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TRACER DISTRIBUTIONS IN BRUSH CREEK VALLEY DRAINAGE FLOW DERIVED FROM 1984 ASCOT DATA

K. Shankar Rao
R. Seshu Tangirala*
Rayford P. Hosker Jr.
Atmospheric Turbulence and Diffusion Division
Oak Ridge, Tennessee

*Jawaharlal Nehru University
New Delhi, India

Air Resources Laboratory
Silver Spring, Maryland
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NOTATION

ATDL2	Atmospheric Turbulence and Diffusion Laboratory (Suffix 2 denotes ATDL's valley site)
C	Surface tracer concentration $(p\ell/\ell)$
CSU	Colorado State University
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
MST	Mountain Standard Time
PACK	Pack Canyon
PNL1	Pacific Northwest Laboratory (Suffix 1 denotes PNL's valley site)
Q	Tracer release rate (g/s)
WPL	Wave Propagation Labortaory

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K. Shankar Rao, R. Seshu Tangirala, and Rayford P. Hosker Jr.

ABSTRACT. Observed concentrations of two perfluorocarbon tracers, which were released simultaneously at the same site at two different heights within drainage flow in Brush Creek Valley during the 1984 ASCOT experiment, were analyzed. Along-valley-axis and across-valley average tracer concentration isopleths from elevated and surface releases were plotted every 1.5 hrs from 0100 to 1000 MST for two experimental dates, 26 September and 30 September. These tracer distributions are presented in this report, and are discussed in relation to the release height, topography, and meteorological conditions. The results and analysis given here are intended to aid in understanding pollutant transport and dispersion in deep valleys, and in evaluating model simulations.

1. INTRODUCTION

In the autumn of 1984, the Atmospheric Studies in Complex Terrain (ASCOT) program of the U.S. Department of Energy conducted a major field experiment in Brush Creek Valley, a 25 km long canyon located about 50 km NNE of Grand Junction, Colorado. Brush Creek drains into Roan Creek, which subsequently drains into the Colorado River Valley.

The overall objective of the 1984 ASCOT experiment was to improve knowledge of pollutant transport and diffusion in valley flows. A large number of instruments including a Doppler lidar, several Doppler acoustic sounders (sodars), tethered balloons, and micrometeorological towers, were deployed within the valley to obtain wind and temperature distributions and turbulence data. Two conservative gaseous tracers were simultaneously released at different heights at a site within the valley. The resulting surface concentrations were sampled at 90 sites, and vertical concentration profiles were measured at 11 sites. Most of these sampling sites were located within the Brush Creek Valley. The tracers were released at a nominal rate of 0.2 g/s from approximately 0000–0900 MST in five tests on different dates (see Table 1) during the 1984 ASCOT field study. Clements *et al.* (1989) described the design of the ASCOT experiment in Brush Creek Valley, including technical objectives and associated measurements.

This report presents detailed tracer distributions within the Brush Creek Valley on two experimental dates, 26 September and 30 September, 1984, when well-established drainage flows were observed. These distributions are briefly discussed in relation to tracer release height, topography, and meteorology. The plots and analysis given in this report are intended for use in developing and testing models of pollutant transport and dispersion in valley environments.

Table 1. Tracer tests during 1984 ASCOT experiment

Test No.	Date
1	20 September
2	26 September
3	28 September
4	30 September
5	6 October

2. 1984 ASCOT TRACER EXPERIMENTS

The tracer experiments were conducted within the lowest 10 km length of the Brush Creek Valley (39.5° N, 108.5° W), which is oriented from NW to SE and has an average depth of 600 m. This part of the valley has a floor grade of about 2% and steep sidewalls with slopes of 30° to 40° cut by numerous small tributaries. The width of the valley floor gradually increases from about 300 m at mid-valley to about 700 m near its mouth, where the valley is about 650 m deep.

The Brush Creek Valley tracer experiments were designed to evaluate the transport and diffusion within the nocturnal valley flows and the transition layer above, and the rate of ventilation of tracers out of the valley during the morning transition period. Two highly detectable perfluorocarbon tracer gases were simultaneously released at site S (719.06 km UTME, 4383.92 km UTMN, 1926 m ASL; see Fig. 1) within the valley. One of them, perfluoromethylcyclohexane (PMCH, or PP2), was released near the surface (5 m AGL), and the other, perfluorodimethylcyclohexane (PDCH, or PP3), from a balloon-supported release hose suspended at a height of 200 m directly above the surface release site. The actual release heights varied from these nominal heights due to difficulties in stabilizing the balloon carrying the tracer hose. The detailed release conditions for the two tracer tests analyzed in this report are given in Section 3.

The surface sampling network consisted of 34 BATS (Brookhaven Atmospheric Tracer Samplers) and 20 ARL (Air Resources Laboratory) samplers within the Brush Creek Valley. Of these 54 surface samplers, 25 were situated on arc 1. Arcs 2 and 3 contained 13 and 6 surface samplers, respectively. The remaining samplers were located along the valley axis. The three arcs were roughly perpendicular to the valley axis at distances of 7.2 km, 4 km, and 2.5 km, respectively, from S (Fig. 1). Figure 2 shows locations of the surface samplers on the three arcs. Tracer samplers near the center of

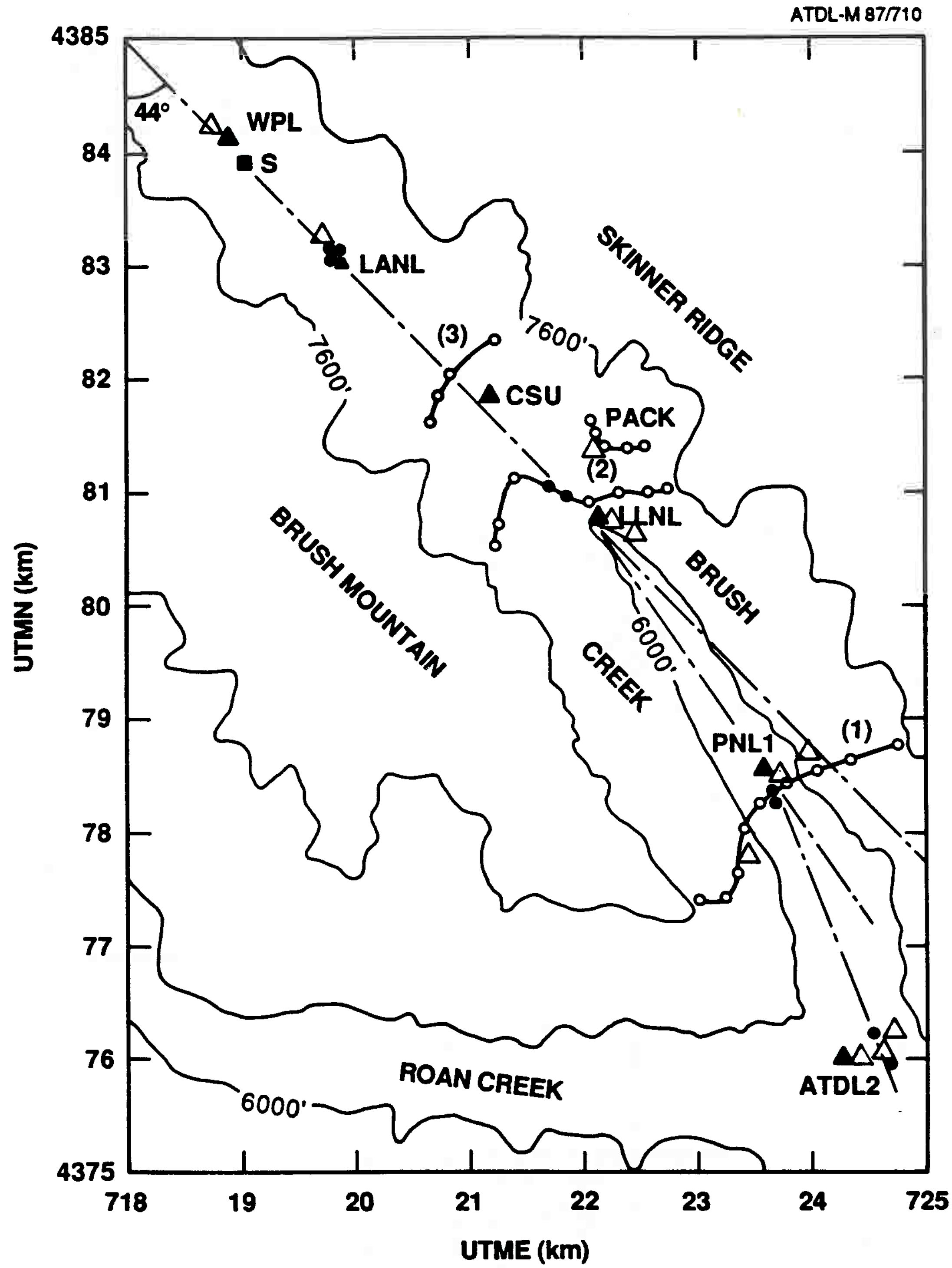


Figure 1. Brush Creek Valley showing the tracer release site (S) and sampling arcs (1), (2), and (3). The arc samplers are denoted by o, and valley-axis samplers by •. The vertical samplers are denoted by Δ, and the tethered-balloon sites by ▲.

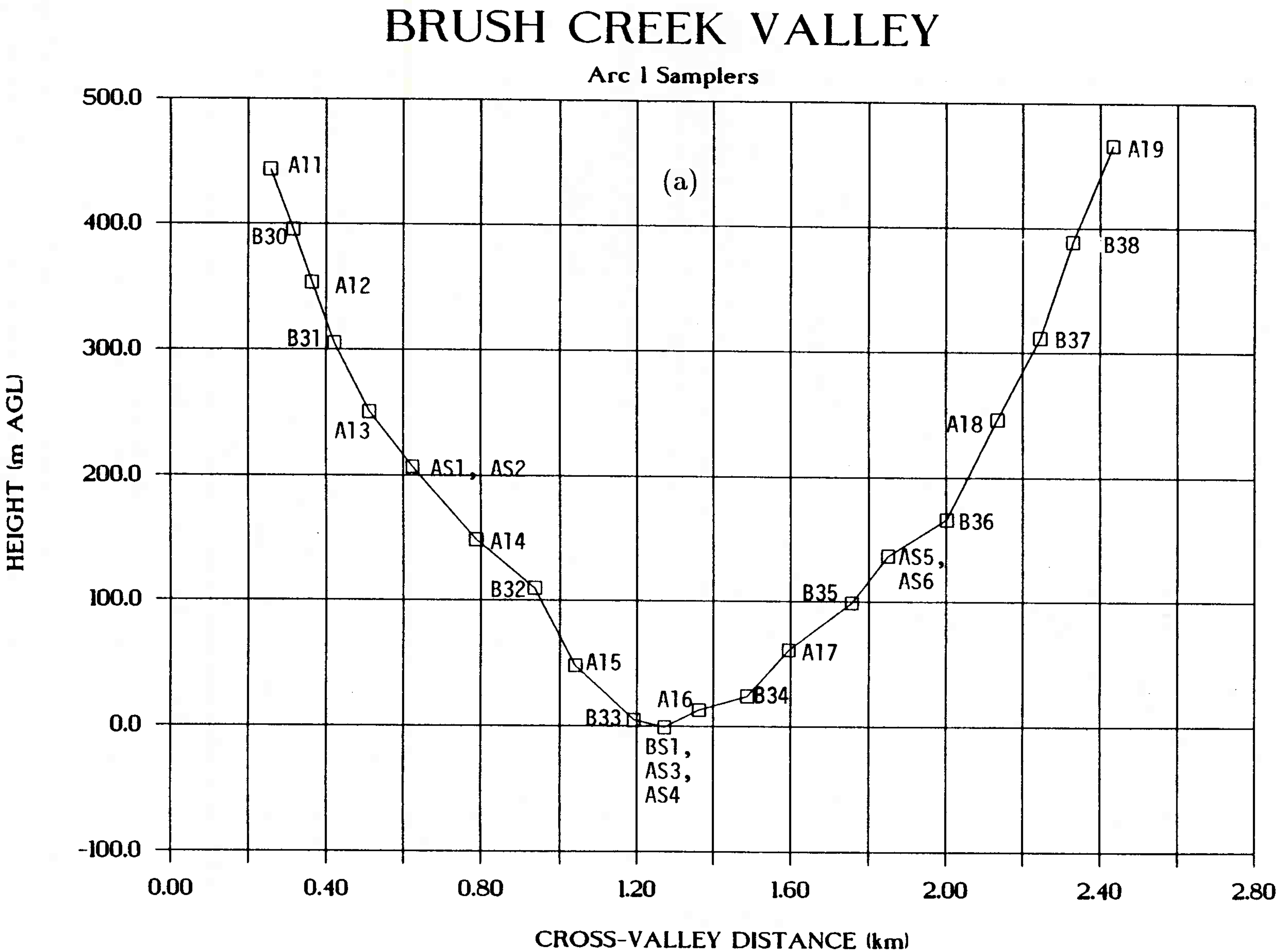


Figure 2. Surface tracer-sampling network in the 1984 ASCOT experiment: (a) samplers on arc 1, (b) samplers on arc 2, and (c) samplers on arc 3. See Table 2 for an explanation of the sampler notation.

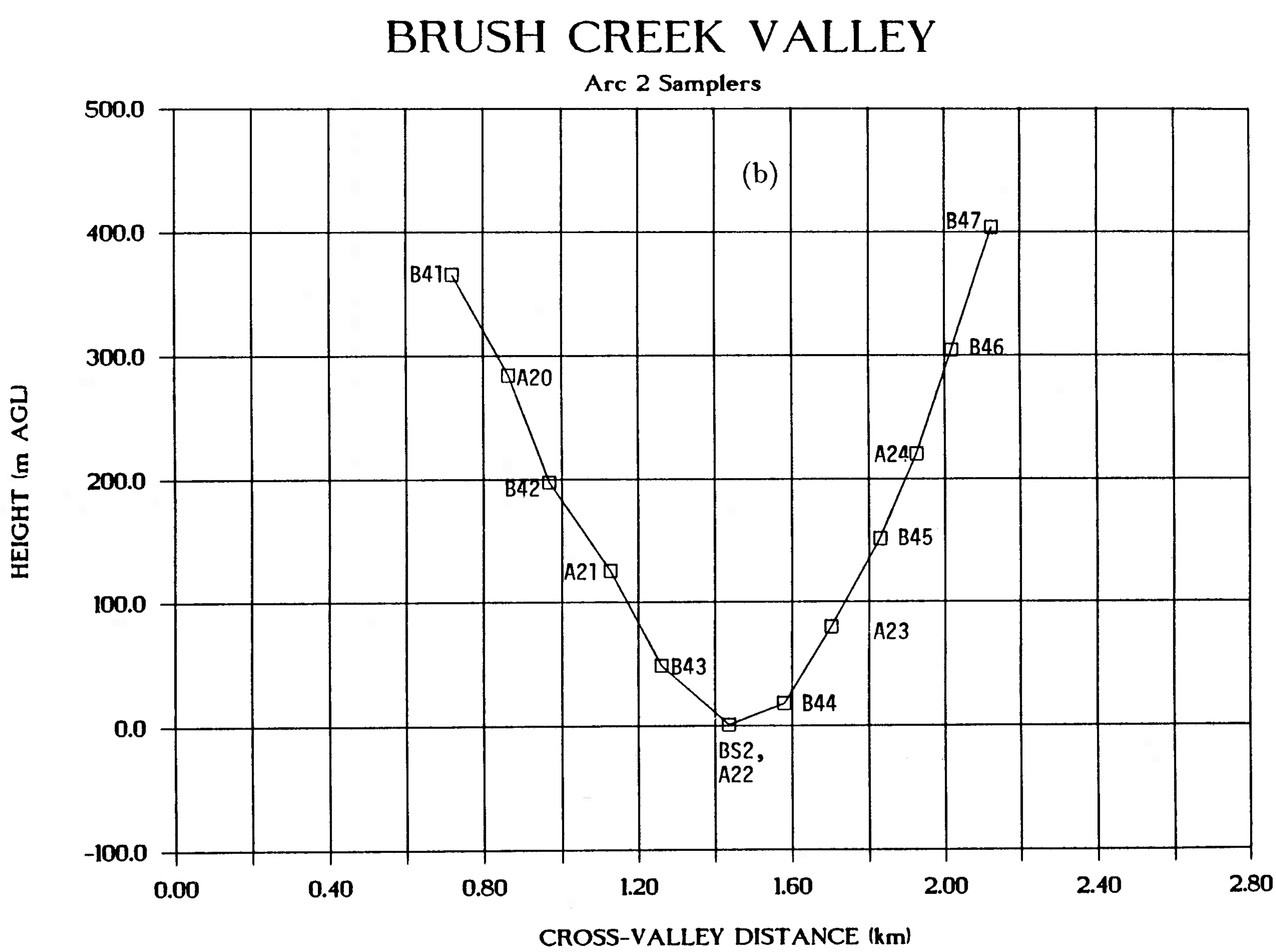

BRUSH CREEK VALLEY
Arc 2 Samplers
(b)
500.0
400.0
300.0
200.0
100.0
0.0
-100.0
HEIGHT (m AGL)
0.00
0.40
0.80
1.20
1.60
2.00
2.40
2.80
CROSS-VALLEY DISTANCE (km)
B41
A20
B42
A21
B43
BS2,
A22
B44
A23
B45
A24
B46
B47

Figure 2(b)

