A Comparison of Nocturnal Drainage Flow in Three Tributaries*

RICHARD L. COULTER AND TIMOTHY J. MARTIN

Environmental Research Division, Argonne National Laboratory, Argonne, Illinois

WILLIAM M. PORCH

Los Alamos National Laboratory, Los Alamos, New Mexico

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ABSTRACT

The characteristics of tributary drainage flow in stable, nocturnal conditions in three closely located tributaries are compared. The orientation of the tributaries with respect to Kimball Creek, into which they drain, appears to be a controlling factor in the tributary flow. In particular, oscillations in the drainage flow are found to be weakest and drainage mass per unit area greatest in the tributary most closely aligned with the main canyon.

1. Introduction

Understanding the contribution of tributary flow to the strength, amount, and dynamics of valley drainage flow is an important goal of the Atmospheric Studies in COmplex Terrain (ASCOT) program. Studies in Brush Creek Valley, Colorado, in 1982 and 1984 (Orgill et al. 1985; Porch et al. 1989a; Coulter et al. 1989; Porch et al. 1989b) have shown that in at least one tributary (Pack Canyon) there were complex interactions between the tributary and both the main valley flow and the mesoscale flow above the valley system. Within the tributary, flow oscillations with a period of about 15 min were prevalent. In a nearby valley, similar tributary flow oscillations were associated with oscillations in the main valley flow (Porch et al. 1991). Evidence from the Brush Creek study suggests that the tributary flow includes a vertical circulation cell, oriented perpendicular to the main valley drainage, that can contribute to significant subsidence above the tributary and in turn can make a seemingly inordinate contribution from a single tributary to the total drainage mass flux of the main valley, depending upon the mesoscale wind speed and direction. These complexities of flow dynamics are usually not included in numerical models for pollutant dispersion because the scale of the interactions is less than the grid size. However, this is precisely the scale of importance when conditions in the immediate neighborhood of a potential pollutant source are of concern. For example, locating a possible source of hazardous chemicals near the head of a tributary may, under certain conditions, lead to large concentrations many kilometers away because of enhanced subsidence in that tributary and subsequent drainage with little mechanical mixing in the drainage complex.

The ASCOT campaign in 1988 was designed to evaluate the relative valley drainage as a function of valley shape and orientation to the mesoscale wind direction. A part of this campaign was devoted to the investigation of the relative importance of different tributaries to a single main valley drainage system. Several questions are apparent: Do some tributaries drain more efficiently than others? Is flow in some tributaries more turbulent than flow in others? Is periodicity a prevalent feature of all draining tributaries? How does each of these questions depend upon the height and orientation of the tributary sidewalls and the orientation of the tributary with respect to the main valley, to the prevailing mesoscale wind direction, and to the slope of the tributary relative to the main valley? Three different tributaries were studied during the experiment period (19 July 1988–1 August 1988) at different times but under similar, though not identical, conditions, in an attempt to answer some of these questions.

2. Study description

The tributary drainage study was centered around the main valley of Kimball Creek (KC), oriented east–

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Corresponding author address: Mr. Richard L. Coulter, BEM/CER, 203, Argonne National Laboratory, 9700 South Cass, Argonne, Illinois 60439.

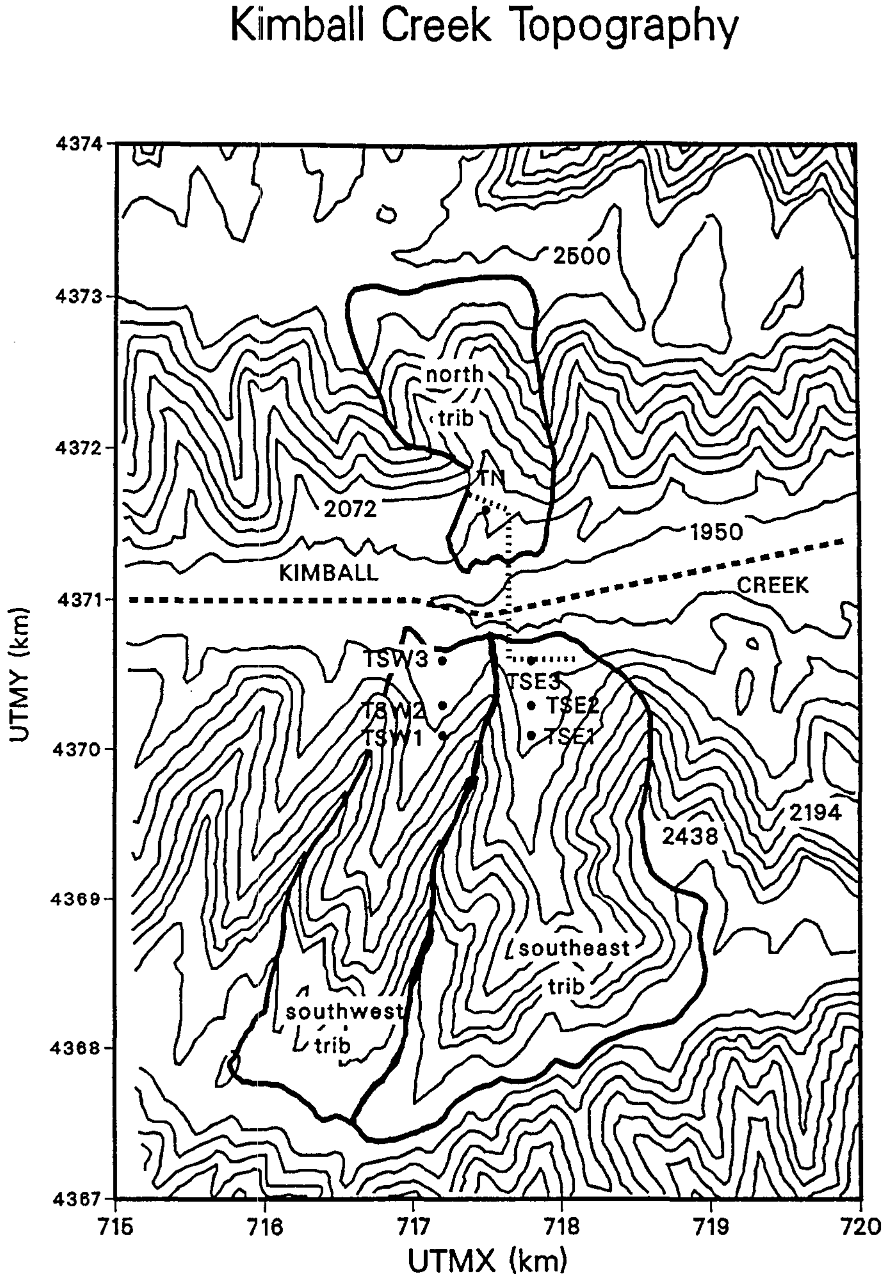

FIG. 1. Topography of the site location including instrument site locations. The location of this figure within the larger scale topography can be seen in Fig. 1 of the companion paper to this one (Porch et al. 1990). The drainage areas are outlined in thick lines; the laser anemometer paths are shown as light dotted lines across the tributary mouths and Kimball Creek. UTMX, UTMY are Universal Transverse Mercator coordinates (km east and north respectively).

west, approximately 18 km west of its confluence with Roan Creek Valley. One tributary (TN) was located to the north of KC with a drainage direction from 4° relative to true north; the second (TSE) was located to the south of KC with a drainage direction from 180°, located about 0.5 km east (downwind) of TN; the third (TSW) was also located to the south of KC, oriented at about 205°, roughly opposite TN and just west of TSE, as shown in Fig. 1. Pertinent characteristics of the tributaries are summarized in Table 1. The general dimensions are similar to those of Pack Canyon, a tributary of Brush Creek studied in 1988 (Coulter et al.

