Nighttime Valley Waves

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ABSTRACT

This paper describes a regular oscillation observed in nighttime drainage airflow in a valley under relatively light upper-level wind conditions. The period of these oscillations is about 20 minutes with at least one harmonic at about 10 minutes. A strong coherence between tributary flow and main valley fluctuations was observed, with the phase of the tributary flow leading the valley oscillation; this indicates the importance of tributaries as major contributors to the dynamics of cold air flow in valleys.

1. Introduction

Regular long and short period oscillations in nighttime valley flows and their effects on tracer samples have been a feature of studies performed as part of the Department of Energy's Atmospheric Studies in Complex Terrain (ASCOT) program (Clements et al. 1989). Long period oscillations were observed in a valley–basin system near The Geysers area of Northern California (Doran and Horst 1981; Porch 1982; and Neff and King 1985). These oscillations had periods of 1–2 h and were thought to result from regular oscillations in forcing winds, a seiche effect in the basin, or slope adiabatic heating effects.

Later field experiments in a deeper more isolated valley (Brush Creek, Colorado) showed higher-frequency, regular oscillations in the wind (Porch et al. 1989b; Coulter et al. 1989; and Stone and Hoard 1989). These oscillations had periods of 10–20 min and were best defined in a tributary flow entering the main valley. Possible causes of these oscillations include: 1) interaction between the tributary and main valley flows, 2) amplification in the tributaries of meandering main valley flow effects, and 3) interaction of both the tributary and main valley flows with a larger-scale flow regularity.

For the data presented here, larger-scale wind regularities cannot, at present, be ruled out as no upper-level wind data were available with the temporal resolution necessary to see 10- and 20-min oscillations. However, evidence presented in this paper favors tributary flow influences on the main valley flow rather than the reverse at higher frequencies (less than 30-min period).

There have been several prior observations of tributary–valley interactions and fluctuations. Heywood (1933) presented data from a small valley with a clear 20-min cycle in speed. Hoschele (1980) showed data revealing the influence of tributary flows deep in the Rhine Valley at night. Freytag (1987) has used measurements in the MERKUR experiments to estimate tributary contributions to the nighttime valley flow mass budget.

Evidence is accumulating that shows that, at least in some valleys, most of the cold air flowing down the valleys has entered through the tributaries (Coulter et al. 1989; and Porch et al. 1989a). This has important consequences to pollution source siting in narrow valleys (e. g., how important is it for plumes to avoid regions above tributaries?). The fact that many valley tributaries are too small for present numerical models to resolve adds to the potential importance of their systematic study. Also, regular oscillations in the range of 20 min are in the awkward time frame of being too long for parameterized diffusion but too short for most diagnostic transport models to resolve even if the data were available.

Studies of drainage flows in Brush Creek, Colorado, shown a regular 15–20 min cycle in wind flow out of a major tributary to Brush Creek Valley during well-developed drainage conditions. Towers in the main valley and optical crosswind sensors across the valley and across the tributary indicated a negative correlation between down-valley flow and flow out of the tributary. However, these instruments were not ideally placed to document this relationship.

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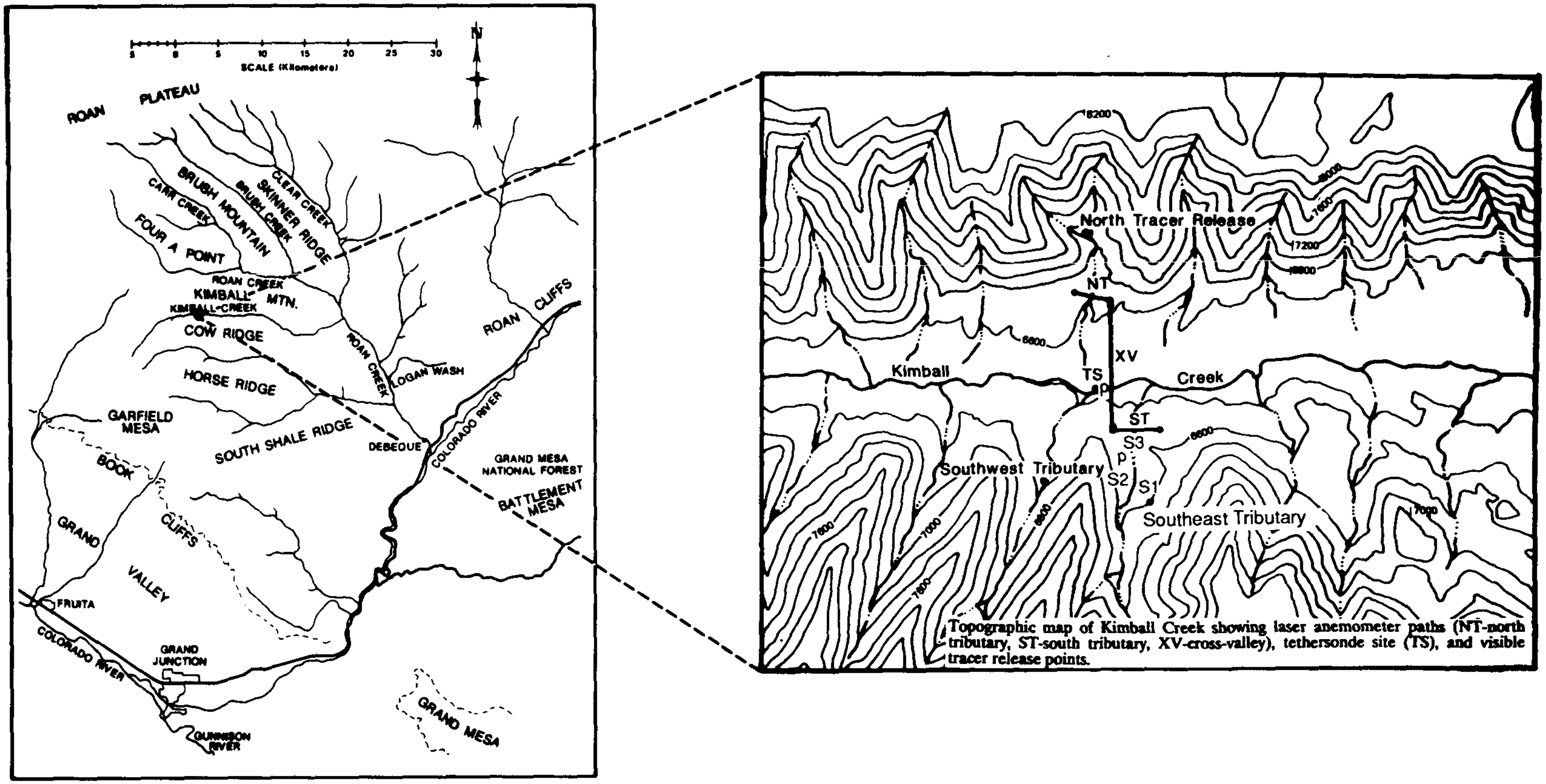


Topographic map of Kimball Creek showing laser anemometer paths (NT-north tributary, ST-south tributary, XV-cross-valley), tethersonde site (TS), and visible tracer release points.