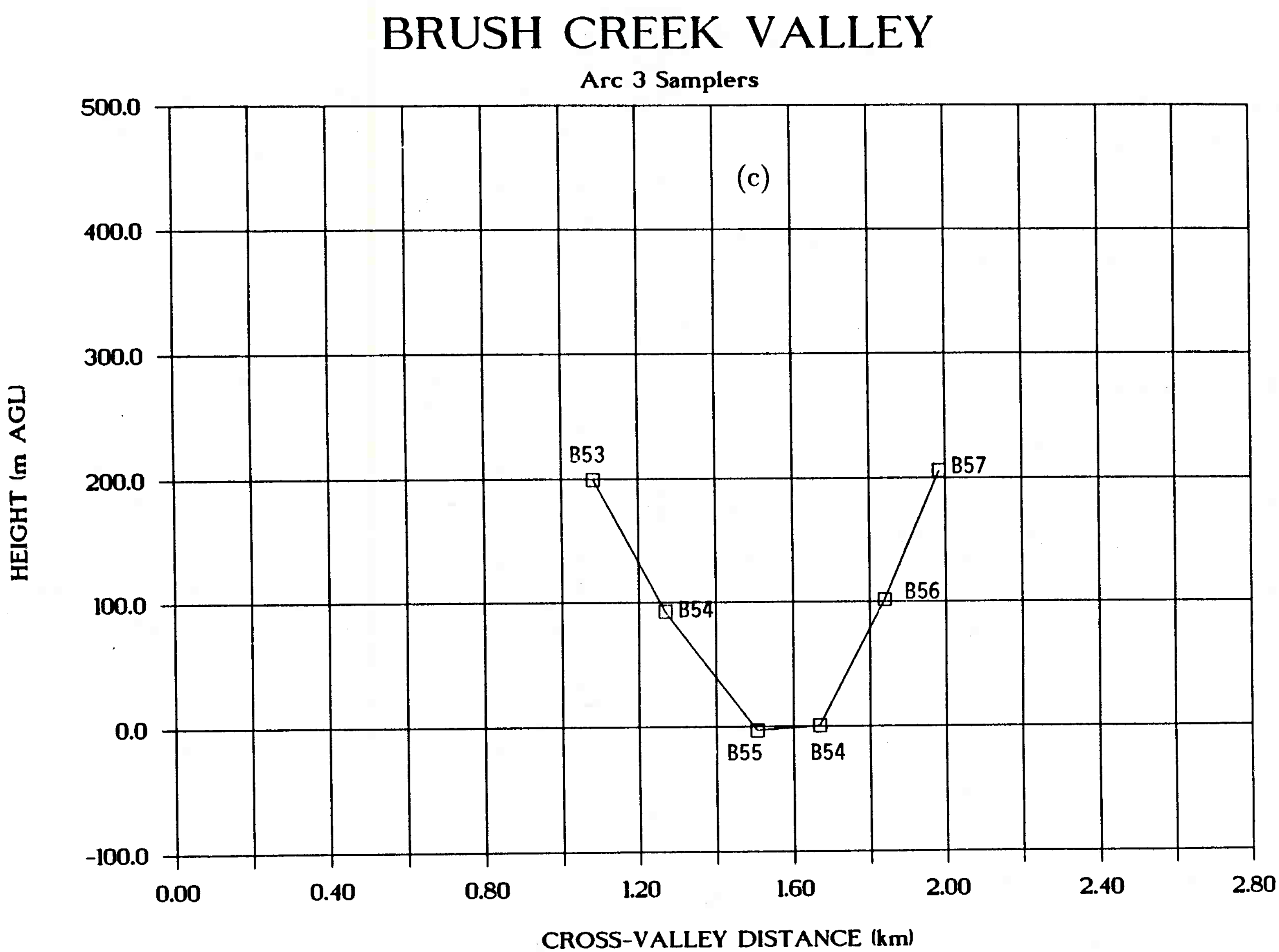

BRUSH CREEK VALLEY
Arc 3 Samplers
(c)
HEIGHT (m AGL)
500.0
400.0
300.0
200.0
100.0
0.0
-100.0
B53
B54
B55
B54
B56
B57
0.00
0.40
0.80
1.20
1.60
2.00
2.40
2.80
CROSS-VALLEY DISTANCE (km)

Figure 2(c)

each arc were located at the bottom of the approximately bowl-shaped cross-section on the valley floor, while the samplers near the ends of the arc extended up the valley sidewalls. Several samplers were also deployed on the ridges and in the adjacent valleys to study the tracer transport out of Brush Creek Valley. The sample collection times varied from 15 to 60 min. Table 2 gives information on the surface samplers, sample collection times, and sampling periods.

Table 2. Surface samplers in Brush Creek Valley and sampling information

Sampler ID No.*	Sample collection time (min)	Sampling period (MST)
Arc 1		
A11 – A19	30	0500 – 1100
B30 – B38	60	0000 – 1000
AS1, AS3, AS5	15	0500 – 0800
AS2, AS4, AS6	15	0800 – 1100
BS1	15	0000 – 0500
Arc 2		
A20 – A24	30	0500 – 1100
B41 – B47	60	0000 – 1000
BS2	15	0000 – 0500
Arc 3		
B53 – B57	60	0000 – 1000
BS4	15	0000 – 0500
Valley Axis		
B2, B3, B12, B14, B29, B39, B40, B48, B58, B59	60	0000 – 1000

*Prefixes A and B denote ARL and BATS samplers, respectively; AS and BS denote the corresponding sequential samplers.

The locations of the 10 vertical profilers which collected samples to represent sequences at given locations in the valley are shown in Fig. 1. Five of the profilers were EML (Environmental Measurements Laboratory) systems which collected samples simultaneously at fixed heights. Vertical profiles were obtained sequentially at 2-hr intervals starting at 0000 MST, with the last profile starting at 1000 MST (a total of 6 profiles per test). The remaining five profilers operated sampling systems developed by SNL (Sandia National Laboratory), which utilized vertically ascending balloon-borne samplers. Each of these systems periodically switched to a new sampling tube upon command from the ground-based operator. These profiles were obtained every 1.5 hrs starting at 0100 MST, with the last profile starting at 1000 MST (a total of 7 profiles per test). The resulting samples, which were not simultaneous in time, tend to represent height-averaged concentrations.

Clements *et al.* (1987) listed the UTM coordinates and MSL elevations of all tracer sampler sites in the 1984 ASCOT experiment. The tracer data analysis in this report utilized the samplers along the valley axis, and the samplers located on arc 1. There were three vertical samplers located along this arc (see Fig. 1), which provided tracer concentrations averaged over very short periods (less than 3 min) in different layers above the ground. Surface samplers provided tracer concentrations averaged over periods of 15 min or more (Table 2). Utilizing the available vertical soundings and the time-averaged values of surface tracer concentrations, isopleths are drawn across arc 1 and along the valley-axis for sampling periods starting at 0100, 0230, 0400, 0530, 0700, 0830, and 1000 MST. The concentration isopleths across arc 1 were plotted using UTME (km) coordinates along the abscissa, and elevations (km MSL) along the ordinate; the vertical scale was exaggerated by a factor of 1.6. For the isopleths along the valley-axis, the UTMN (km) coordinates were plotted along the abscissa with origin at 4385 km and decreasing to the right, and elevations (km MSL) along the ordinate; the vertical scale was exaggerated by a factor of 7.5. The volumetric tracer concentrations were expressed relative to NTP (293° K and 1 atm) in pico-litres ($10^{-12}\ell$) of tracer per litre of air ($p\ell/\ell$). The molecular weights of PMCH (C_7F_{14}) and PDCH (C_8F_{16}) tracers are 350 g and 400 g, respectively.

3. TRACER DISTRIBUTIONS AND DISCUSSION

The tethered balloons (A.I.R. Tethersondes) in Brush Creek Valley (Fig. 1) measured wind speed, wind direction, temperature, wet-bulb temperature, and pressure-altitude. These data were collected during the slow ascent (0.3 m/s) of the balloon up to a maximum altitude of about 800 m above the site with each ascent requiring about 45 min. There were eight ascents, spaced 90 min apart, on each experimental night, with the first ascent starting at 2330 MST and the final ascent starting at 1000 MST the following morning. Barr and Orgill (1989) and Gudiksen and Shearer (1989) discussed the general weather conditions and flow characteristics during the five experimental dates shown in Table 1.

3.1 Test 2 (26 September 1984)

The tracer release conditions for the elevated and surface release experiments of Test 2 are given in Table 3. Tracer Test 2 was conducted under southeasterly to southwesterly winds aloft which varied from 2 to 10 m/s. Clear skies prevailed initially, but high cirrus appeared during the morning transition period. These conditions somewhat inhibited the development of drainage flows, which were hence weaker than those observed on other experimental nights.

Table 3. Tracer release conditions for Test 2

Tracer	Release period (MST)	Release height (m AGL)	Release rate (g/s)
PDCH	0000 – 0200	183	0.240
(PP3)	0200 – 0600	168 – 183	0.245
	0600 – 0900	183	0.240
PMCH	0000 – 0050	75	0.210
(PP2)	0050 – 0900	5	0.226

Figure 3 presents the wind and temperature profiles measured at the WPL tethered balloon site, near the tracer source. They reveal an established drainage flow from the NW until 0700 MST, with a down-valley jet of about 6 m/s intensity located at a height of about 75 m above the valley floor. The top of the drainage layer, characterized by near-zero wind speed and a sharp discontinuity in wind direction, was at a height of about 325 m AGL. The ambient flows predominated above this level. The winds were light and variable at 0830 MST (well after local sunrise), and indicate an apparent transition in direction. The winds increased to about 5 m/s and turned up-valley by 1000 MST. The corresponding profiles at PNL site (near arc 1), shown in Fig. 4, reveal a complicated behavior. Before 0830 MST, there was some variability in wind direction at the PNL site at several heights. The wind speed profiles at 0230 and 0400 MST displayed multiple peaks, perhaps resulting from interaction with intruding cold air from Roan Creek near the Brush Creek exit. The average mixing depth, assumed to be given by the mean depth of drainage flow in Brush Creek Valley, was 375 m during Test 2.

3.1.1 Elevated release

Figures 5-A to 5-G present the concentration contours for the elevated release of PP3 tracer in Test 2. Each of these seven figures shows the concentration isopleths at a given time (start of sampling period) for valley cross-sections (a) across arc 1, and (b) along the valley-axis.

Peak tracer concentrations at arc 1 were observed near the bottom of Brush Creek Canyon toward the east sidewall. The valley drainage flow tended to favor the eastern sidewall, perhaps partly because it had a gentler slope than the western sidewall, and partly because of the slight horizontal curvature of the valley. Doppler lidar wind data

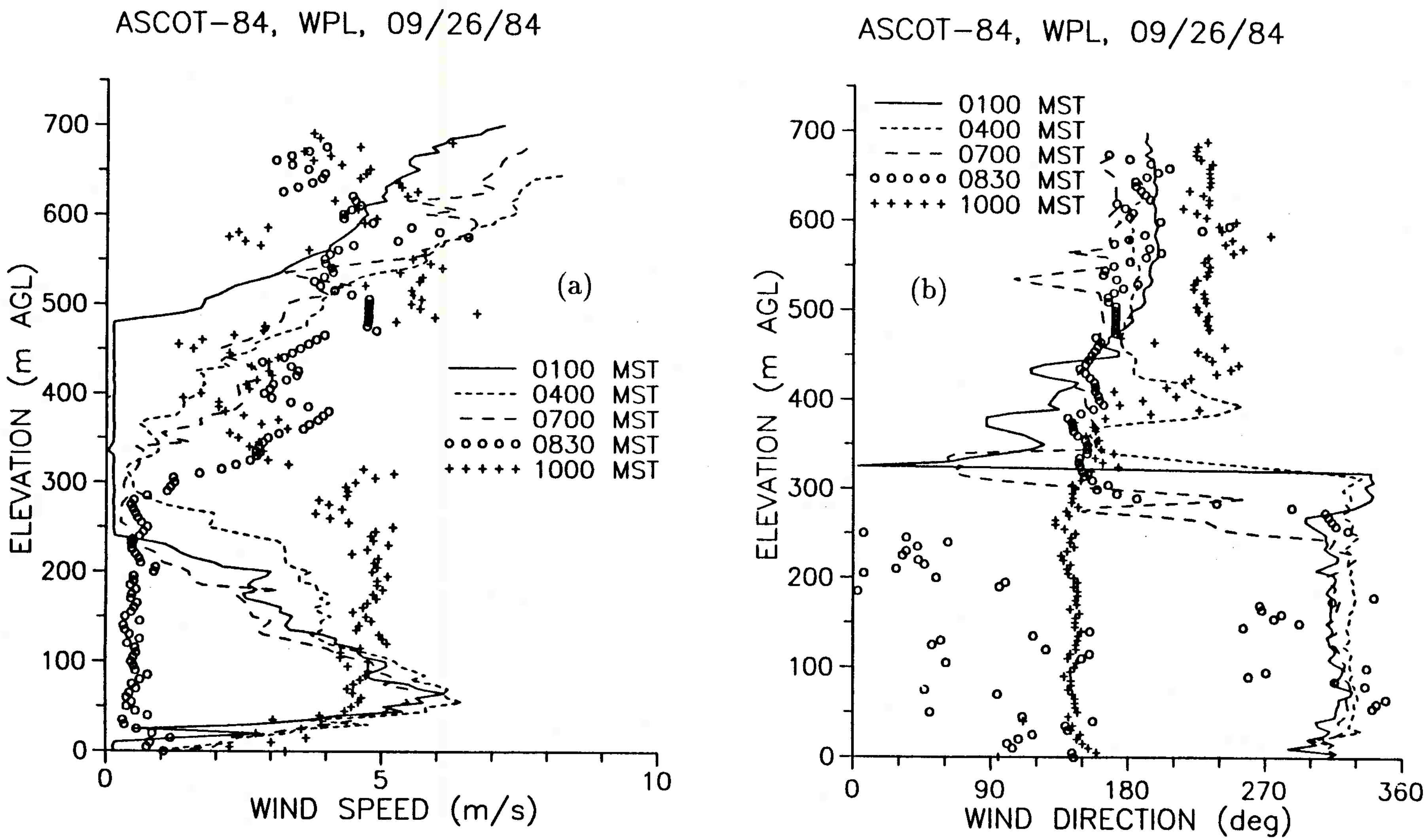
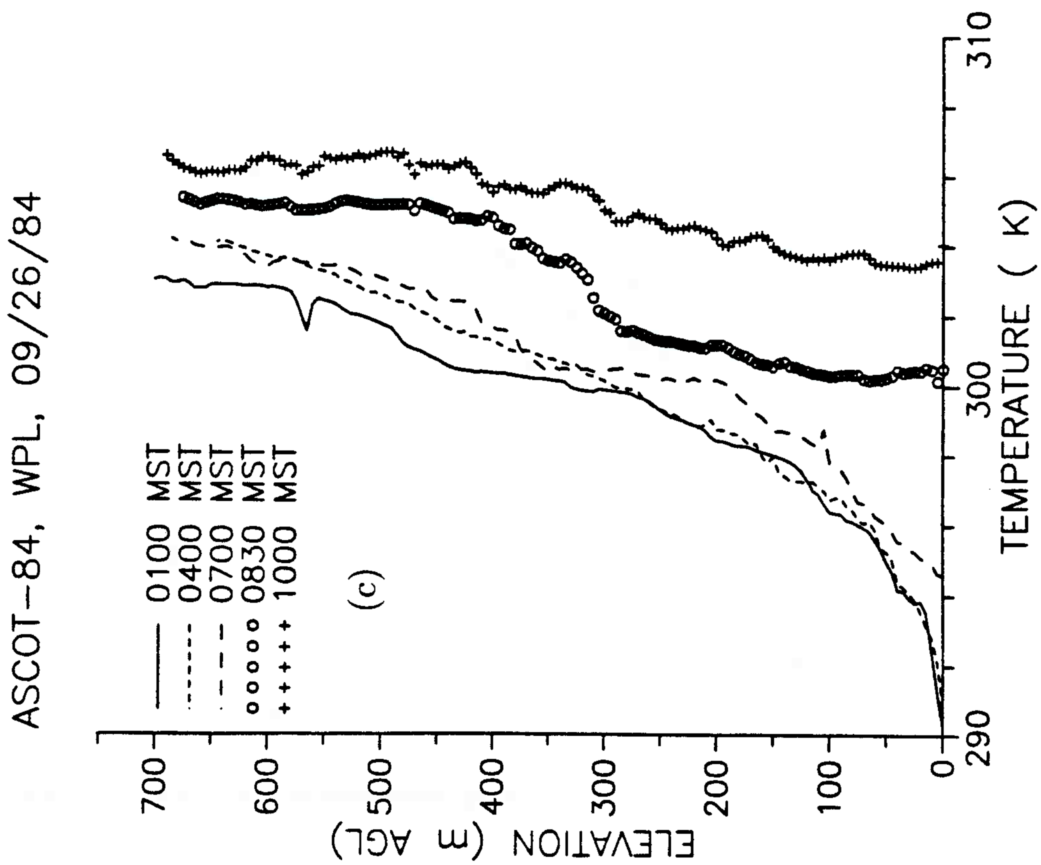


Figure 3. Vertical profiles at the WPL balloon site on 26 September: (a) wind speed, (b) wind direction, and (c) potential temperature.



