Morning Transition Tracer Experiments in a Deep Narrow Valley

C. DAVID WHITEMAN

Pacific Northwest Laboratory, Richland, Washington

(Manuscript received 11 April 1988, in final form 24 June 1988)

ABSTRACT

Three sulfur hexafluoride atmospheric tracer experiments were conducted during the post-sunrise temperature inversion breakup period in the deep, narrow Brush Creek Valley of Colorado. Experiments were conducted under clear, undisturbed weather conditions.

A continuous elevated tracer plume was produced along the axis of the valley before sunrise and the behavior of the plume during the inversion breakup period was detected down-valley from the release point using an array of radio-controlled sequential bag samplers, a vertical SF_6 profiling system carried on a tethered balloon, two portable gas chromatographs operated on a sidewall of the valley, and a continuous real-time SF_6 monitor operated from a research aircraft. Supporting meteorological data came primarily from tethered balloon profilers.

The nocturnal elevated plume was carried and diffused in down-valley flows. After sunrise, convective boundary layers grew upward from the sunlit valley surfaces, fumigating the elevated plume onto the valley floor and sidewalls. Upslope flow developed in the growing convective boundary layers, carrying fumigated SF_6 up the sidewalls and causing a compensating subsidence over the valley center. High post-sunrise SF_6 concentrations were experienced on the northeast-facing sidewall of the northwest–southeast oriented valley as a result of cross-valley flow, which developed due to differential solar heating of the sidewalls. Reversal of the down-valley wind system brought air with lower SF_6 concentrations into the lower valley.

1. Introduction

Three atmospheric tracer experiments were conducted in the Brush Creek Valley of western Colorado in the summer of 1982 to obtain data to evaluate parameterizations of physical mechanisms in the VALMET model (Whiteman and Allwine 1985). The development of VALMET, a valley air pollution model, and the tracer experiments were part of the U.S. Environmental Protection Agency's complex terrain program. The field study was conducted in conjunction with the U.S. Department of Energy's Atmospheric Studies in Complex Terrain (ASCOT) program. The experiments were designed to determine how nighttime tracer concentrations on the valley floor and sidewalls, down-valley from an elevated continuous point source, would change following sunrise during the temperature inversion breakup period. The temperature inversion breakup period was known from earlier experiments (e.g., Hewson and Gill 1944) to be a critical time of day when fumigations could produce high pollutant concentrations on the valley floor and sidewalls. Earlier experiments dealing with atmospheric tracer investigations in deep valleys during the morning inversion breakup period have been described by Sivertsen et al. (1983) and Willson et al. (1983).

Tracer release parameters (time period of release, release elevation, and release rate) and the choice and placement of meteorological and tracer sampling equipment were determined from VALMET model simulations. Because the model was developed for use on a valley cross section down-valley of an elevated source, the main instrumentation was located on a single valley cross section. Tethersondes were used to observe convective boundary layer (CBL) growth over the valley floor and one sidewall, the development of an upslope flow over one sidewall, and subsidence over the valley center (by observing the sinking of the inversion top), and to determine the wind speed at the tracer release elevation. A balloon-borne SF_6 sampling device was used to observe the elevated nocturnal plume and its change of position with time after sunrise. A network of sequential bag samplers located primarily on a single valley cross section, was utilized to determine how mean SF_6 concentrations would change with time on the valley floor and sidewalls during the inversion breakup period. Two manually operated gas chromatographs were located on one sidewall to determine details of the time evolution of SF_6 concentrations during the fumigation period. Finally, a Cessna 411 research aircraft was flown in and above the valley to determine if SF_6 would be carried up the slopes and into the above ridgetop flows late in the inversion breakup period. A comprehensive report on the tracer and meteorological data collected during the tracer experiments has been published by Whiteman et al. (1984).

Corresponding author address: Dr. C. David Whiteman, Battelle Pacific Northwest Laboratory, P.O. Box 999, Richland, WA 99352.