TABLE 1. Some physical characteristics of tributary and main canyon sites.

Location	Length (km)[1]		Drainage area[2] (km^2)		Slope (deg)		Aspect ratio[3]
	Rear wall	Total	Total	Upper	Lower	Upper	
TSE	1.9	3.1	4.44	0.58	6.7	—	0.67
TSW	1.5	3.0	2.76	0.41	7.3	4	0.65
TN	0.8	2.1	1.71	0.31	7.6	4	0.33
Pack Canyon	0.8	2.4	3.28	1.80	11.8	4	0.84
Kimball Creek	23.0	23.0	116.00	—	1.0	4	0.29
Brush Creek	23.0	23.0	97.00	—	1.0	4	0.13

[1] Length as measured from KC-tributary junction. Rear wall is point along centerline where slope becomes rapidly larger.
[2] Upper drainage region is above rear wall, and lower region is between rear wall and junction.
[3] Values of the ratio of tributary sidewall height to tributary width are representative only, because they vary with position.

1989). Pack Canyon was more susceptible than the KC tributaries to external influences of the mesoscale wind field during the study period, however, because its orientation (45°) was aligned more closely to the mean mesoscale wind direction and a much larger proportion of its total drainage area was located in the upper portion of the drainage, more exposed to external flow. Figure 1 shows that TSW and TN have sidewalls of approximately equal height, while TSE has higher sidewalls to the east (down KC) than to the west. Tributaries TSW and TSE share a common sidewall that extends somewhat less into KC than do the sidewalls to the west of TSW and the east of TSE. Note also the protrusion into KC from the south about 1 km east (downstream) of TSE.

Measurements of three components of the wind, temperature, and moisture at 3 m were made from towers at the mouth of each tributary. Laser anemometers pointed across the mouths of TSE and TN and across KC measured the along-canyon component of the wind (Porch et al. 1991), and a portable minisodar (Coulter and Martin 1986) measured the mean and variance of the three components of the wind at selected sites (Table 2) in each tributary. All of this instrumentation collected 1-min averages. A fourth tower in the center of KC measured 30-min averages of winds and temperature at 4 m. On 25–26 July, a tethersonde was operated near the KC tower, providing profiles of wind, temperature, and moisture every 2 h.

The minisodar is the primary data source for the results to follow; it is a small version of the instrument described by Coulter et al. (1988) and uses a single, phase-controlled, 16-element acoustic array and a lightweight enclosure, 0.75 m high, that permits rapid transport and deployment (10 min) in rugged terrain. Operation in TN was at a single location for 6 h on 21 July; during operation in the south tributaries the minisodar was moved from one location to another and operated for 1–2 h at each site (Table 2). Thus, it is necessary to use data from the other instruments that remained stationary to "normalize" and intercompare the minisodar data from site to site. Similarly, the data taken within the different tributaries with the minisodar were necessarily observed on different nights; hence, the other data sources are used to make relative assessments.

TABLE 2. Minisodar measurement times, locations, characteristics, and conditions.

Site	Location UTMX	Location UTMY	Date	Time (MST)	Height above KC (m)	Distance along KC (m)	KC drainage[1] ($m\ s^{-1}$)	Cloud cover
TSE3	717.8	4370.6	25 July 1988	2206–2359	12	156	2.9	clear
TSE2	717.8	4370.3	26 July 1988	0035–0200	25	469	3.46	clear
TSE1	717.8	4370.2	26 July 1988	0232–0336	28	614	4.0	clear
TSW3	717.2	4370.6	22 July 1988	2149–2252	12	132	—	ptly cldy
TSW3A	717.2	4370.6	28 July 1988	2056–2303	12	132	1.41	ptly cldy
TSW2	717.2	4370.3	22 July 1988	2324–0026	36	422	—	ptly cldy
TSW2A	717.2	4370.3	28 July 1988	2331–0034	36	422	2.57	clear
TSW1	717.2	4370.1	23 July 1988	0050–0210	49	578	—	ptly cldy
TSW1A	717.2	4370.1	28 July 1988	0055–0210	49	578	3.74	clear
TN	717.5	4371.6	21 July 1988	2209–0441	73	480		clear

[1] Average across-Kimball Creek laser anemometer values.

3. Discussion

The synoptic conditions throughout the measurement period (19 July–1 August 1988) were generally favorable for nocturnal drainage. The skies were generally clear, and winds were primarily westerly. Light easterly winds sometimes developed above the valleys, apparently in response to the overall terrain forcing west of the continental divide, as noted in past studies in this area (Clements et al. 1989). Toward the end of the measurement period, thunderstorm activity increased slightly.

The drainage flow in KC dominated the conditions governing measurements in the tributary. During the nights discussed here, drainage flow in KC from 270° was well developed with a depth of 300 m or more and a maximum speed of 4–8 m s^{-1} at a height of 50–100 m above the surface. Thus, the KC drainage was approximately perpendicular to the much lighter flow (1–2 m s^{-1} maximum) from the tributaries. Drainage flow in KC usually developed by 2000 MST, increased until about midnight, and remained steady until sunrise (0500 MST).

a. Mean profiles

Table 2 summarizes the conditions in KC on the nights the minisodar was operated in the tributaries. Figures 2–4 show the mean wind profiles at all the tributary sites visited, as well as the cross section of the topography perpendicular to the drainage direction at each site as viewed from the mouth of the tributary. Figure 5 illustrates the flow in and around the south tributaries as deduced from this dataset and will prove useful in the following discussions.

For the most part, the sidewalls provide effective blocking to main valley winds. Particularly in TN, the drainage flow is limited to 50 m or less by the west sidewall, above which the KC flow dominates. The upper TSE tributary flow (TSE1, TSE2) is predominantly into KC up to approximately one-half the height of the upwind (west) sidewall, above which the mean profile turns gradually to the west and even the northwest above 200 m. This is possibly in response to the very high east sidewall that prohibits westerly flow above the tributary sidewalls. At the lowest TSE site (TSE3), winds are apparently controlled by the downwind sidewall rather than the very low west sidewall. Also note that the near-surface mean wind direction at TSE1 apparently turns rapidly with height from westerly to southerly (down TSE) between the surface and 40 m; less dramatic, near-surface directional shear occurs at TSE2 and TSE3. As will be discussed below, this is misleading; the flow actually oscillates near the surface between north and south. The TSW mean flow direction on 28 July responds to the sidewalls in a similar manner, particularly at heights near and above the west sidewall, finally becoming northwest above 200 m. The large sidewall to the east of TSE and the protrusion 1 km east may well effectively prohibit direct influences of the KC flow above both TSE and TSW; instead, a small portion of the KC flow follows the larger-scale terrain features presented by the TSE east sidewall, which force a northwest direction.