ASCOT-84, WPL, 09/26/84
0100 MST
0400 MST
0700 MST
0830 MST
1000 MST
(c)
ELEVATION (m AGL)
700
600
500
400
300
200
100
0
290
300
310
TEMPERATURE (K)

Figure 3(c)

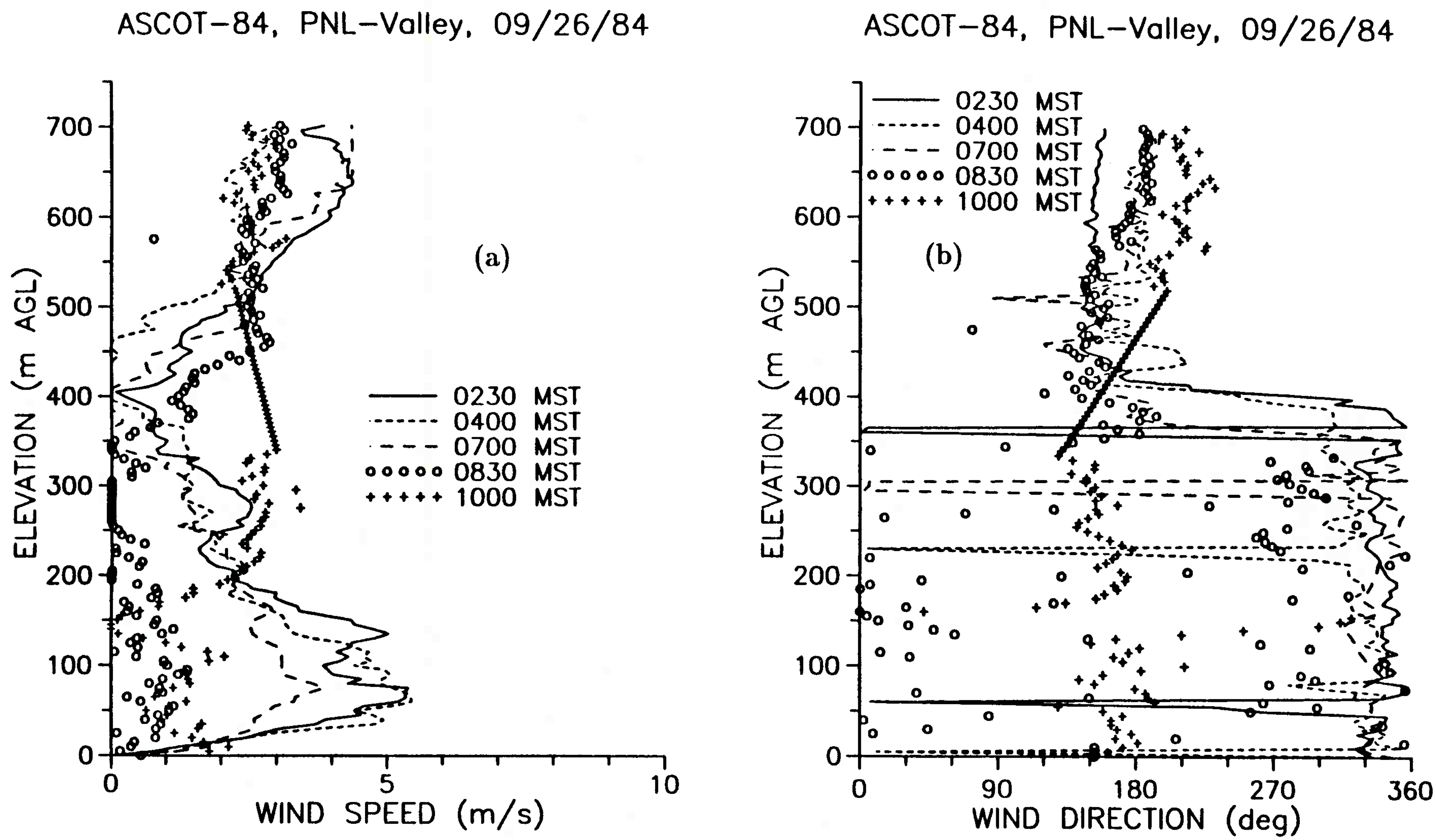


Figure 4. Vertical profiles at the PNL balloon site on 26 September: (a) wind speed, (b) wind direction, and (c) potential temperature.

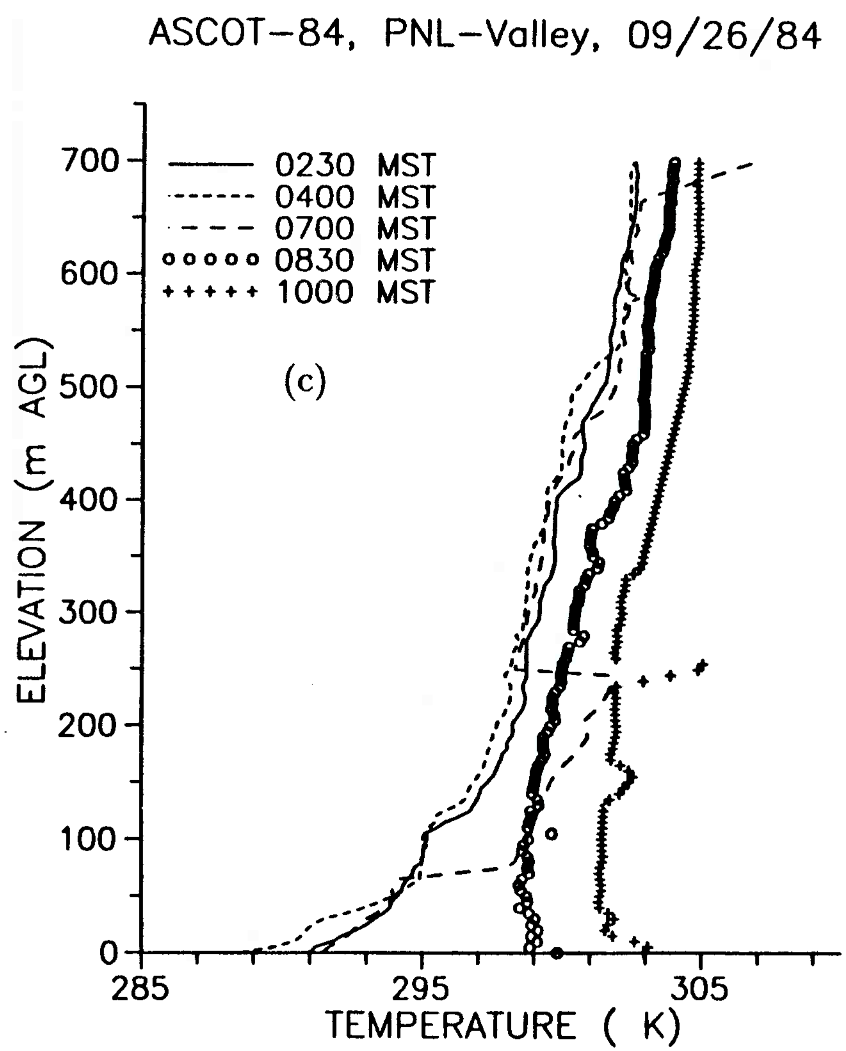

ASCOT−84, PNL−Valley, 09/26/84
0230 MST
0400 MST
0700 MST
0830 MST
1000 MST
(c)
ELEVATION (m AGL)
0
100
200
300
400
500
600
700
285
295
305
TEMPERATURE (K)

Figure 4(c)

in Brush Creek revealed that the nocturnal drainage jet was often located towards the eastern sidewall (see, *e.g.,* Dobosy *et al.*, 1989). During the sampling periods starting at 0230, 0400, and 0530 MST concentration isopleths exhibit oscillations which might have been caused by rotors and internal buoyancy waves, as postulated by Barr and Orgill (1989) and Stone and Hoard (1989).

Even after the local sunrise, which occurred approximately at 0700 MST, maximum concentrations were still observed near the same location on the eastern sidewall. However, a secondary maximum was noticed at the bottom of the western sidewall. By 0830 MST, the western wall was heated enough to cause part of the tracer to be carried up the sidewall by the convective upslope flows. This was clearly noticeable in the concentration contours (Fig. 5-F). Concentrations remained high in the lower part of the valley until up-valley winds became well-established. As the entire valley floor was exposed to the sunshine by 1000 MST, tracer concentrations decreased to small, nearly uniform values across the valley cross-section, because of the cross-valley circulations and convective mixing in the valley.

The tracer distributions along the valley-axis (given in the lower panels (b) of Figs. 5-A to 5-G) show that ground-level samplers located close to the elevated source S recorded fairly high concentrations. Rao *et al.* (1989) suggested this might be due to the occurrence of either a strong subsidence in the valley near the source, or a leak of tracer at the ground (near the release point) that was not accounted for. Estimates of subsidence rates in Brush Creek Valley ranged from 0.01 to 0.1 m/s (see Dobosy *et al.*, 1989). Nappo *et al.* (1989) demonstrated that, for pollutants released from a point source in the middle of the drainage layer over a simple slope, subsidence in the flow leads to relatively high surface concentrations of pollutants close to the stack, especially on a shallow slope. The maximum ground-level concentrations at 0100, 0230, and 0400 MST occurred at about 2 km downwind of S. After the tracer plume centerline descends to the ground, the concentration contours in the outer layer of plume follow the typical velocity contours in a simple drainage flow. No significant concentrations were found at elevations above the tracer release point before sunrise.

The nocturnal drainage flow weakened during the morning transition period, giving way to upslope flows on the western sidewall that led to the ventilation of tracers out of the valley. The maximum ground-level concentrations at 0700 and 0830 MST occurred within about 1 km from S (Figs. 5-E and 5-F). Because of dilution resulting from convective mixing of the surface plume with air above, the ground-level tracer concentrations at 0830 MST were only about half of the concentrations at 0700 MST. As the surface flow direction reversed to an up-valley direction starting at about 0830 MST, the concentration contours (Figs. 5-F and 5-G) suggest that the tracer plume near the surface was stalled and then advected back from the mouth of the valley. After the tracer release ended at 0900 MST, the tracer was confined to the middle part of the valley. By 1000 MST, the tracer concentrations decreased to low levels, because of convective mixing and ventilation into the mesoscale flows aloft.

Test 2, 09/26/84, 0100 MST, PP3

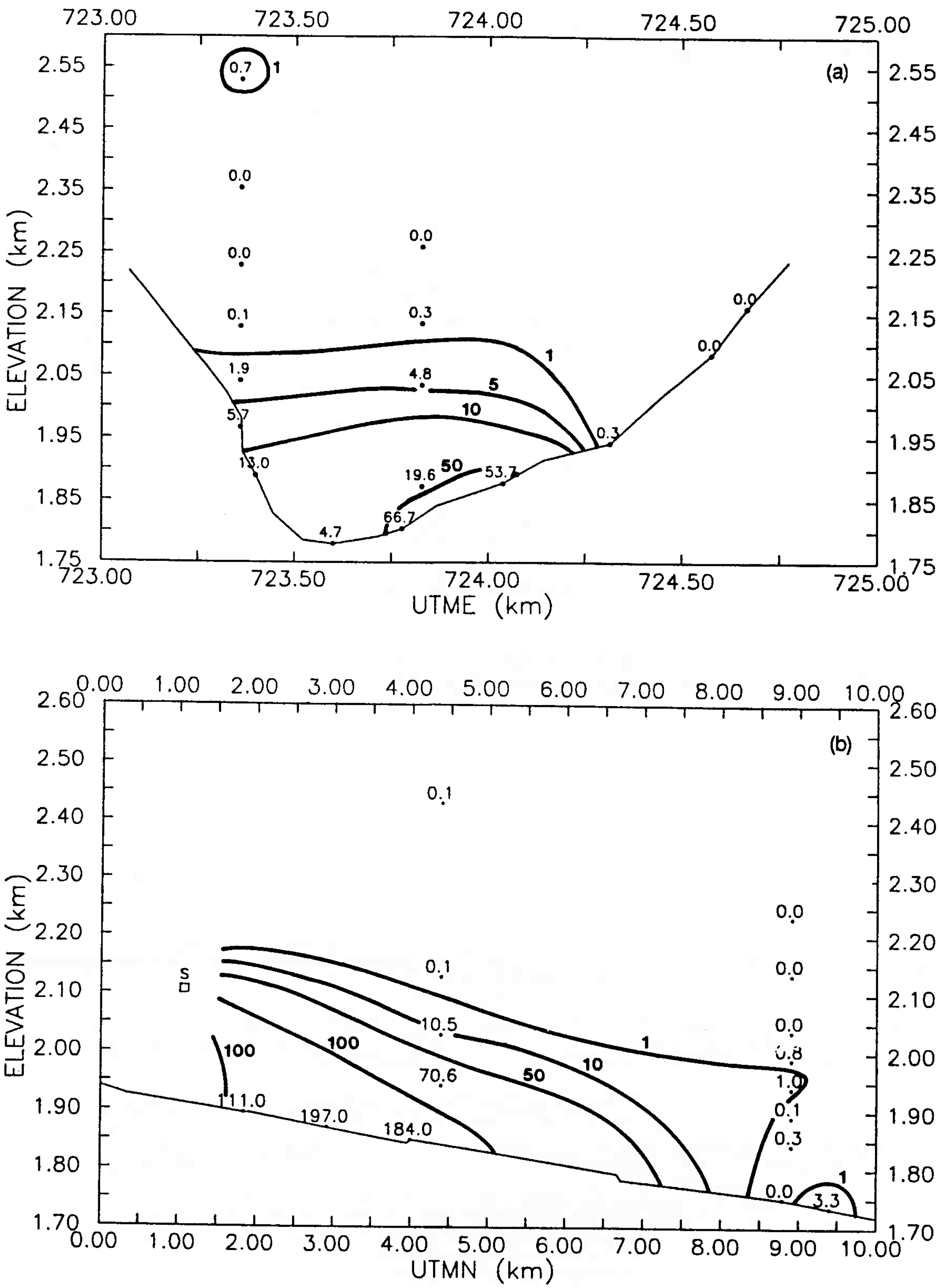


Figure 5. Observed concentrations (in $p\ell/\ell$) of PP3 tracer in Brush Creek Valley for the elevated release in Test 2. Concentration isopleths are shown for valley cross sections (a) along arc 1, and (b) along valley axis at a given time (start of sampling period). Figs. 5-A to 5-G present these plots 90 min apart starting from 0100 MST.