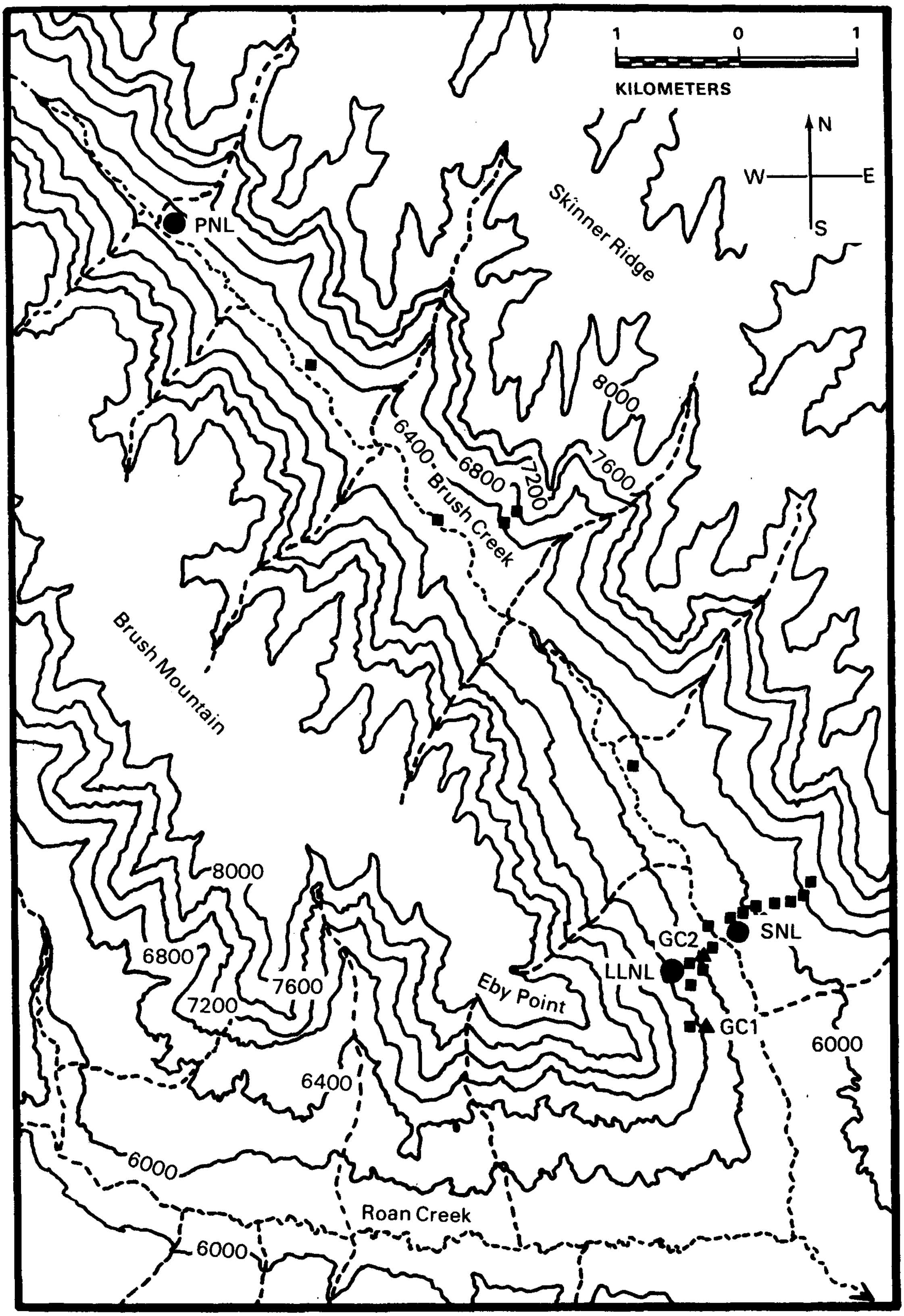

FIG. 1. Location of SF_6 sampling systems. Squares indicate the locations of the bag samplers. Triangles indicate the locations of the manually operated gas chromatographs and solid circles indicate the locations of tethered balloon sounding systems referenced in this paper. Tethersonde site names refer to organizations that collected the data. U.S. DOE laboratories include Pacific Northwest Laboratory (PNL), Sandia National Laboratory (SNL) and Lawrence Livermore National Laboratory (LLNL). The elevated tracer release occurred at the PNL site. Contours in feet MSL.

In this paper we present the results of the tracer concentration and meteorological measurements, focusing on the physical mechanisms discussed above. We begin with a description of the Brush Creek Valley and the equipment locations. We then discuss the tracer release equipment and procedures, and present data on the physical mechanisms as determined from meteorological observations and analysis of the tracer concentrations. Finally, we discuss the uncertainties in the results and their application to other valleys, and point out physical mechanisms that should be included to produce realistic pollutant concentration predictions in valley air pollution models.

2. The Brush Creek Valley

The Brush Creek Valley is a 650-m-deep, narrow, northwest to southeast-draining, near-linear valley of 25 km length having no major tributaries. Brush Creek is located approximately 50 to 60 km NNE of Grand Junction, Colorado. The valley drains the Roan Plateau and is one of the main tributaries to the Roan Creek Valley. A topographic map of the Brush Creek Valley is shown in Fig. 1. The locations of tracer and meteorological sampling equipment are also shown on the figure. A summary of the topographic characteristics of the Brush Creek Valley in the vicinity of the main data collection arc (see Fig. 1) is given below in Table 1.

3. Equipment

Sulfur hexafluoride (SF_6) was used in the experiments as an atmospheric tracer. SF_6 is a low-background, conservative, atmospheric tracer material that can be detected using gas chromatography with an electron capture detector at concentrations in the parts per trillion (ppt) range. Releases were made on the clear or partly cloudy mornings of 31 July, 4 August, and 6 August 1982. Release data are shown below in Table 2. In Table 3 we present the times of sunrise at various locations in the valley, as this information will assist in data analysis.

TABLE 1. *Brush Valley characteristics at SNL site.*

Characteristic	Value
Total valley length (km)	25
Valley floor width (m)	400
Valley depth (m)	650
Up-valley direction (deg)	330
Valley floor slope ($\Delta z/\Delta x$)	0.014
Drainage area (km^2)	95.3
East sidewall	
Aspect angle (deg true)	240
Slope angle (deg)	28
West sidewall	
Aspect angle (deg true)	60
Slope angle (deg)	27

TABLE 2. SF_6 release data.

Date	Release period (LST)	SF_6 released (kg)	Release duration (h)	Release rate (kg h^{-1})	Release height (m)
31 July	0458–0757	8.77	2.98	2.94	102
4 August	0428–0806	32.77	3.63	9.03	105
6 August	0410–0946	42.59	5.60	7.61	112

SF_6 releases were made from the valley center above the PNL site (Fig. 1) by means of a dual tethered balloon release system. Using this system, described by Whiteman and Glover (1983), SF_6 was dispensed continuously through a hose, one end of which was carried aloft by two helium-filled, blimp-shaped balloons.

It is of interest to know the release point's position in space as a function of time since, with a balloon system, the release point can change position as the balloon responds to ambient wind conditions. Winds in the Brush Valley were strong and nearly bidirectional (up- and down-valley). During the nighttime, winds were channeled down the valley and were in the form of a jet with peak speeds of about 6–7 m s^{-1} at 100 m. Winds decreased after sunrise, reversed at 0730 to 0800 LST, and increased again following reversal. Since the winds were blowing either up or down the valley axis, the balloon maintained a position above the valley center with little movement from side to side. The release point varied in its position up- and down-valley from the PNL site depending on the strength and direction of the bidirectional valley wind system. The balloon's position in no case varied more than 200 m up or down the valley from the PNL site. This along-valley variation of the balloon's position is expected to produce a negligible effect on the interpretation of SF_6 patterns on the main valley cross section, located 7.7 km down the valley from the PNL site.