FIG. 1. Map showing the locations of the Kimball Creek tributary experiment and the surrounding region of Western Colorado. Solid lines refer to optical cross wind sensor laser paths; TS for tethered balloon; S1, S2, and S3 for Doppler acoustic sounder locations (referred to as TSE1, TSE2, and TSE3 in Figs. 7 and 8); and P for photographic locations. The meteorological towers were located at the lowest part of the tributaries beneath the optical paths in the north and southeast tributaries, and at the solid dot indicated in the southwest tributary.

In July 1988 the study was moved to a similar valley south of Brush Creek Valley named Kimball Creek Valley (Grant et al. 1989), where enough instrumentation was collocated to determine the timing and coherence of tributary and valley flows. This experiment documented the existence of waves induced by the interaction of tributary and valley cold air flows. The use of the word "waves" in this study means regular oscillations occurring night after night with similar periods exhibiting a 90° phase between vertical velocity and temperature (i.e., an absolute vertical wind speed maximum as the temperature transitions from warm to cold and visa versa).

2. Experiment description

The instruments supporting this experiment included three optical crosswind sensors, an instrumented tethered balloon, four tower-based meteorological measurement systems, and a minisodar located as shown in Fig. 1. Data from one tower that was sited in Kimball Creek Valley are not discussed because only 30-min averages were stored. For selected periods during the experiment, the mini-Doppler acoustic sounder (Coulter et al. 1989) was operated at several locations within the tributaries. Also, on two nights smoke releases were performed for flow visualization using a full moon for illumination.

The optical crosswind sensors use a technique described by Lawrence et al. (1972). A helium–neon laser points across a valley and is received with two closely spaced sensors with the proper optical spatial filtering to allow an average wind component parallel to the valley to be calculated. The spatial weighting function for this average depends upon the distribution of optical turbulence.

For a uniform distribution of optical turbulence across the valley, the weighting function will be a smooth function that peaks at the center of the path and goes to zero at both ends. This causes the effective height of the system to correspond to slightly less than the height of the laser beam at the valley center for narrow valleys, and lower still as the valleys become wider. The effective height of the optical path has been derived from nighttime comparisons of optical crosswind sensor data with tethered balloon data in two wide valleys (Porch et al. 1988) and in a tributary to Brush Creek (Porch et al. 1989b).

The three optical crosswind sensors were deployed at nearly the same geopotential height across the valley and across two tributaries on either side (north and south) of the valley as shown in Fig. 1. The tethered balloon system was located next to Kimball Creek, near the center of the valley. Automated meteorological instruments were located on a 4-m tower near the tethered balloon system and 3-m towers in the north,

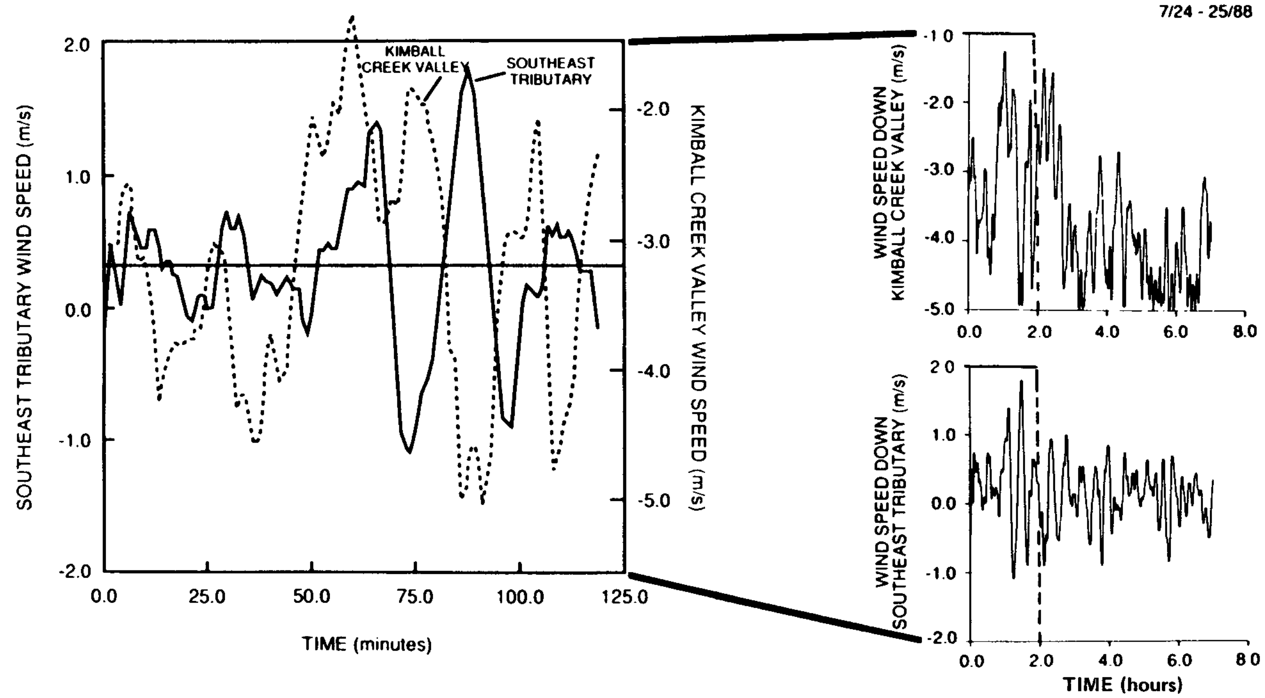


FIG. 2. Seven hours of data from 2200 to 0500 MST on the night of 24–25 July 1988 in Kimball Creek Valley during well-developed drainage for the cross-valley path and the southeast tributary with a blowup of the first two hours showing the negative correlations between the two flows.

southeast, and southwest tributaries. Data were averaged over one minute for the tributary tower and laser anemometer systems.

