

FIELD STUDIES OF TRANSPORT AND DISPERSION OF ATMOSPHERIC TRACERS IN NOCTURNAL DRAINAGE FLOWS

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Abstract—A series of tracer experiments were carried out as part of the Atmospheric Studies in Complex Terrain (ASCOT) program to evaluate pollutant transport and dispersion characteristics of nocturnal drainage flows within a valley in northern California. The results indicate that the degree of interaction of the drainage flows with the larger scale regional flows are strongly dependent on how well the shallow drainage flows are shielded by the surrounding topography from the external environment. For the valley under study, the drainage flows from about mid-slope elevations and below were generally decoupled from the externally generated flows; as evidenced by the similarity of the surface tracer distributions produced during widely varying regional flow conditions. However, tracers released immediately above the drainage flows near the ridge top did reveal considerable mixing between the transition layer flows and the underlying surface drainage flows. Likewise, the transport and dispersion of the tracers at elevated heights within the valley basin were extremely dependent on the influences of the regional scale flows on the valley circulations. The dispersion rates associated with the transition layer flows were dependent on topographic constraints but were appreciably higher than those reported for homogeneous flat terrain situations.

1. INTRODUCTION

The ASCOT program has conducted a series of field experiments in the Anderson Creek valley of The Geysers geothermal area in northern California for the purpose of studying pollutant transport and dispersion associated with nocturnal drainage flows. One of these field experiments, conducted during September 1980, included a series of tracer studies that are reported in this work. The studies included the use of two perfluorocarbons, two heavy methanes, and SF₆ gases that were measured using conventional sampling techniques; as well as oil fog tracked by lidar, and tetroons tracked by radar. The principal objectives of these studies were to evaluate:

- (i) the spatial and temporal variations of the tracer distributions within the drainage flows;
- (ii) the effects of a forest canopy on the transport and dispersion processes;
- (iii) the extent of mixing between the drainage flows and the overlying transition layer flows and
- (iv) the dispersion characteristics as implied by the tracer distributions.

The experimental plan included five separate and identical experiments. Each experiment consisted of the simultaneous release of each of the gaseous and oil fog tracers over a 1-h period after the drainage flows had been established; while the tetroons were released at selected times prior, during, and after these tracer releases. These experiments were coordinated with a

series of extensive surface and upper air meteorological observations.

The Anderson Creek valley has the characteristics of a basin. Its topographic features and the layout of the tracer studies are shown in Fig. 1. The valley is bounded by Cobb Mountain on the north, by a ridge on the west and south, and by Boggs Mountain on the east. The Anderson, Gunning and Putah Creeks, which form the principal drainage areas, merge near Anderson Springs with outflow toward the southeast. The studies included tracer releases within each of these drainage areas. One of the perfluorocarbon tracers (PMCH; C_7F_{14}) was released into the nocturnal drainage flows from an open, but very sheltered area in Anderson Creek; while the other perfluorocarbon tracer (PDCH; C_8F_{16}) was released within a thick forest canopy in Gunning Creek. These sites are roughly halfway up the slopes. The downwind concentrations of the tracers were sampled with automatic sequential samplers at an array of more than 50 sites located throughout the experimental area. At most locations a series of samples were collected over a period of 2 h beginning at the time the tracer release was initiated. At five locations up to 22 shorter duration samples were collected for each experiment to provide a more detailed history of the tracer concentrations. These experiments were carried out as a cooperative effort involving the NOAA Air Resources Laboratories, the Department of Energy Environmental Measurements Laboratory, and the Brookhaven National Laboratory. The perfluorocarbon tracer capability has been reported by Ferber *et al.* (1981) and by Lovelock and Ferber (1982). The two

heavy methane tracers, methane-20 ($^{12}CD_4$) and methane-21 ($^{13}CD_4$), were released within the upper reaches of the Anderson Creek drainage area by investigators from the Los Alamos National Laboratory.

The methane-21 was released over a 1-h period at the surface directly into the drainage flows; while methane-20 was released simultaneously into the transition layer flows at a height of 60–75 m above the surface. A network of 33 surface samplers was operated within the Anderson Creek drainage area to define the spatial distribution of the two tracers. Most of the samplers integrated the air concentrations over an 8-h period that started at the beginning of the tracer releases. At two locations time histories of the tracer concentrations were provided by collecting 30 min sequential samples over a period of 8 h. The sampling and analytical techniques associated with the use of these tracers have been reported by Cowan *et al.* (1976) and Fowler (1979). The SF_6 was released in the upper part of the Putah Creek valley by investigators from Meteorology Research, Inc. and Environmental Systems and Service. Due to accessibility constraints, it was only possible to measure the surface air concentrations along the highway passing through the Putah Creek valley. Approximately 30 samplers measured 1-h integrated air concentrations; while four collected shorter duration samples for detailed plume evolution studies.

In addition to the surface sampling networks, two vertical profiling systems were used to define the temporal variations in the vertical distributions of the tracers within the valley basin and outflow region.

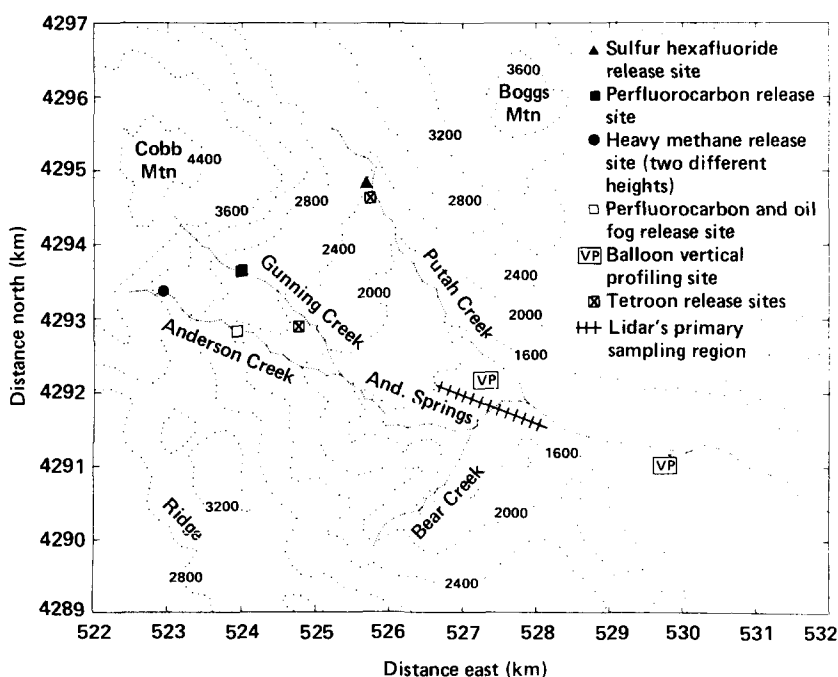


Fig. 1. The layout of the tracer experiments within the Anderson Creek valley. The elevation contours are in units of feet.

These consisted of balloon borne sampling systems. The one operated within the valley basin was developed at the Brookhaven National Laboratory. It consisted of a sampling cable, suspended from a tethered balloon to enable air samplers, located on the ground, to collect samples from four 400 ft (120 m) altitude bands up to a height of 480 m above the surface of the basin. The other profiling system, which was operated by the Sandia National Laboratories within the valley's outflow region, utilized on-board samplers to collect samples at specific height intervals as the balloon was hauled up or down.

In order to acquire more detailed structural information about the three-dimensional evolution of these tracers, oil fog was released at the same site and simultaneously with the PMCH perfluorocarbon tracer and tracked by lidar. The NOAA Wave Propagation Laboratory lidar, described by Eberhard (1981), was used for this purpose. The spatial and temporal evolution of the oil fog was derived from the intensities of the backscattered signals from the oil fog droplets. For each release the lidar, which was situated near the valley outflow region, performed a series of scans in various vertical planes to observe the evolution of the plume. These scans commenced at the initiation of each release and continued 1–2 h after the release when the backscatter signals produced by the plume were too faint to detect. Thus, cross-sections of the plumes along various radials were defined as a function of time. However, the region of most frequent sampling by the lidar and, hence, the most detailed analysis is shown in Fig. 1. The remaining studies included the release of tetroons that were tracked by radar within the Anderson and Putah Creek valleys by researchers from the U.S. Forest Service (Riverside). These were released individually as well as in clusters of three at a height of 100 m from the two sites shown in Fig. 1. Thus, the tetroons were flown in the transition layer overlying the drainage flows within the two valleys, and provided direct measurements of individual air parcel trajectories and the dispersion charac-

teristics of these air parcels. A description of the radar and the data analysis techniques are reported by Fosberg and Lanham (1983).

To illustrate the general characteristics of the tracer distributions observed during the five experiments, it was convenient to select one experiment for discussion purposes. This is Experiment 4 which was conducted on 19–20 September 1980. Thus, this report provides a description of the results obtained from this experiment; while significant differences observed in the other experiments, particularly Experiment 2, conducted on 15–16 September 1980, will be pointed out. An attempt is also made to place these results in perspective from the meteorological observations point of view and to identify the principal findings derived from these tracer studies as related to the program objectives. To assist the reader with following the discussions, Table 1 has been included to provide a summary of the tracer release characteristics.

2. RESULTS AND DISCUSSION

Perfluorocarbon tracer studies

The perfluorocarbon surface tracer distributions, acquired during Experiment 4 for the first 2-h period after the initiation of the 1-h releases (2300 PST), are given in Fig. 2. The 2 tracers showed very similar concentration patterns with the plume centerlines following the creeks rather closely. The two plumes merge near the confluence of the Anderson and Gunning Creeks, then proceed in a southeasterly direction toward the Anderson Springs area. However, a significant northward transport may be noted by the bending of the plumes up into the Putah Creek drainage area. Note also that the plumes are relatively narrow within the first 2 km of the source and then appear to spread out horizontally at an accelerated rate with an attendant decrease in the concentrations. A comparison of the relative PDCH and PMCH concentration isopleths reveal that the PDCH plume

Table 1. Summary of tracer release characteristics

Tracer	Release site	Release height (m)
Perfluorocarbons		
PMCH	Anderson Creek	5
PDCH	Gunning Creek	5
Heavy methanes		
Methane-20	Anderson Creek	60–75
Methane-21	Anderson Creek	4
Surface hexafluoride	Putah Creek	5
Oil fog	Anderson Creek	1
Tetroons	Anderson Creek and Putah Creek	100

The duration of the gaseous and oil fog releases was one hour (2300–0000 PST). The amounts released during each experiment varied somewhat, but were roughly 500 g of each perfluorocarbon, 10 g of methane-20, 1 g of methane-21, and 14 kg of SF₆.