The tracer release height varied with time and was determined primarily from triangulation using a sequence of theodolite sitings of balloon elevation combined with measurements of the distance from the theodolite to the balloon subpoint. Results of these triangulations and estimates of the means and standard deviations of the release heights are shown in Table 4. Note that the height of the peak of the jet was quite

TABLE 3. Sunrise times.

Location	Time (LST)
Astronomical sunrise	0504
Main sampling arc	
Rock rim—upper west sidewall	0530
Uppermost sampling site on west sidewall	0606
SNL	0643
Release site	
PNL	0744

TABLE 4. Release heights.

Date	Time (LST)	Release height* (m)
31 July	0458	106
	0600	106
	0700	106
	0725	88 avg 102 ± 9 m
4 August	0428	105
	0457	105
	0541	96
	0603	108
	0645	108
	0700	119 avg 107 ± 7 m
6 August	0410	120
	0507	115
	0546	103
	0705	109 avg 112 ± 7 m

* Average and standard deviation shown for each experiment.

near the SF_6 release height. Further detail on short-time-period oscillations in balloon height was gained by attaching a meteorological sonde to the dual balloon release system, recording the pressure oscillations and using the hydrostatic equation to calculate the corresponding height oscillations. Whiteman and Glover (1983) presented such data for a 1-h 40-min period on 4 August 1982 and found a mean release height of 104.7 m with a standard deviation of 4.2 m, in close agreement with a corresponding theodolite height determination. From the sonde observations and the information in Table 4 we estimate that the mean release height for the three experiments was generally in the range from 100 to 115 m and that the standard deviation of height oscillations was less than 10 m.

4. Analysis of data

Results of the three experiments were similar, so that, for the purposes of this paper, data from the three experiments will be used interchangeably to illustrate the physics of the phenomena. We begin by presenting data that illustrate the valley meteorology during the inversion breakup period, and follow with SF_6 observations interpreted in a meteorological context.

a. Meteorological data analysis

1) DOWN-VALLEY WIND SYSTEM AND ITS REVERSAL

Hourly wind and temperature profiles were available on 29 and 31 July on the west sidewall and at up to 6 other locations along the valley axis as part of the U.S. Department of Energy's Atmospheric Studies in Complex Terrain (ASCOT) experiment. No profiles were available on the east sidewall, however. On 4 and 6 August, profiles were available only at the PNL and SNL sites. During the experiments, nocturnal down-valley winds in Brush Creek Valley followed a "jet" profile with winds of 5–8 m s^{-1} at about the 100-m level, decaying to near-zero velocities at ridgetop level and at the ground. Winds blew nearly parallel to the valley axis. An example of a typical nocturnal wind sounding at the tracer release site is shown in Fig. 2.

Reversal of nocturnal down-valley winds at tracer release height on all experimental days occurred with a gradual decrease in down-valley wind speeds from 0630 to 0730 LST (Fig. 3). Winds then changed direction at the release height and the up-valley winds began to increase in strength. Wind profiles taken at other locations along the valley axis show a similar wind reversal. The wind reversal occurred rather suddenly through the valley depth along the entire valley length. The tethered balloon sounding frequency (once per hour) on 31 July was insufficient to determine any differences in reversal times along the valley length. On 4 August the wind reversal took place nearly simultaneously at the SNL and tracer release sites at about 0730 LST. Reversal occurred first at the upper levels of the soundings. On 6 August reversal occurred at both sites over the interval from 0730 to 0750 LST. The slow rates of ascent and descent of the sounding balloon and an unsteadiness in PNL wind soundings made it difficult to ascertain whether the reversal first occurred near the surface or aloft.

2) TEMPERATURE PROFILE EVOLUTION

Figure 4 illustrates the evolution of the temperature profiles at the SNL valley floor site (elevation, 1780 m) on 31 July. Nocturnal temperature profiles were characterized by a 12 K potential temperature inversion in the lowest 250 m of the valley with an isothermal layer ($\partial\theta/\partial z \approx 10$ K km^{-1}) above. After sunrise, grow-

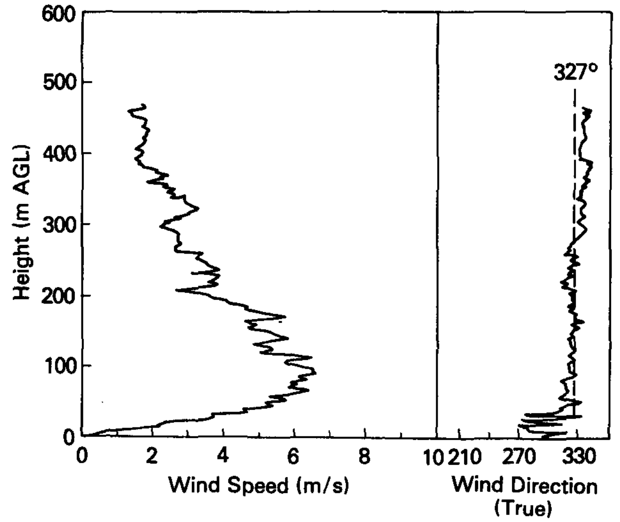

FIG. 2. Typical nocturnal wind profile above the PNL tracer release site, 0518–0540 LST, 6 August 1982. Winds blow down the valley (327° valley axis orientation) through the depth of the sounding with peak winds of 6–7 m s^{-1} at about the 100-m level.