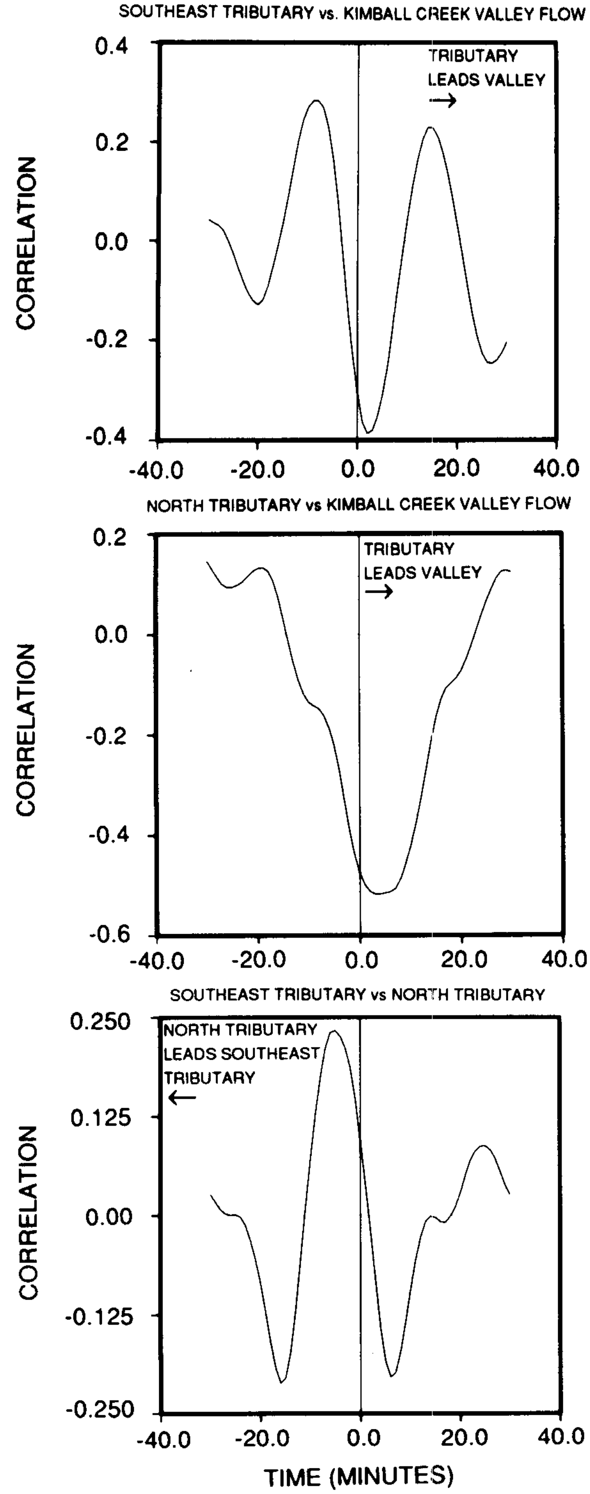


FIG. 3. Time-lagged correlations for data shown in Fig. 3.

The mini-Doppler acoustic sounder was operated on three nights in the two southern tributaries spending one to two hours at three locations (Fig. 1). The sounder was also operated at a single location on one night in the north tributary for about five hours. Data from the minisodar consisted of 1-min averages of three components of wind speed and their variances as well as the signal intensity. The minisodar was oriented on north–south, east–west axes in all cases since the North Star was used to determine the direction of one of the transmit axes.

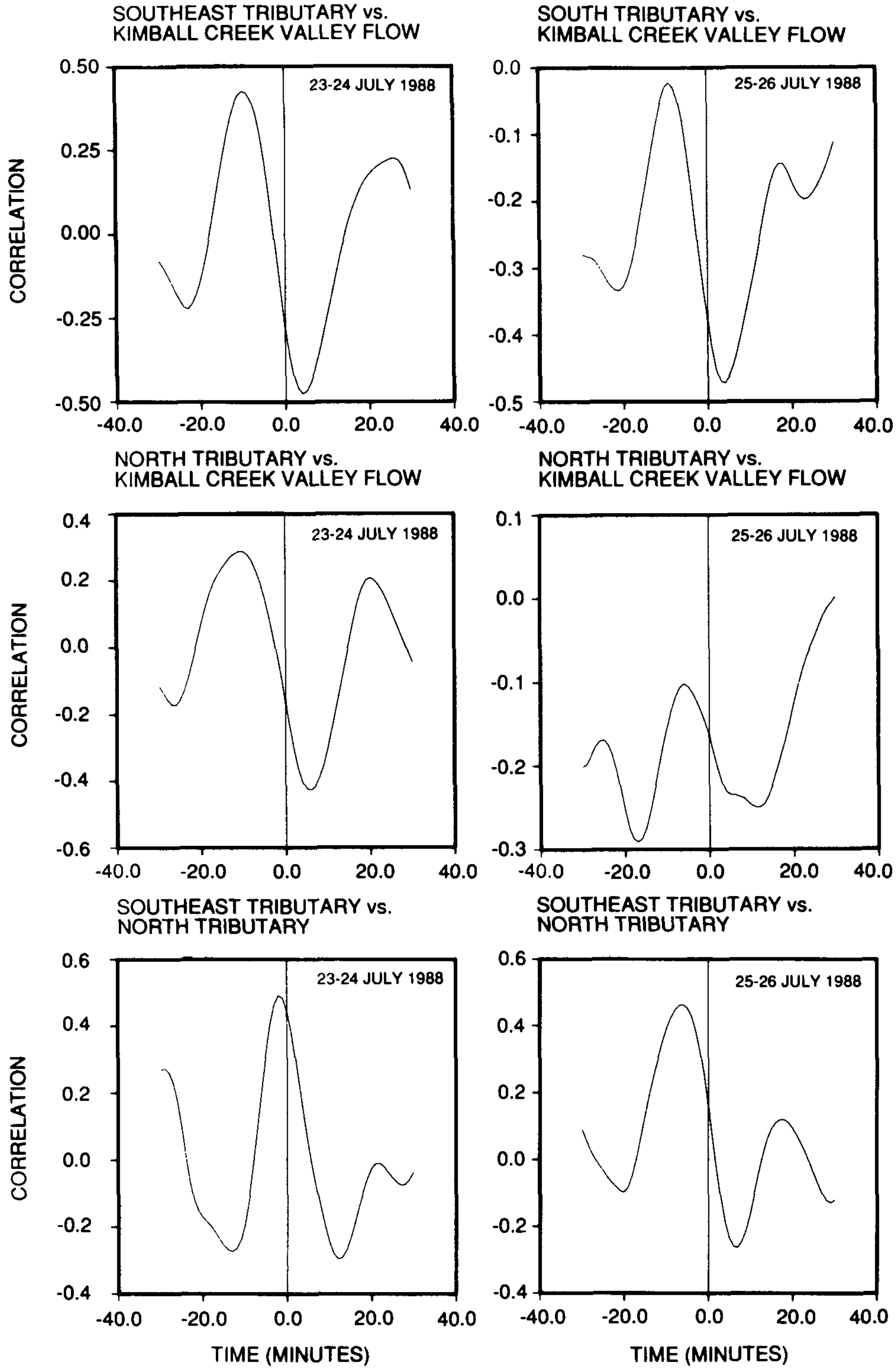
On one night when the sounder was not operating, two smoke releases were conducted in the southeast tributary. Each smoke release had about a 20-min duration. These smoke releases were photographed every minute with 30-s time-exposures using 1000 ASA film. The first smoke release was photographed at dusk, and the second was photographed at about 0200 LDT in full moonlight.

3. Results

The present results focus mainly on the optical crosswind sensor data and comparisons with the other instrument systems to provide the vertical profile of the winds. The effective height of the optical crosswind sensors (about 70 m above Kimball Creek, 30 m above the tributaries) is about the height of the maximum in the down-valley drainage jet and close to the height of maximum wind component into the tributaries from the main valley. Relative timing of changes in the valley and tributary flows determined from the laser anemometers can reveal much about the flow interactions; however, since the optical systems only provide the drainage wind component at a single effective height, the vertical profile must be estimated using other data.