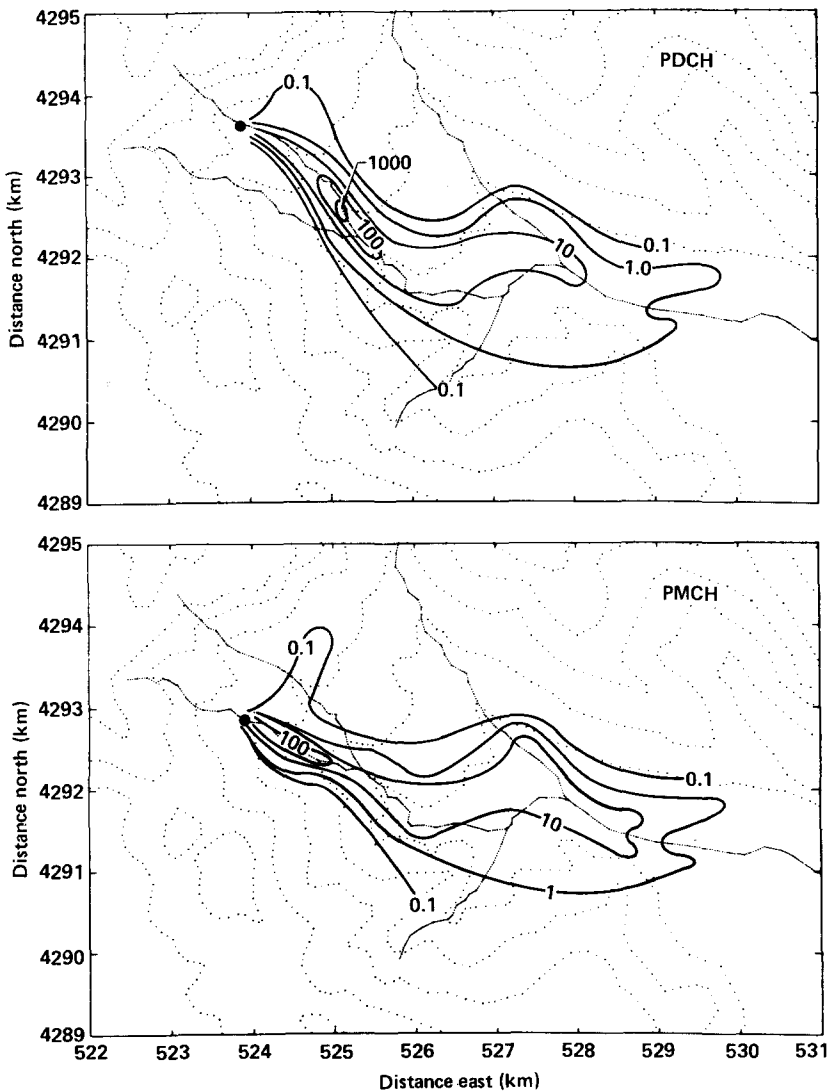


Fig. 2. Surface concentration patterns of the PDCH released from Gunning Creek (top) and the PMCH released from Anderson Creek (bottom) during Experiment 4. The concentrations are in units of ppt and are averaged over the first 2 h (2300–0100 PST) after the initiation of the releases. A total of 471 g of PDCH and 416 g of PMCH were released over the 1-h release period.

exhibits centerline concentrations within the thickly forested Gunning Creek drainage area that are about 3–10 times higher than the corresponding PMCH concentrations in the Anderson Creek drainage areas for the first 1–2 km from the release sites; thereafter, the concentrations of the two tracers are essentially identical. Thus, in this particular case, it appears that the principal effect of the forest canopy on the transport and dispersion of the tracer was to inhibit mixing within the canopy to produce the more concentrated plume.

The down-valley progression of the two tracers can readily be seen in the 2-h averaged samples collected at each sampling location. For the sake of brevity, Fig. 3 only shows the tracer distributions observed 6–8 h after the release. Note the peak concentrations of both

tracers have decreased by several orders of magnitude from those initially observed. It appears, that especially in the case of the PDCH tracer, a small fraction of the tracers seems to be held back near the release sites after the initial plumes have departed. Note also the persistent bending of the residual plumes up into the Putah Creek drainage area. These surface concentration patterns appear surprisingly similar from one experiment to another, both spatially and temporally as well as in magnitude in spite of rather wide variations in the regional flows. Thus, the drainage flows responsible for the transport and dispersion of the perfluorocarbon tracers appeared to be fairly well decoupled from the external environment. This may not always be the case, however, depending upon the physical exposure of the release site and the transport

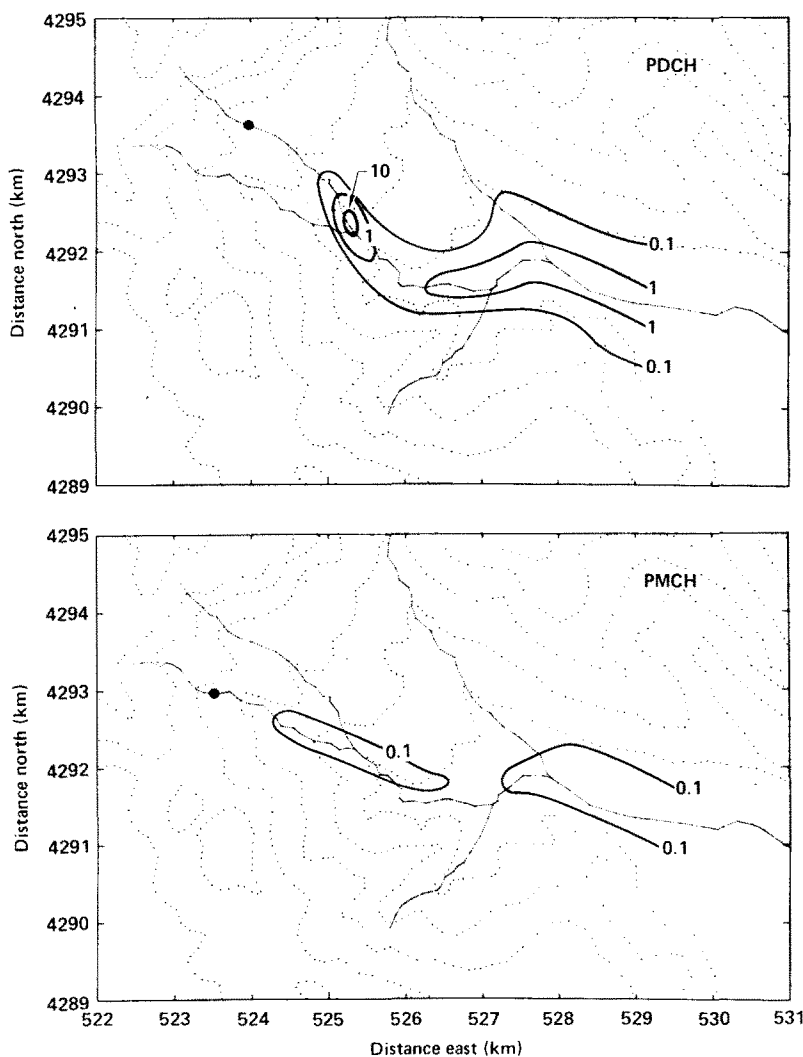


Fig. 3. Surface concentration patterns of PDCH (top) and PMCH (bottom) 6–8 h (0500–0700 PST) after the release during Experiment 4. The units are in ppt.

path to the larger scale flows. The sequential samplers, situated at selected downslope distances from the release sites, indicate an average transport speed of about 1 m s^{-1} to the valley floor. The plume passage times within the valley basin and the outflow region were about 5–6 h for the 1-h releases, which supports the concept, proposed by Barr (1983) of a slowly drifting and meandering tracer plume within the valley basin prior to flowing out of the basin toward the southeast.

This similarity in the surface distribution from one experiment to another was not apparent in the vertical tracer distributions observed over the valley basin during each experiment. The vertical distribution measured during Experiment 4 in the vicinity of the confluence of the Anderson and Putah Creeks in the valley basin are shown by the time–height cross-sections given in Fig. 4. Since the winds increased with altitude, the tracers were initially detected slightly above the surface; however, within 1–2 h the highest

concentrations appeared at the surface as the material transported by the slower surface winds arrived at the observation site. Note also the rapid decrease in the concentrations of the two tracers with altitude indicating considerable vertical stability. This contrasts significantly with the lower concentrations and the more homogeneous distributions shown in Fig. 5 for Experiment 2 when the tracers apparently became involved in fairly complex circulation systems over the valley basin. The remaining experiments showed distributions that were intermediate to those observed during Experiments 2 and 4.

Heavy methane tracer studies

The methane-20 and methane-21 surface concentration distributions observed during Experiment 4 are shown in Fig. 6. These are integrated over an 8-h sampling period (2300–0700 PST). The methane-21 which was released at the surface within the upper reaches of the Anderson Creek drainage area, shows