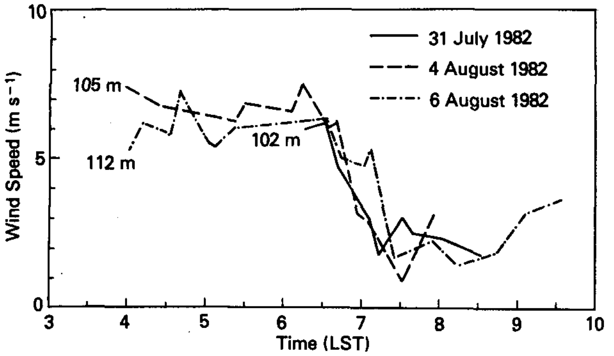

FIG. 3. Wind speed as a function of time at the tracer release height above the PNL site on 31 July, 4 August, and 6 August 1982.

ing CBLs (depths indicated by asterisks in Figs. 4 and 5) were observed over the valley floor and the west sidewall. These layers were characterized by a shallow superadiabatic sublayer adjacent to the ground, surmounted by a rapidly growing, well mixed, constant potential temperature layer. A descent of the top of the isothermal stability layer over the valley center after sunrise (indicated by arrows on Figs. 4 and 5) was a feature of the inversion breakup at most tethered balloon atmospheric sounding stations in the valley. This feature, interpreted as a compensatory sinking motion caused by upslope flows over the sidewalls, is not particularly well marked in the Brush Creek Valley. It has been observed previously in other valleys by Machalek (1974), Whiteman (1982), Brehm and Freytag (1982), and Müller and Whiteman (1988). Thermodynamic (Whiteman and McKee 1982) and dynamic models (Bader and McKee 1983, 1985) have been used successfully to explain the rate of growth of the CBLs and the rate of descent of the inversion top.

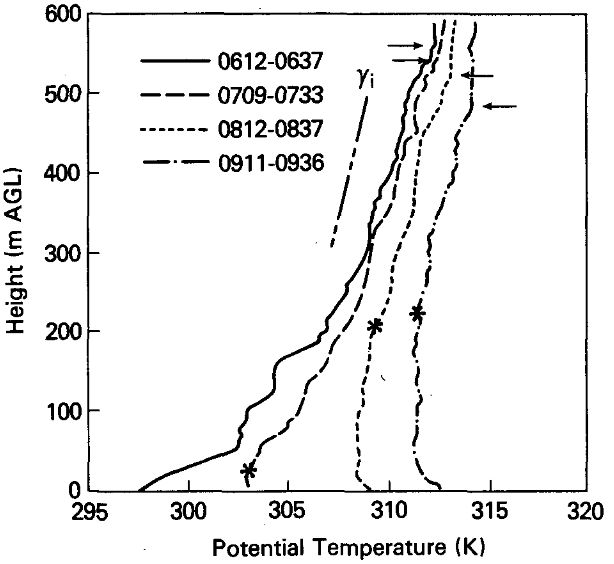

FIG. 4. Potential temperature structure evolution at the SNL valley floor site, 31 July 1982. The beginning and ending times of the upsoundings are indicated. CBL depths and temperature inversion depths are indicated by asterisks and arrows, respectively, as determined from wind and temperature profiles. The isothermal lapse rate is given for reference.

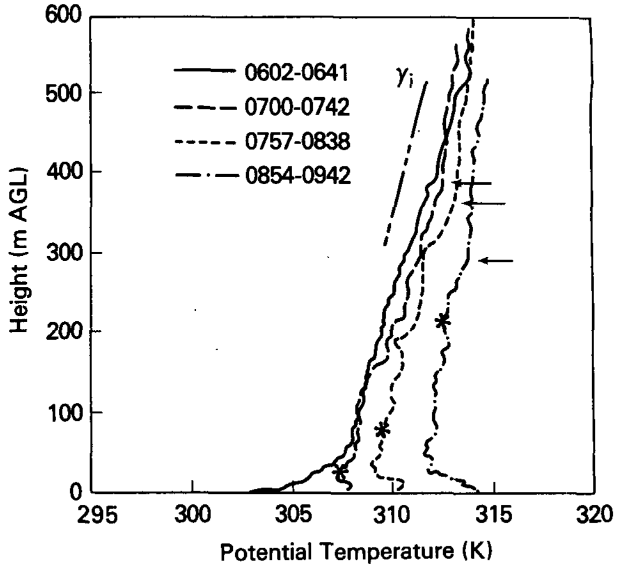

FIG. 5. Same as Fig. 4, for the LLNL west sidewall site located 142 m above the SNL valley floor site, 31 July 1982.

Figure 5 illustrates the evolution of temperature profiles over the west slope at the LLNL site. This site (Fig. 1) was located on the west sidewall at an elevation of 1922 m. The bulk of the strongly stable valley inversion was below the altitude of this site. Thus, the early morning profile shows a 60-m deep, strong stability layer capped by a deep isothermal layer. CBL growth and inversion top descent were characteristic of this site, as for the valley floor sites.

