows estimated from the depth and timing of smoke release movement out of the tributary (i.e., the smoke took about 15 minutes to travel 1 km within a depth of about 200 m over the part of the tributary with an equivalent rectangular width of about 800 m). Gudiksen and Shearer (1989) also calculated the volume flow using the mean perfluorocarbon tracer concentration cross section shown in Fig. 7 and the known tracer release rate yielding a value of 133 000 m^3 s^{-1}. The flow rates calculated by these different methods agree better than we have a right to expect given the great uncertainty associated with the assumption that the shape of the wind speed profile is similar for different drainage periods and can be scaled by the spatially averaged wind at a single height. The similarity in the determined flows, however, provides at least circumstantial evidence that the flow out of this tributary approaches 15% of the flow down the main Brush Creek Valley at the tracer arc location near the valley mouth (about 1 000 000 m^3 s^{-1}). This is close to the ratio of the cross-sectional areas of the tributary and valley below the drainage layer depth (~300 m). This implies that, given the number of similarly-sized tributaries along Brush Creek, almost all the flow going down the valley can be matched by flow out of the tributaries (if

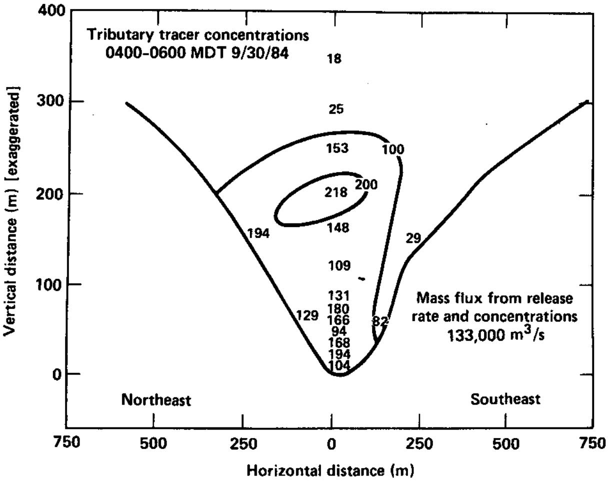

FIG. 7. Tracer concentration in ppt within Pack Canyon (looking east) which was used to calculate a volume flow for this period of about 133 000 m^3 s^{-1} using the known source release rate.

they all contribute as efficiently per cross-sectional area as Pack Canyon).

Comparison of these flow estimates out of the tributary mouth are a factor of 3 to 6 higher than 300 m inside Pack Canyon. This large flux difference is difficult to explain. It requires either a sidewall flow of 2 m s^{-1} over 100 m deep layer, an average subsidence of about 0.3 m s^{-1}, or a cross-canyon velocity profile different at the two different locations. On 29/30 September 1984, the minisodar showed that though subsidence was observed at the tethersonde location, it was only about 0.1 m s^{-1} at a height of 150 m. At the same time, the sidewall tower data showed only a shallow sidewall flow up to about 10 m less than 1 m s^{-1}. This implies that either 1) the subsidence is greater closer to the tributary mouth, 2) the cross-canyon distribution of outflow isn't horizontally similar at the two locations, 3) there is a sidewall flow either above or in a different location than the 10 m towers, or 4) the implied flux difference isn't real. The experiment in September 1986 showed that there really is a large flux difference between the two locations.

c. *1986 experiment*

When two tethersondes were run at the same time in 1986 at the two locations, the mean profiles and implied volume flows shown in Fig. 8 resulted. Not only were the out-of-tributary wind speeds larger, but they also extended about 100 m higher. This caused a difference factor of 4 in the volume flow at the two locations. The standard deviation in the tethersonde wind speeds at the highest optical path in this case was about 1.2 m s^{-1}. The night these measurements were made 16/17 September 1986 was not ideal in the sense that the regional scale winds above the tributary were much higher than on 29/30 September 1984 (6–10 m s^{-1} as opposed to 1–3 m s^{-1}). This may partially account for the somewhat different shape of the wind profile and the lower overall fluxes. The ratio of volume flow to the cross-path wind speed determined from the cross-tributary path is somewhat higher than determined in June 1986 (130 000 m^2 as opposed to 107 000 m^2). The profile shown in Fig. 8 is a smoothed average of individual tethersonde runs over 9 hours. There was a much larger difference between the flows at the two locations during drainage wind periods. Both locations showed a similar cross-tributary flow from north to south. This cross valley flow was also observed in 1984 and 1985 from the tethered balloon data. It does not seem to be due to flow down Brush Creek because the down-valley drainage flow is quite weak at these heights near the valley sides. It may either imply that the less vegetated north side of the tributary is producing more flow than the south side (which was observed in the analysis of the wind speeds from the two side optical paths in 1986) or an influence of the southerly synoptic wind generating a northerly counter flow at these heights.