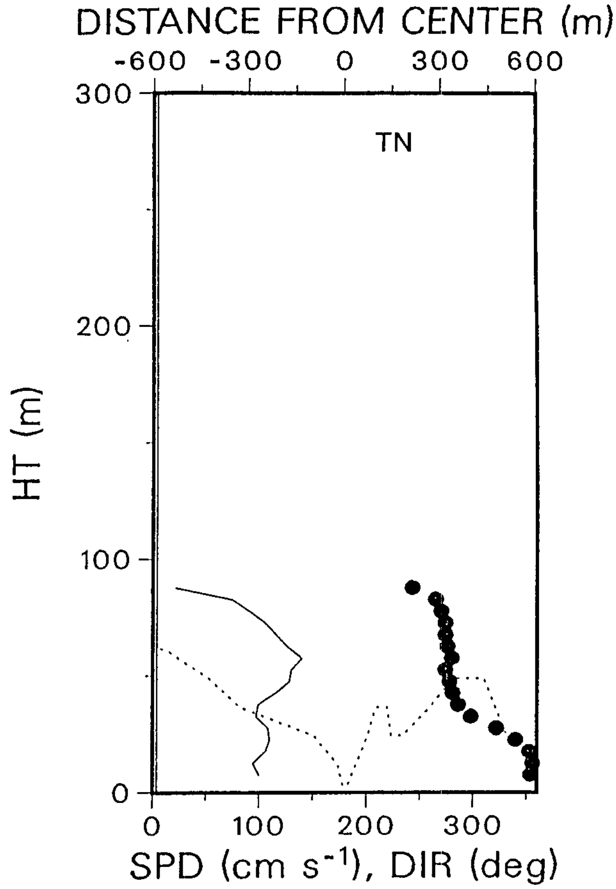

FIG. 2. Mean profiles of wind speed (solid line) and direction (dots) at north tributary (TN) over the entire period during which measurements were taken (Table 1). Cross section of topography through site as viewed from the tributary mouth is shown by the dotted line. The thin vertical (at 4°) line coincides with the tributary drainage centerline.

The TSW flow on 22 July is somewhat anomalous. A very shallow drainage layer in which the flow is steady and downslope along the tributary centerline is evident near the mouth and at TSW2 but is less than that on 28 July; however, at TSW1 the direction is very poorly defined, showing little dependence upon surrounding topography. A thin overcast on this night probably reduced drainage here. During the time of operation at TSW1 there was also a small but significant wind direction shift at the tower in KC, indicating that conditions may not have been stationary during that measurement period. On both nights in TSW, the near-

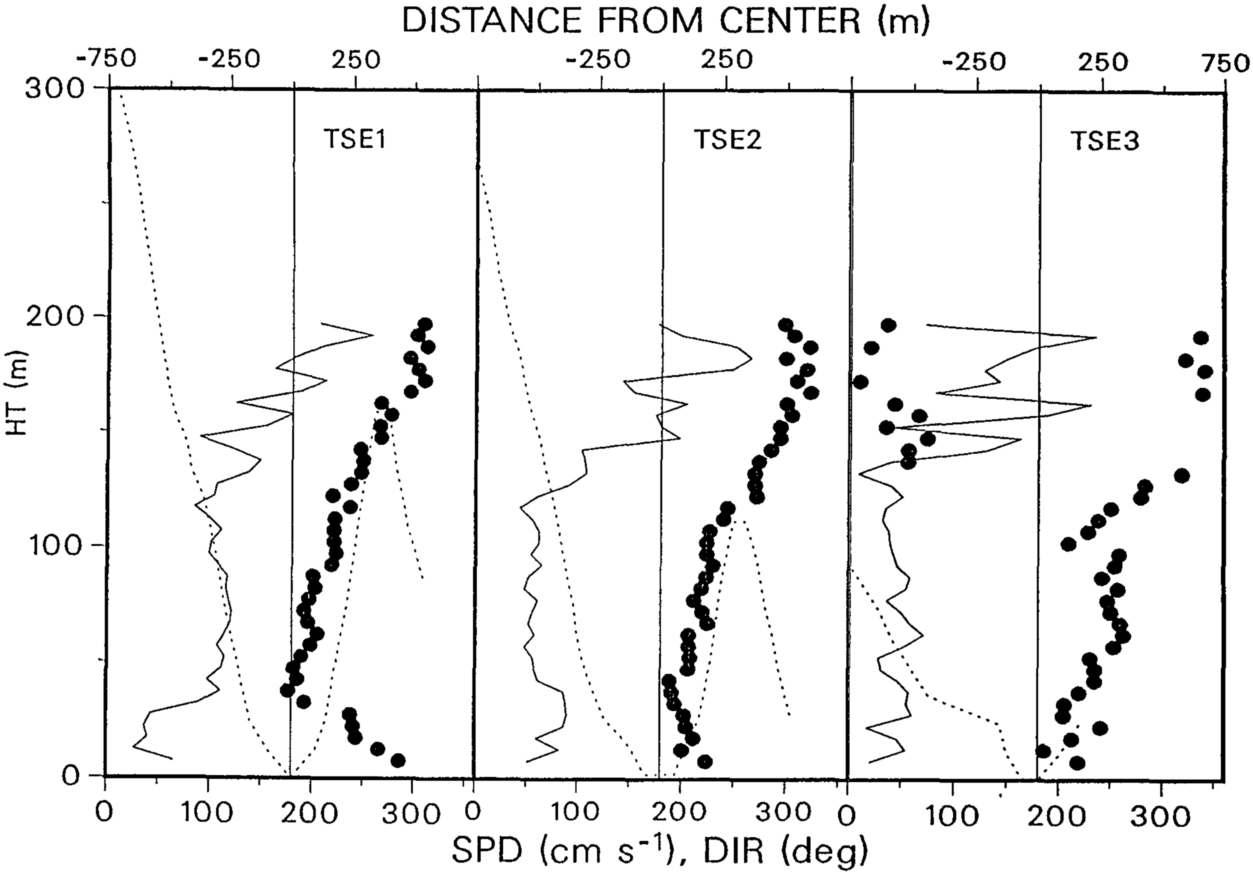

FIG. 3. As in Fig. 2 except for the southeast (TSE) tributary sites.

surface flow direction appears to respond to the local terrain within the tributary; at TSW1 and TSW2 the direction is more westerly than the drainage direction, while at TSW3 the flow tends to follow the creek (Fig. 1) and shows an easterly component.

The wind speed profiles at TSW1 and TSW2 on 28 July show a classic drainage wind profile with a maximum at about 40 m. This is in contrast to the essentially flat profiles at TSE1 and TSE2, similar to those often observed in Pack Canyon in 1984 (Coulter et al. 1988), which resulted from the oscillatory nature of the flow.

b. Periodicity

Porch et al. (1991) studied the oscillatory nature of the flow in TSE, the main valley, and the apparent interactions between them. They showed that flow from KC intrudes into and returns from TSE on a regular, 20-min basis. The distributions of turbulence and along-axis flow in TSE (Fig. 6) support this interpretation. When the KC flow begins to move into TSE, the turbulence intensity increases as the two air masses, having different temperatures, interact. During the return flow, the level of turbulence is less pronounced because mixing has reduced the differences between the two flows during the residence time of the KC air within TSE (about 20 min). Although the sodar was in TSE on only one night, the laser anemometer data indicate that this type of activity is prevalent.