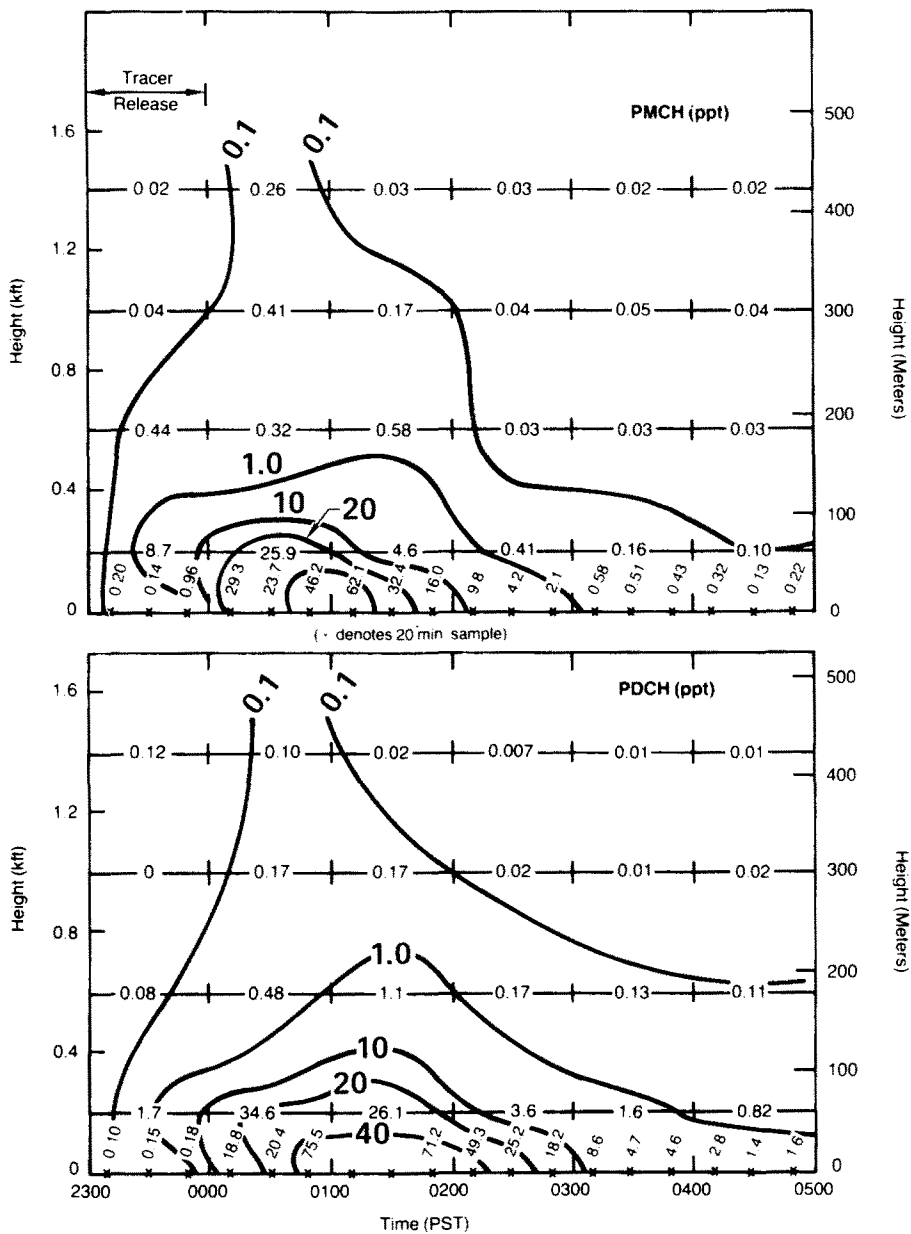


Fig. 4. Time-height cross-sections of the perfluorocarbon tracer concentrations over the valley basin during Experiment 4.

characteristics that are somewhat similar to the PMCH distributions. Note the general downslope transport follows the Anderson Creek in a southeasterly direction toward the Anderson Springs area and the slight indication of the northward transport into the Putah Creek drainage area before exiting the valley toward the southeast. However, the pattern appears to be somewhat wider than those for the PMCH tracer within the first 2 km of the release site. This may possibly be due to the 8-h averaging process, but may also indicate the possibility of increased exposure of the methane-21 to the transition layer flows near the ridge top. The surface distribution pattern produced by the methane-20, which was released at a height of

60–75 m within the lower levels of the transition layer, is also shown in Fig. 6. It is somewhat broader and displays lower centerline concentrations relative to the methane-21 pattern. A direct comparison of the concentrations provides a pattern that is typical of all experiments. The methane-21 to methane-20 ratios are mostly near unity, except near the centerline of the plumes where the ratios are typically within the 3–5 range. This indicates that considerable mixing did occur between the transition layer flows and the underlying drainage flows; possibly, because the tracers were released near the ridge top where the drainage flows may be more exposed to external conditions. Ratios less than unity, observed on the

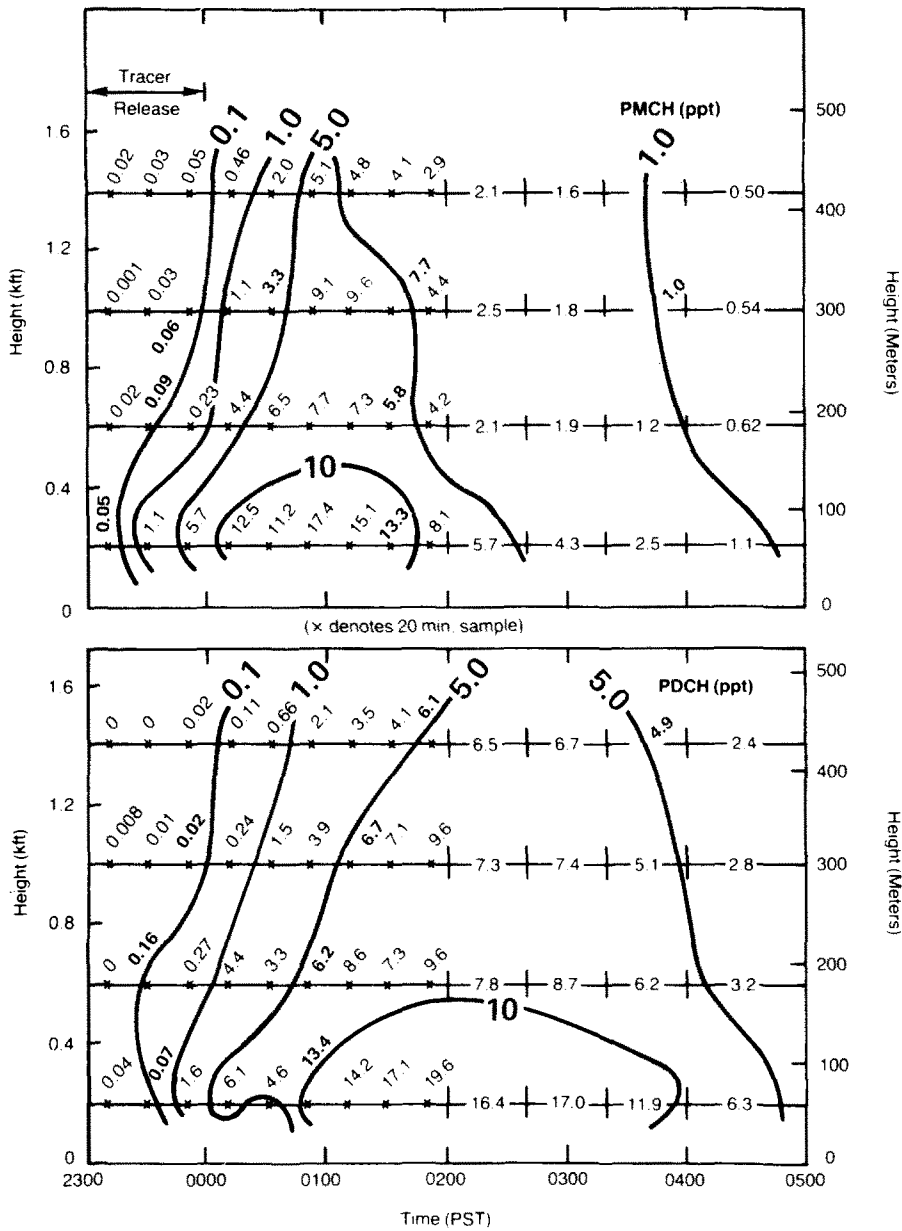


Fig. 5. Time-height cross-sections of perfluorocarbon tracer concentrations over the valley basin during Experiment 2.

fringes of the plumes, reveal enhanced horizontal dispersion of the methane-20 tracer at the elevated heights. The spatial distribution patterns of the surface concentrations of both heavy methanes were similar for all experiments, except in magnitude. For instance, the concentrations measured during Experiment 2 were generally a factor 5 to 10 less than those observed during Experiment 4. As will be explained later, this is believed to be due to the influences of the regional scale flows in the vicinity of the release site. The average surface transport speed from the release site to the valley basin for both methane tracers was about 1 m s^{-1} which is similar to that for the perfluorocarbon

tracers. The plume passage times were about 4–6 h on the valley floor and within the outflow region; again, indicating slowly drifting and meandering plumes within the valley.

The vertical distributions of these tracers over the valley basin displayed many similarities with those observed for the perfluorocarbons. The heavy methane distributions measured during Experiment 4 may be viewed by means of the time-height cross-sections shown in Fig. 7. Both methanes were initially detected slightly above the surface prior to the arrival of the bulk of the tracers at the surface; roughly 1–2 h later. In addition, the tracers were mostly situated within the

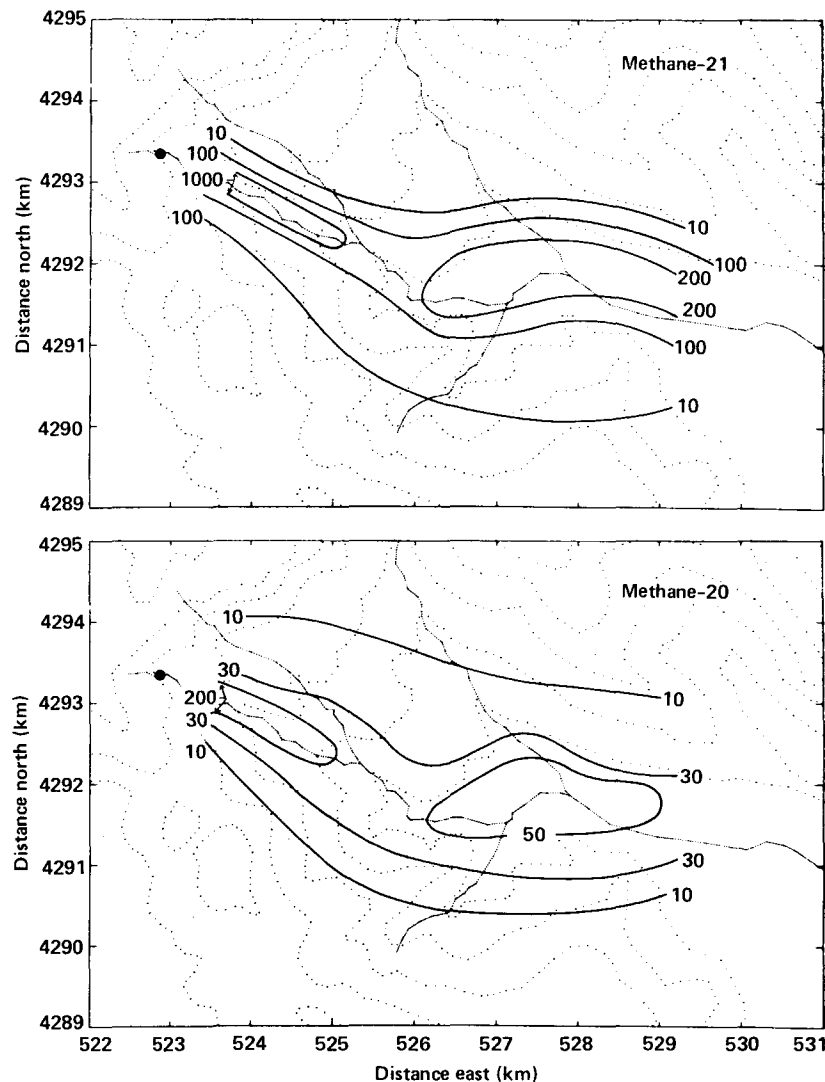


Fig. 6. 8-h averaged surface concentration patterns for methane-21 (top) and methane-20 (bottom) observed from 2300 to 0700 PST during Experiment 4. The units are in ppt based on 1 kg releases. The actual amounts released were 1.27 g of methane-21 and 9.24 g of methane-20.