Test 2, 09/26/84, 0230 MST, PP3

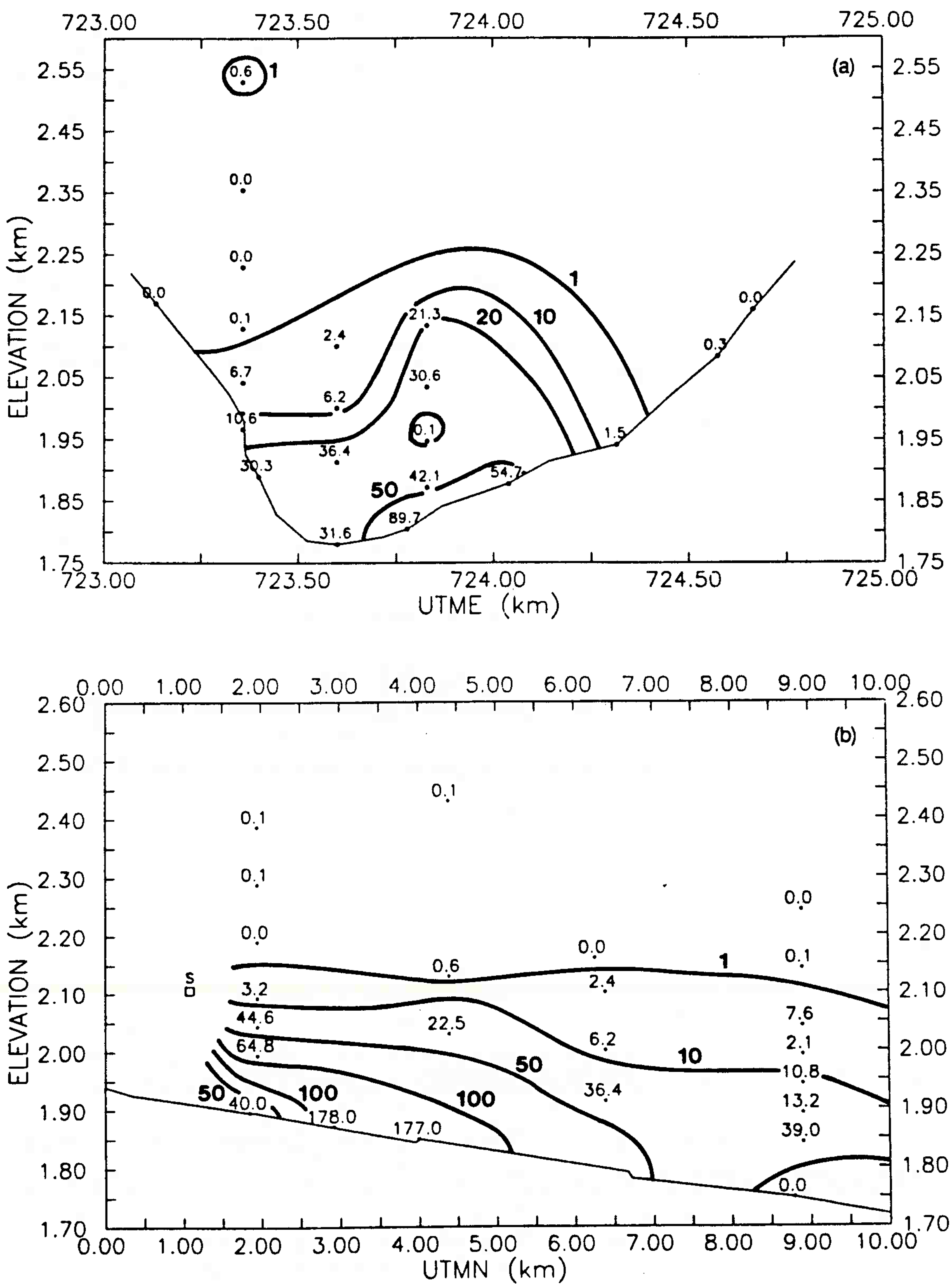


Figure 5-B

Test 2, 09/26/84, 0400 MST, PP3

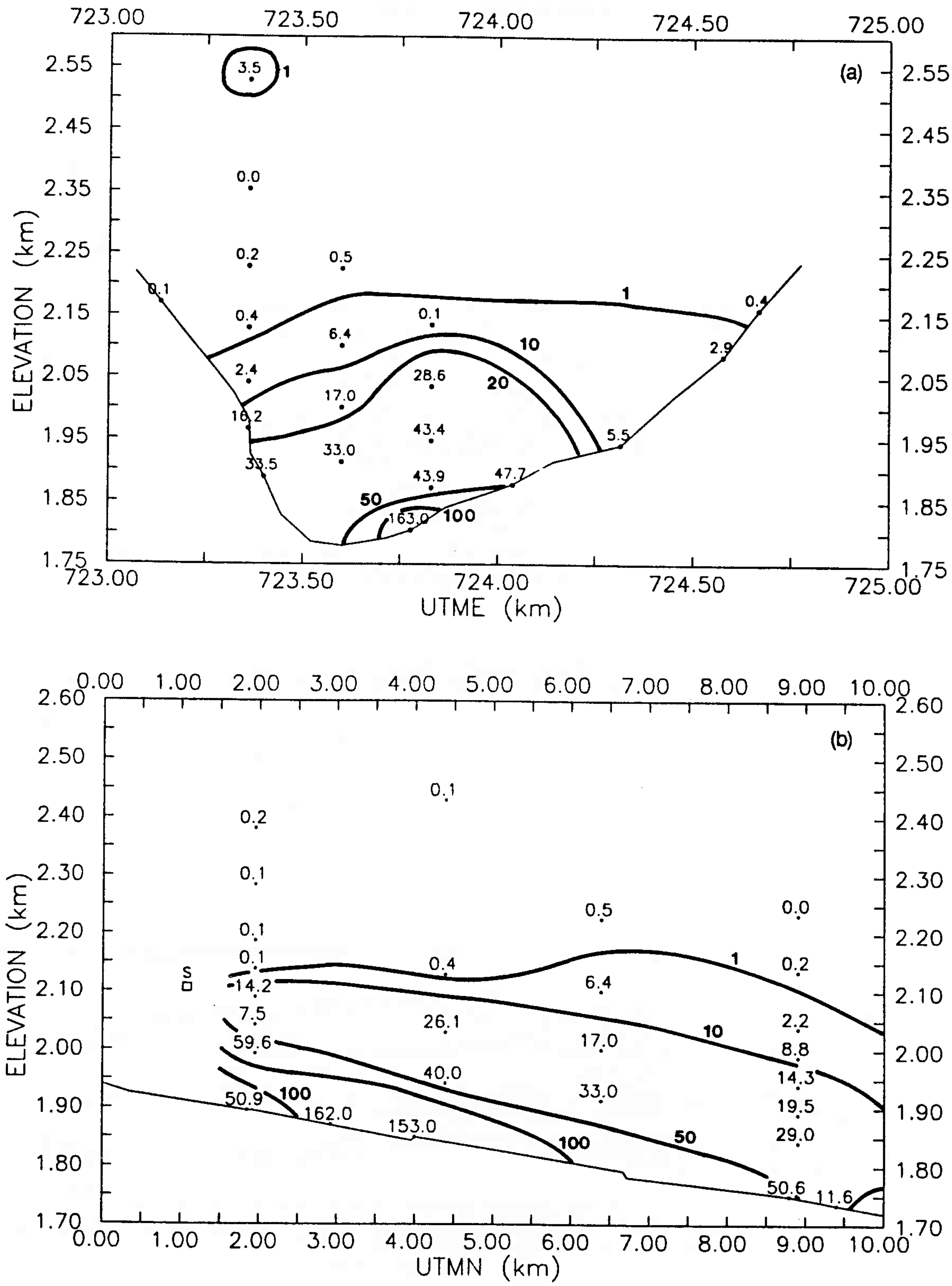
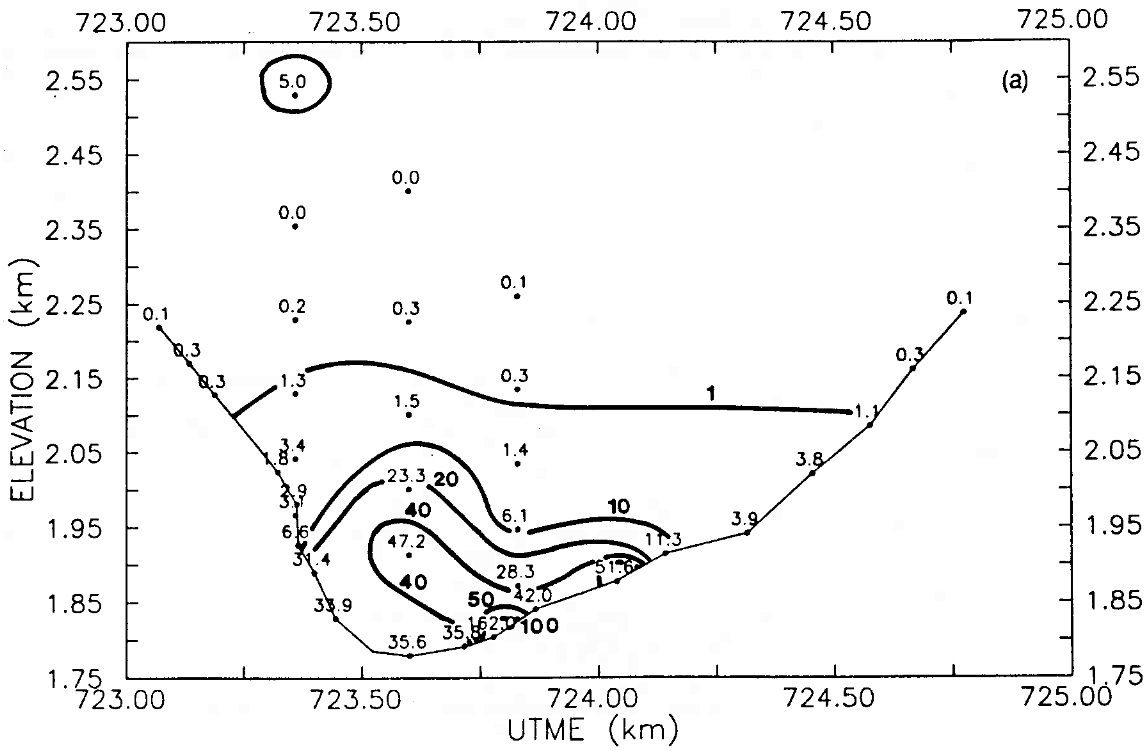