The TSW tributary, on the other hand, shows little evidence of organized penetration of KC flow near the surface except possibly near TSW3 near the surface. The well-defined drainage jet and the constant mean wind direction near the surface on 28 July argue against this effect on this night; on July 22 the KC drainage was stronger and may contribute to less well-developed drainage flow in the tributary. The distributions of wind direction accumulated through selected levels in the tributaries (Figs. 7–9) support this conclusion. A single broad peak around the drainage direction in the lowest levels at TSW1 on 28 July (TSW1A) and little opposing flow (0°–80°) indicate that fluctuations exist principally from the tributary drainage direction (205°) through the local slope drainage (250°); this contrasts with a bimodal distribution between 180° and 340° at TSE1 in the lowest levels. At the middle and upper levels, TSW1 shows evidence of bimodality from the

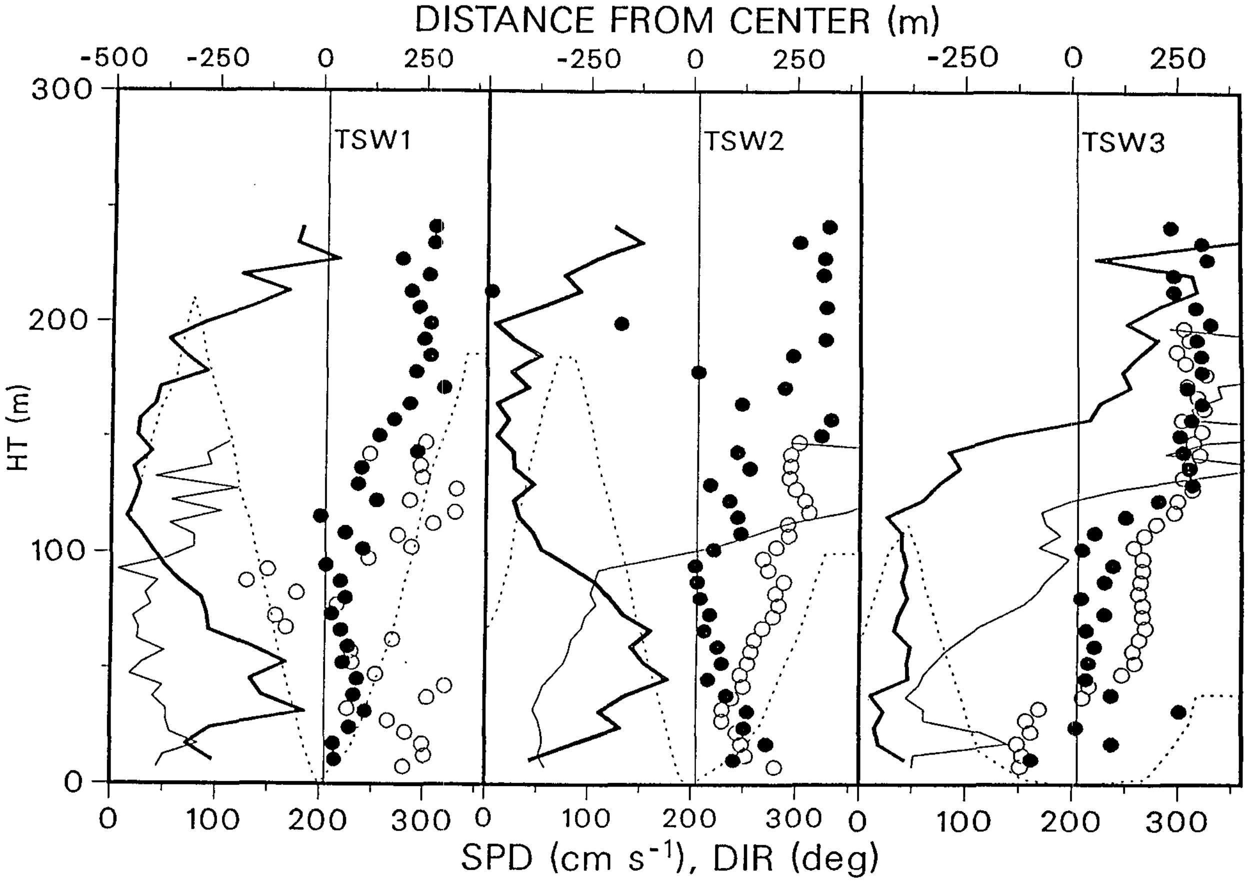

FIG. 4. As in Fig. 2 except for southwest tributary. Thick solid lines and solid dots are for 28–29 July, and thin lines and open circles are for 22–23 July.

southeast and northwest, then becomes primarily northwest above 240 m because the surrounding topography is less effective in trapping flow. The TSW2 and TSW3 sites are similar on both nights, with some counterflow in the lowest levels evident at TSW3. It should be noted that the sites nearest the tributary mouth are relatively unprotected from KC flow; thus flow is often variable and not well defined there. The bimodality in flow in the lowest levels at the TSW sites is principally a switch between drainage and KC (270°) flow. The weak southeasterly occurrences in the upper levels are apparently due to return flow from the higher east sidewall of TSW or from the much higher east sidewall of TSE, although similar directions were not observed in TSE. If oscillatory motion exists within TSW at low levels, it apparently is not very effective in penetrating a significant distance into the tributary. This may be because the orientation of TSW is more to the southwest than that of TSE, presenting additional resistance to the intrusion of the westerly KC flow or possibly to the weaker KC flow during the measurement periods.

Figure 10 shows the spectra of the drainage wind components from the tributary sites in the lowest levels. Even though the time series are of limited length (less than 2 h), the contrast between TSE and TSW at low frequencies is apparent. There is a well-defined peak at 15–30 min at all three sites in TSE; in TSW, however, only site TSW3A (28 July) shows much relative energy at these periods, again indicating that KC flow is not particularly effective in penetrating into TSW. The tower spectra confirm that 22 July was not as strongly characterized by oscillating drainage flow; although TSE shows a relative peak at 20–30 min, it is not as dominant as on 28 July.

The north tributary displays considerable energy at periods less than 20 min, even in the laser anemometer data, which is low-pass filtered by spatial-averaging effects. The minisodar velocity field in TN shows occasional occurrences of flow reversal at the lowest levels when drainage flow is replaced by KC flow from the west and KC flow above the sidewalls is replaced by TN flow from the north. In these cases the penetration occurs first near the surface and works its way to higher