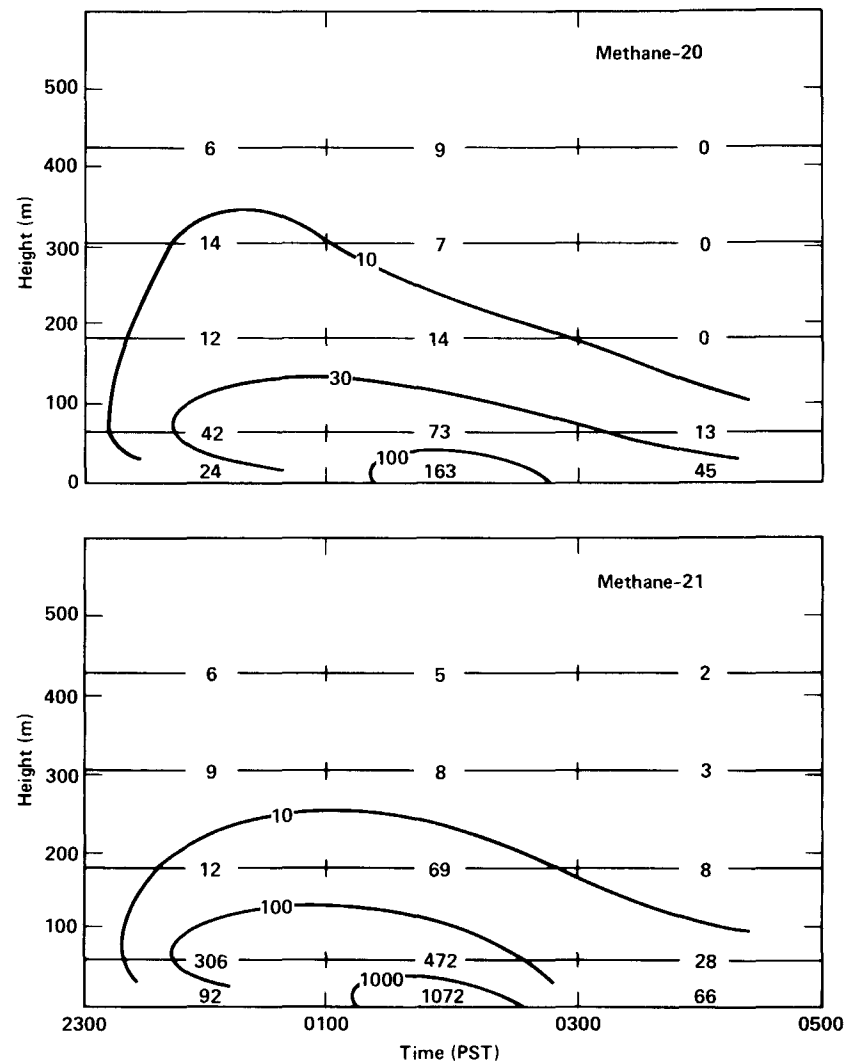


Fig. 7. Time-height cross-sections of methane-20 (top) and methane-21 (bottom) concentrations over the valley basin during Experiment 4. The units are in ppt based on 1 kg releases. The actual amounts released were 1.27 g of methane-21 and 9.24 g of methane-20.

lowest 200 m indicating considerable vertical stability over the basin. However, during Experiment 2, the concentrations are somewhat lower, except during the first 2 h, as well as more homogeneously distributed with height, as illustrated in Fig. 8.

Sulfur hexafluoride tracer studies

The SF_6 tracer was released within the upper reaches of the Putah Creek drainage area. The upper part of this drainage area may be characterized as a narrow steep canyon situated between Boggs and Cobb Mountains. The nocturnal down valley flows within this canyon are very strong and are most due to a mixture of drainage flows and channeling of the regional scale flows. As shown in Fig. 9, the SF_6 surface concentrations observed between the release site and the Anderson Springs area during Experiment 4 reveal

a highly concentrated and sharply defined plume along the center of the drainage area. The measurements show high variability because some of the samplers were located out of the plume along the west sidewall. Due to the high wind velocities observed within this narrow canyon, the plume disappears quickly as is also shown in Fig. 9 by the concentrations measured 3–4 h after the start of the 1-h release. The average surface transport speeds, between the release site and the valley basin, appear to be about $2\text{--}4\text{ m s}^{-1}$. However, as these flows merge with those from the Anderson Creek drainage area, the average velocities seem to decrease due to involvement with the valley basin circulations prior to outflow toward the southeast.

The vertical distribution of the SF_6 concentrations observed during Experiment 4 over the valley basin is shown in Fig. 10. This distribution contrasts somewhat

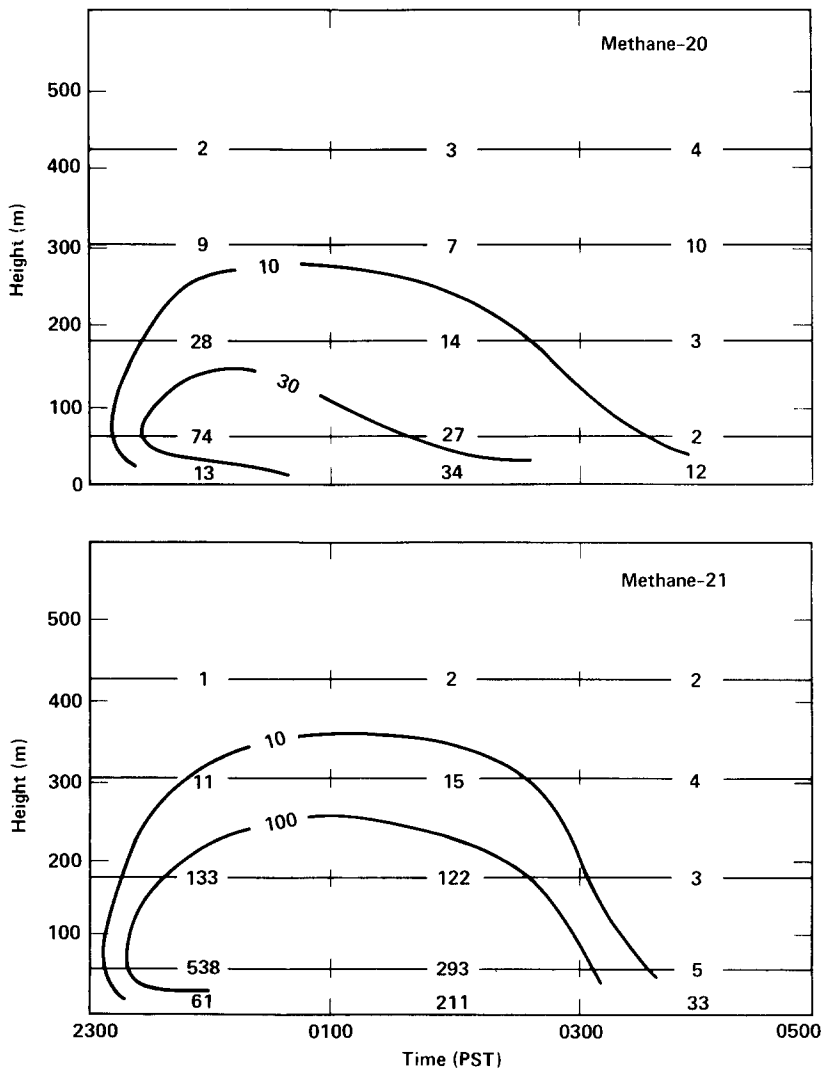


Fig. 8. Time-height cross-sections of normalized methane-20 (top) and methane-21 (bottom) concentrations over the valley basin during Experiment 2. The units are in ppt based on 1 kg releases. The actual amounts released were 1.36 g of methane-21 and 9.52 g of methane-20.