All the tributary phenomena discussed above describe either the mean or nightly trend in the flow. We will now discuss some of the oscillatory behavior and suggested interactions of the tributary/valley flows using the one minute time resolution from the optical anemometer data in 1985 and 1986. Figure 9 is a comparison of the spectra from the three paths for the June 1985 experiment during steady drainage shown in Fig.

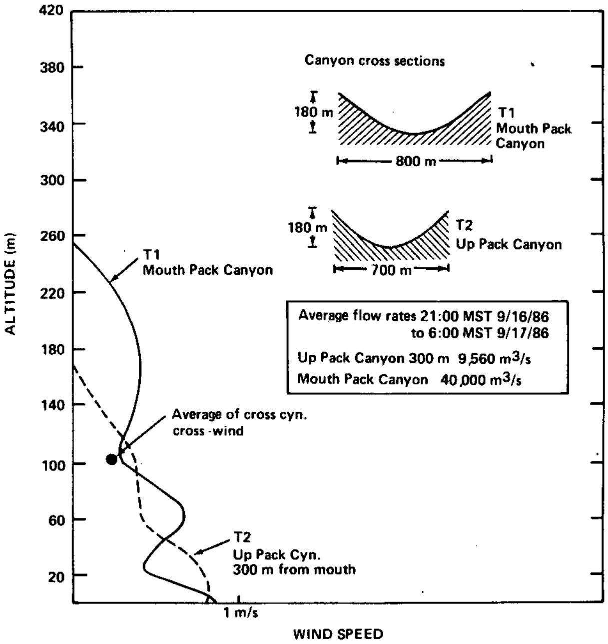

FIG. 8. Vertical profiles of tethered balloon determined winds in September 1986 from the tethersonde locations shown in Fig. 3 showing the much greater flow at the valley mouth location only about 300 m from the location farther up the tributary.

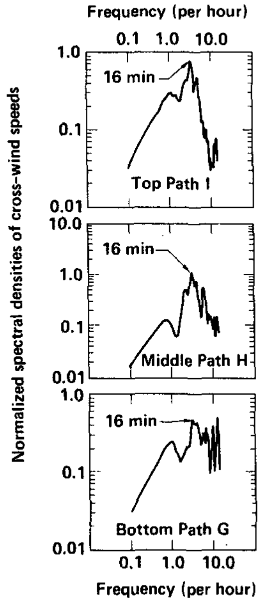

FIG. 9. Spectral analysis of three tributary paths on 2/3 June 1985 shown in Fig. 2 for only the period of steady drainage from 2000 to 0600 MST.

5. The most obvious feature is the strong ~16 minute cycle. This oscillation peak was also observed (though considerably less peaked) in the valley component of the tower data on the Brush Creek Valley sidewalls (Stone and Hoard 1989) and the minisodar data in Pack Canyon. This seems to imply a selected valley/tributary flow interaction on a 16 minute time scale caused by the geometry of the valley and tributary or the regular spacing of tributaries along the valley (or both). The wind convergence into the triangle formed by the three paths contained both the 16 and 8 min oscillations and averaged about 0.005 s^{-1}.

Figure 10 shows the spectral analysis of the winds measured in June 1986 from each path shown in Fig. 3. These spectra show that the side paths show a spectral peak at twice the frequency of the flow oscillation out the tributary ($1/8$ min compared to $1/16$ min). This may be due to an anticorrelation in Pack Canyon between the strength of the sidewall flow and the strength of the down canyon drainage wind similar to that found for two optical paths on the east and west side of Brush Creek Valley in 1984. This would imply a peak in the tributary sidewall winds at each minimum in the tributary outflow. These spectra show that the period of oscillation associated with the interactions of the main valley flow and the tributary is halved at the tributary sidewalls. As the flow moves faster and slower out of the tributary it causes flow close to the sidewalls to accelerate either in or out of the tributary yielding an 8 minute period.