Figure 2 shows a comparison of data from a time period selected from data taken of the flow out of the southeast tributary and flow down Kimball Creek Valley on the night of 24–25 July 1988. The insert illustrates the negative correlation over a combined 2-h segment illustrating the development of an obvious anticorrelation as regular oscillations develop in the flow. Examination of Fig. 2 shows an obvious regular oscillation of about a 20-min period with a higher and lower frequency modulation. The spatially averaged flow is actually slightly into the southeast tributary (about 0.1 m s^{-1}). Counter flows are common in tributaries near the height of maximum flow in the main valley (Porch et al. 1989a). Smoke releases, to be described later, showed that most of the flow out of the southeast tributary was above the laser path on a similar night.

The negative correlation between the major maxima in the down Kimball Creek Valley winds and the flow out of the two tributaries is further documented in the time-lagged correlation plots (Fig. 3). Figure 4 shows the analogous correlation functions for two other



SOUTHEAST TRIBUTARY vs. KIMBALL CREEK VALLEY FLOW

SOUTH TRIBUTARY vs. KIMBALL CREEK VALLEY FLOW

NORTH TRIBUTARY vs. KIMBALL CREEK VALLEY FLOW

NORTH TRIBUTARY vs. KIMBALL CREEK VALLEY FLOW

SOUTHEAST TRIBUTARY vs. NORTH TRIBUTARY

SOUTHEAST TRIBUTARY vs. NORTH TRIBUTARY

FIG. 4. Time-lagged correlations analogous to Fig. 3 for the previous and following nights.

nights. These figures demonstrate the night to night persistence of the observed oscillations. The negative correlation peak is not at zero time lag between the valley and the tributary; rather, the valley flow lags both the southeast and north tributary flow changes by 3–7 min. This means that the tributary flow changes precede the flow changes in the valley. This feature is consistent on three consecutive nights with weak syn-

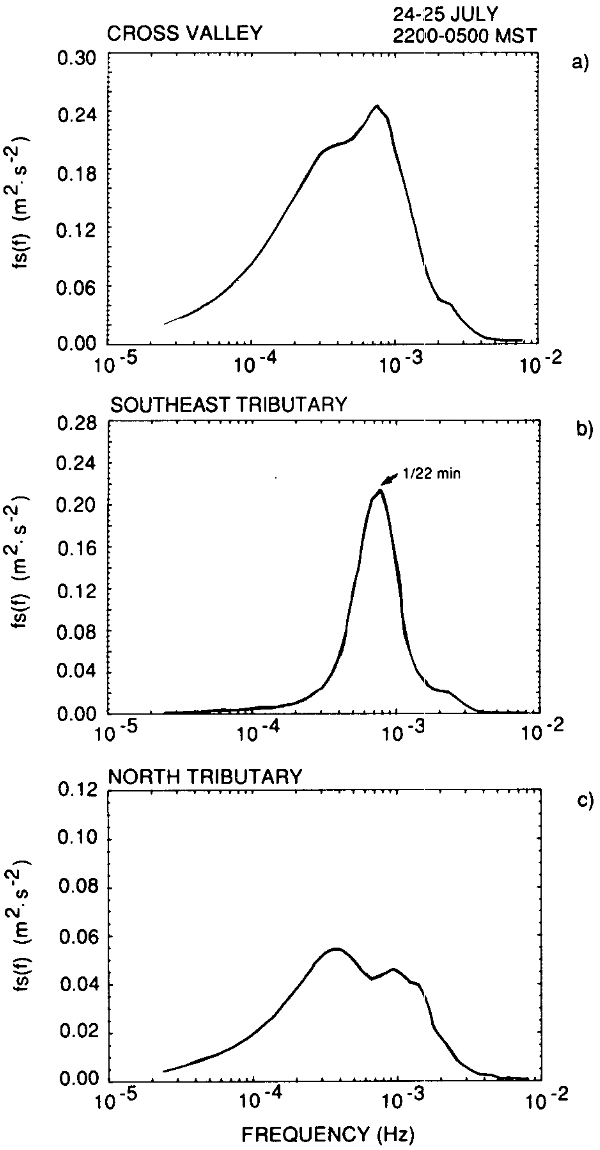


FIG. 5. Power spectra of (a) the valley, (b) the southeast tributary, and (c) the north tributary crosswind speeds (i.e. down-valley and down-tributary wind speeds) for the night of 24–25 July.

optic flows and is not attributable to data logging errors on a particular night.

The time lag for maximum correlation in Figs. 3 and 4 implies that changes occur first in the tributaries, and later in the valley flow. This is consistent with the hypothesis that cold air builds up over about a 20-min period in the tributaries and then flows into the main valley, which causes the main valley flow speed to decrease in order to conserve momentum. As will be shown later, there is also a well-documented intrusion of main-valley air into at least some of the tributaries during the other phase of the cycle.

The spectral characteristics of the valley and tributary flows in Fig. 2 are shown in Fig. 5. These spectra show that the major period of oscillation in these data is about 20 min, especially in the southeast tributary. The north tributary has significant energy at a period of 22 min but actually peaks at 18 min and at a low-frequency harmonic of about 44 min. Comparison with spectra from other nights (Porch and Clements 1990) indicates that the period of the north tributary oscillations was more variable than the southeast tributary. This may be due to its greater exposure to counter flow from the predominant southerly winds above ridgetop and its smaller size. The spatial averaging associated with laser anemometer causes frequencies in this region to be more sharply resolved by suppressing higher frequency oscillations (Porch 1982).

The valley and the north tributary wind spectra are also influenced by a long period oscillation of about a 45 min period and a harmonic of about a 10-min period oscillation. This harmonic behavior was also observed in previous measurements in a tributary to Brush Creek and seemed to be related to flows both into and out of the tributary, inhibiting flow contributions from the tributary sidewalls (Porch et al. 1989b).

Data comparisons were also made between tower and optical crosswind measurements in the tributaries. Figure 6 shows the power spectra for the optical crosswind sensors, the down-tributary component of the wind velocity measured with a cup–vane system, and the temperature from the 3-m towers in the north and southeast tributaries. The optical anemometer and tower wind speed component spectra are similar to the spectra in Fig. 5 for the same period on 24–25 July, with the exception of enhanced high-frequency oscillations at the tower. The temperature spectra, however, are quite different. The temperature spectra show a tendency to emphasize 8–12 min periods rather than the about 20-min oscillations in the wind component spectra.

Coherence between the down-tributary velocities measured by the optical anemometer and tower anemometer were significant for periods between 10 and 16 min (about 0.4). This relatively low direct correlation is consistent with comparisons of correlations between optical crosswind sensors at different heights in the same tributary (Porch et al. 1989b). The coherence between optical anemometer winds and temperature was statistically significant for the north tributary (about 0.6) and south tributaries (about 0.4) with flow out of the tributaries at the height of the crosswind sensors corresponding to lower temperatures.