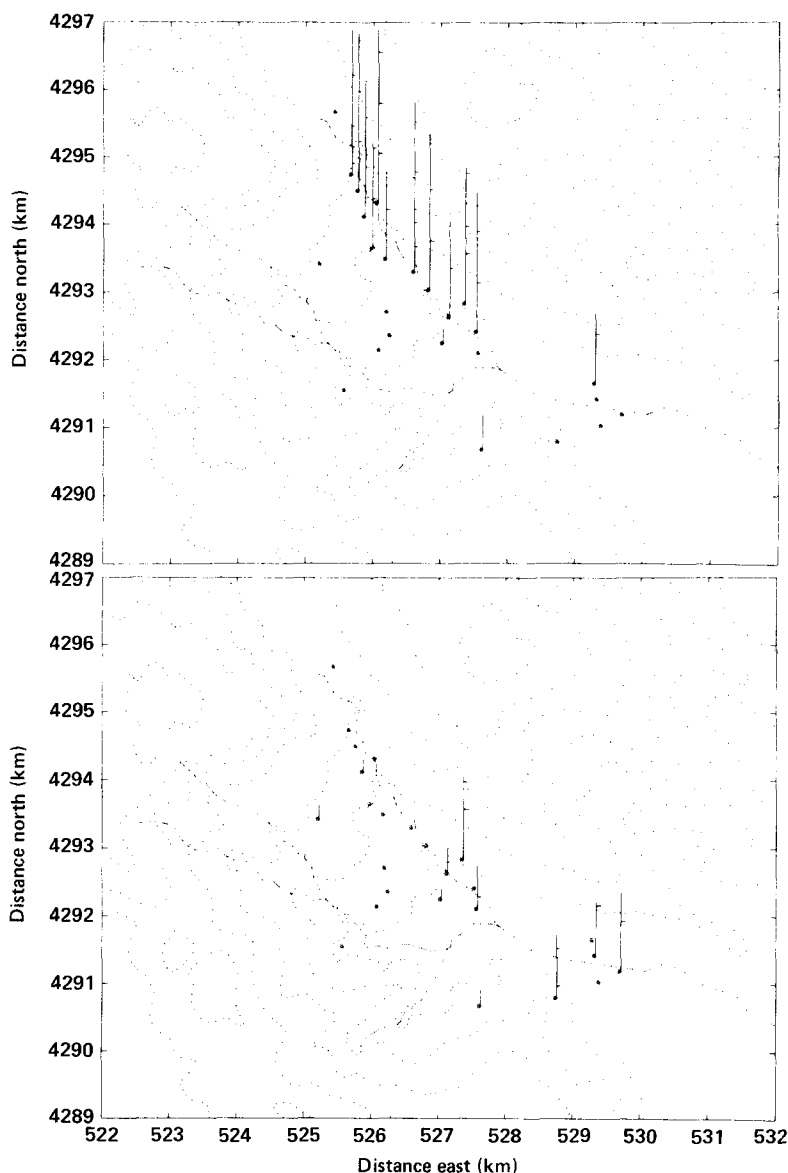


Fig. 9. An analog presentation of the surface SF_6 concentrations (ppt) measured at various locations during the first hour (top) and 3–4 h (bottom) after the initiation of the Experiment 4 release. The vertical lines are drawn on a log scale with each tick mark representing a factor of 10 starting with unity. A total of 14 kg of SF_6 was released.

with those observed for the other gases. Of primary interest is the rapid arrival of the SF_6 within the elevated layer situated between 50 and 300 m with essentially no impact at the surface. This is followed by a rapid decrease of the SF_6 concentrations within the elevated layers; an indicator of fast removal from the valley basin. Thus, at least during Experiment 4, the leading edge of the SF_6 , methane, and perfluorocarbon plumes appear to merge over the valley basin at roughly the same elevations, but with the SF_6 passing through first and showing considerably less impact at the surface relative to the other tracers. The vertical distribution observed during Experiment 2 is also shown in Fig. 10. This distribution, which appears

similar to those for the methanes and the perfluorocarbons, shows enhanced vertical mixing with considerable impact at the surface, even during the first 2 h after the start of the release. Thus, in Experiment 2, the various plumes seem to merge over the basin at more or less the same altitude and time. Considering the rapid removal of the SF_6 from the valley basin during Experiment 4, this tracer probably did not get involved extensively in any valley recirculation systems; while it probably did during Experiment 2.

Oil fog tracked by lidar studies

The oil fog was released at the same site and simultaneously with the PMCH perfluorocarbon

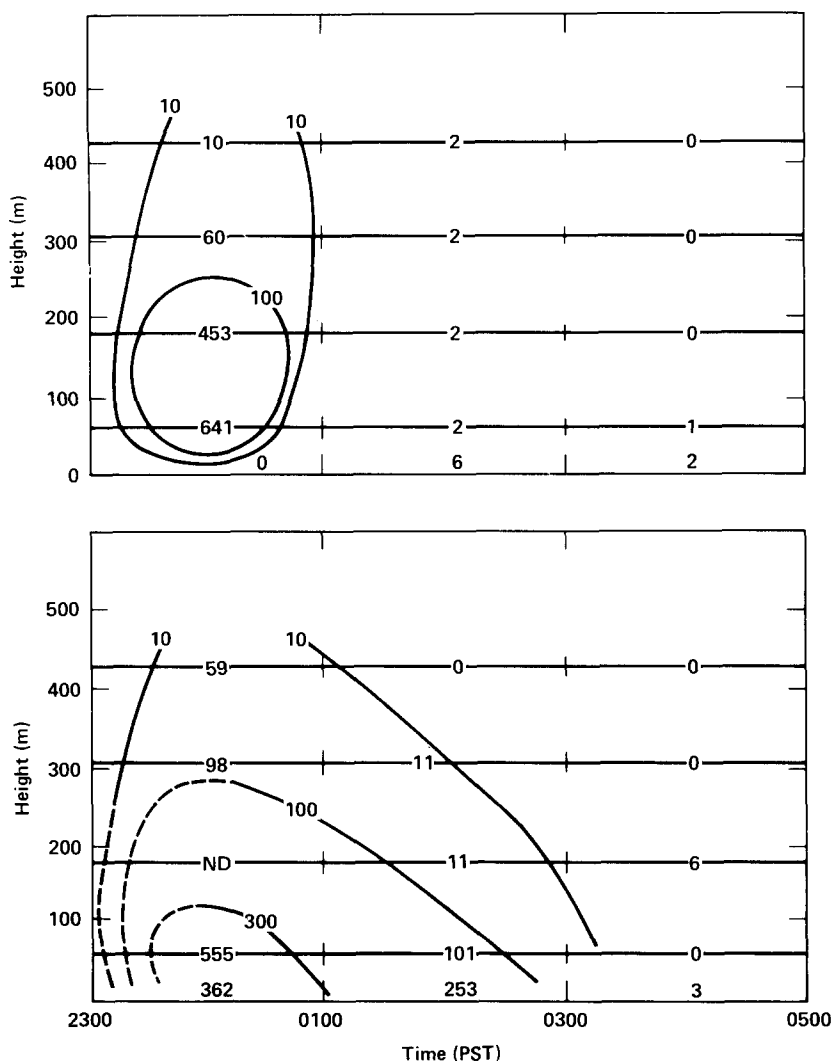


Fig. 10. Time-height cross-sections of SF_6 concentrations (ppt) over the valley basin during Experiment 4 (top) and Experiment 2 (bottom). The units are in ppt. A total of 14 kg of SF_6 was released. ND indicates no data.

tracer in the Anderson Creek drainage area, but the two tracers did not always show identical downwind distributions. In Experiment 4 the oil fog displayed a rather broad horizontal front to the lidar since some of it spread over into the Gunning Creek drainage area. The main plume front, however, traveled southeastward toward the Anderson Springs area while also turning somewhat northward into the Putah Creek drainage area in an analogous manner to the PMCH tracer. The fog appeared to be quite patchy or lumpy, especially during the first 1/2 h after the release was initiated. The horizontal scales of these lumps varied considerably, but were characteristically about 300 m within the first 3 km down valley from the release point and 600 m at further distances. In general, the vertical distributions were unimodal with smaller scale variations superimposed; although bimodal distributions were not uncommon when it appeared that patches or

elevated layers were overriding one another. At a distance of about 1 km downslope from the release point, the top of the plume increased from an initial height of 40 m to 150 m at the end of the first hour and to a maximum of 270 m towards the end of the second hour after the release was initiated. Shortly thereafter the fog began to recede and became too dilute for lidar detection.

The vertical distribution of the oil fog over the valley basin during Experiment 4 is depicted by the time-height cross-section given in the top portion of Fig. 11. This distribution was derived by averaging the backscatter coefficients over a roughly 1 km path length centered over the Anderson Springs area; a distance of about 1/2 km from the PMCH vertical profiling system. Each of the vertical scans given in the figure represents data acquired over a period of approximately 2 min. This cross-section differs con-

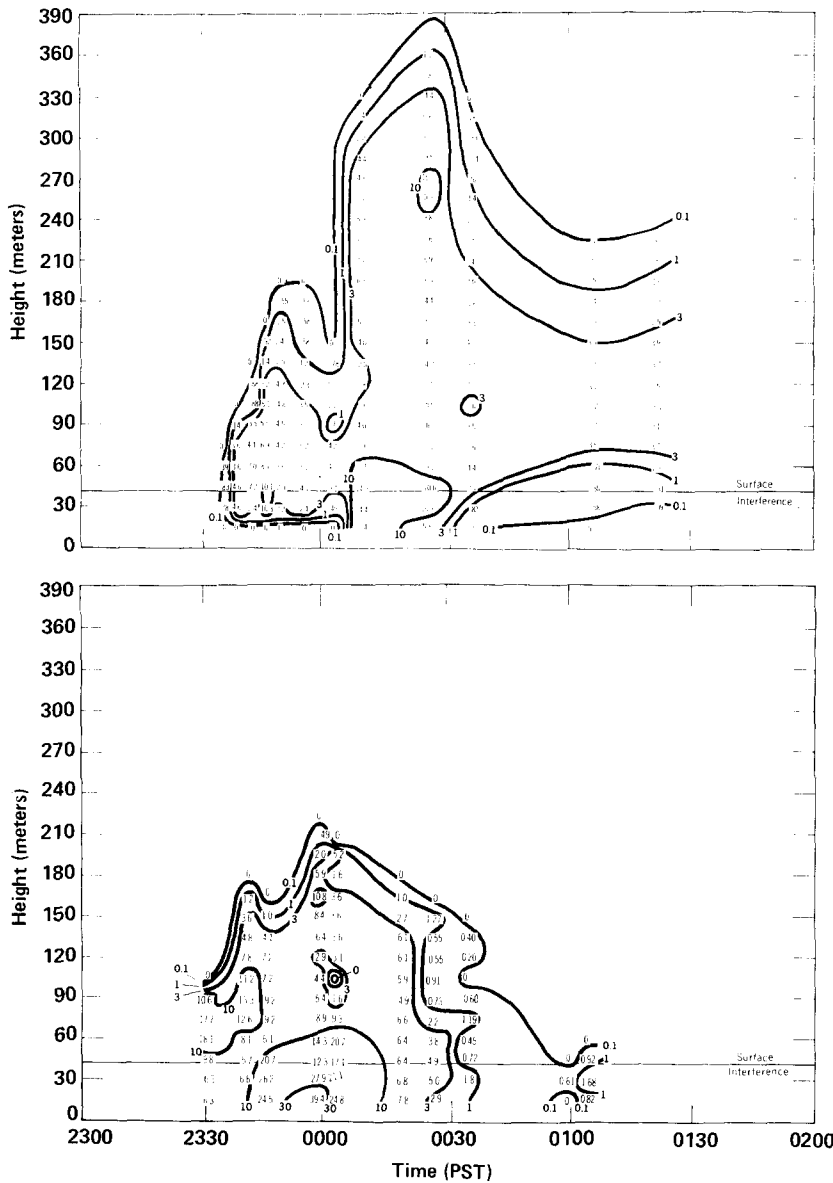


Fig. 11. Time–height cross-sections of the backscatter signals detected by the lidar from the oil fog plume over the valley basin during Experiment 4 (top) and Experiment 2 (bottom).

siderably from that given in Fig. 4 for the PMCH tracer. The oil fog first arrived in an elevated layer above the valley basin within 35 min leading to an average transport velocity of approximately 1.6 m s^{-1} . This is about a factor of 2 higher than that for the PMCH at the surface. In addition, the oil fog plume appeared to increase its vertical dimensions in a step-wise fashion by rapidly growing to a height of 150 m and remaining at this height for about 30 min before rising again to over 300 m. The plume top stalled at this height before decaying gradually over the next hour or more. The main difference is that the oil fog appears to have undergone more vertical mixing than the PMCH as judged by the increased vertical dimensions and the absence of concentration gradients near the surface.