If these regular oscillations are caused by interaction with the valley flow one might expect high positive correlations between the valley flow and the tributary flow. In fact, the valley flow and the tributary flow appear to be negatively correlated for periods less than an hour. This has been previously observed in comparisons of valley and tributary flow in Big Sulfur Creek

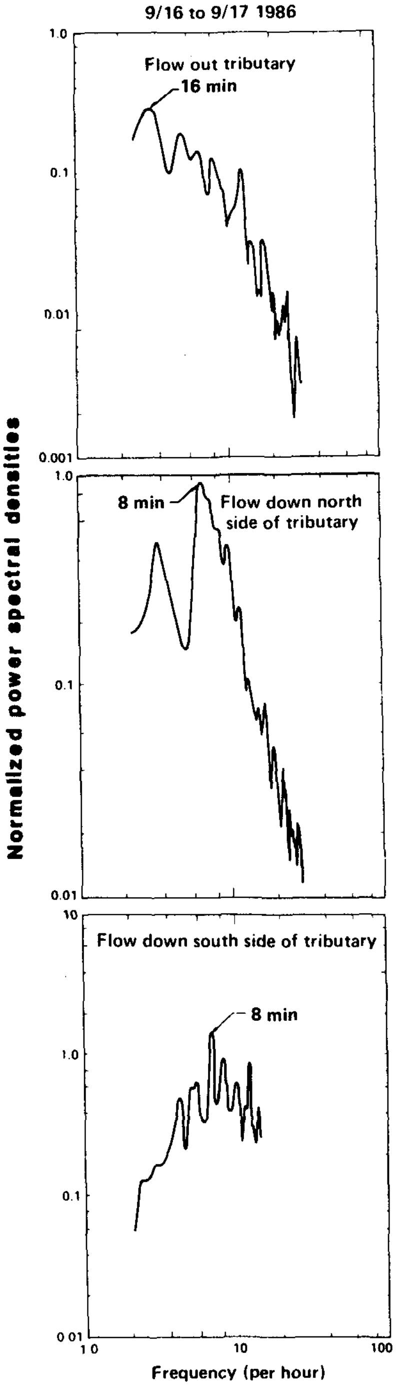

FIG. 10. Power spectral analysis of the three optical cross-path winds determined from the triangular array shown in Fig. 2 showing that the tributary side flows peak at twice the frequency as the oscillation frequency of the flow in and out of the tributary at this height.

TABLE 2. Correlation matrix of optical cross-path wind sensor data for drainage period 2300–0600 MST on the night of 29/30 September, 1984 using 10 minute averages.

	Brush Creek paths		Sidewall paths		Tributary
	D-Path (Avg. = 4.2 m s^{-1})	J-Path (Avg. = 4.6 m s^{-1})	F-Path (Avg. = 0.1 m s^{-1})	C-Path (Avg. = 0.2 m s^{-1})	I-Path (Avg. = 1.6 m s^{-1})
D-Path					
1.4 km down-valley from tributary	1.0				
Height 110 m†	0.6	0.2	−0.4	−0.2	0.2
J-Path					
0.9 km up-valley from tributary		1.0	−0.2	−0.04	−0.1
Height 65 m * ‡	0.2				
F-Path					
0.7 km down-valley from tributary			1.0	0.4	0.2
East sidewall					
Height 13 m* ‡					
C-Path					
2-km down-valley from tributary				1.0	0.2
West sidewall					
Height 47 m* ‡					
I-Path					
Tributary outflow	0.3	−0.05	−0.2		1.0
Height 110 m					

† E-Path, below D-path, height 24 m, (Avg. = 2.75 m s^{-1}).
* H-Path, tributary, middle, height 67 m (Avg. = 0.1 m s^{-1}).
‡ G-path, tributary, lowest, height 20 m (Avg. = 0.45 cm s^{-1}).