3) SLOPE WIND SYSTEMS

Upslope winds developed after sunrise within the growing sidewall CBL. These upslope winds are illustrated in Fig. 6 for one sounding at the LLNL site on 31 July 1982. An observer at site GC2 noted that upslope winds developed on all experimental days shortly after the site was illuminated.

b. Tracer data analysis

Tracer data were collected from a number of SF_6 sampling instruments operated in the field. Portable gas chromatographs operated on the valley sidewalls and in the aircraft were calibrated at intervals during each experiment with known SF_6/air mixtures. Between calibrations, air sample analyses with these chromatographs could be made as frequently as once every two minutes. A balloon-borne profiler was de-

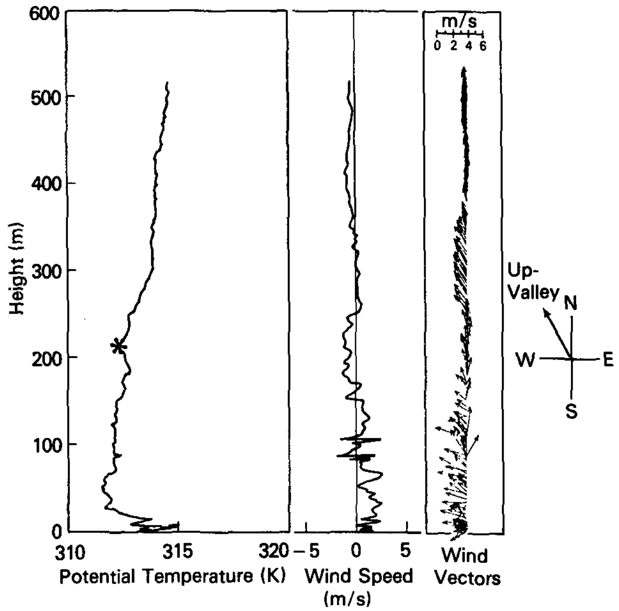

FIG. 6. Up-sounding of potential temperature, upslope wind components, and vector winds, for the LLNL west sidewall site, 0854–0942 LST, 31 July 1982. Winds within the sidewall CBL (depth indicated by asterisk) have an appreciable upslope component.

signed and operated by Sandia National Laboratory (Gay 1982). Syringe and bag samples collected on the tethered balloon, on the sidewalls, and from the aircraft were analyzed with a laboratory-grade gas chromatograph operated at a fixed site approximately 60 km distant from the Brush Valley. Special precautions were taken to avoid sample contamination during handling and storage, and all analyses were completed within 40 hours of the end of each tracer experiment. Occasional problems were encountered with pumps used for collecting air samples on the sidewalls. Separate pumps were used for each of the five sampling bags at individual sidewall stations. Some of the pumps failed to operate, or produced sample volumes that we considered to be inadequate for confident analysis. These low confidence samples were excluded from the analyses which follow.

1) TIME-VARYING CONCENTRATIONS ON SIDEWALL

The results of SF_6 analyses are shown in Figs. 7–9. Figure 7 shows SF_6 concentration as a function of time for the three experiments at gas chromatograph site GC1, located on the west sidewall 7.7 km down-valley from the tracer release site. The figure illustrates the rapid increase in concentrations on the west sidewall following sunrise. High concentrations decreased after 0700 LST. The nocturnal down-valley winds in the valley reversed to up-valley at 0730 LST. Concentrations at the west sidewall sites decreased to near-zero by 0930 LST.

2) VERTICAL PROFILES OF SF_6 CONCENTRATION

Figure 8 shows the results of a series of five vertical profiles through the tracer plume taken from the center of the valley floor at the SNL site. These profiles were taken using six syringes that were filled sequentially from a continuously ascending tethered balloon. The first profile was used to verify that no SF_6 was present in the valley before the tracer release was initiated. The next two profiles were taken in the nighttime or twilight before direct sunlight arrived on the instrumented arc; see Table 3 for sunrise times. The last two profiles, taken after sunrise, have characteristics associated with fumigation. Specifically, in the first of the two profiles, valley floor concentrations increase and the lowest layer of the valley atmosphere becomes well mixed as a convective boundary layer grows upward into the elevated plume. The final profile shows lower concentrations on the valley floor as the growing CBL mixes the SF_6 more uniformly through the valley's depth.

3) MEAN STRUCTURE EVOLUTION ON CROSS SECTION

Figure 9 presents a time series of cross section analyses of plume concentrations on 4 August. The valley cross section is drawn through the SNL site. Data in the figure are a composite of available data, with the individual subfigures corresponding in time to the sampling periods for the ground-based bag samplers. Time series data from the manually operated gas chromatographs GC1 and GC2 were averaged over the appropriate periods and are plotted on the figure with the bag sample data. Three of the five vertical concentration profiles above the valley center are plotted on

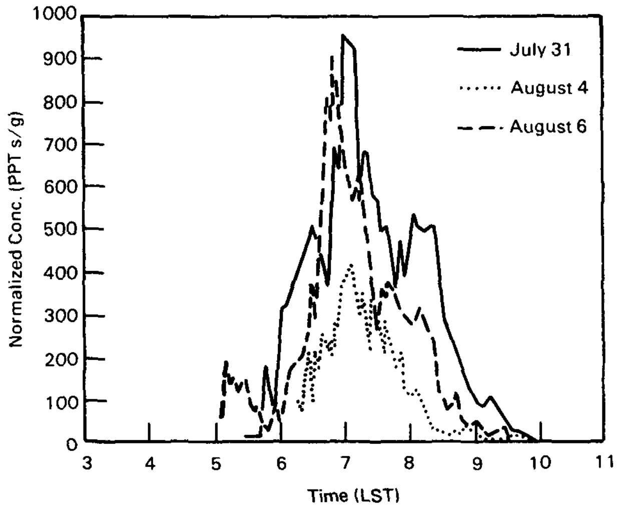

FIG. 7. SF_6 concentration normalized by tracer release rate (ppt s/g) versus time, Site GC1, 1982.