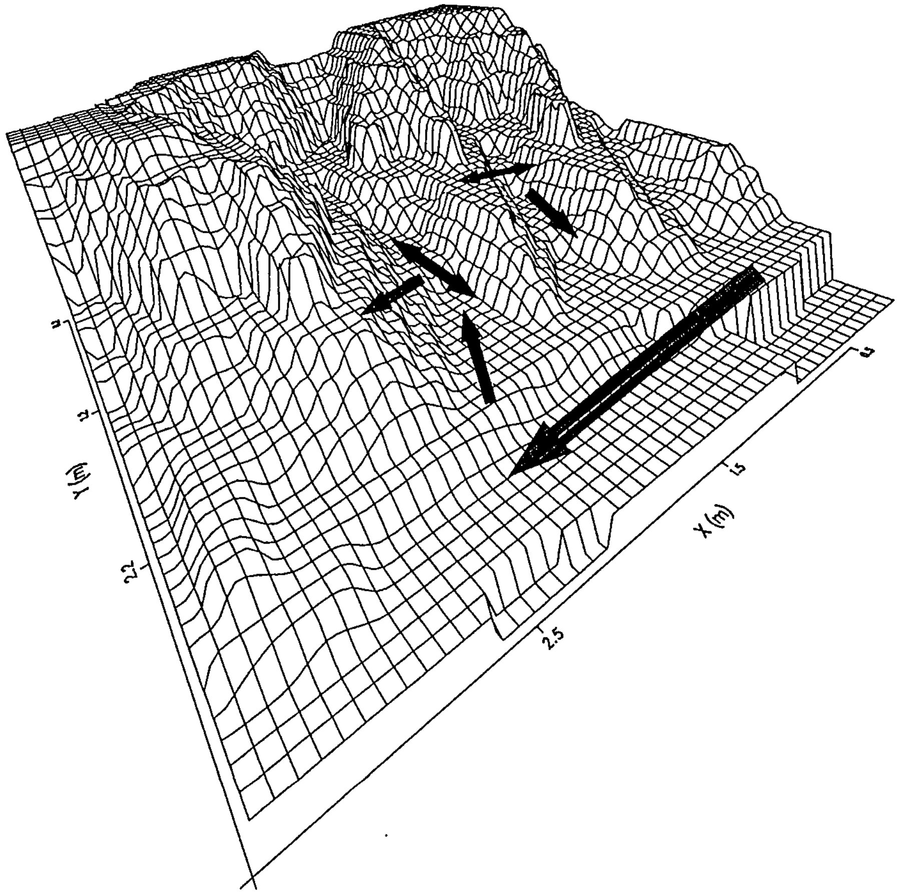

FIG. 5. Three-dimensional view of the southern tributaries and Kimball Creek as seen from the northeast and above the maximum terrain elevations. The vectors depict the flow in the region, including the strong KC flow, a presumed recirculation toward the south forced by the intrusion of terrain into KC to the east of TSE, oscillatory motion in TSE, and, primarily, drainage flow in TSW. Short east–west vectors show the flow above the sidewalls of the tributary, including entrainment out of TSE into KC.

levels. Most often, however, the periodicity is characterized by variations in the magnitude of the down-tributary flow rather than by complete flow reversal. Occurrences of easterly flow are also observed here, particularly at heights larger than half the sidewall height. Since the TN drainage is quite light and the measurement position is near the mouth of TN, an eddy flow behind the north sidewall is the most likely explanation. The KC tower data, averaged to 30 min, indicate that flow with a dominant easterly component in TN occurs during increases in the magnitude of drainage flow in KC. This would increase the magnitude of topographically induced turbulence exchange and subsequent mixing into the tributary in an eddy-like flow. Unfortunately, there are no cross-valley laser anemometer data from that night to help verify this conclusion.

c. *Mass flux*

By following the formulations of Coulter et al. (1989), the drainage mass flux M, through the plane perpendicular to the drainage direction that includes each measurement site, was calculated as

$$M = 0.75\rho \int_0^{h_0} W(z)u(z)dz, \qquad (1)$$

where h_0 is the height at which the drainage component of the wind is zero, W is the width of the canyon at height z, u is the component of the measured wind perpendicular to the measurement plane, ρ is the air density, and the 0.75 factor approximates the edge effects of the tributary (Clements et al. 1989; King 1989). Since each measurement was made at a different time,

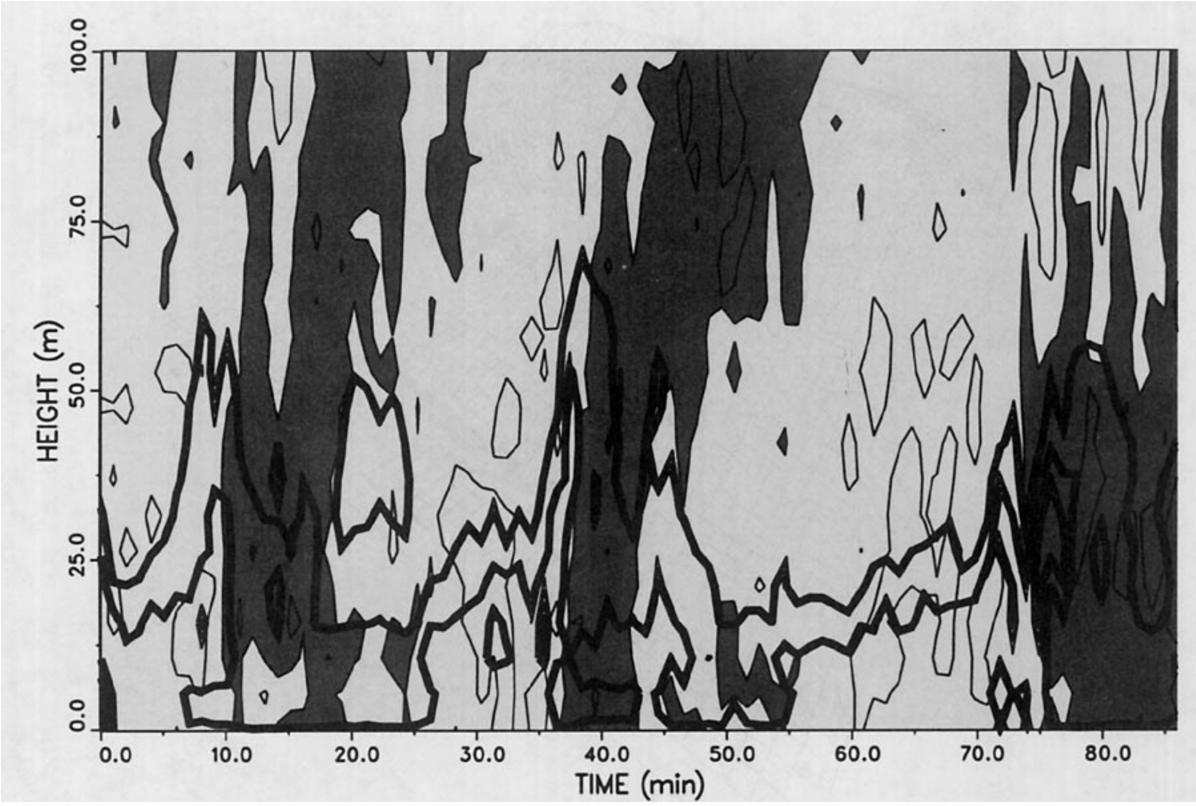

FIG. 6. Drainage component winds and overall turbulence levels as determined from sodar data at TSE1. Winds down the tributary are lightly shaded, and reverse flow up the tributary is darkly shaded. Contours of constant amplitude (thick solid lines) are separated by 200 units (relative); intervals decrease with increasing height. Note the increase in turbulence intensity just prior to and at the beginning of flow reversal.

the laser anemometer across KC was used to normalize results and permit comparisons. In spite of the observations of Porch et al. (1991) that the flow 30 m above the surface in TSE is inversely correlated with that of KC, it is reasonable, even necessary, to assume that the integrated flow in the tributaries is proportional to the long-term averaged KC flow. On 22 July, the cross-KC anemometer was inoperable, so normalizations were not performed on the data from that night; however, the KC tower measurements indicate that the magnitude of flow in KC was similar on 22 July and 28 July.

Table 3 summarizes the calculated values of mass flux at each position in the tributaries. Also listed are the calculated values of the effective drainage velocity, v_e, defined as

$$v_e = 0.75 \sum_{0}^{h_0} [U(z)W(z)\Delta z] / \sum [W(z)\Delta z]. \quad (2)$$

The height to which the summation is carried out in (2) is somewhat arbitrary, particularly for positions TSW3 and TSE3, because the tributaries have unequal height sidewalls, and the drainage flux is considerably deeper than the west sidewall. For position 3, the summation height was chosen as the lesser of the height of the east sidewall or the height at which the drainage component became negligible; for the other sites drainage was within or near the height of the west sidewall. The mass flux calculation is made over the same height range as are estimates of v_e. By comparison, a typical value of v_e in main valley drainage in Brush Creek in 1984 was about 2.3 m s^{-1}. The tributary flow is generally much deeper than might be expected; it rises above the convergence that occurs at the confluence of the tributary and the main valley in order to join the main flow, which results in diminished values of v_e that are due to the increased cross-sectional area.