Valley in the Geyser region of Northern California (Porch 1982b). Tables 2 and 3 show the correlation coefficient matrix between the cross-path wind sensor data in 1984 for paths in Fig. 1 for the drainage period on 29/30 September and between the top tributary path, the east sidewall path and meteorologic tower data in the valley and on the valley sides, respectively. Table 2 shows that though there is a strong correlation

TABLE 3. Correlation matrix including meteorological tower data for the same conditions as in Table 1.

	Tower L4 Down-slope (Avg. = 0.32 m s^{-1})	Tower L4 Down-valley (Avg. = 0.35 m s^{-1})	Tower L6 Down-slope (Avg. = 0.37 m s^{-1})	Tower L6 Down-valley (Avg. = 0.08 m s^{-1})	F-Path Sidewall (Avg. = 0.09 m s^{-1})	I-Path Tributary (Avg. = 1.6 m s^{-}
ower L4 Down-slope 152 m above creek Height 9 m	1.0					
ower L4 Down-valley	0.8	1.0				
'ower L6 Down-slope 207 m above creek Height 2 m	0.2	0.3	1.0			
'ower L6 Down-valley	0.02	0.03	0.05	1.0		
-Path Sidewall Height 13 m	−0.02	0.2	−0.1	−0.3	1.0	
Path Tributary Height 110 m	0.2	0.1	0.02	−0.2	0.2	1.0

among vertically displaced paths in the valley there is practically no or weakly negative correlation between the three tributary paths. There also appears to be a positive correlation between the two valley side paths and (as described before) a negative correlation between the side paths and the down-valley flow. Though spatial separation undoubtedly reduces these correlations somewhat, the main valley air flows over 3 km at the height of the optical paths during the 10 minute averaging time used in these calculations. Table 3 shows that two towers on the west side of Brush Creek down valley from Pack Canyon show almost as little correlation as the stacked optical path winds in Pack Canyon. The high positive correlation of the down-valley and down-slope wind component at the two towers is related to the fact that the mean down-slope wind is almost as high as the down-valley component at this location.

If most of the drainage flow feeding the valley flow comes through the tributaries, why does there appear to be a weak negative rather than positive correlation? Figure 11 shows the time history of the tributary outflow from the top optical path (I) and the down-valley and cross-valley wind speeds from a 9 m tower in the center of Brush Creek Valley at the mouth of Pack Canyon. This plot shows that, though the short term correlations tend to be negative with the down-valley and positive with the cross-valley, the overall correlation is weakly positive. There is also some evidence that the tributary outflow regions tend to be regions of lower down-valley wind speeds (King 1987).

A negative correlation between down-valley flow and tributary outflow is actually supporting evidence for the importance of the tributary flow to the main valley flow, although it is difficult at first to picture. What the negative correlation says is that flow momentum and not velocity is being conserved. As a mass of cold air is delivered from the tributary to the valley the valley flow at first slows down and then accelerates down-valley from the tributary.

From the analysis, described above, of the apparent pivotal role of tributary outflow on both the flow volume and the turbulence observed in Brush Creek Valley, the question obviously arises as to why the tribu-