Figure 5-C

Test 2, 09/26/84, 0530 MST, PP3



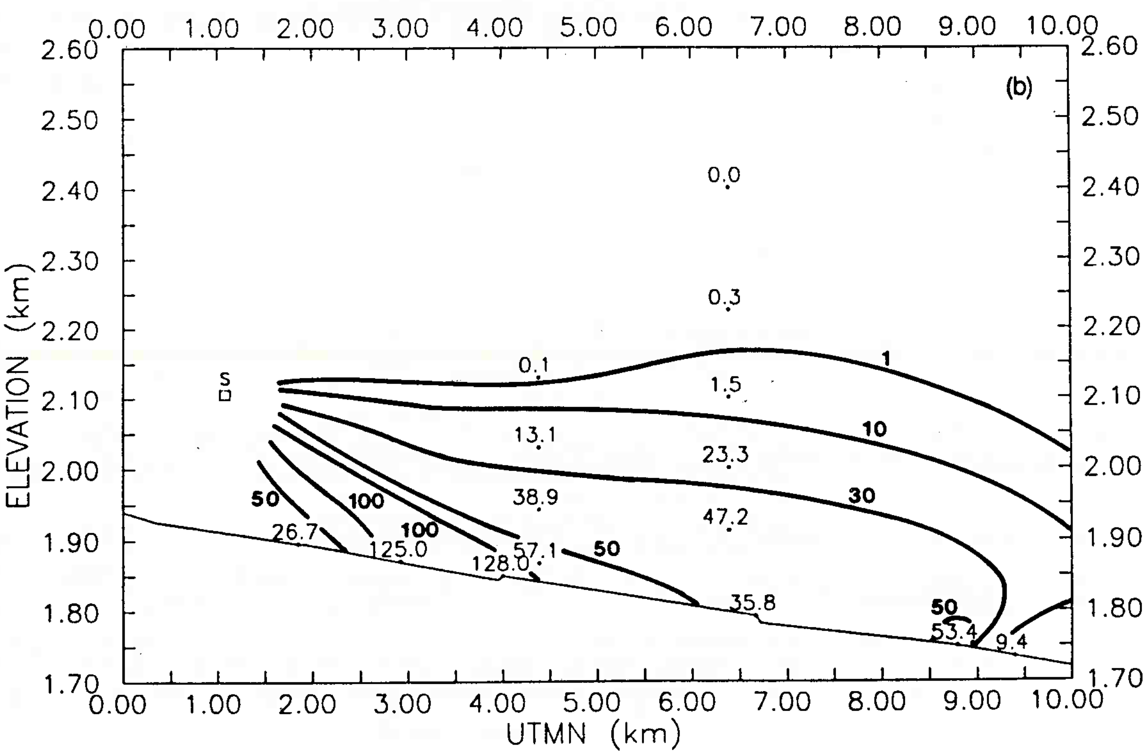


Figure 5-D

Test 2, 09/26/84, 0700 MST, PP3

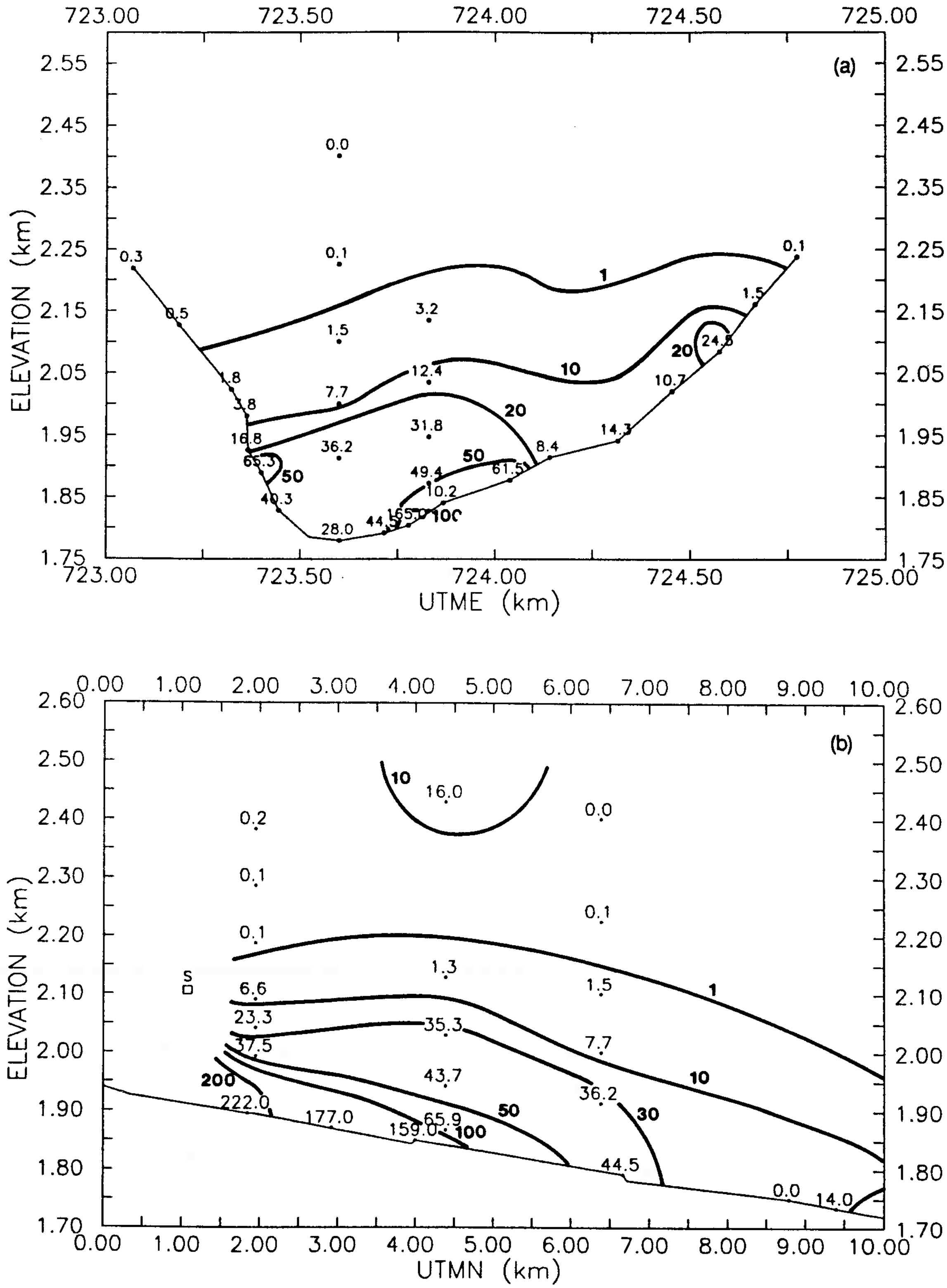


Figure 5-E

Test 2, 09/26/84, 0830 MST, PP3

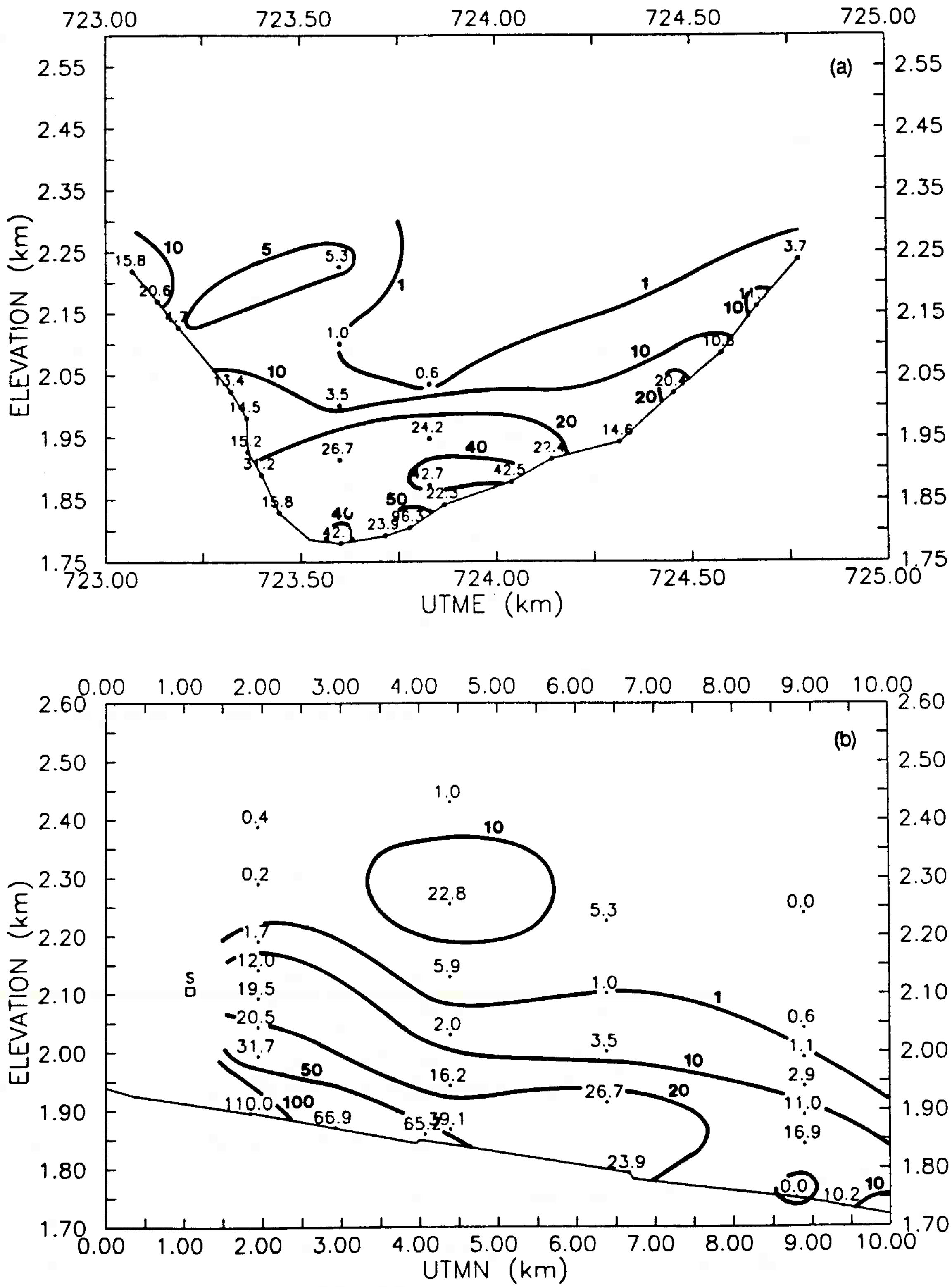


Figure 5-F

Test 2, 09/26/84, 1000 MST, PP3

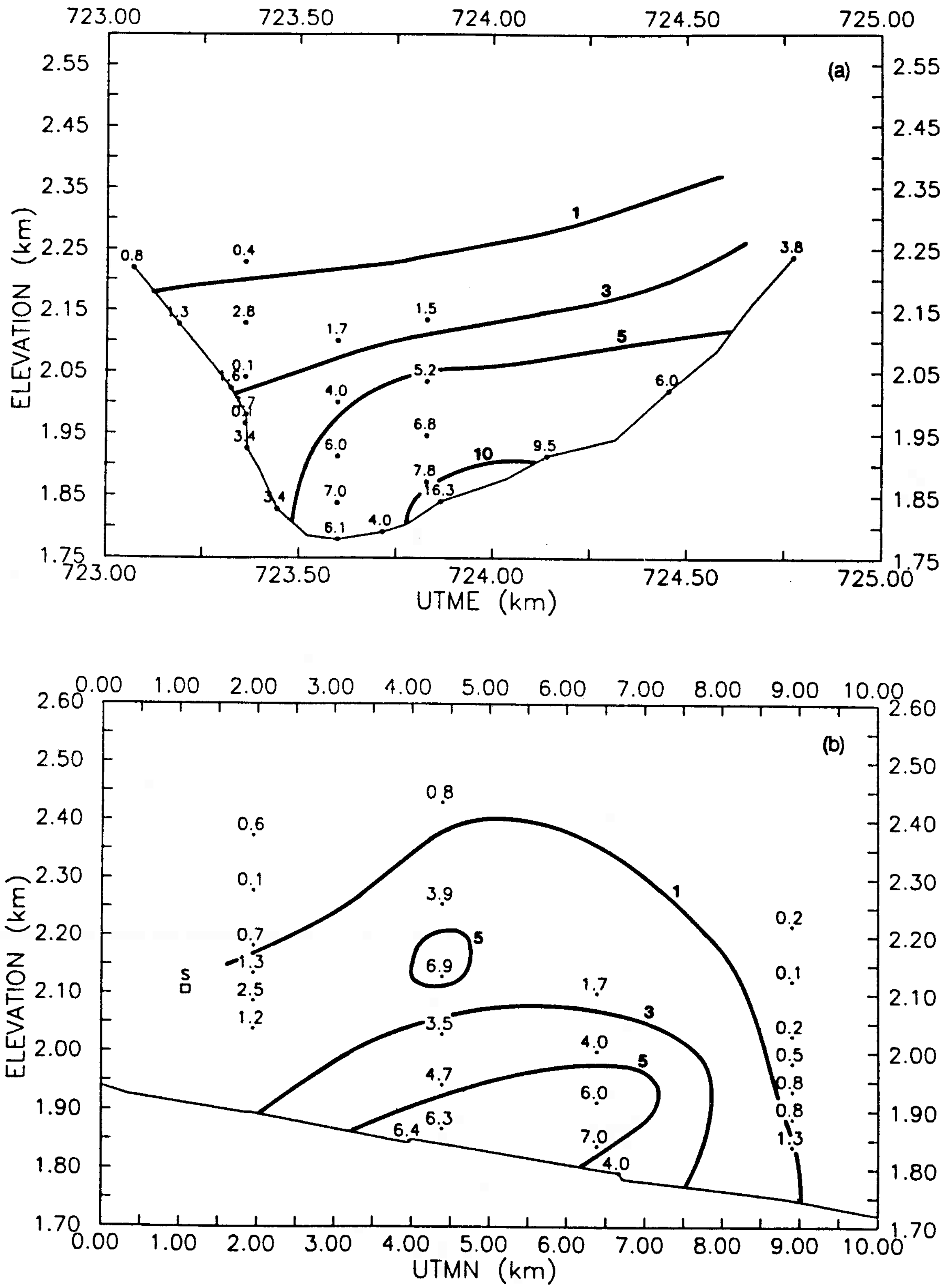


Figure 5-G

3.1.2 Surface release

Figures 6-A to 6-G present the concentration contours for the near-surface release of PP2 tracer in Test 2. Each of these seven figures shows the concentration isopleths at a given time (start of sampling period) for valley cross-sections (a) across arc 1, and (b) along the valley-axis.

Peak concentration at arc 1 was consistently observed at the bottom of the canyon at the foot of the east sidewall, and increased with time (from the start of release) to a maximum value of 359 $p\ell/\ell$ at 0400 MST. Concentrations decreased rapidly on all sides away from this location of the peak value. The plume was confined to a depth of about 250 m at arc 1. Though the tracer release rate remained constant, concentrations in the valley decreased significantly between 0700 and 0830 MST (Figs. 6-E and 6-F), while increasing on the western sidewall. A vigorous convective mixing of the tracer plume with the air aloft within the drainage layer was evident during this period.

The tracer distributions along the valley-axis (shown in the lower panels (b) of Figs. 6-A to 6-G) reveal that peak concentrations were recorded by the surface samplers very close to the release point S. Because the tracer was released at 75 m height during the first 50 min of the experiment (see Table 3), the initial behavior of the tracer plume (with respect to the location of the maximum surface concentration) was similar to that of the elevated release case. Otherwise, the concentration contours were typical of those expected for a surface plume on an inclined plane, with a smaller plume depth than that for the elevated release. Nappo *et al.* (1989) demonstrated that pollutants released at ground-level can spread through the entire depth of the drainage layer on a simple slope, and this vertical diffusion is very effective for a shallow slope (such as that of Brush Creek Valley floor). The cold tracer plume displayed a well-defined leading edge (front), typical of a gravity current on an incline (Britter and Linden, 1980). Because the wind speed near the ground (at 10 m AGL) was low (see Figs. 3 and 4), the tracer plume core near the surface was advected over relatively small distances. However, as wind speed increased sharply to a maximum value at about 60 m AGL, the upper part of the tracer plume near the height of the jet was transported over a longer distance. The ventilation of tracer out of the valley after sunrise was similar to that of the elevated release case discussed before. There was considerable convective mixing and vertical transport of the tracer to higher elevations in the middle segment of Brush Creek Valley. The concentrations decreased to very low levels by 1000 MST.

3.2 Test 4 (30 September 1984)

The tracer release conditions for the elevated and surface release experiments of Test 4 are given in Table 4. During tracer Test 4, the winds above the valley were light and from the southeast, and the sky was clear. These conditions favored the development of strong drainage flows that were maintained throughout the entire night.

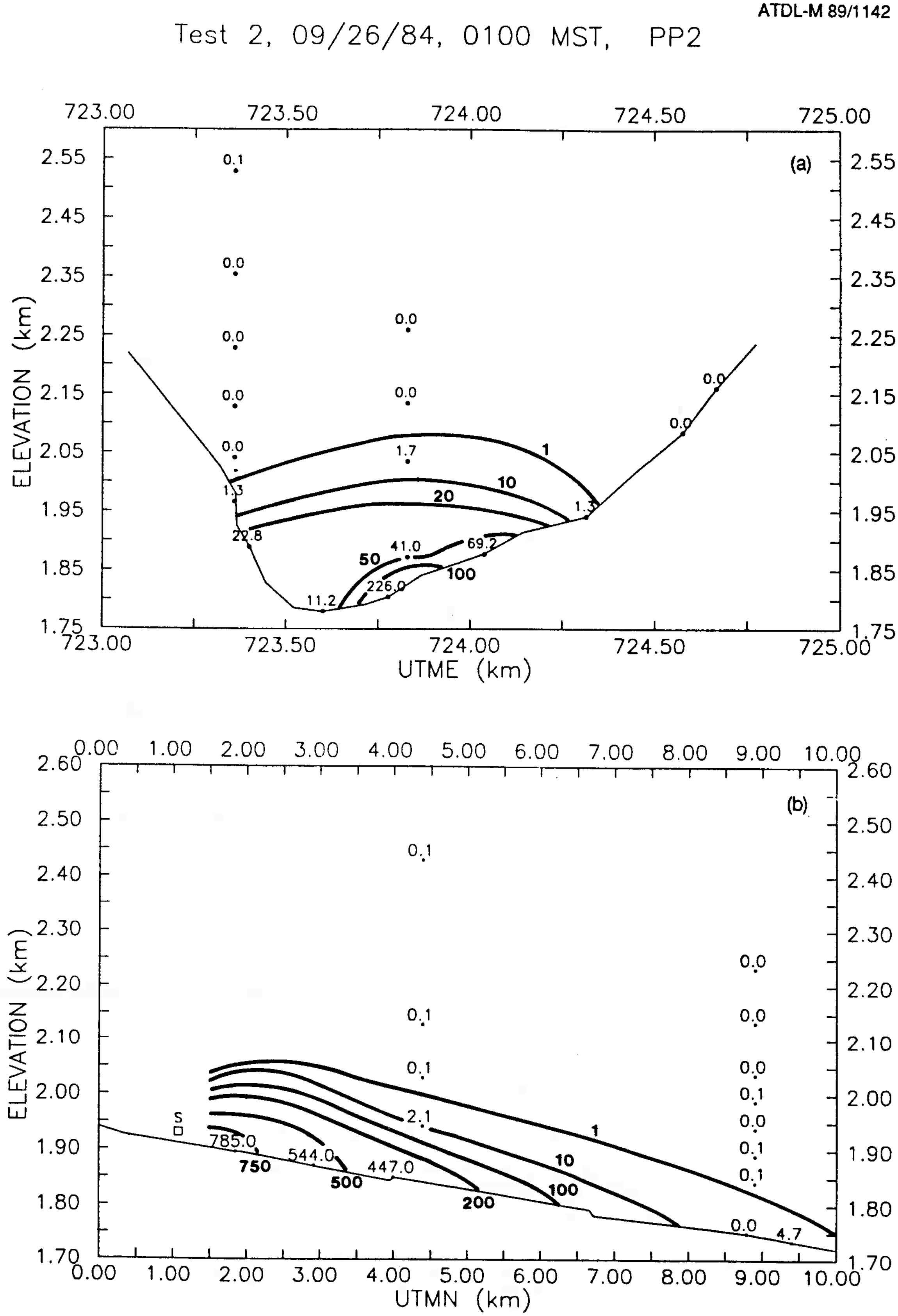


Figure 6. Observed concentrations (in $p\ell/\ell$) of PP2 tracer in Brush Creek Valley for the surface release in Test 2. Concentration isopleths are shown for valley cross sections (a) along arc 1, and (b) along valley axis at a given time (start of sampling period). Figs. 6-A to 6-G present these plots 90 min apart starting from 0100 MST.

Test 2, 09/26/84, 0230 MST, PP2

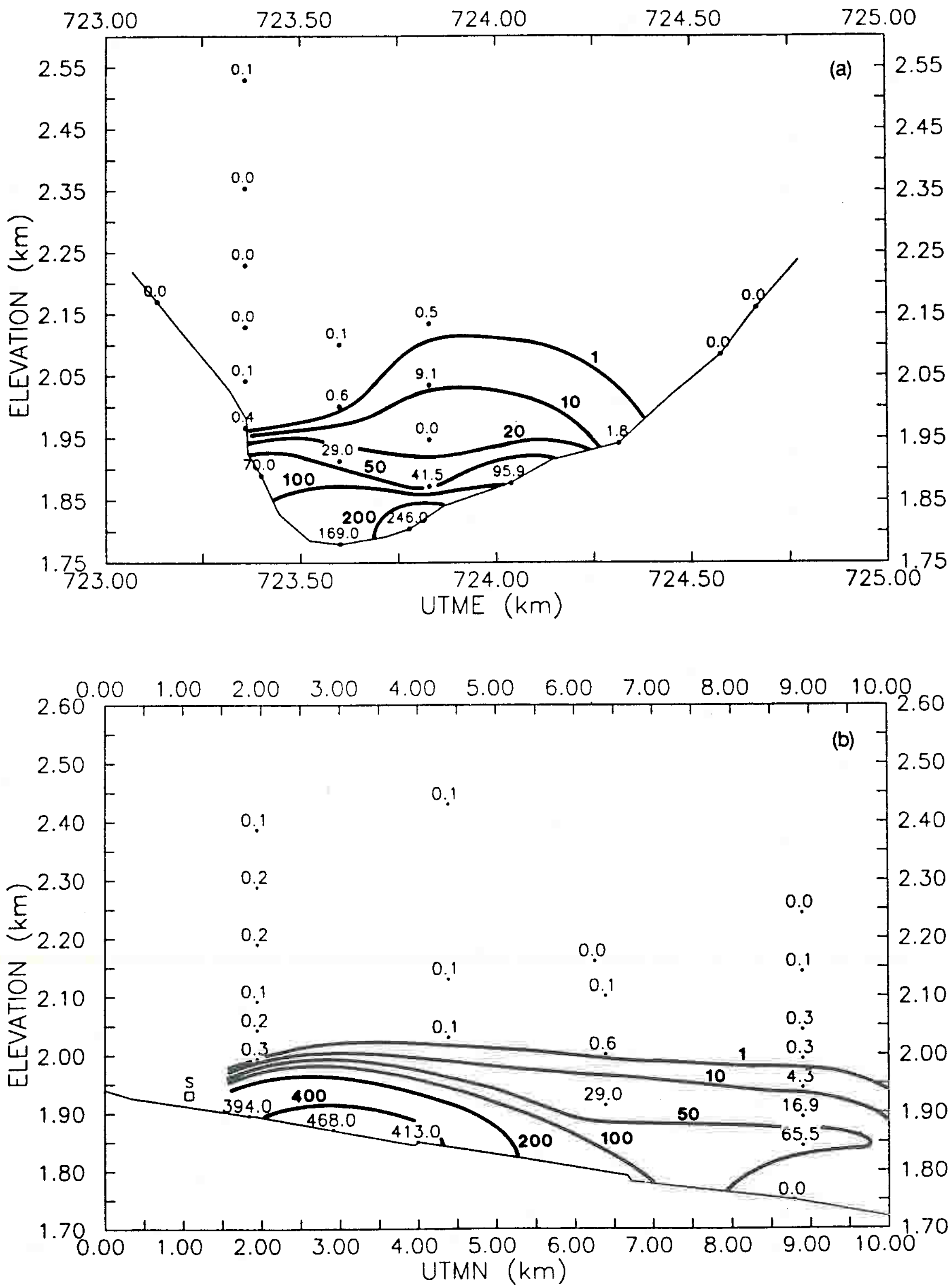


Figure 6-B

Test 2, 09/26/84, 0400 MST, PP2

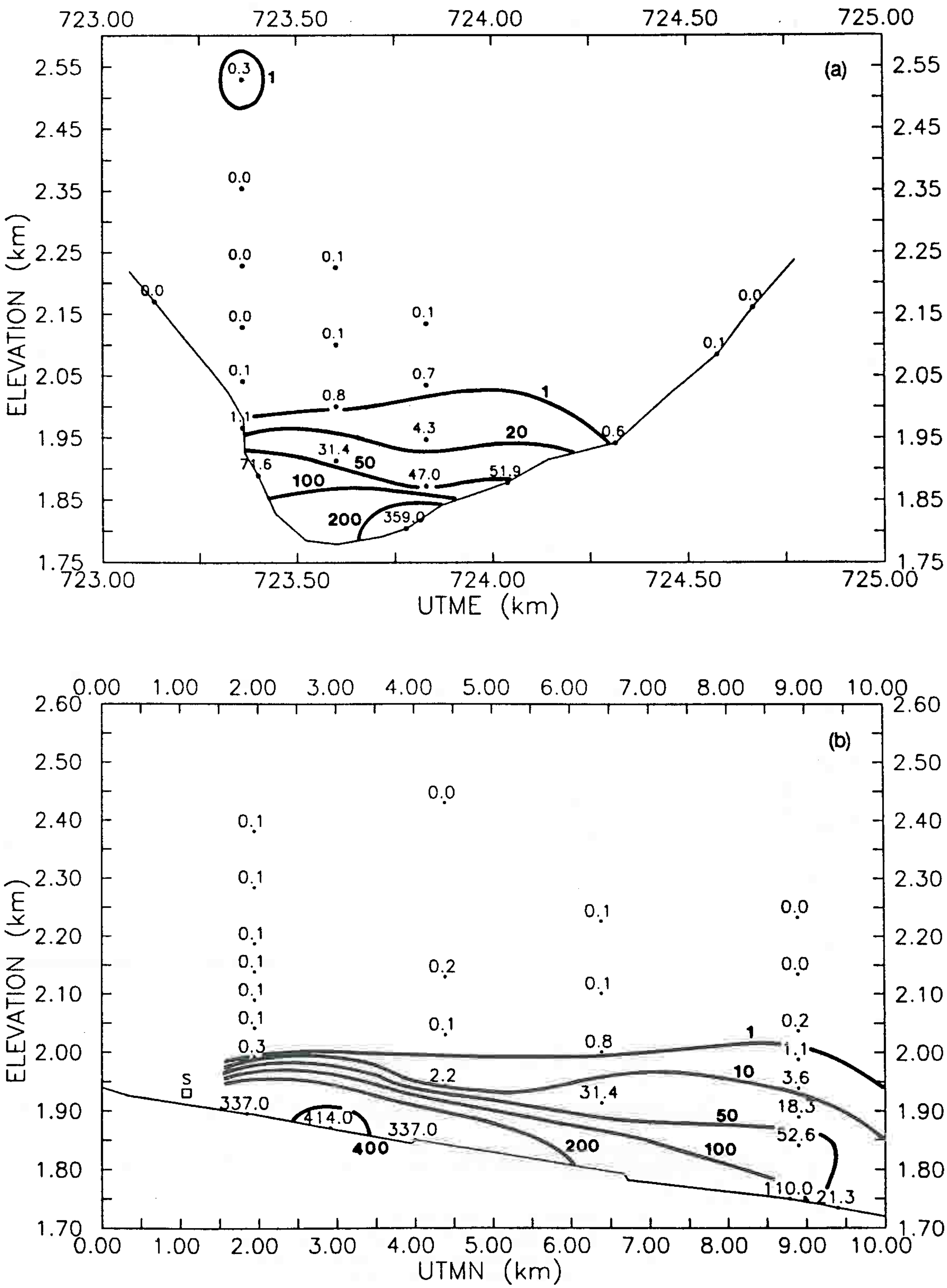
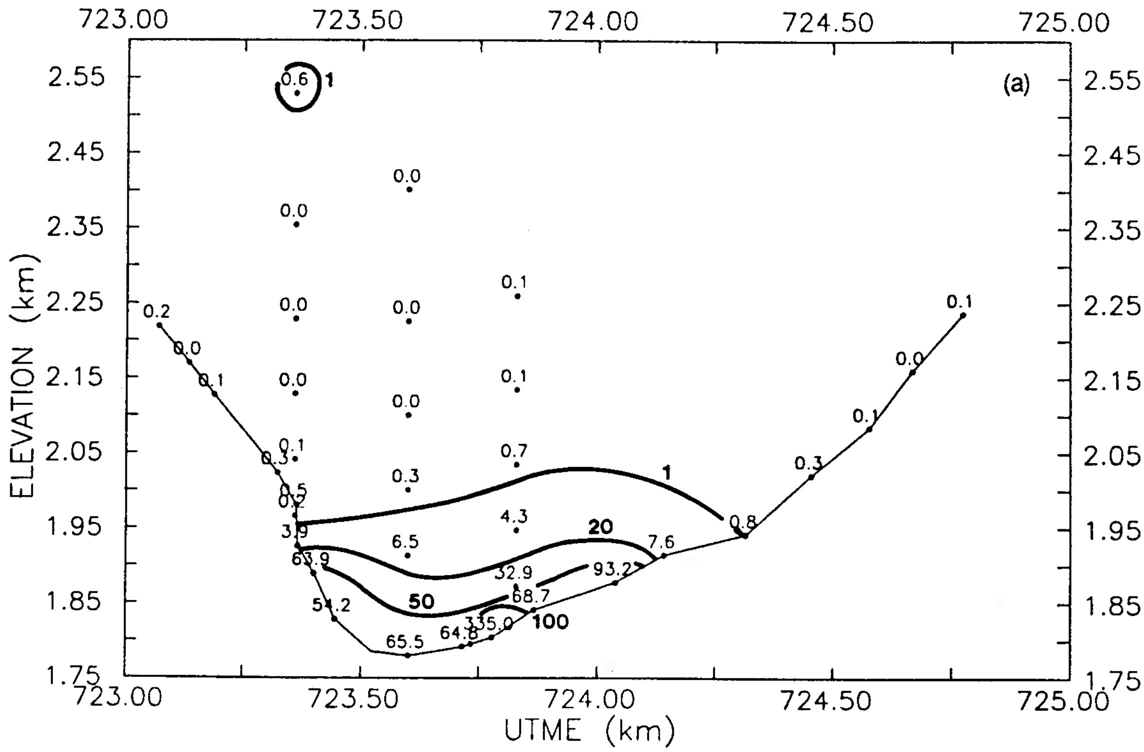