Time-lagged correlation functions for the parameters measured at the 3-m towers were also analyzed (Porch and Clements 1990). The highest correlations were between the down-tributary wind component and the vertical velocity determined with horizontal and vertical propellers (correlation coefficients about 0.6 in all three tributaries). The sign of the correlation implies that as the flow moves down the tributary, the vertical

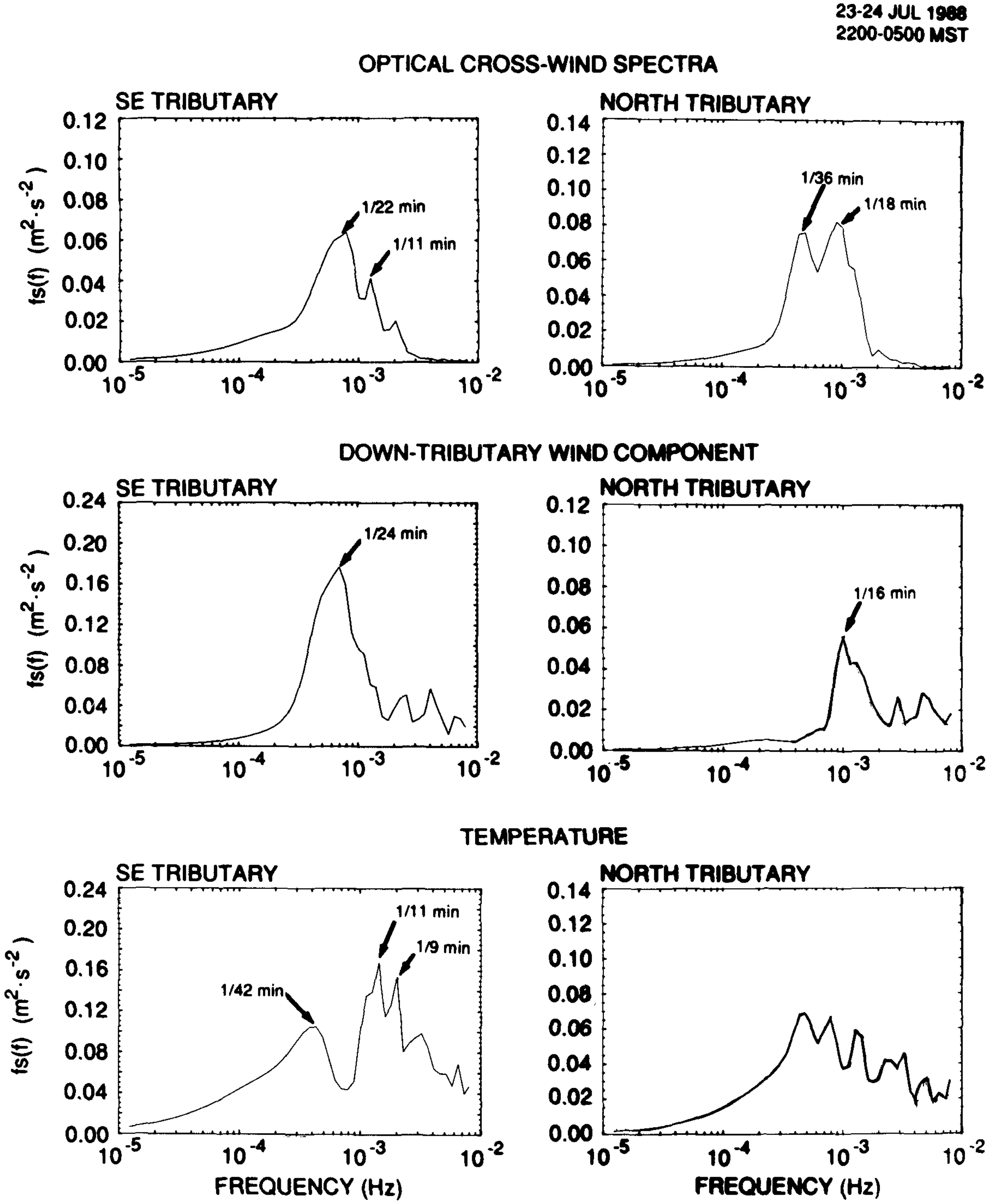


FIG. 6. Comparisons of power spectra for 420 1-min down-valley wind components derived from the optical crosswind sensors and this wind component and temperature from tributary meteorological towers between 2200 MST on 23 July and 0500 MST on 24 July 1988.

velocity is downward also, as it must if the flow follows the terrain (i.e., air going down the tributary is also going downhill).

The next highest correlations came from wind speeds and temperature comparisons within the tributaries (correlation coefficients about −0.5, implying decreasing temperatures with increasing wind speeds). The shape of the correlation functions imply that the down-tributary component of the wind changes first in the southwest tributary, and the temperature changes first

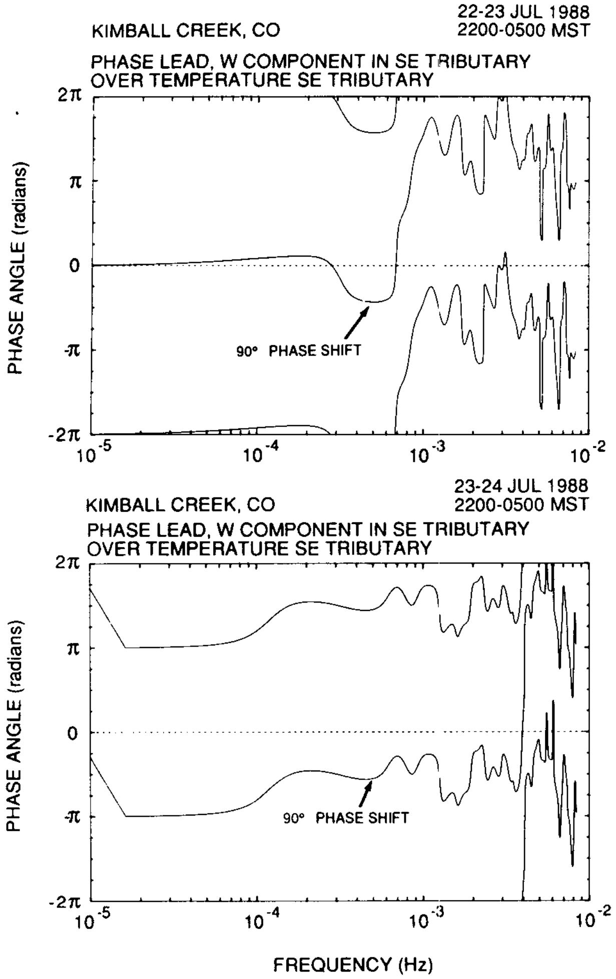


FIG. 7. Comparison of the phase spectra for vertical velocity and temperature measured at the tower in the southeast tributary on 22–23 July and 23–24 July 1988 showing the expected 90° phase shift for linear waves at frequencies near the peak in the down-tributary wind speed spectra.

in the southeast tributary. Since the southeast tributary is down valley from the southwest tributary, the temperature data lag is somewhat surprising and appears to be dominated by two or three warming events.