For Experiment 2, the vertical distribution of the oil fog is also shown in Fig. 11. It is only similar to the PMCH distribution, given in Fig. 5, during the first hour after the release commenced. Again, the oil fog arrived in an elevated layer over the valley basin within the first 1/2 h and proceeded to rapidly pass over the Anderson Springs area. The fog was clearly confined within the lowest 250 m of the atmosphere; a sharp contrast to the thoroughly mixed PMCH tracer. The cause of these differences is not known at this time; however, it may be reasonable to assume two factors were significant contributors. First, the effective release height of the oil fog may have been higher than that for the PMCH due to being released in a hot high velocity jet that was pointed horizontally from the

canyon's wall. Secondly, the vertical distributions of the oil fog were acquired about 1/2 km from the PMCH vertical profiling site and represent quite different spatial and temporal averaging processes relative to the corresponding PMCH distributions. During Experiment 4, a slight amount of plume buoyancy might account for the differences. On the basis of acoustic sounder records from the upper part of the valley, a multi-layered inversion structure perturbed by internal waves with periods of a few min were present. These oscillations may at times have caused the drainage flows at the release point to become shallower than normal with depths of only a few tens of m. Thus, if buoyancy were a factor, at least part of the oil fog plume could have risen into the faster moving transition layer flows to account for the earlier arrival times and the higher vertical distributions over the valley basin. The differences between the oil fog and the PMCH vertical distributions observed during Experiment 2 are less clearly understood. The transition layer flows, observed by the acoustic sounders over the valley basin, appear to have a longer period oscillation imposed on it suggesting an 'almost stationary' wave pattern. It is possible, although highly speculative, that such a wave pattern could have produced an inversion height difference of about 200 m over the 1/2 km separation distance between the two measurement sites.

Tetroons tracked by radar studies

Approximately 100 tetroons were tracked by radar within the Anderson and Putah Creek drainage areas during the five September 1980 experiments. Since the tetroons were released at a height of 100 m above the surface, the tracks were all in the transition layer overlying the downslope drainage flows. Primary interest was placed on the stationarity of the individual tetroon trajectories during the course of a particular experiment. Analysis of the trajectories acquired during Experiments 1, 4 and 5 indicated strong and persistent down canyon flows within the upper part of the Putah Creek drainage area and somewhat slower and more variable flows within the Putah Creek-Anderson Creek confluence area. This is illustrated in Fig. 12 by the trajectories observed during Experiment 4 for the tetroons released within these two drainage areas. The tracks obtained from the tetroons released within the Anderson Creek drainage area showed considerably more variability. During Experiment 4 these tetroons generally flowed across Gunning Creek before proceeding north of Anderson Springs leading into the Putah Creek-Anderson Creek confluence area followed by egress from the study area toward the southeast. However, several tetroons became involved in localized circulations within the Anderson Creek drainage area; indicating considerable mixing occurring at times. In fact, a number of tetroons entered the underlying drainage flows with subsequent impact with the surface. These trajectories may be

contrasted with those acquired during Experiment 2, shown in Fig. 13, when all of the trajectories lead toward the SW as a result of NE flows within the transition layer.

Initial insight into the rates of dispersion can be acquired from analysis of the tetroon trajectories. Both individual tetroon flights and clusters of tetroons were used to derive the dispersion coefficients (σ_y) related to Gaussian dispersion models. The dispersion coefficients calculated from the tetroon trajectories within Putah Creek were smaller than those derived for Anderson Creek due to the steep topography. For discussion purposes, it is convenient to compare the values obtained in complex terrain with those acquired by Pasquill-Gifford-Turner over flat homogeneous terrain (Turner, 1969). The values obtained from the single trajectory analyses were greater than the Pasquill-Gifford-Turner stability category A by a factor of two. However, the dispersion estimates derived from the tetroon clusters were somewhat lower and appeared to more closely approximate the Pasquill-Gifford-Turner curves. The slope of the mean estimated σ_y values as a function of distance falls near the A and B stability curves as shown in Fig. 14. Also note the large uncertainty inherent in these values.

Additional σ_y values were determined from the perfluorocarbon tracer distribution patterns measured during the first 2-h period after the release. These σ_y values, also shown in Fig. 14, were acquired by assuming a Gaussian cross-wind concentration profile near the point of maximum centerline concentration. Thus, all values were obtained within about 1.5 km of the release sites before the plumes became involved in complex circulation systems over the valley basin. Note that the values seem to be significantly lower than the corresponding values derived from the tetroon data. This is only reasonable in view of the tetroons reflecting the role of the larger scale eddies in the transport and dispersion processes within the transition layer; while the perfluorocarbon tracers, released at the surface directly into the drainage flows, reflect dispersion inhibited by terrain and canopy influences. Thus, the σ_y values obtained from the PDCH patterns fall between the C and F stability category, while the somewhat larger values derived from the PMCH distributions fall between the B and C curves.

Correlation of tracer studies with meteorology

The measured tracer distributions reflect the integrated effects of a wide spectrum of transport and dispersion processes associated with not only the shallow drainage flows but also the transition layer flows as well as the regional and even the synoptic scale flows. These flows were characterized during the September 1980 experiments by means of extensive networks of acoustic sounders, tethersondes, rawinsondes, optical anemometers, and surface meteorological stations. To correlate the tracer distributions with the meteorological observations, we utilized the

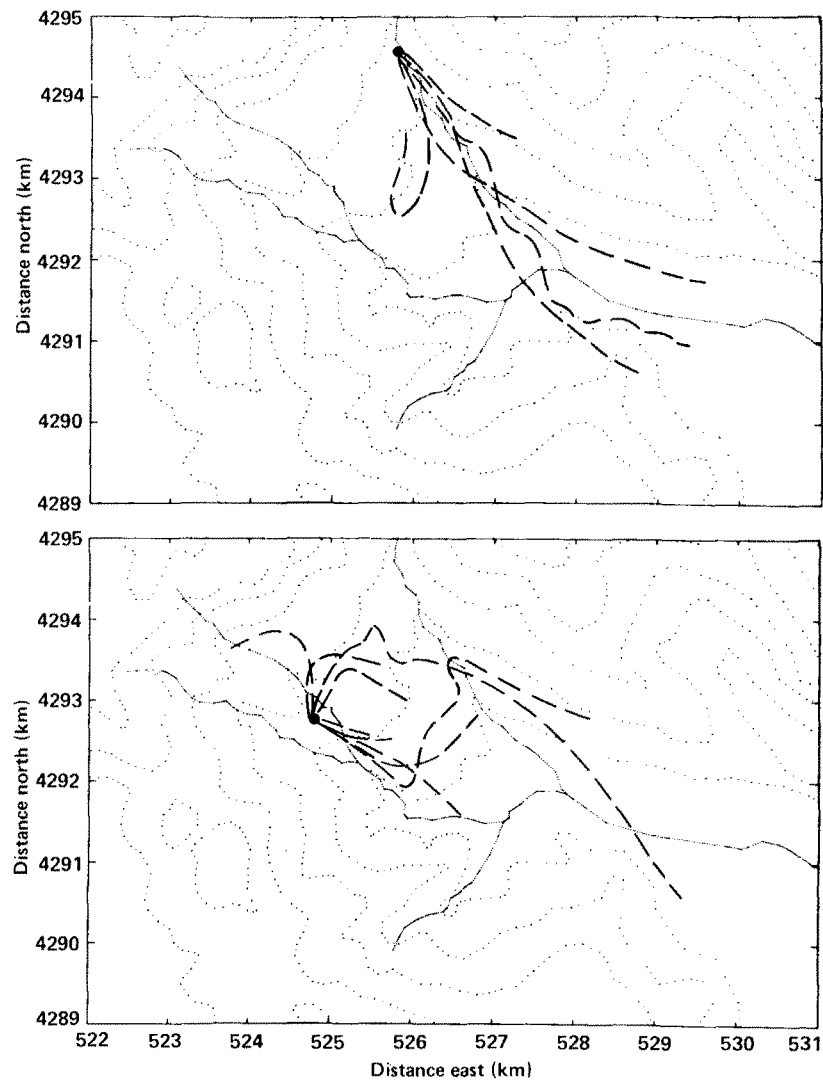


Fig. 12. Tetraon trajectories observed during Experiment 4 from the Putah Creek release site (top) and Anderson Creek release site (bottom).