Figure 11 shows the relative flux out of the tributaries as a function of position along the tributary. Values are normalized by the value closest to the mouth of the tributary, and the difference in time of measurement is accounted for by the ratio of cross-KC laser anemometer values at the respective measurement times when available (22 July values assume constant KC winds). The increase of flux in TSW as the mouth is approached indicates that its drainage is better protected from KC flow than is TSE flow; that is, the upper

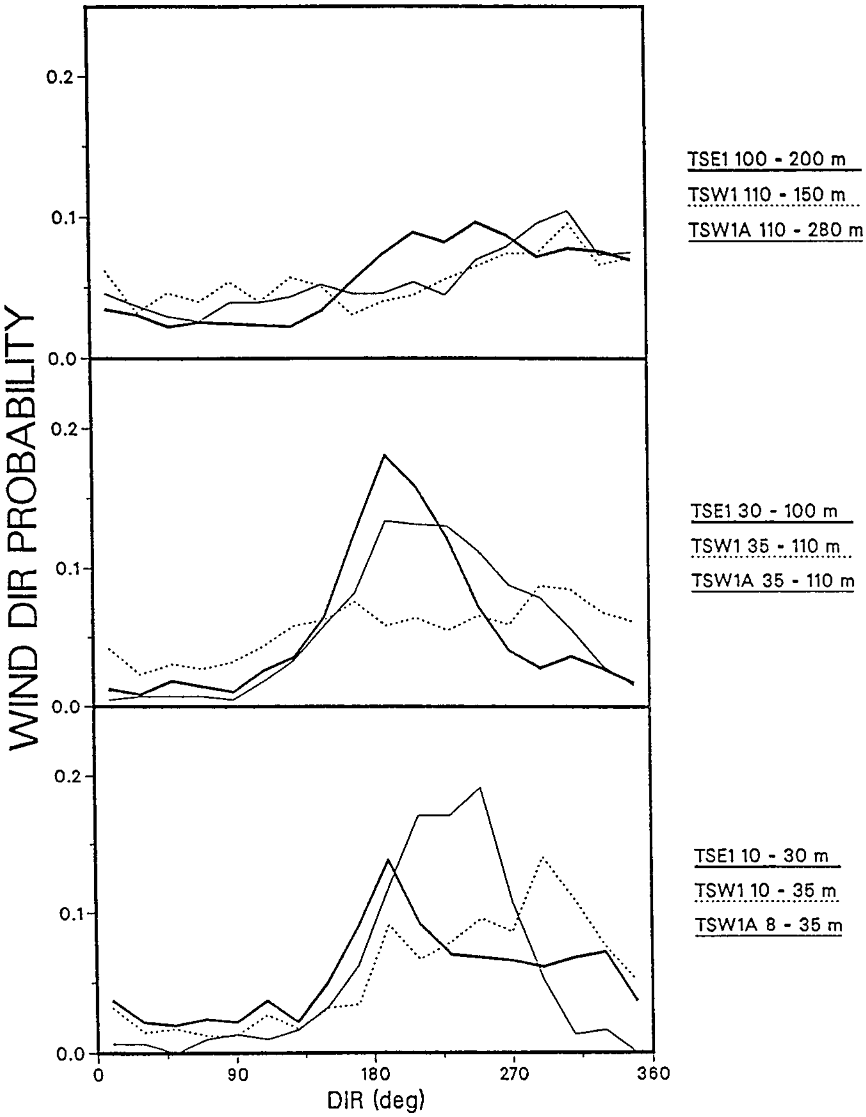

FIG. 7. Wind direction probability distribution at different height ranges for the measurement locations farthest removed from the tributary–main canyon confluence.

levels of TSE flow are entrained into KC flow and out of the tributary. The increase in flux of a factor of four as the flow approaches the mouth of TSW is similar to the increase observed in the Brush Creek tributary (Coulter et al. 1989; Porch et al. 1989b). Figures 1 and 5 indicate that TSW is slightly better "protected" from entrainment into KC flow above the sidewalls than is TSE because of its position upwind of TSE with an orientation more aligned with KC flow by about 20°. Thus, the orientation that acts against KC penetration at low levels acts to isolate it from entrainment losses at higher levels.

In order to estimate the total flux from the tributaries, one must estimate the amount of entrainment that occurs from the tributary into the main canyon flow before the drainage flow reaches the measurement site. For TSW, where these losses appear to be minimized (that is, the flux increases as the mouth of TSE is approached), the measurement point closest to KC is used and entrainment losses are estimated by differences in v_e (that is, v_e is assumed to be equal throughout if there were no entrainment). Thus

$$F_w = F_{\mathrm{TSW3}} + \rho(\Delta v_e)A, \qquad (3)$$

where F_w is the total flux, F_{TSW3} is the "measured" flux at TSW3, A is the area in the vertical plane at TSW3, and Δv_e is the difference in v_e between TSW2 and

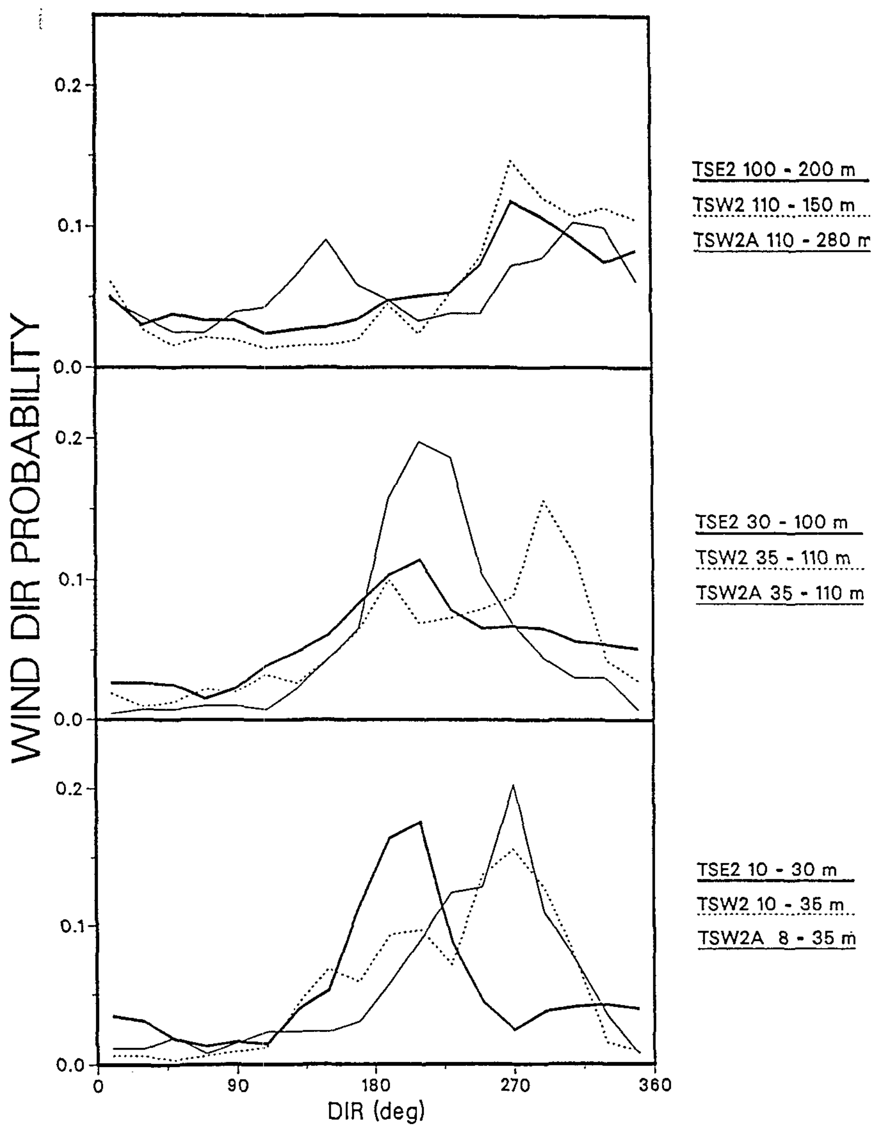

FIG. 8. As for Fig. 7, except for the middle measurement positions in tributaries.