Figure 6-C

Test 2, 09/26/84, 0530 MST, PP2



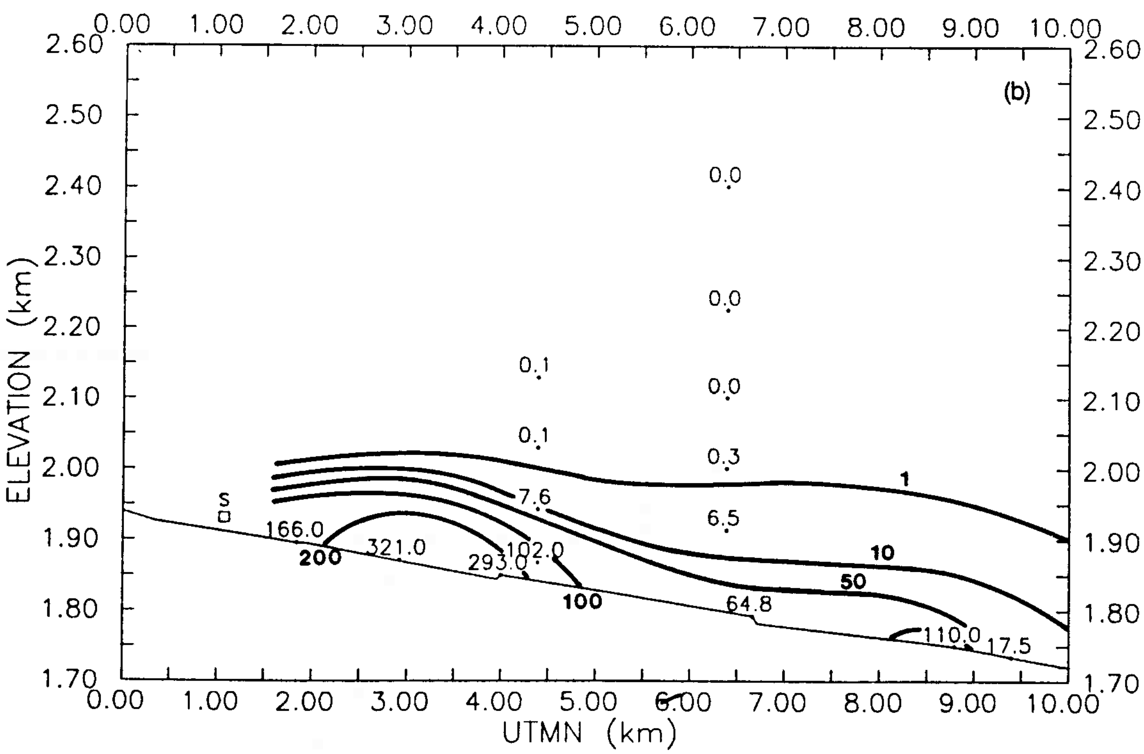


Figure 6-D

Test 2, 09/26/84, 0700 MST, PP2

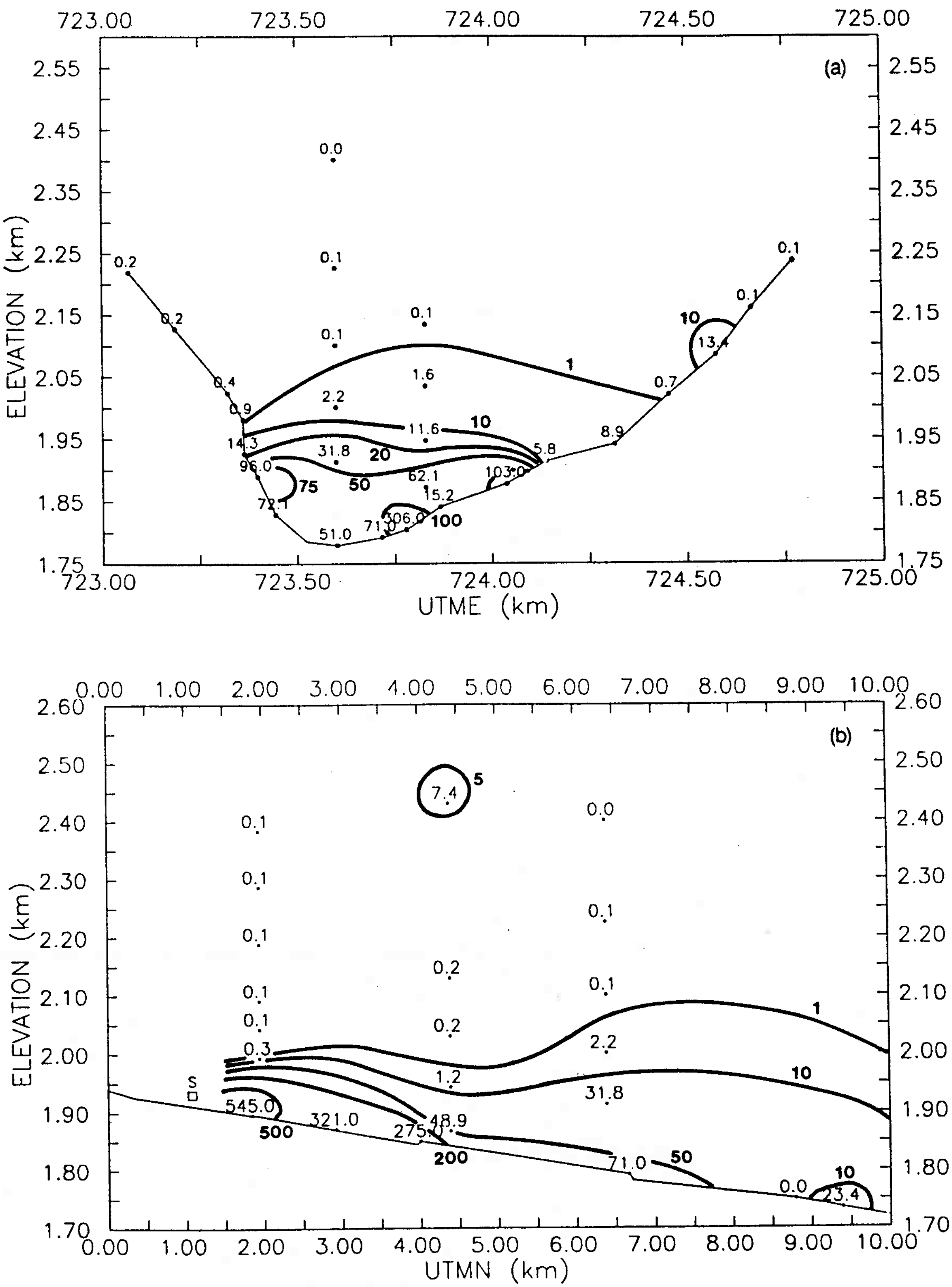
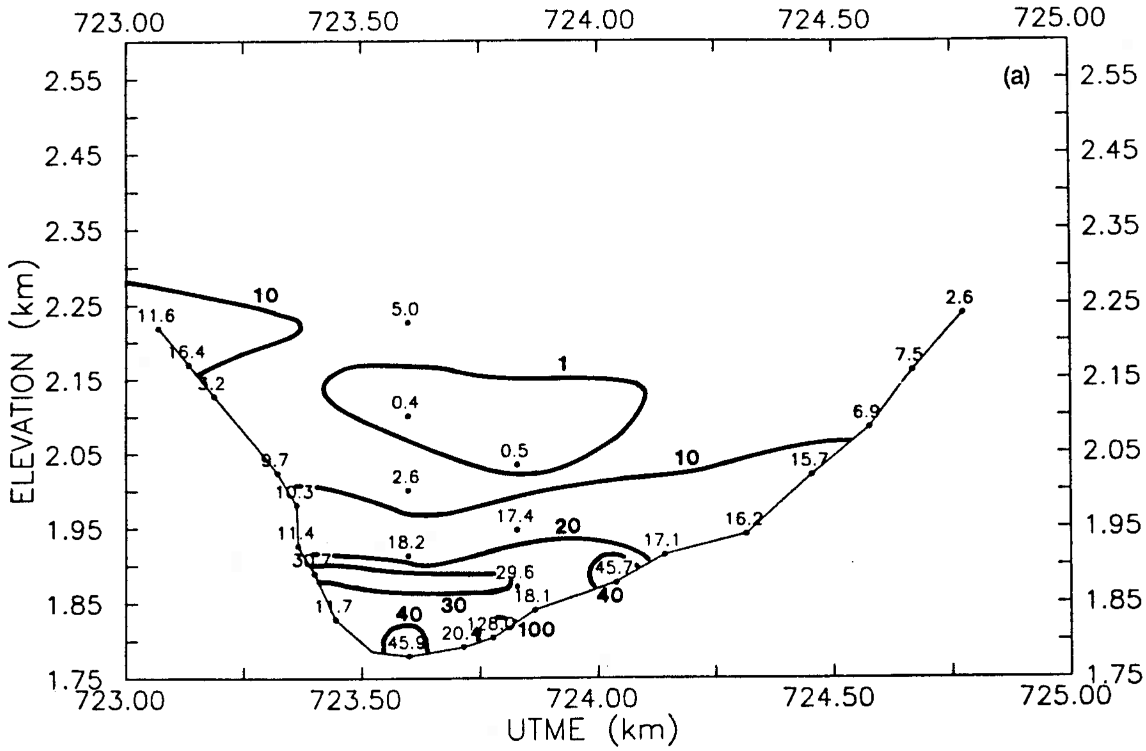


Figure 6-E

Test 2, 09/26/84, 0830 MST, PP2



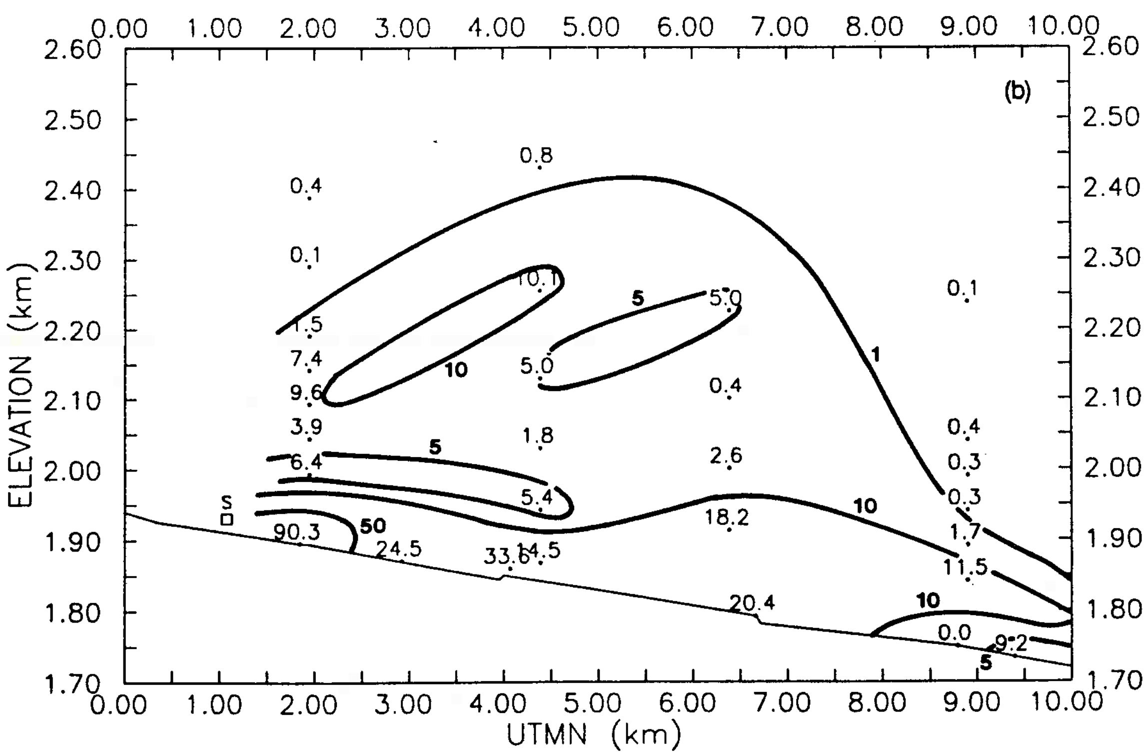
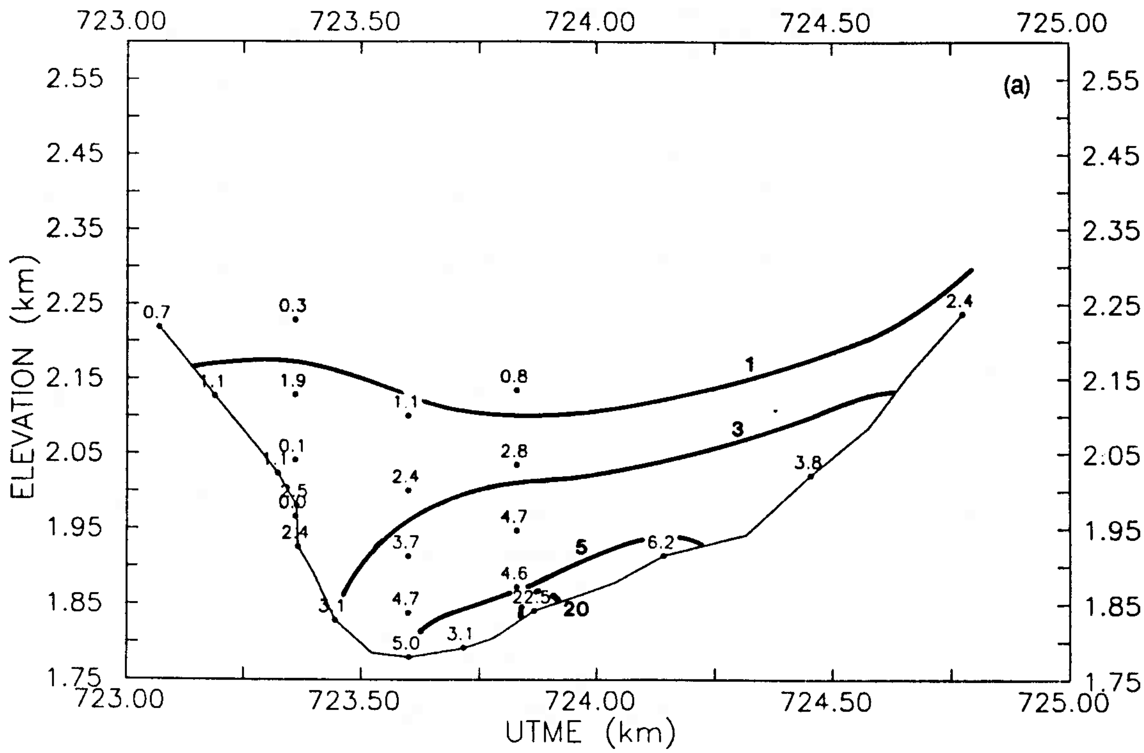