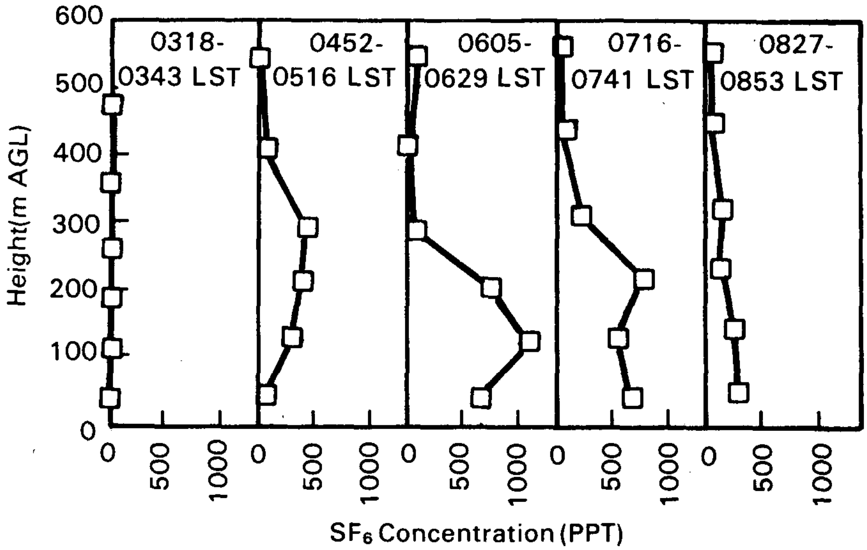

FIG. 8. Vertical profiles of SF_6 concentration (ppt), 6 August 1982.

the subfigures at the times closest to the balloon soundings. Instantaneous SF_6 concentration data obtained by aircraft in the vicinity of the valley cross section are indicated at the appropriate heights on the subfigures by plus (+) symbols.

One should recognize the limitations imposed on the analysis by the small number of observations and the fact that the observing systems have different inherent averaging times. Additional vertical profiles on the valley cross section would have been especially valuable. The analysis, nonetheless, uses knowledge of the meteorological processes identified in section 4a as well as the measured tracer data in section 4b, and represents our best efforts at drawing a coherent picture of tracer gas dispersion on the cross section. Bag sample concentrations indicated with an asterisk in Fig. 9 indicate failed sampling pumps or pumps producing very low sample volumes. These data are not used in the analysis.

The nocturnal tracer plume (Fig. 9a) was carried down the valley to the cross section, traveling adjacent to the east sidewall in the lowest 200 or 300 m of the valley. The plume was released 7.7 km up the valley from the cross section at an elevation 245 m higher than the SNL site (i.e., about 100 m above the valley floor at the PNL site). The mean plume centerline on the cross section was generally found about 100 to 150 m above the valley floor, indicating that the nocturnal plume traveled in a path nearly parallel to the valley floor, rather than maintaining a constant MSL height. The plume centerline concentration was about 900–1000 ppt on the cross section. As sunlight progressed down the west sidewall (Fig. 9b–e) a cross valley flow developed, advecting the tracer plume toward the sunny sidewall. High concentrations occurred on the west sidewall as the nocturnal plume was entrained into the growing CBL, fumigating the surface. Upslope flows in the growing CBL carried the tracer farther up the sidewall, increasing concentrations in the upper regions of the valley. After 0730 LST the wind reversal (to up-valley) was an additional factor that caused a rapid diminution in concentrations within the lower half of the valley.

5. Discussion of results

The major physical processes affecting the breakup of the nocturnal SF_6 plume are clear from the meteorological and tracer analyses. These processes include plume transport in the locally developed wind systems, the development of convective boundary layers over heated surfaces, fumigations into developing boundary layers, transport in upslope flows that develop within the growing boundary layers, and cross-valley transport caused by differential heating of the valley sidewalls. Plume breakup is affected by the combined action of all of these processes.

Clearly, a primary factor affecting concentrations in the nocturnal tracer plume is the strength of the down-valley flow at the release point. The cross-valley-integrated SF_6 mass χ depends inversely on wind speed u, as expressed by the formula

$$\chi = \frac{Q}{u},$$

where Q is the source strength. Since the along-valley windspeed at the release point varies with time during the inversion breakup period (Fig. 3), concentrations experienced on a given downwind cross section are a function not only of the changing distribution of SF_6 about the plume's center of mass during its travel, but