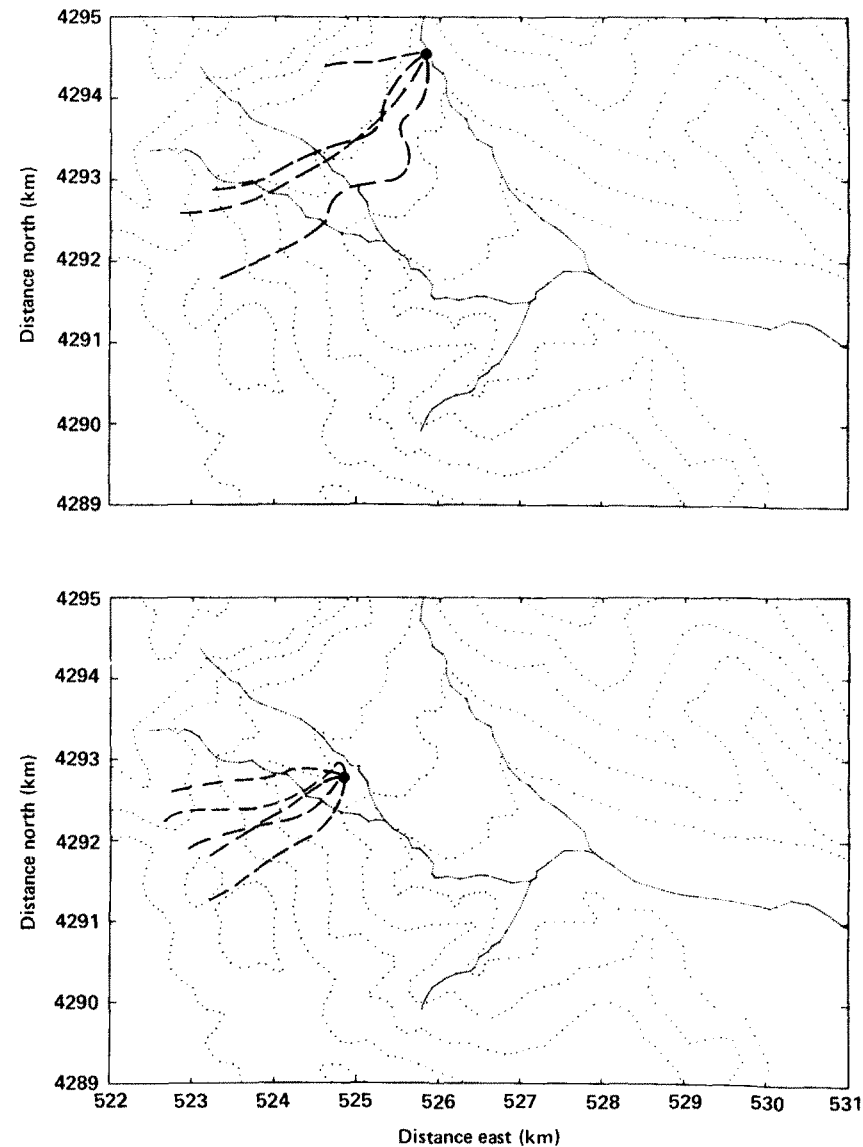


Fig. 13. Tetraon trajectories observed during Experiment 2 from the Putah Creek release site (top) and Anderson Creek release site (bottom).

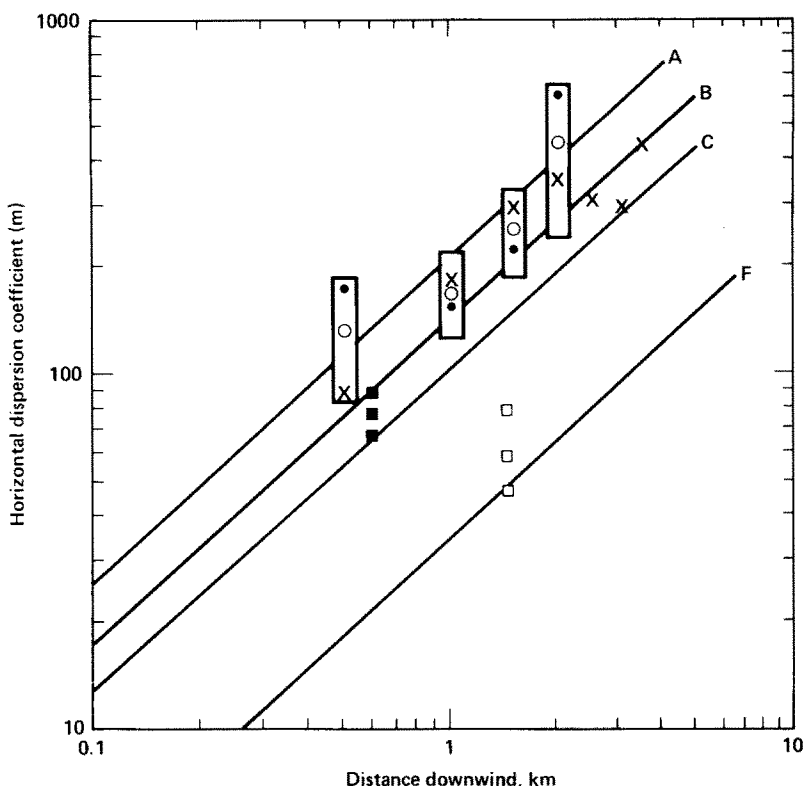


Fig. 14. A comparison of the dispersion coefficients derived from the tetraol clusters and perfluorocarbons released during all experiments with the Pasquill-Gifford-Turner dispersion curves. Values derived from the clusters released in Putah Creek are denoted by (x) and in Anderson Creek by (o); while (o) represents the means for both drainages. The vertical bars denote one standard deviation about the mean. The (□) denote values derived from the PDCH distributions, and (■) denote values derived from the PMCH distributions.

data from about 35 surface and 8 upper air observation sites in conjunction with three dimensional mass consistent flow modeling to derive the flow patterns at the surface and at selected heights above the surface. Using Experiment 4 as the basis for discussion, the flow patterns at the surface and 100 m above the surface during the tracer release period are displayed in Fig. 15. Note the general NW to N ridge flows that are aligned with and possibly reinforce the surface downslope flows predominating within the valley. Hence, one observes the strong down canyon flows within the Putah Creek drainage area which account for the rapid transport of the SF_6 tracer in a southeasterly direction toward the outflow region. Also note that the surface flows within the Anderson Creek area display a relatively weak northeasterly component in the vicinity of Anderson Springs that is most likely responsible for the northward transport of the perfluorocarbon, heavy methane and oil fog tracers into the Putah Creek drainage area. The flow pattern at the 100 m level seems to be in reasonable accord with the trajectories produced by the tetraols released within the Putah and Anderson Creek drainage areas. The qualitative features of these flow patterns persisted

until the morning break-up of the drainage flows. In general, the downslope surface flow pattern was typical for all experiments for the mid-valley and lower elevations; while the flows observed within the upper reaches of the valley were primarily governed by the synoptically induced regional scale flows over the ridges. Thus, the flow structure in the vertical showed considerable variability from one experiment to another due to the constantly changing synoptic situation. This is amply demonstrated by the situation that prevailed during Experiment 2 when N-NE flows predominated over the ridges, as shown in Fig. 16 while downslope surface flows prevailed within the lower portions of the valleys. Thus, the northeasterly flows at the 100 m level above the Putah and Anderson Creek tetraol release sites were responsible for the southwesterly tetraol trajectories given in Fig. 13. Likewise, the lower heavy methane concentrations measured during Experiment 2 within the valley basin relative to those observed during Experiment 4 may be due to some fraction of both tracers being transported toward the southwest. Unfortunately, no sampler was situated in this sector to confirm this hypothesis, but appears likely since the methane release site was

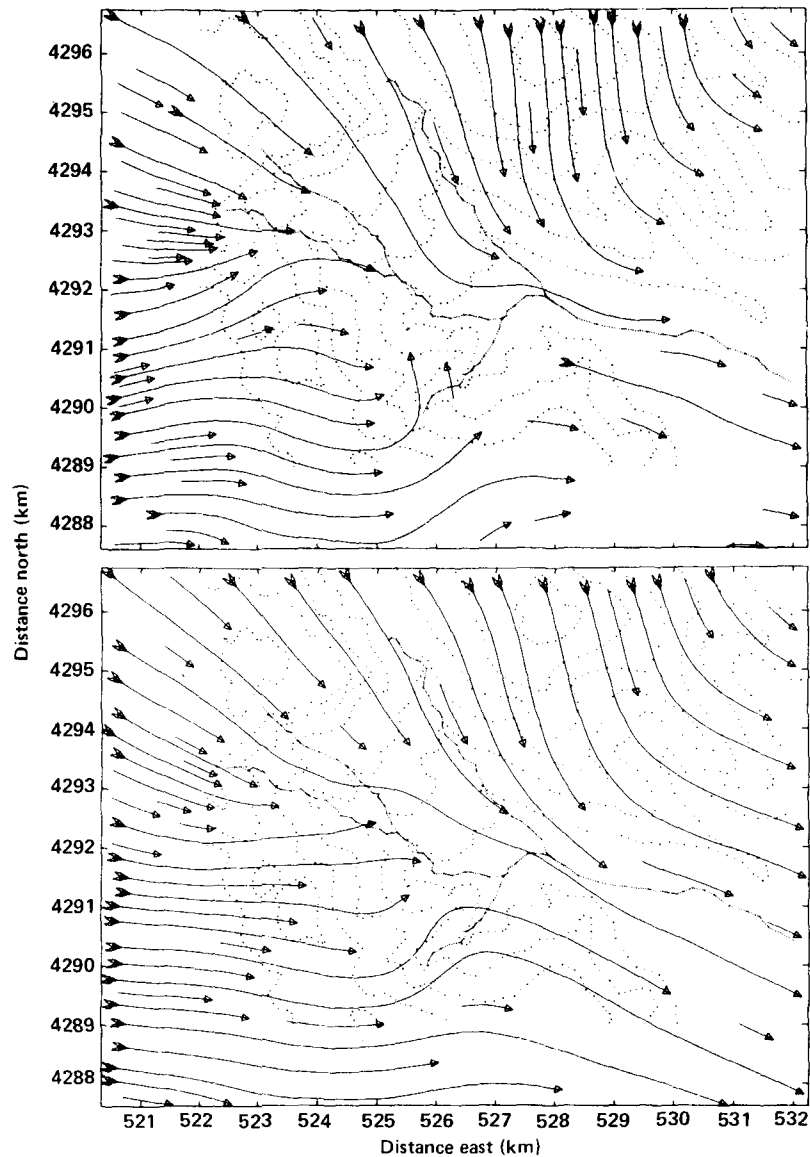


Fig. 15. Flow lines of surface wind velocities (top) and at 100 m above the surface (bottom) during the Experiment 4 tracer release period.