Figure 6-F

Test 2, 09/26/84, 1000 MST, PP2



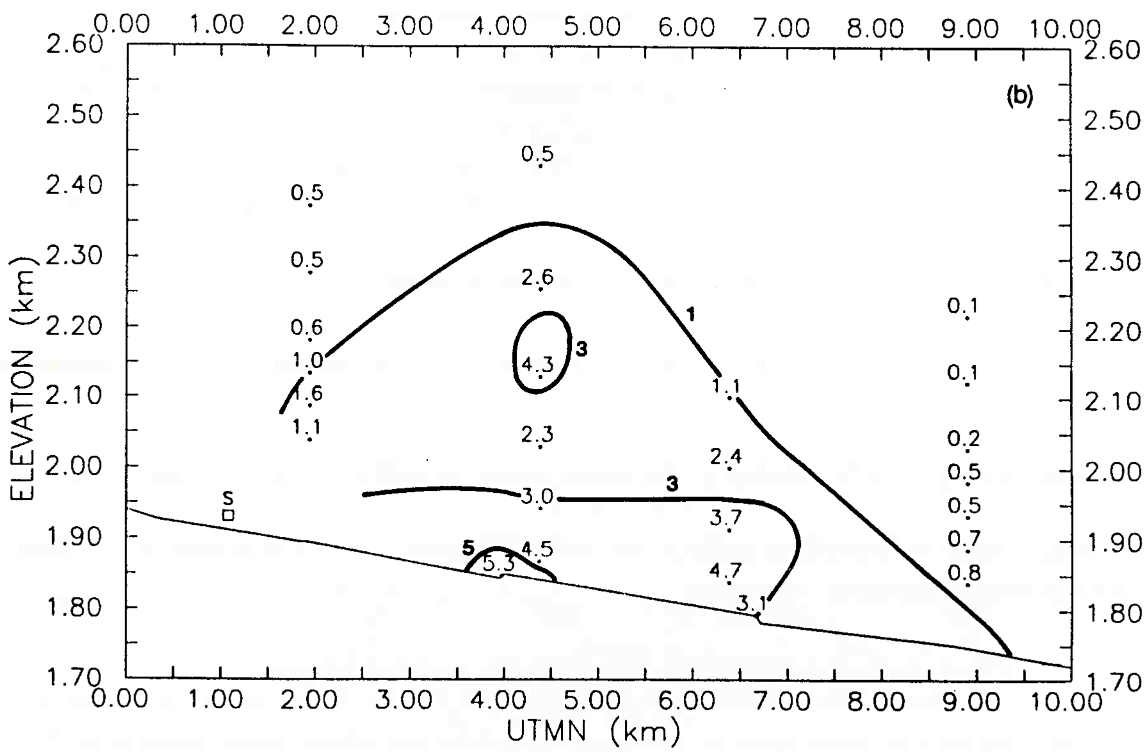


Figure 6-G

Table 4. Tracer release conditions for Test 4

Tracer	Release period (MST)	Release height (m AGL)	Release rate (g/s)
PDCH (PP3)	0000 – 0045	200	0.27
	0045 – 0400	120	0.20
	0400 – 0500	No release	0.00
	0500 – 0800	200	0.23
PMCH (PP2)	0030 – 0800	5	0.23

Figure 7 presents the wind and temperature profiles measured at the WPL tethered balloon site near the source. The profiles reveal a well-developed northwesterly drainage flow through the night, with a down-valley jet of 6.5 m/s velocity at a height of about 75 to 100 m AGL. A complete reversal in direction to up-valley flow occurred by 0830 MST, when the surface inversion was completely destroyed. The top of the drainage layer, clearly characterized by near-zero wind speed and a sharp discontinuity in wind direction, ranged from 350 to 400 m. There was an ambient flow varying from 1 to 6 m/s from the southeast (in the up-valley direction) above this level. The wind and temperature profiles at the PNL site (near arc 1) are shown in Fig. 8. The drainage flow at this location was somewhat weaker, and completely reversed to up-valley direction by 0830 MST. The flow essentially remained down-valley before that time, except for some variability in wind direction at several heights near the ground. These flow direction variations probably resulted from the scouring of the drainage flow by intrusions of the southeasterly (up-valley) ambient wind to the valley surface, or from cold air backing up from Roan Creek into Brush Creek Valley near its outlet, thus leading to speed minima at these heights. The mean depth of drainage flow in valley was 435 m during Test 4.

3.2.1 Elevated release

Figures 9-A to 9-G present the concentration contours for the elevated release of PP3 tracer in Test 4. Each of these seven figures shows the concentration isopleths at a given time (start of sampling period) for valley cross-sections (a) across arc 1, and (b) along the valley-axis.

The cross-canyon concentration isopleths for this experiment were more typical of an elevated release than those of Test 2 (Section 3.1.1). Peak tracer concentrations were observed in the lower part of the canyon above the valley floor, indicating that the plume centerline was just above the ground at arc 1. As the morning progressed, the heights of the peak concentrations moved upwards; at 0530 and 0700 MST

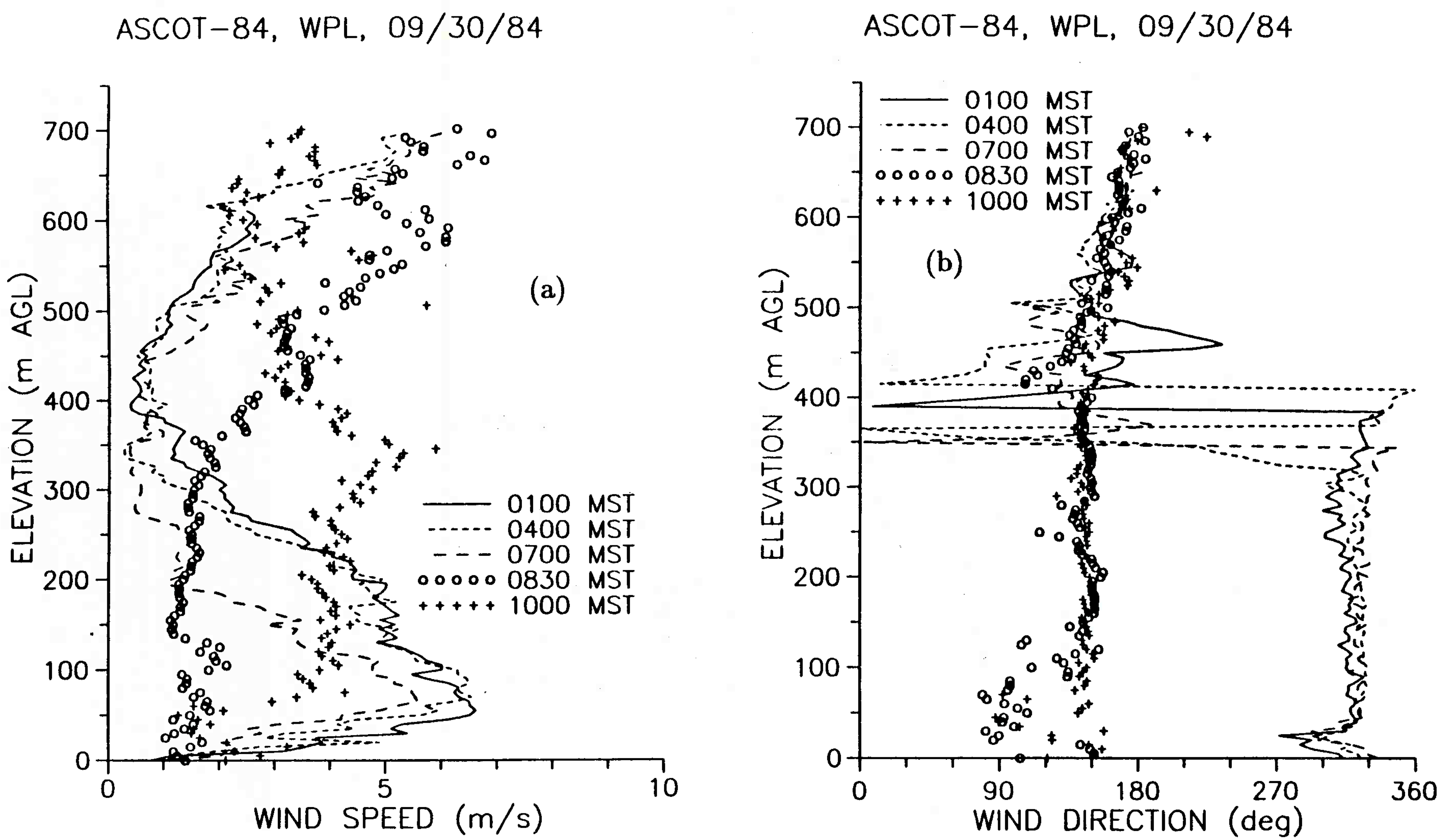


Figure 7. Vertical profiles at the WPL balloon site on 30 September: (a) wind speed, (b) wind direction, and (c) potential temperature.

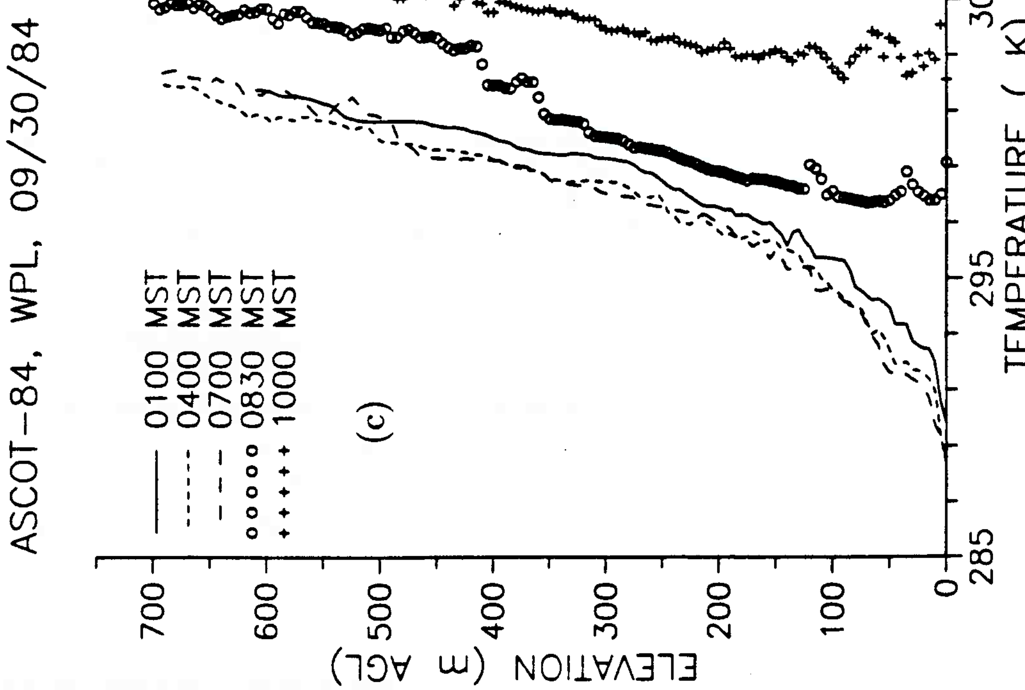

ASCOT-84, WPL, 09/30/84
0100 MST
0400 MST
0700 MST
0830 MST
1000 MST
(c)
ELEVATION (m AGL)
0
100
200
300
400
500
600
700
285
295
305
TEMPERATURE (K)

Figure 7(c)

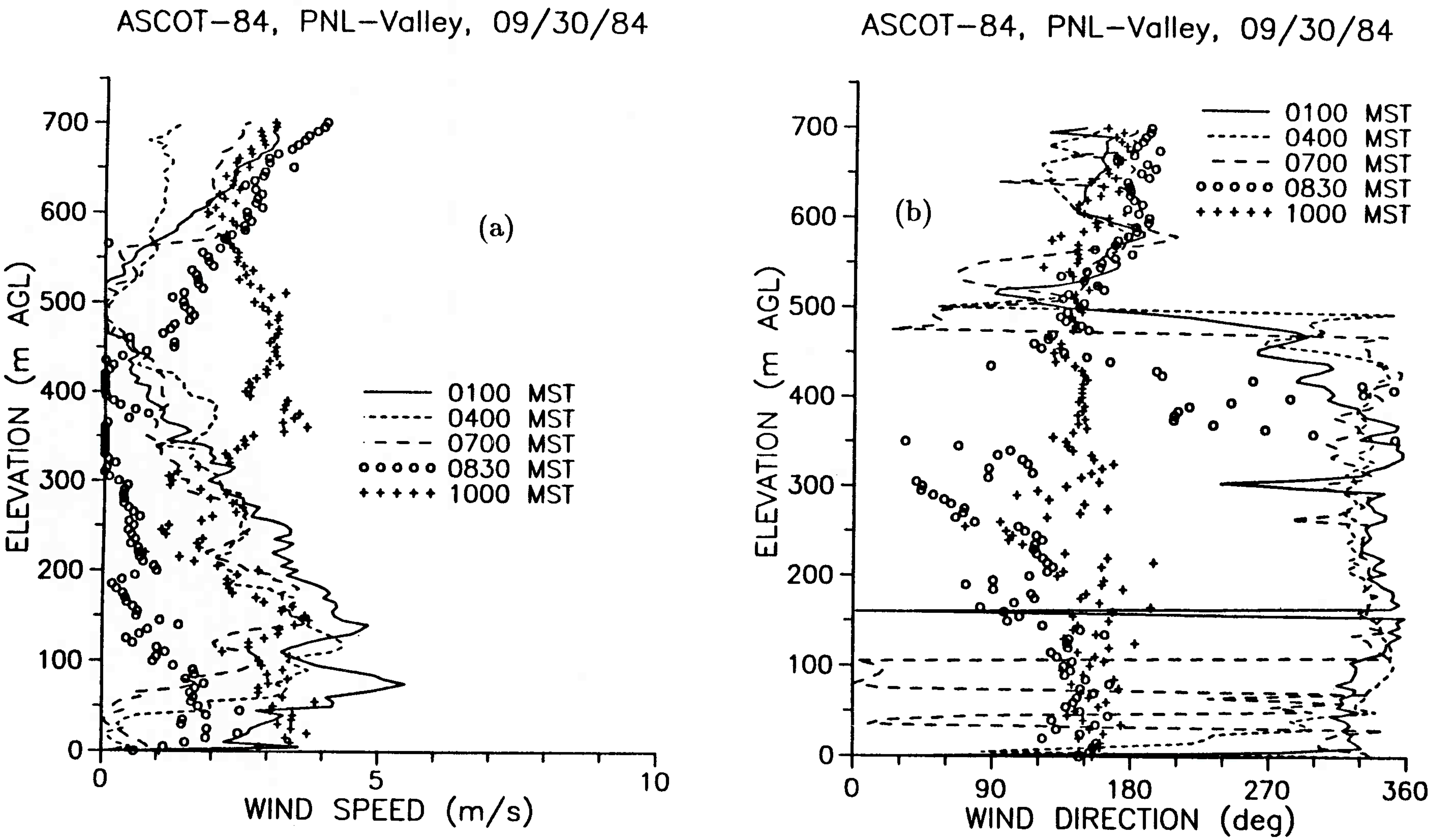


Figure 8. Vertical profiles at the PNL balloon site on 30 September: (a) wind speed, (b) wind direction, and (c) potential temperature.

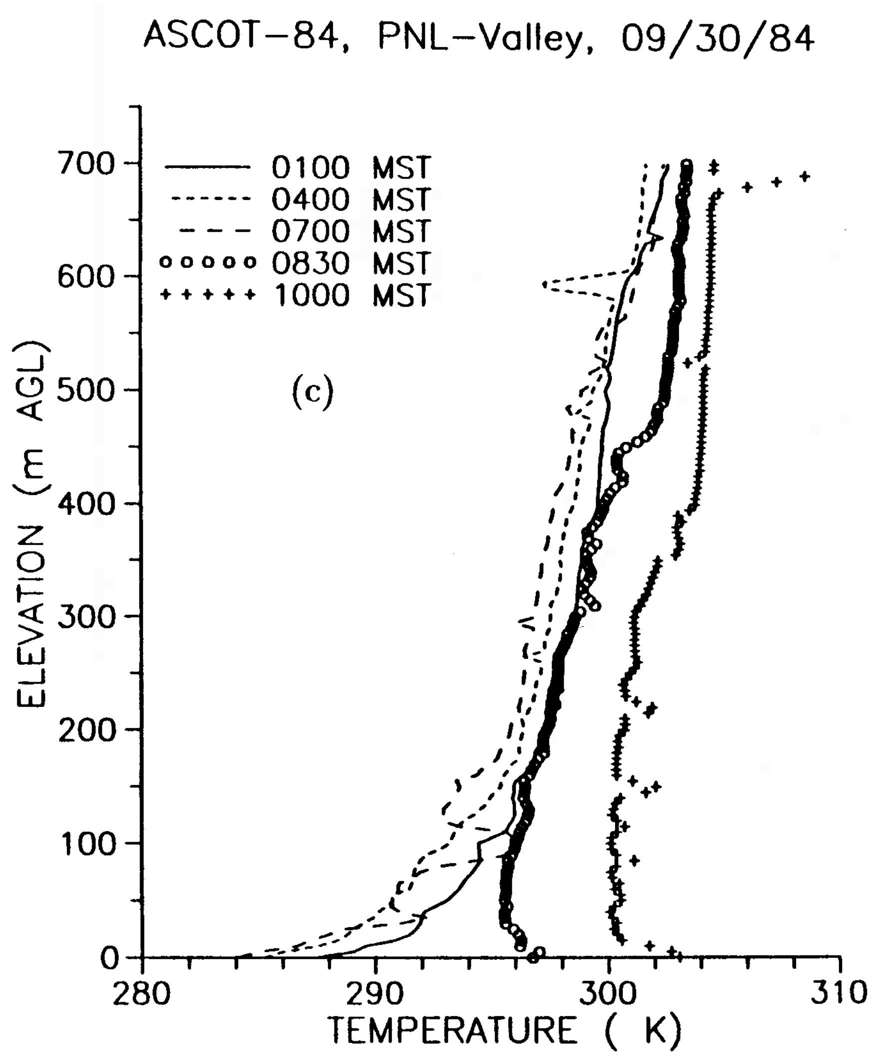

ASCOT-84, PNL-Valley, 09/30/84
0100 MST
0400 MST
0700 MST
0830 MST
1000 MST
(c)
ELEVATION (m AGL)
700
600
500
400
300
200
100
0
280
290
300
310
TEMPERATURE (K)

Figure 8(c)

(Figs. 9-D and 9-E), the tracer plume core was located close to the source elevation, and the concentrations were nearly uniform across the lower part of the canyon at arc 1. Thus, the height of the plume centerline varied considerably during the tracer release. As already noted, vertical samplers recorded only snap-shot (nearly instantaneous) concentration data, while the surface samplers provided the time-averaged concentrations.