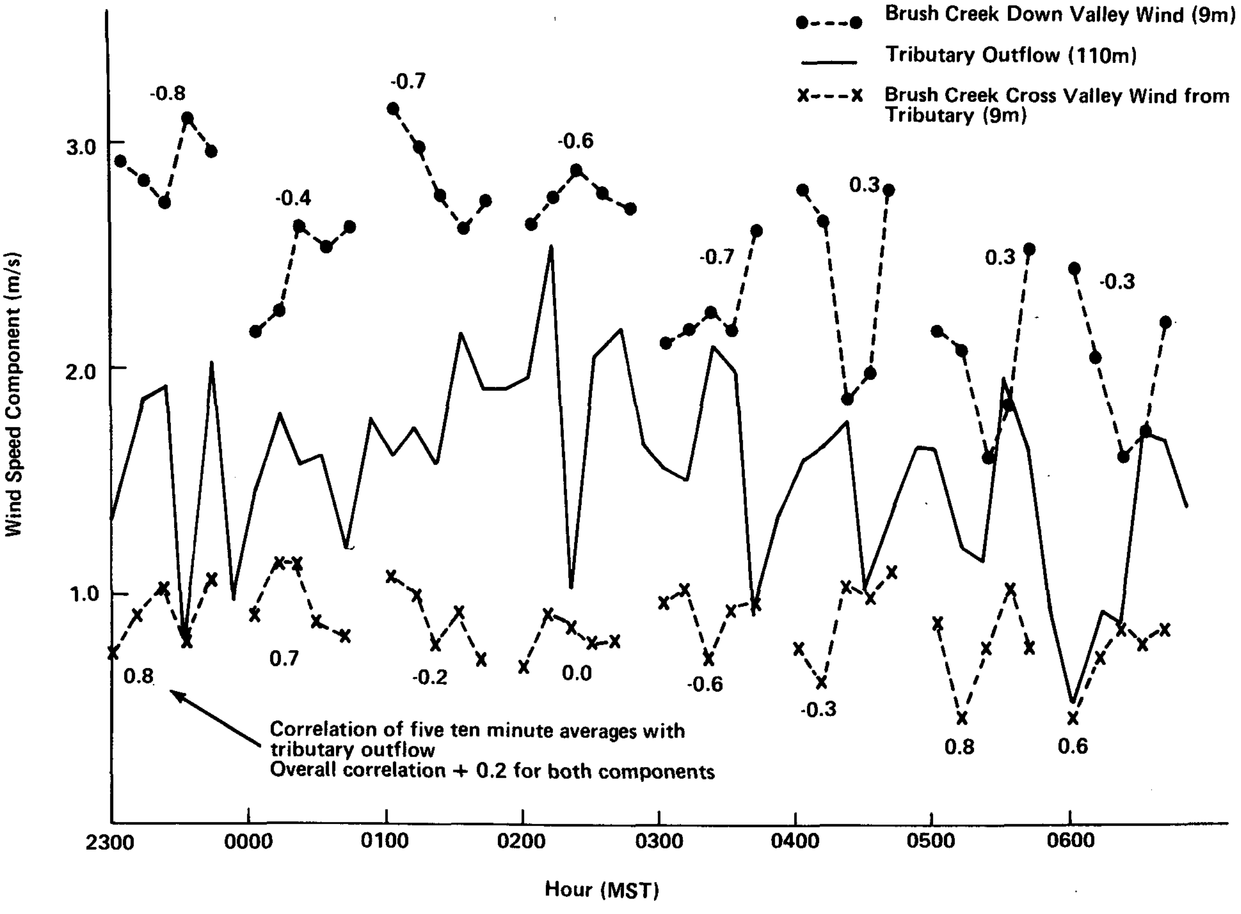

FIG. 11. Time history of the spatially averaged outflow wind speeds from Pack Canyon on 29/30 September 1984 (Path I in Fig. 5) and the down- and cross-Brush Creek flow at 9 m from a meteorological tower in the center of the valley near Pack Canyon.

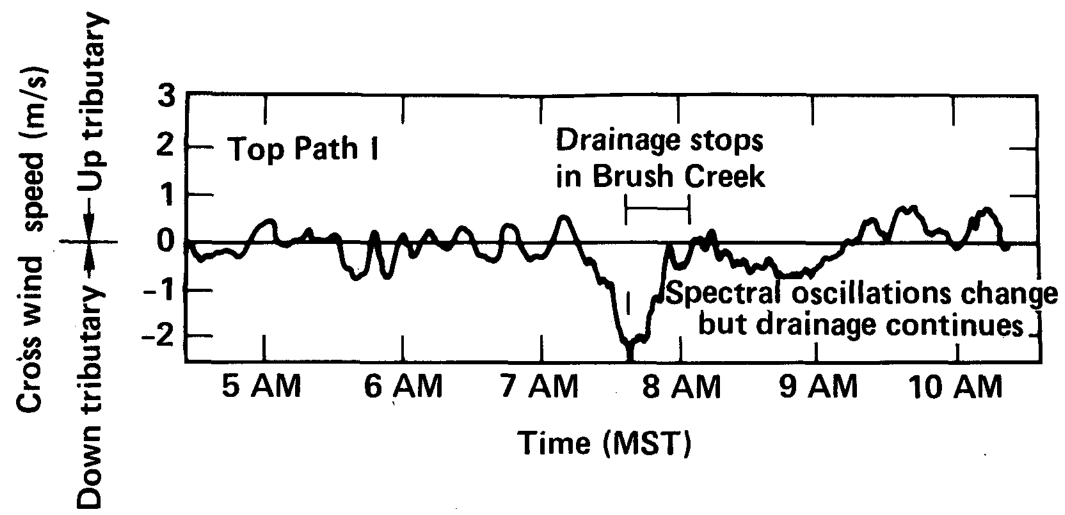

FIG. 12. Time history of the spatially averaged outflow wind speeds of Pack Canyon at 110 m (Path I) above the tributary floor during weak drainage conditions on 2/3 June 1985.