TSW3. For TSE, on the other hand, entrainment losses into KC are considerable. Thus, site TSE1 is used as the best available site, and the surface drainage contribution between TSE1 and TSE3 must be estimated. This contribution is somewhat arbitrarily estimated as the difference in mass flux (ΔF) in the lowest 50 m between sites TSE3 and TSE1, which is equivalent to the product of the surface area (SA) of the tributary between the sites up to 50 m above the tributary centerline and a slope effective velocity (v_{se}) defined as

$$v_{se} = \rho^{-1}\Delta F(SA)^{-1}. \quad (4)$$

Values of v_{se} for the tributaries (Table 3) are generally around 0.02 m s^{-1}. The total flux in TSE is then given by

$$F_E = F_{\text{TSE1}} + \rho v_{se}(SA). \quad (5)$$

Since all the mass exiting the tributary must be replaced from above, the mean subsidence above the tributary can be calculated from the ratio of estimates of total flux from the tributaries to the total tributary drainage surface areas. These values are 1.1 cm s^{-1} for TSE and both nights of TSW and 0.12 cm s^{-1} for TN. Although the values for TSE and TSW are equal, the amount of flux per unit area from TSW on any given night is about 35% greater than from TSE because the KC drainage on 25 July was about 35% greater than that on 22 and 28 July, when TSW measurements were made, if KC drainage is proportional to the cross-KC

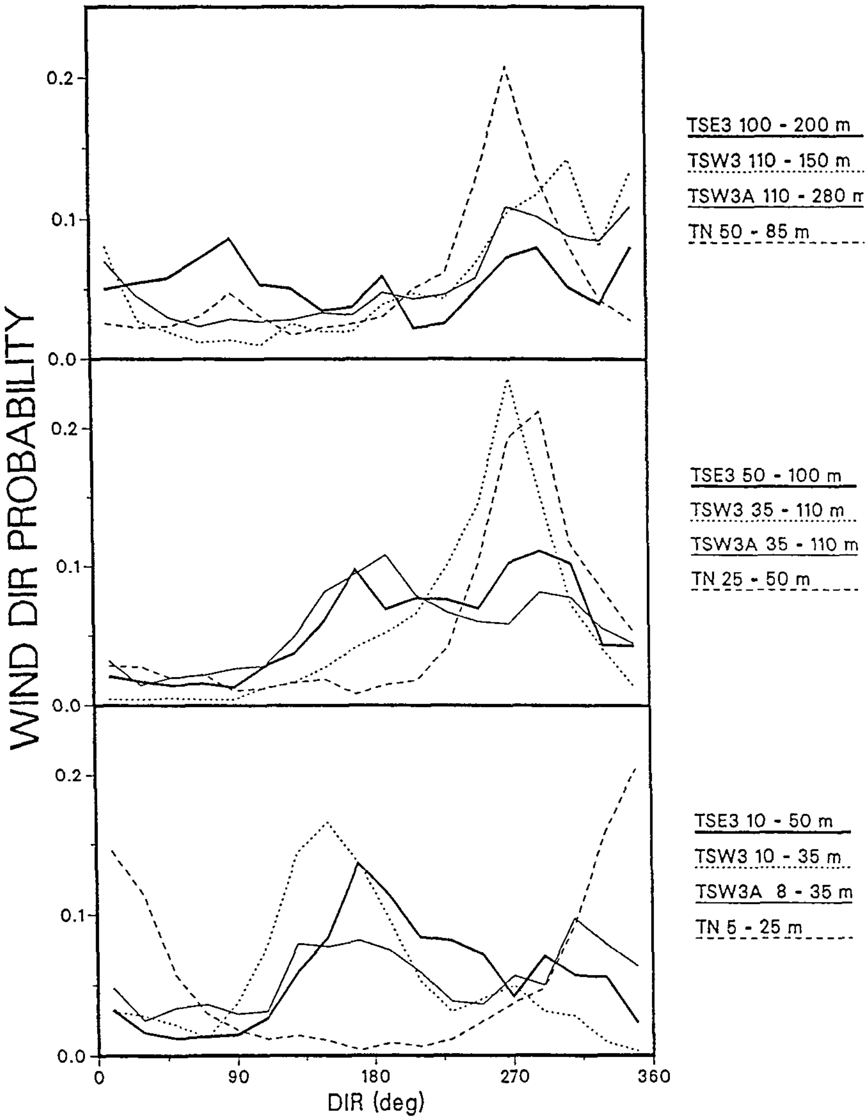

FIG. 9. As for Fig. 7, except for the measurement positions closest to tributary–main canyon confluence.

laser anemometer velocities. This result is supported by the simultaneous measurements from the towers at TSE3 and TSW3, which show that the drainage component, averaged over the measurement periods on both 25 July and 28 July, was about 25% stronger at 3 m in TSW than in TSE (24 cm s^{-1} versus 30 cm s^{-1}).

The TN tributary, on the other hand, has very small values of mass flux. However, it was not possible to estimate the amount of entrainment of flow out of TN into KC above the sidewalls because only a single site was used; this was probably significant, since the single measurement point was not very far into the tributary proper.

4. Conclusion

Tributary flow in drainage conditions is highly dependent upon the surrounding topography, its relationship to the main canyon, and local winds. Well away from the confluence of the south tributaries and KC, the drainage depth is almost as deep as the sidewalls. Closer to the mouth, however, the depth exceeds the upwind sidewall. Because of convergence of the flows in low levels, much of the drainage exits 50 m and more above the surface and is quite light.