A similar sign difference in cospectrum (to that observed for down-tributary velocity and temperature) was observed for vertical velocity and temperature. Examination of phase differences between vertical velocity and temperature at the towers showed the expected 90° phase shift for linear waves over the complete range of periods 15–88 min for the southeast tributary (Fig. 7). The north tributary showed about a 90° phase shift in a narrow period range around 22 min and for periods longer than 55 min. The southwest tributary showed a 90° phase shift in the range 18–33 min. The coherence spectra between the down-tributary and down-valley winds peaked at a period close to 20 min on both nights shown in Fig. 7 at significant levels between 0.5 and 0.7. Comparison of the individual spectra, coherence spectra, and time-lagged correlation for the two nights shown in Fig. 7 show a consistent picture of linear waves occasionally influenced by changes in larger scale meteorological conditions (Porch and Clements 1990).

The oscillatory nature of flow out of the tributaries was also revealed in the Doppler minisodar data. The vertical time sections depicting the minisodar intensity returns on 25 July 1988 are shown in Fig. 8. During the time periods shown, the minisodar was located at positions S3 and S2 in the southeast tributary (see Fig. 1). The dominant feature in these data is the periodic occurrence of enhanced turbulence that apparently begins at, or near, the surface and works its way upward with time, penetrating as high as 100 m or more. These oscillations are more apparent near the mouth of the tributary (TSE3 or S3 in Fig. 1) than near the back (TSE2 or S2).

A possible interpretation of this activity is that enhanced turbulence is associated with the interaction of main valley and tributary flow, having different temperatures and momentum, which results in an interfacial zone of turbulent interactions and mixing. For both flow into and out of the tributary, the increased turbulence aloft follows the increase near the surface. This process is discussed in detail in Coulter et al. (1991).

The mean wind direction (Fig. 9) below 50 m varies from 270° (near the surface) to 180° (down-tributary, near 40 m). This is due to averaging of the data over 90 min and does not show that the actual motion is rarely from 270° near the surface, but rather is from either 0° or 180°. The decreasing effectiveness of penetration of the Kimball Creek Valley airflow with height causes a maximum in the down-tributary component between 30 and 50 m, above which the tributary sidewalls become a less effective shield from the Kimball Creek flow; hence, the mean wind direction begins to turn to a true 270°. The negative vertical velocity below 50 m shows that subsidence along the sloping terrain measured at the tower extends through the surface drainage wind layer.

The time-lagged correlation of the along-tributary flow at sites S1, S2, and S3 with the laser anemometer measurements above site S3 (Fig. 10) show an increasing lag in flow at positions S2 and S1 relative to position S3. The indicated lag of laser anemometer measurements at S3 with respect to sodar values is due either to the difference in operating times of the instruments (since no time synchronization was performed) or to the line averaging characteristics of measurements with the laser anemometer. The flow along the tributary center quite possibly leads the flow along the edges because of frictional effects. This would also explain the smaller magnitudes of flow observed by the laser

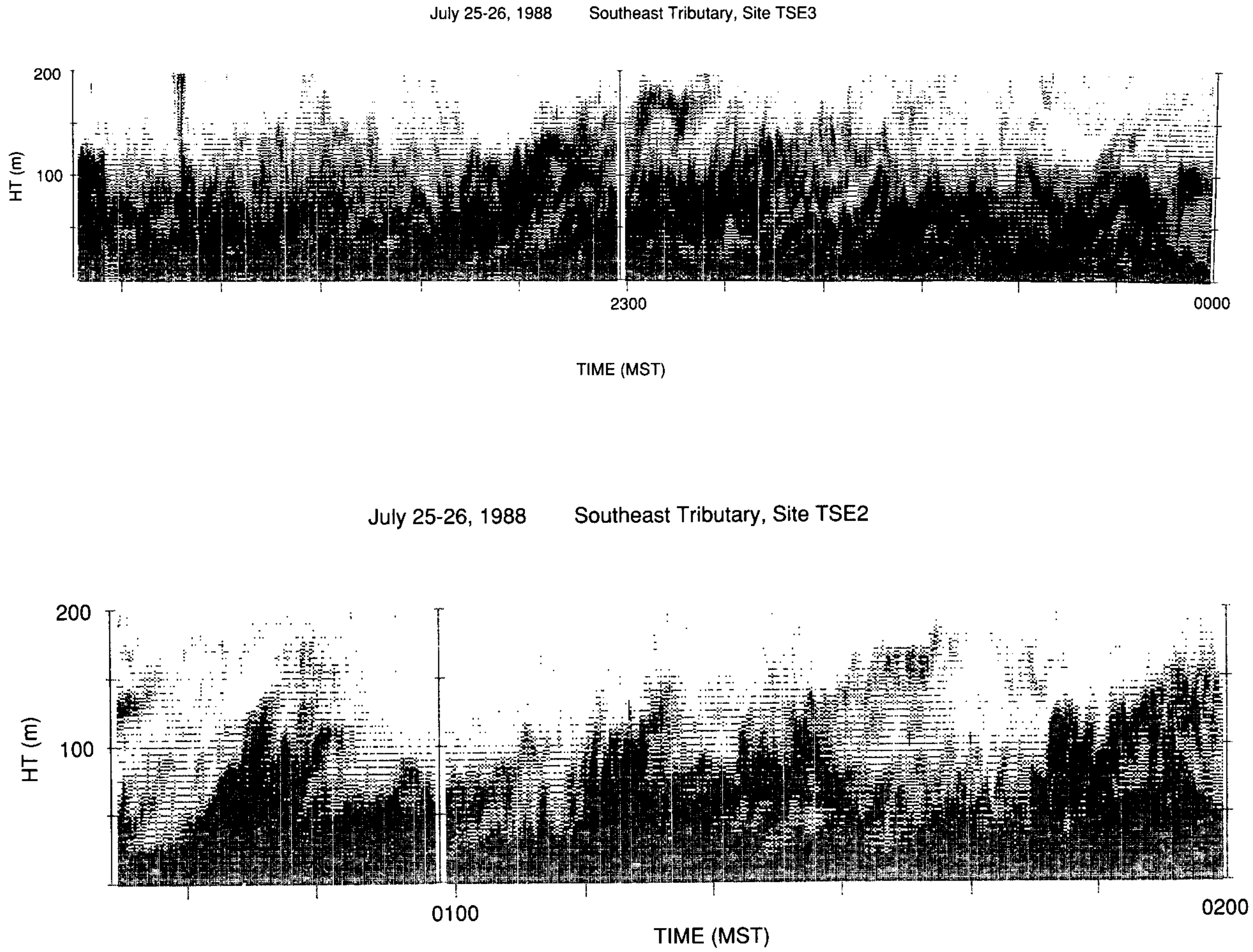


FIG. 8. Analog acoustic turbulence plots for 25 July showing the wave structure of turbulence in the southeast tributary.

anemometer compared to the minisodar or tower measurements.

The size of the lag at position S1 and S2 would correspond to a wave speed of about 0.8–1.0 m s^{-1} compared with a maximum wind speed measured of about 1–2 m s^{-1} within the wave. Site S3 leads the upper tributary sites in flow both up and down the tributary. This supports the idea that the wave penetration is not a case of isolated "blobs" of air penetrating into the tributary and then returning after a change of kinetic energy into potential energy. Rather, the motion within much of the tributary near the surface is controlled by the interactions at the confluence of the tributary and main valley.