taries should dominate the exposed valley sidewall in contributing to the flow. One possibility is that ambient winds may cause the tributaries to collect a sizeable portion of the sidewall flows or even entrain air from the main valley flow. Also, the sidewalls within the tributary are more sheltered from ambient winds and the down-valley drainage flow. Also the shape of the tributaries in Brush Creek may be important from a radiant flux standpoint. The V-shaped sidewalls allow a more efficient cooling of the air volume compared to the U-shaped valley sidewalls (Kyle 1987). Also, a Mendenhall wedge (Taylor 1987) effect may occur which increases the relative emissivity through multiple reflections in the tributary area over a similar area of the ridge slope. The higher emissivity combined with the higher temperatures above the tributary than just above the ridge slopes could lead to a greater infrared radiant flux over the tributaries at night. Also, because the back of the tributary is farther from the opposite wall of Brush Creek, it can cool more effectively than the valley sidewalls which are closer. The possible importance of radiant heat transfer difference may be supported by the fact that on nights with low ambient winds the maximum flow out of this east side tributary begins almost four hours later than west wide drainage begins (corresponding to local sunset on the two sides). The tributary outflow tends to decrease after midnight (as does the main valley flow), but after sunrise on the ridge slopes, and the main valley flow has reversed from down- to up-valley, the shaded tributary continues to drain for up to two hours. Also, as the drainage flow in the Brush Creek Valley stops, the regular oscillations in the tributary flow also ceases.

Coulter et al. (1989) describe this phenomena in detail. Figure 12 shows the time history of wind flow out of Pack Canyon measured at the 110 m location above the tributary floor on 2 June 1985 taken directly from a strip chart recording. This shows the regular oscillations derived in the spectral analysis are disrupted when drainage flow in Brush Creek ceases around 0720 MST.

4. Conclusions

The major result of our study has been to show how very complicated the flow structure and interactions are between tributary, valley sidewall and main valley drainage flow. Because of this complexity, and the possibility that the results apply only to one tributary of Brush Creek Valley, the following conclusions must be considered only suggestive of a pivotal role of tributaries to mean valley flow and turbulence.

1) Several different methods of estimating the volume flow out of the tributary indicate that 5%–15% of the main valley flow can be produced by a single tributary which is not much larger than the 4 to 8 other tributaries of Brush Creek Valley. This factor of 3 uncertainty is due mainly to the spatial and temporal variability of flow in a small tributary interacting with a large valley flow.

2) There is a factor of 4 or more difference in the volume flow at the mouth of the tributary than only 300 m farther up canyon into the tributary. This indicates, when coupled with the measurements of light, shallow tributary sidewall winds, either large subsidence ($\sim$0.3 m s^{-1}) between the two locations or a nonuniform horizontal profile across the tributary at the inner tributary location.

3) The tributary and main valley flows appear to interact at a fairly regular oscillation with a period of about 16 minutes.

4) Both the tributary outflow and valley sidewall drainage component appear to be negatively correlated with the spatially averaged down-valley drainage flow.

All of the above indicate that valley sidewall and tributary flow adds mass to the valley flow initially slowing the valley flow only to accelerate the flow farther down the valley. Also, several factors seem to give the tributary the advantage over valley sidewalls in producing cold air flow at night. These factors include the topographic connection of the tributary to upper ridge slope drainage, the fact that the tributary walls are more sheltered from both synoptic and valley drainage winds, and the shape and possible radiative exposure of the tributary. This implies that, unless appropriate parameterization of tributary flows are made at sub-grid scales, numerical models which do not resolve the tributaries will incorrectly model the main valley and above ridge flows.

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