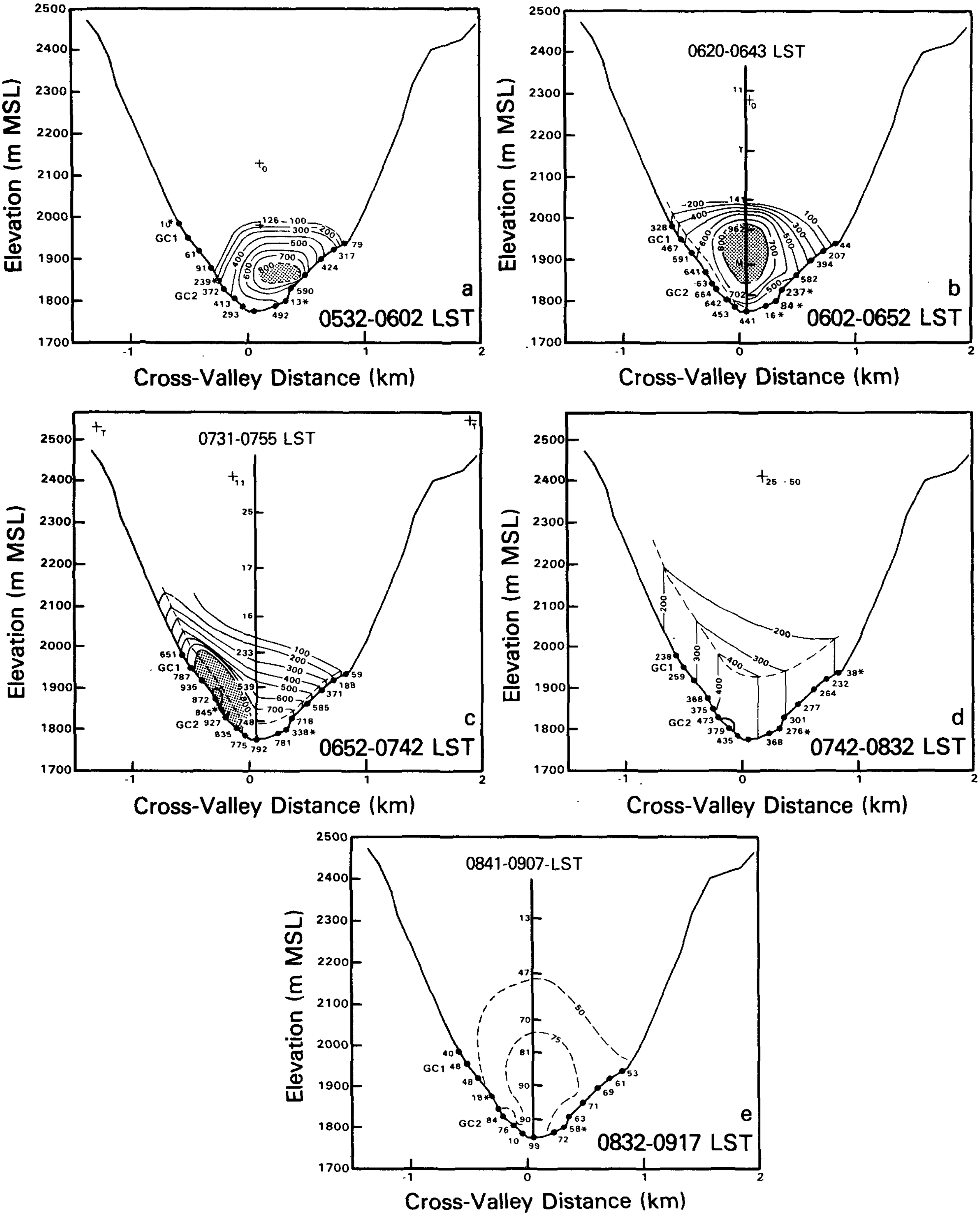

FIG. 9. Valley cross-section analysis of SF_6 concentration (ppt), 4 August 1982. See text. View looking up-valley. Valley cross section is from SW to NE (left to right). Surface concentration values marked with an asterisk are suspect due to the low volume sample collected and are not included in the analysis. The dashed line in the figure represents CBL height as estimated from hourly atmospheric soundings at the SNL site, and from tethered balloon observations taken on the west sidewall on 31 July 1982.

also on the mass of SF_6 introduced per unit length of air at the elevated source. The effect of the decrease of down-valley wind speed at source height during the inversion breakup period is thus to increase mean concentrations on downwind cross sections as the slower moving plume arrives there. This increase occurs at the same time that fumigations are increasing concentrations on the sidewalls. It should be noted that, while the windspeed at the source is an important determinant of plume concentrations, decreases in windspeed during the subsequent travel of the plume will not increase mean plume concentrations. Dispersion about the plume centerline, however, may be increased by a number of processes including enhanced cross valley advection, import of clean air from above due to along-valley atmospheric mass flux divergence, increased convective boundary layer growth, and destabilization of the air mass into which pollutants were introduced, among others.

The decrease in concentrations after 0730 LST (Fig. 7) is quite rapid. This rapid decrease is caused by a number of factors, including the mixing of low concentration air above the SF_6 plume centerline into the deepening convective boundary layer, and the transport of SF_6 from the lower portions of the valley in the upslope flows that develop over the sidewalls. Another factor is related to the topography of this valley. Specifically, the down-valley transport of the SF_6 plume at night and during the early part of the morning transition period results in the SF_6 plume being carried out the exit of the Brush Creek Valley and down the Roan Creek Valley. The plume continues to diffuse during this transport. Reversal of the local wind systems would carry much of this plume into the upper Roan Creek Valley rather than returning it up the Brush Creek Valley. Concentrations in the Brush Creek Valley would therefore decrease as cleaner air is advected up the Brush Creek Valley after the time of wind reversal.

A major source of uncertainty in the cross-section analyses is the paucity of vertical SF_6 sounding data. Additional sounders on the cross section would increase analysis confidence. Nevertheless, the basic features of the analysis, including the shift of the plume toward the heated sidewall, are supported by ground-based samplers, as well as by the limited vertical sounding data. Translation of the plume toward the sunlit sidewall at the plume centerline level appears to be at the rate of about 0.11 $m\ s^{-1}$, as calculated from the successive plume positions in Fig. 9a–c. Such low velocities would be difficult to observe using routine instruments, although the literature includes both theoretical and conceptual investigations of thermally forced cross valley circulations. Gleeson (1951) proposed a simple theory of such cross valley circulations in which the strength of the cross-valley flow was a function of the difference of insolation on the opposing slopes and their distance apart. Meteorological experiments by Urfer-Henneberger (1970) in an Alpine valley rather similar in size, shape, and orientation to the Brush Creek Valley resulted in a conceptual model of valley circulations in which a postulated cross valley flow was a major component. This conceptual model for Switzerland's Dischma Valley was supported by wind observations on the valley's slopes, although no observations were available over the valley's center. The Brush Creek Valley is a rather extreme example of a valley where strong cross-valley winds might be expected. The valley is narrow, its orientation results in strong differential solar heating of the sidewalls during the morning, and the energy budget of the semiarid valley produces large sensible heat fluxes.

6. Conclusions

Sulfer hexafluoride atmospheric tracer experiments were conducted in Colorado's Brush Creek Valley during the nighttime and morning transition periods. The early morning plume was carried down the valley in the nocturnal down-valley wind system. The elevated plume was carried nearly parallel to the sloping valley floor in the lowest 200 to 300 m of the 650-m-deep valley.