The oscillations revealed in the minisodar data are supported by nighttime photographs of smoke releases. The time evolution of a single oscillation is shown in Fig. 11. These photographs were taken at two locations shown in Fig. 1 (marked P). The photographs on the left-hand side were taken from the location on the west side of the southeast tributary. The photographs on the right of Fig. 11 were taken from the valley location near the tethered balloon site. The photographs from the tributary's west side show that the smoke initially flowed smoothly in a shallow plume that closely followed the tributary floor. The photographs at 0204 and 0208 MDT show that this flow then lifted and flowed out the east side of the tributary (the camera angle moved from the source to the tributary exit). The photograph at 0212 MDT shows that the flow was blocked by air moving into the tributary. The photographs from the valley show the smoke flowing smoothly out the east side of the tributary until about 0212 MDT, and then building again through 0219 MDT. The smoke release ceased at about 0220 MDT.

4. Conclusions

This paper shows that, at least in the valley studied, low-frequency oscillations are a consistent characteristic of well-developed nighttime valley drainage flows. The period of these oscillations is about 20 min with higher- and lower-frequency harmonics of about 10-

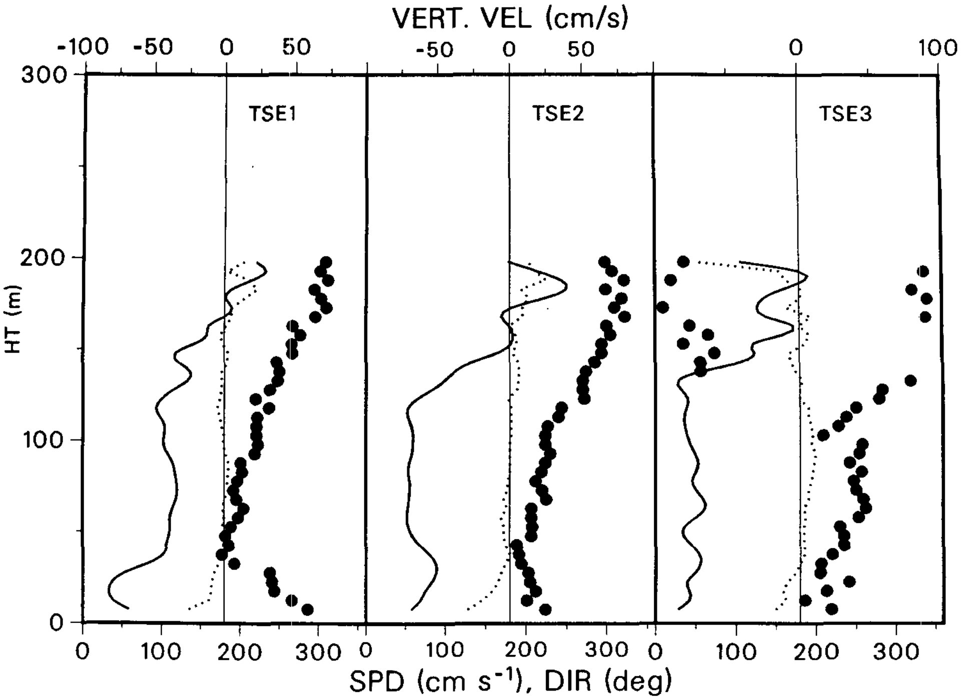


FIG. 9. Vertical profiles of horizontal wind speed (solid line), vertical wind speed (small dotted line), and wind direction (large dotted line) for the same period as Fig. 8 derived from the mini-sodar.

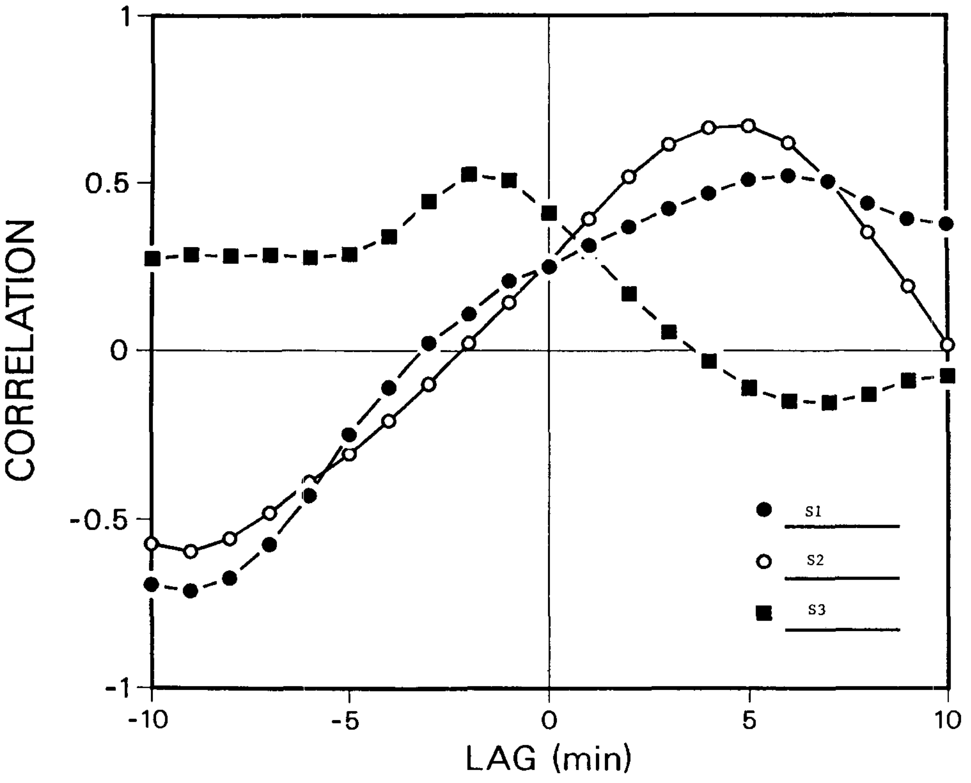


FIG. 10. Time-lagged correlation plots comparing the mini-sodar and the optical crosswind sensor at approximately the same height.