The differing characteristics of the drainage flow in tributaries TSE and TSW are apparently considerably affected by their relative locations and orientations. The

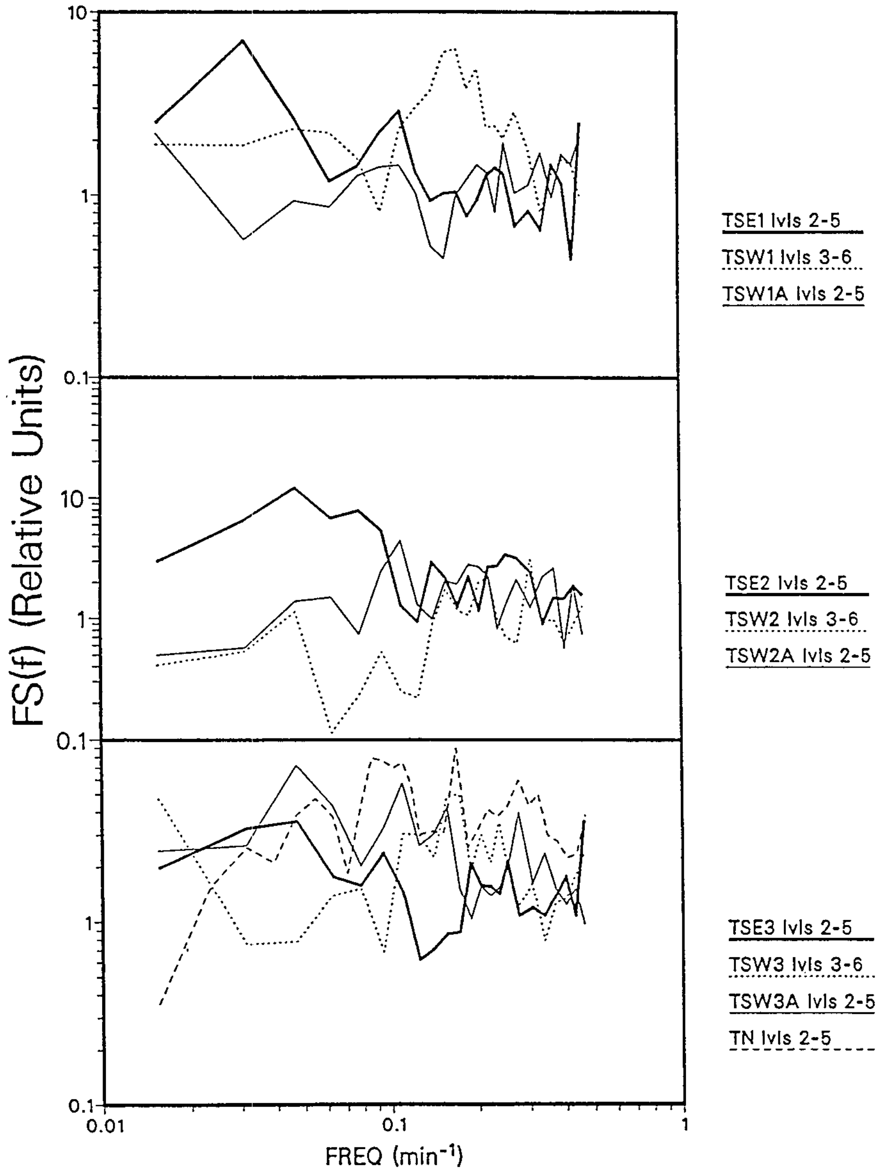

FIG. 10. Spectra of the drainage component in the lowest levels for the various locations and time periods. Locations near the confluence of tributary and main canyon are in the lowest panel, and positions farther removed from the confluence are in higher panels.

absence of significant oscillations in TSW drainage away fom the mouth on the nights investigated points to the fact that KC flow cannot penetrate as effectively into TSW as into TSE. This is probably due to the orientation of TSW 15°–20° "more parallel" to KC than TSE and possibly also to the protrusion into KC about 1 km down valley from TSE, which may force some KC flow to turn primarily toward TSE. In fact, a very weak circulation cell caused by this protrusion may lead to the southeasterly flow occasionally observed at large heights above TSW.

The observation that TSW is up to three times more efficient in draining than TSE is also possibly due to its orientation with respect to KC and the resultant relative absence of KC resistance to drainage. However, the estimates of TSE drainage do not include possible entrainment farther up the tributary than TSE3, nor was it possible to make simultaneous profile measurements in TSW and TSE to verify this conclusion.

This study has shown that seemingly small differences in topography within and near tributaries can have meaningful effects upon the transport and dispersion within nocturnal drainage flows, in part because the flows within the tributaries are so weak that they are responsive to small external influences. Although only a few of the possible variations were observed (no

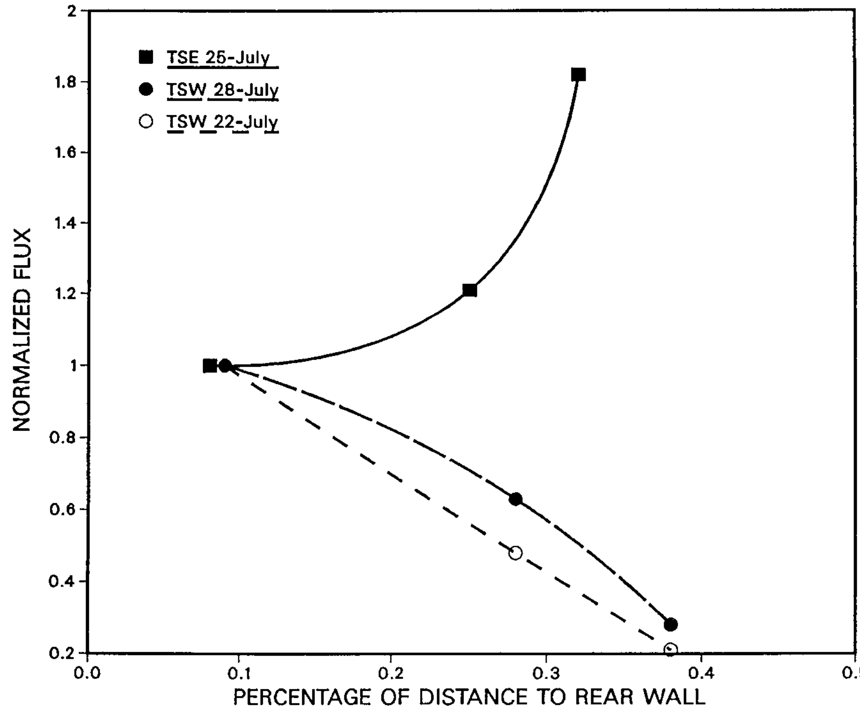

FIG 11. Values of mass flux from the tributaries as a function of position along the tributary. Values are normalized as described in the text.

counter-tributary mesoscale flow was encountered, for example), the study points to the following interesting questions:

1) What changes occur in main canyon flow in the absence of tributaries?

2) Do all tributaries within a single valley–tributary system "breathe" together; i.e., are oscillations in the tributary and main canyon in phase throughout the system?

3) How does the periodicity of flow in tributaries depend upon the relative angle of the main canyon and the tributary?

4) How does the depth of the tributary drainage flow depend upon the tributary slope and its relative angle of intersection?

TABLE 3. Characteristics of drainage at each measurement site.

Site	Drainage depth (m)	v_e (m s^{-1})	v_{se} (m s^{-1})	Mass flux[1] (mg s^{-1})	Total flux (mg s^{-1})
TSE1	165	0.63	—	78.0	—
TSE2	108	0.46	0.086	54.0	—
TSE3	94	0.50[2]	−0.019	7.8	49.0
TSW1	110	0.28	—	22.0	—
TSW2	90	0.31	0.035	23.0	—
TSW3	120	0.29	0.023	19.0	29.9
TSW1A	140	0.31	—	59.0	—
TSW2A	160	0.92	0.028	23.0	—
TSW3A	130	0.67[2]	0.008	19.0	30.6
TN	35	0.39	—	5.3	—

[1] Values are not corrected for different measurement times (see text).

[2] Values at positions near the tributary–main canyon junction are calculated by extending the depth of consideration above the top of the upwind sidewall to the height of the zero-drainage component and holding the value of the distance to the upwind sidewall constant at its maximum value.

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