The primary physical processes seen in the meteorological and tracer experiments include nocturnal down-valley plume transport and diffusion, post-sunrise CBL growth, fumigation of the elevated plume, upslope flow development within the CBL, subsidence over the valley center, and high post-sunrise concentrations on the west sidewall. Wind reversal (to up-valley) was an additional feature of the inversion breakup period.

The strong asymmetry of the observed plume breakup caused by unequal insolation on the two sidewalls of the narrow northwest–southeast oriented valley and resultant cross-valley advection is an important feature of the observations. This feature has strong implications for post-sunrise air pollution dispersion in valleys, and little practical experience or theoretical modeling is available to determine how strongly this depends on valley orientation and width.

Additional tracer experiments were conducted in the Brush Creek Valley in September and October of 1984 as part of DOE's continuing ASCOT program. The 1984 experiments were more comprehensive, investigating nocturnal and morning dispersion of three tracer materials with a much larger network of meteorological and tracer sampling equipment. These data, when analyzed and reported, should add significantly to the observational results reported in this paper.

Acknowledgments. Research was supported by the U.S. EPA under Interagency Agreement DW930094-01-0 with DOE's Pacific Northwest Laboratory, and supplemented by the U.S. Department of Energy under Contract DE-AC06-76RLO 1830. Pacific Northwest Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy.

Field participants came from DOE's Pacific Northwest Laboratory (R. I. Schreck, D. W. Glover, F. D. Lloyd, R. N. Lee, M. M. Orgill and T. R. Heimbigner), the U.S. EPA (B. Bernardo, J. Notar, R. W. Fisher and A. H. Huber), and Sandia National Laboratory (B. D. Zak, H. Church, L. Jensen and G. Gay). Dr. P. H. Gudiksen, K. Lamson and P. Ellis of Lawrence Livermore National Laboratory provided essential assistance in planning and coordinating the DOE and EPA experiments and providing field logistical support. Special thanks are due Mr. Alan H. Huber, EPA Project Officer, and Mr. R. A. Fisher, EPA Region 8 meteorologist, for their helpful comments and management of the research program, and for their participation in the field program reported here. The many participants of DOE's ASCOT program are thanked for their cooperation and support of the joint experimental program.

Although the research described in this article has been funded wholly or in part by the U.S. EPA, it has not been subjected to EPA review and therefore does not necessarily reflect the views of the EPA and no official endorsement should be inferred.

REFERENCES

Bader, D. C., and T. B. McKee, 1983: Dynamical model simulation of the morning boundary layer development in deep mountain valleys. *J. Climate Appl. Meteor.*, **22**, 341–351.

——, and ——, 1985: Effects of shear, stability and valley characteristics on the destruction of temperature inversions. *J. Climate Appl. Meteor.*, **24**, 822–832.

Brehm, M., and C. Freytag, 1982: Erosion of the night-time thermal circulation in an alpine valley. *Arch. Meteor. Geophys. Bioklim.*, **B31**, 331–352.

Gay, G. T., 1982: Vertical sampling flights in support of the 1981 ASCOT cooling tower experiments: field effort and data. Sandia Rep. SAND82-0172, Sandia National Lab., Albuquerque, NM., 49 pp.

Gleeson, T. A., 1951: On the theory of cross-valley winds arising from differential heating of the slopes. *J. Meteor.*, **8**, 398–405.

Hewson, E. W., and G. C. Gill, 1944: Meteorological investigations in the Columbia River Valley near Trail, B.C. *Bur. Mines Bull., U.S. Dept. of Interior,* **453**, 23–228.

Machalek, A., 1974: Inversionsuntersuchungen in einem Gebirgstal. *Wetter und Leben,* **26**, 157–168.

Müller, H., and C. D. Whiteman, 1988: Breakup of a nocturnal temperature inversion in the Dischma Valley during DISKUS. *J. Appl. Meteor.*, **27**, 188–194.

Sivertsen, B., B. Lamb and K. E. Grønskei, 1983: A tracer study of pollutant transport in a deep, fjord valley. *Atmos. Environ.*, **17**, 1915–1922.

Urfer-Henneberger, 1970: Neuere Beobachtungen über die Entwicklung des Schönwetterwindsystems in einem V-förmigen Alpental (Dischmatal bei Davos). *Arch. Meteor. Geophys. Bioklim.*, **B18**, 21–42.

Whiteman, C. D., 1982: Breakup of temperature inversions in deep mountain valleys. Part I: Observations. *J. Appl. Meteor.*, **21**, 270–289.

——, and T. W. McKee, 1982: Breakup of temperature inversions in deep mountain valleys. Part II: Thermodynamic model. *J. Appl. Meteor.*, **21**, 290–302.

——, and D. W. Glover, 1983: Technique for elevated release of sulfur hexafluoride tracer. *J. Air Poll. Control Assoc.*, **33**, 772–774.

——, and K. J. Allwine, 1985: Green River air quality model development: VALMET—A valley air pollution model. Final Rep. PNL-4728 Rev. 1., Pacific Northwest Lab., Richland, WA, 176 pp. [NTIS No. PB86-104106/AS.]

——, R. N. Lee, M. M. Orgill and B. D. Zak, 1984: Green River air quality model development: Meteorological and tracer data—July/August 1982 field study in Brush Valley, Colorado. PNL-5163, Pacific Northwest Lab., Richland, WA, 138 pp. [NTIS No. PB85-125490].

Willson, R., F. Shair, B. Reynolds and W. Greene, 1983: Characterization of the transport and dispersion of pollutants in a narrow mountain valley region by means of an atmospheric tracer. *Atmos. Environ.*, **17**, 1633–1647.