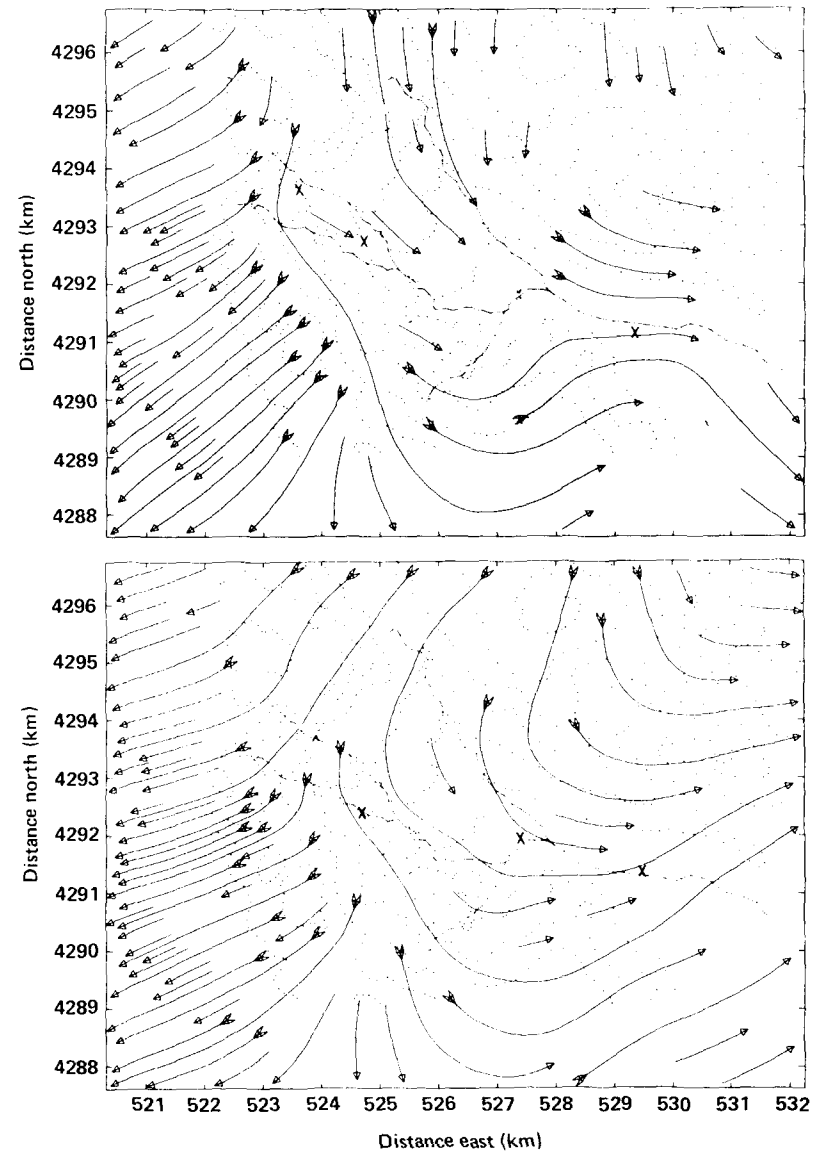


Fig. 16. Flow lines of surface wind velocities (top) and at 100 m above the surface (bottom) during the Experiment 2 tracer release period.

situated far enough up the slopes to be influenced by these flows.

To account for the differences in the vertical distributions of the gaseous tracers observed over the valley basin during Experiments 2 and 4, it is useful to refer to the streamfunction analyses performed by Yamada *et al.* (1982). These analyses, which are based on data acquired by the tethersondes, are shown in Fig. 17 for Experiment 4. This figure represents an E-W cross-section of the valley. During Experiment 4 two recirculation areas appear; one over the slopes and the other over the valley basin. Note the convergence of the downslope drainage flows beneath these recirculation systems. This permitted the tracers to be transported quite independently of these recirculation systems to produce the relatively stable configurations within the valley basin as characterized by the rapid decrease of concentration with height. This is contrasted in Fig. 18

by the situation observed during Experiment 2 when the recirculation system produced rather vigorous vertical mixing within the basin leading to the more homogenous gaseous tracer distributions observed during this experiment.

3. CONCLUSIONS

Analysis of the results of these tracer studies has yielded the following conclusions in regard to transport and dispersion phenomena associated with nocturnal drainage flows within the Anderson Creek valley.

- (1) The degree of interactions of the drainage flows with the larger scale flows are strongly dependent on how well the surrounding topography shields the shallow drainage flows from the external environment.
- (2) The downslope surface flow patterns from

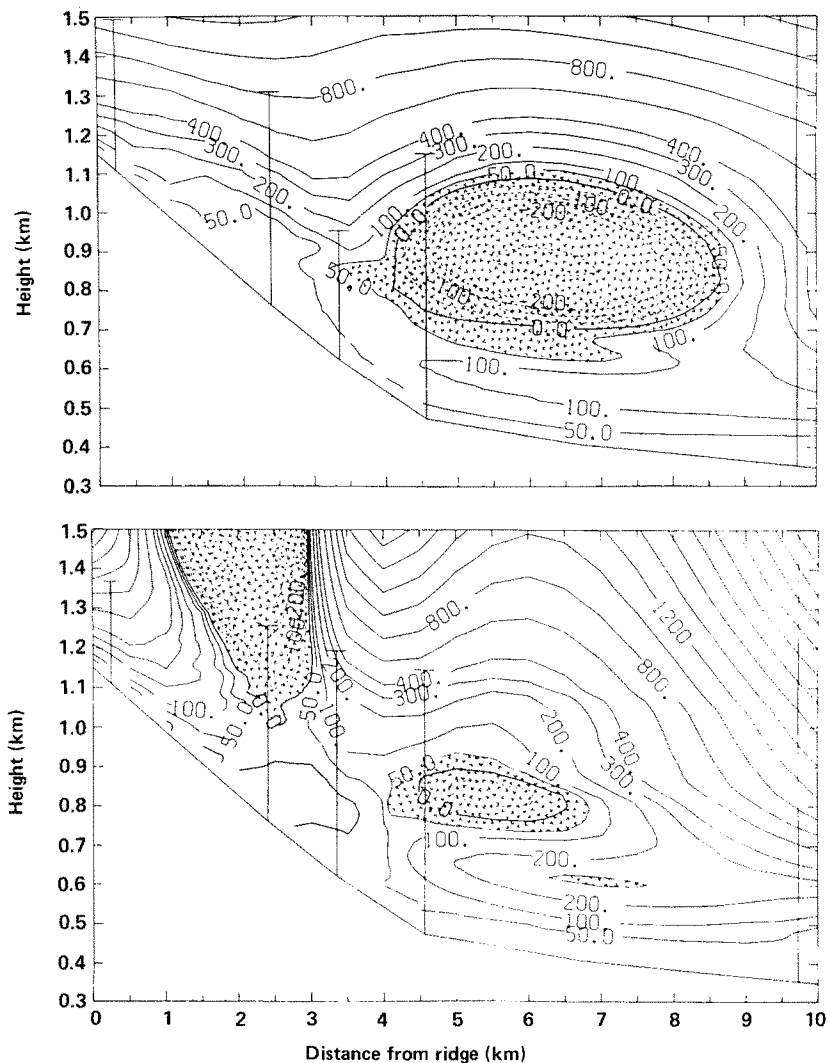


Fig. 17. East-west cross-sections of the Anderson Creek valley showing streamlines for 0100 and 0300 PST during Experiment 4. The stippled areas signify recirculation systems; while the vertical lines denote tethered sonde locations. (Data by T. Yamada *et al.* 1982)

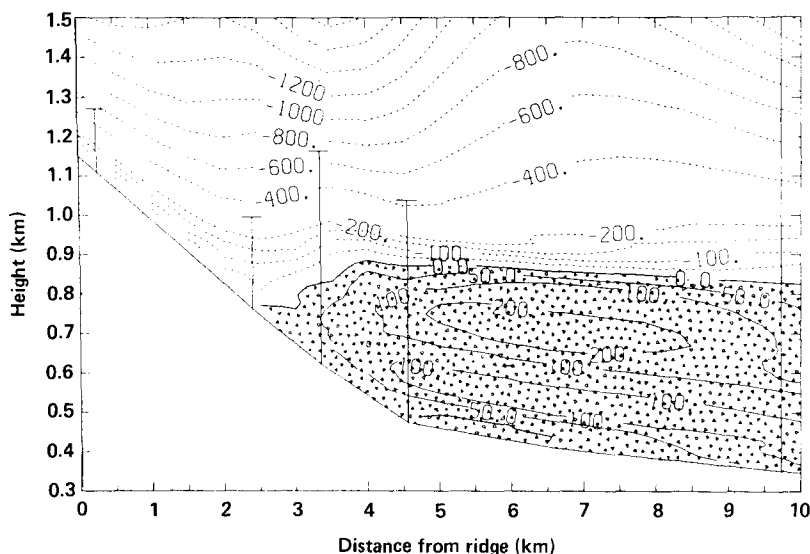


Fig. 18. East-west cross-sections of the Anderson Creek valley showing streamlines for 0100 PST during Experiment 2. The stipled areas denote recirculation systems; while the vertical lines signify tether sonde locations. (Data by T. Yamada *et al.* 1982).

about mid-slope elevation and below were in general fairly well decoupled from the regional flows. Thus, the surface concentration distributions resulting from tracer releases near the mid-slope elevation and below were similar from one drainage flow situation to another.

(3) Considerable mixing does occur between the transition layer flows and the underlying drainage flows observed high up on the slopes near the ridge top. Thus, the surface concentrations within the valley basin resulting from a tracer injected into the lower levels of the transition layer at such a site may only be a factor of 3–5 less than those produced by a tracer injected directly into the drainage flows at the same site.

(4) The vertical distributions of the tracer concentrations over the valley basin are extremely dependent on the influences of the regional scale flows. Very complex circulation systems can be generated aloft due to these influences, which may serve to markedly alter the vertical concentration gradients. In spite of these influences, the tracer plume fronts persistently seemed to be transported within elevated layers over the valley basin with the bulk of the tracer arriving at the surface of the valley basin within the next 1–2 h.

(5) The principal effect of the forest canopy encountered in these experiments was to inhibit the dispersion of the tracer to produce more concentrated plumes. There was also some indication that the canopy caused a slight holdback of a tracer relative to that for a tracer released outside the canopy.

(6) The oil fog plumes were characteristically quite patchy or lumpy in appearance when viewed by the lidar on a timescale of the order of a few min. The horizontal scales of these lumps were generally about 300 m within the first 3 km of the release point and up

to 600 m at greater distances. This heterogeneity did not appear in the gaseous tracer plumes; most likely due to the much longer sampling averaging times.

(7) The dispersion coefficients, derived from the analysis of clusters of tetroons flown within the transition layer reflect the constraints of topography. Lower values were obtained within the narrow and steep Putah Creek canyon relative to those obtained in a similar manner within the wider and broader Anderson Creek drainage area. The ensemble of values fall near the Pasquill–Gifford–Turner A and B stability curves. Dispersion coefficients derived from the surface distribution of the perfluorocarbon tracers fall between the B and F stability curves.

Finally, the general characteristics of the spatial and temporal variations of the tracer distributions could be accounted for by analysis of the flow fields derived from the meteorological observations.

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