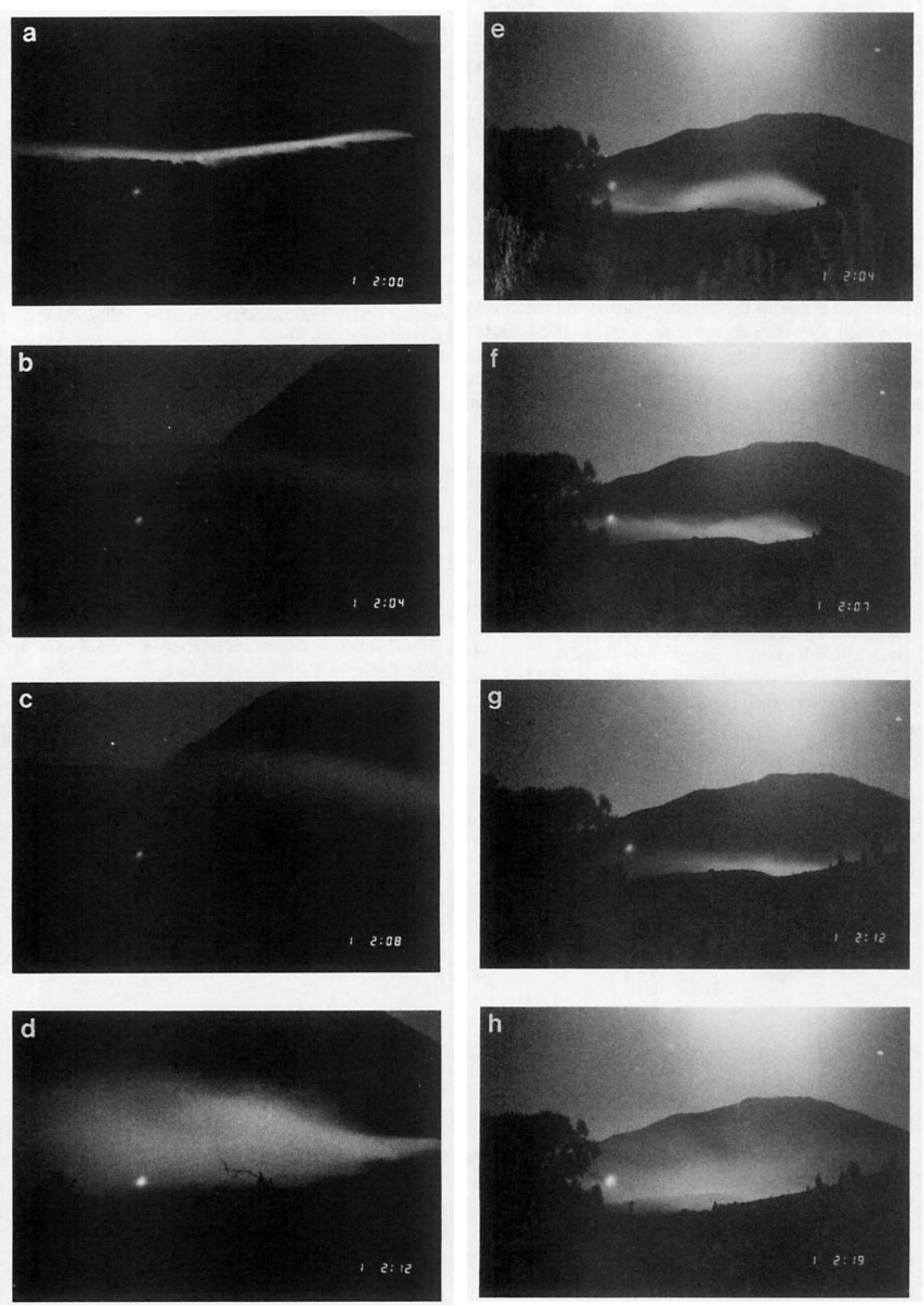


FIG. 11. Consecutive nighttime photographs taken from the photographic location on the west side of the tributary (left side photographs) and in the valley near the tethered balloon site (right side photographs). These photographs were of a smoke release on 1 August 1988 in the southeast tributary. The times on the photographs are in Mountain Daylight Time (MDT).

and 40-min periods, respectively. The timing of these oscillations indicates that the valley oscillation is being modulated by periodic flow out of the tributary. The flow down the valley decreases in a layer corresponding to the outflow height of the tributary flow. This leads to a negative correlation of flow down the valley and flow out of the tributary.

These data are consistent with the hypothesis that cold airflow out of the tributary is blocked by cold airflow down the main valley. After the cold air accumulates, it eventually surges out into the main valley. Conservation of momentum requires that the increased mass of cold air from the tributary slows the main valley flow, which allows even more flow out of the tributary. A better understanding of this process will be needed in the future before the effect of tributaries on drainage flow and dispersion can be parameterized in numerical models.

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REFERENCES

Clements, W. E., J. A. Archuleta and P. H. Gudiksen, 1989: Experimental design of the 1984 ASCOT field study. *J. Appl. Meteorol.*, **28,** 405–413.

Coulter, R. L., M. Oriel and W. Porch, 1989: Tributary fluxes into Brush Creek Valley. *J. Appl. Meteorol.*, **28,** 555–568.

——, T. Martin and W. M. Porch, 1991: A comparison of three tributary in nocturnal drainage flow conditions. *J. Appl. Meteor.*, **30,** 157–169.

Doran, J. C., and T. W. Horst, 1981: Velocity and temperature oscillations in drainage winds. *J. Appl. Meteorol.*, **20,** 361–364.

Freytag, C., 1987: Results from the MERKUR experiment: mass budget and vertical motions in a large valley during mountain and valley wind. *Meteor. Atmos. Phys.*, **37,** 129–140.

Grant, T. A., J. A. Archuleta, W. E. Clements, D. E. Hoard and W. M. Porch, 1989: Atmospheric data collected by Los Alamos national laboratory during the 1988 ASCOT field study. LA-UR-89-901, ASCOT-89-1, Los Alamos National Laboratory, Los Alamos, NM, 187 pp.

Heywood, G. S. P., 1933: Katabatic winds in a valley. *Quart. J. Roy. Meteor. Soc.*, **59,** 47–58.

Hoschele, K., 1980: Influence of characteristic terrain structures on the flow on the eastern edge of the Upper Rhine Valley. *Ann. Meteor., N. F.*, **16,** 72–74.

Lawrence, R. S., G. R. Ochs and S. F. Clifford, 1972: Use of scintillations to measure average wind across a light beam. *App. Opt.*, **11,** 239–243.

Neff, W. D., and C. W. King, 1985: Studies of complex terrain flows using acoustic remote sensors. ASCOT 85-1, Lawrence Livermore National Laboratory, Livermore, CA.

Porch, W. M., 1982: Implications of spatial averaging in complex terrain wind studies. *J. Appl. Meteorol.*, **21,** 1258–1265.

——, and W. E. Clements, 1990: The ASCOT 1988 valley–tributary interaction study. LA-UR-90-53, ASCOT-90-1, Los Alamos National Laboratory, Los Alamos, NM, 34pp.

——, W. D. Neff and C. W. King, 1988: Comparisons of meteorological structure parameters in complex terrain using optical and acoustical techniques. *Appl. Opt.*, **27,** 2222–2228.

——, S. Barr, W. E. Clements, J. A. Archuleta, A. B. Fernandez, C. W. King, W. D. Neff and R. P. Hosker, 1989a: Smoke flow visualization in a tributary of a deep valley. *Bull. Amer. Meteor. Soc.*, **70,** 30–35.

——, R. Fritz, R. L. Coulter and P. H. Gudiksen, 1989b: Tributary, valley, and sidewall air flow interactions in a deep valley. *J. Appl. Meteor.*, **28,** 578–589.

Stone, G. L., and D. E. Hoard, 1989: Low-frequency velocity and temperature fluctuations in katabatic valley flows. *J. Appl. Meteor.*, **28,** 477–488.