The post-sunrise period was characterized by increased tracer concentrations on the west sidewall (see Figs. 9-E to 9-G) due to upslope flows which ventilated the tracer out of the valley. The concentrations at 1000 MST, with sampling period starting two hours after the end of tracer release, decreased to very low levels at arc 1.

The tracer distributions along the valley-axis (given in the lower panels (b) of Figs. 9-A to 9-G) show the influence of subsidence in the valley drainage flow; the plume centerline was brought closer to the valley floor, and the maximum concentrations occurred near ground-level within three kilometers from the source. Subsequently, the plume core lifted off the ground sometimes (see, *e.g.,* Figs. 9-A and 9-C), and displayed a well-defined leading edge. These results suggest that subsidence rates were particularly high in the valley section between the tracer release site and arc 2. The subsidence rates were affected by the variation of the valley cross-section along the flow direction, and the effect of the tributary flows, among other factors. The interaction with the Pack Canyon flow (see Fig. 1) might have caused the tracer spread to levels above the release height. By 1000 MST, the plume was confined to a small region in the lower part of the valley near arc 1, and the tracer concentrations declined to very low levels (Fig. 9-G).

3.2.2 Surface release

Figures 10-A to 10-G depict the concentration contours for the surface release of PP2 tracer in Test 4. Each of these seven figures shows the concentration isopleths at a given time (start of sampling period) for valley cross-sections (a) across arc 1, and (b) along the valley-axis.

Peak tracer concentrations during the pre-sunrise periods were observed at the bottom of the canyon, generally on the east sidewall as in Test 2. Though significant tracer levels were recorded aloft, the plume was essentially confined within the lowest 250 m of the valley drainage flow at arc 1, and the core of the plume was just above the bottom of the canyon. Above and below this core, the concentrations were nearly uniform across the canyon. This distribution was fairly constant through the night, with minor changes in the location of the plume core. These contours suggest that the nocturnal flows near the bottom of this deep and narrow valley were generally well shielded from the external flows.

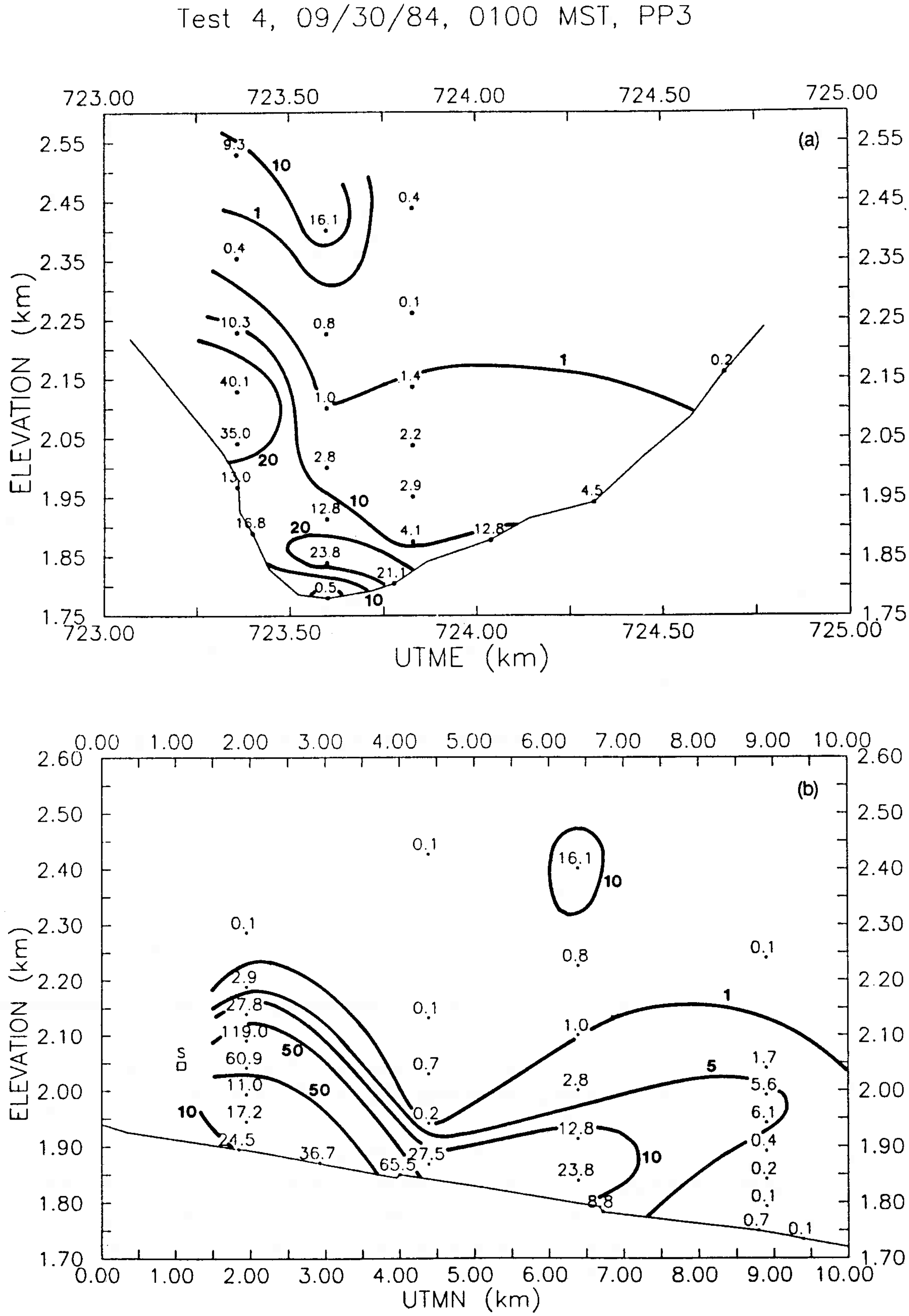


Figure 9. Observed concentrations (in $p\ell/\ell$) of PP3 tracer in Brush Creek Valley for the elevated release in Test 4. Concentration isopleths are shown for valley cross sections (a) along arc 1, and (b) along valley axis at a given time (start of sampling period). Figs. 9-A to 9-G present these plots 90 min apart starting from 0100 MST.

Figure 9-A

Test 4, 09/30/84, 0230 MST, PP3

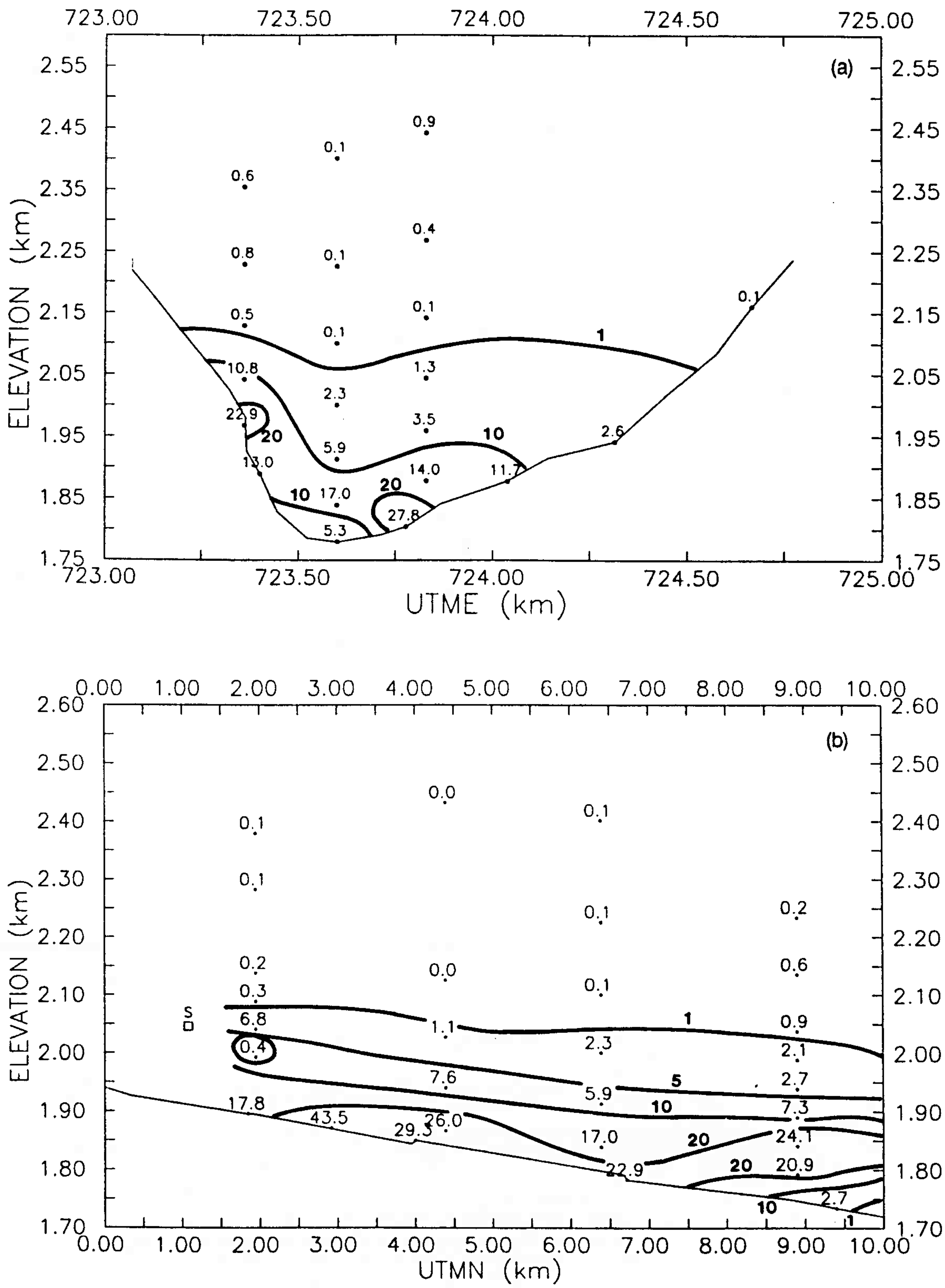


Figure 9-B

Test 4, 09/30/84, 0400 MST, PP3

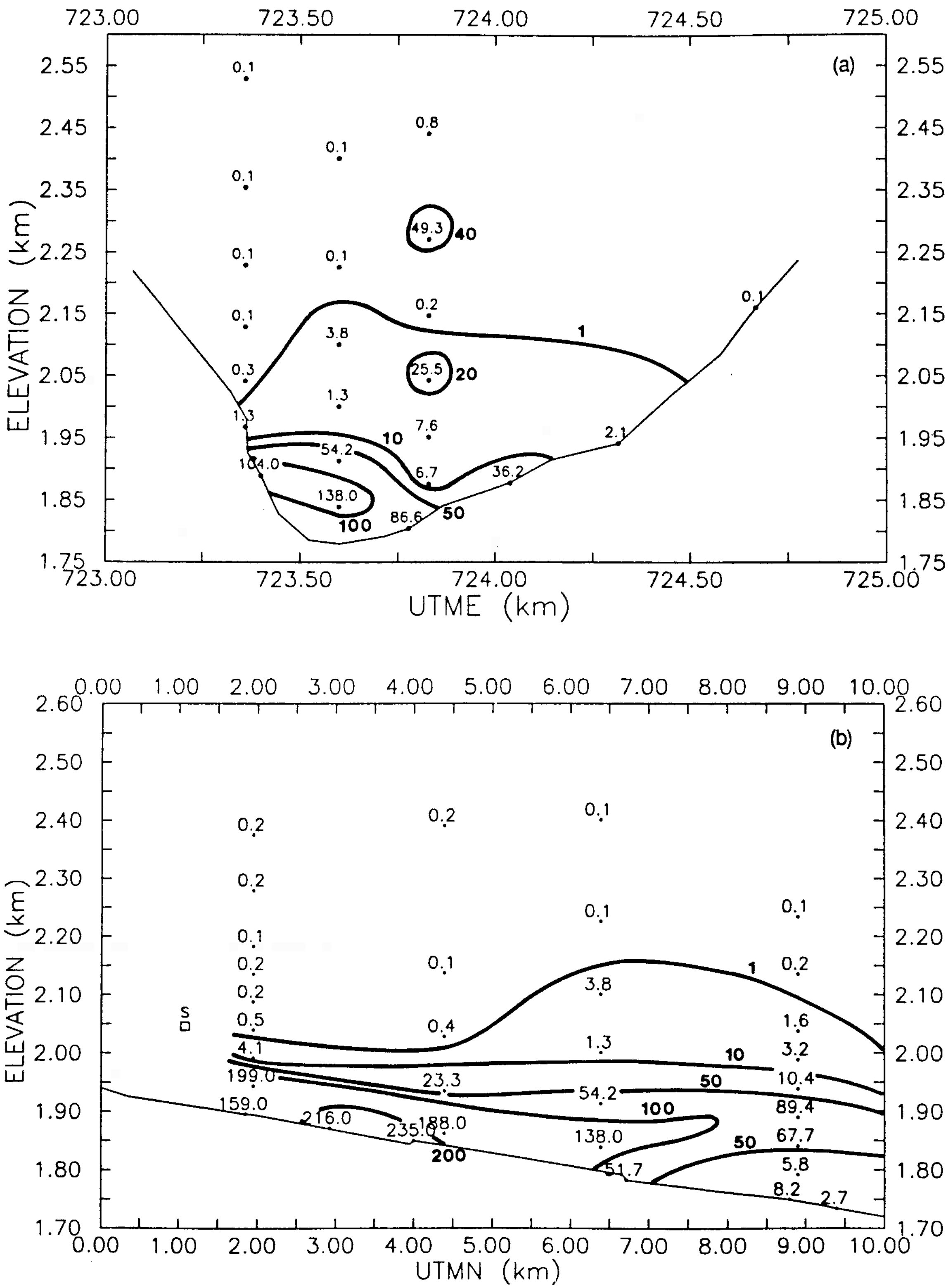


Figure 9-C

Test 4, 09/30/84, 0530 MST, PP3

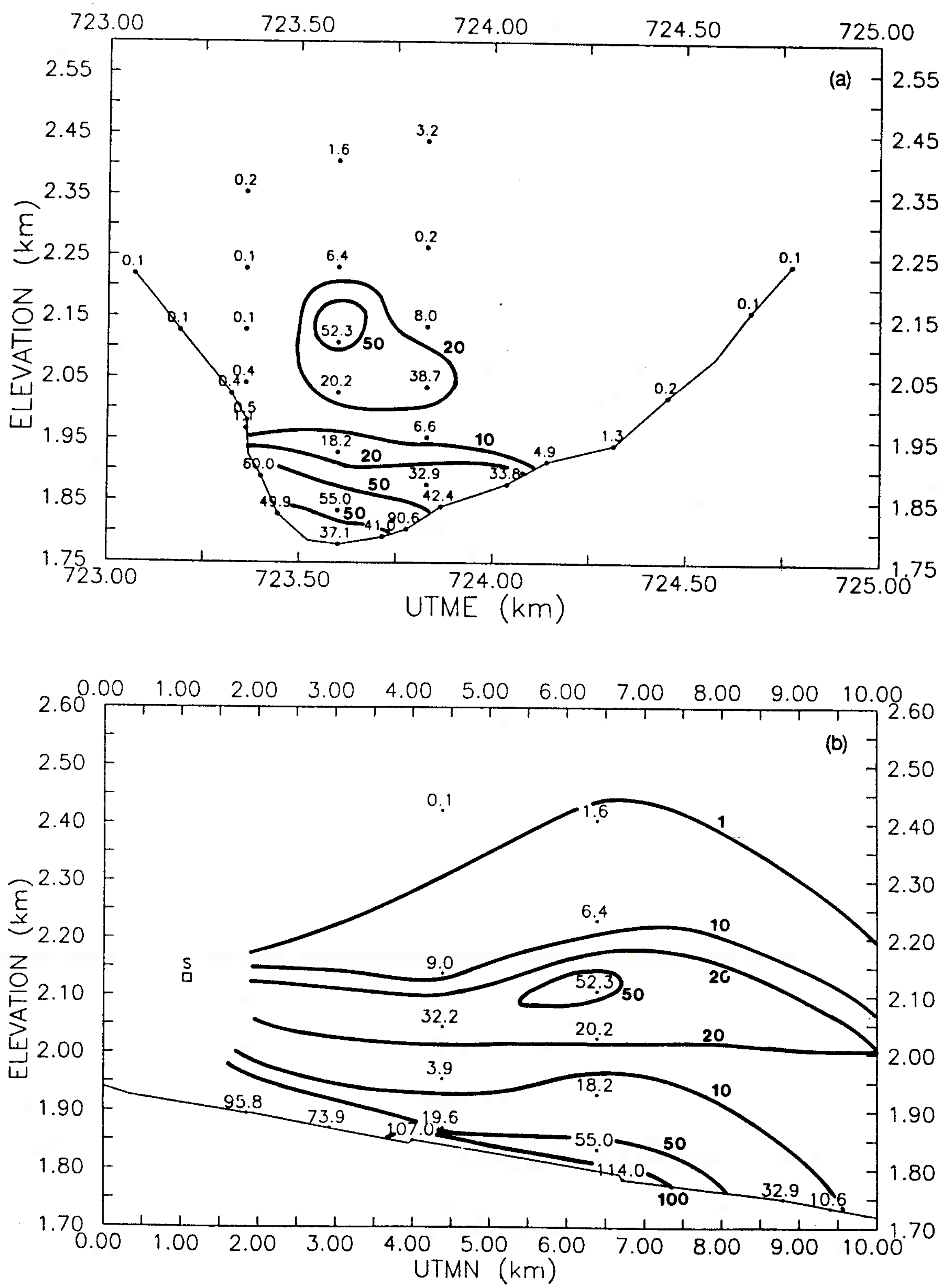
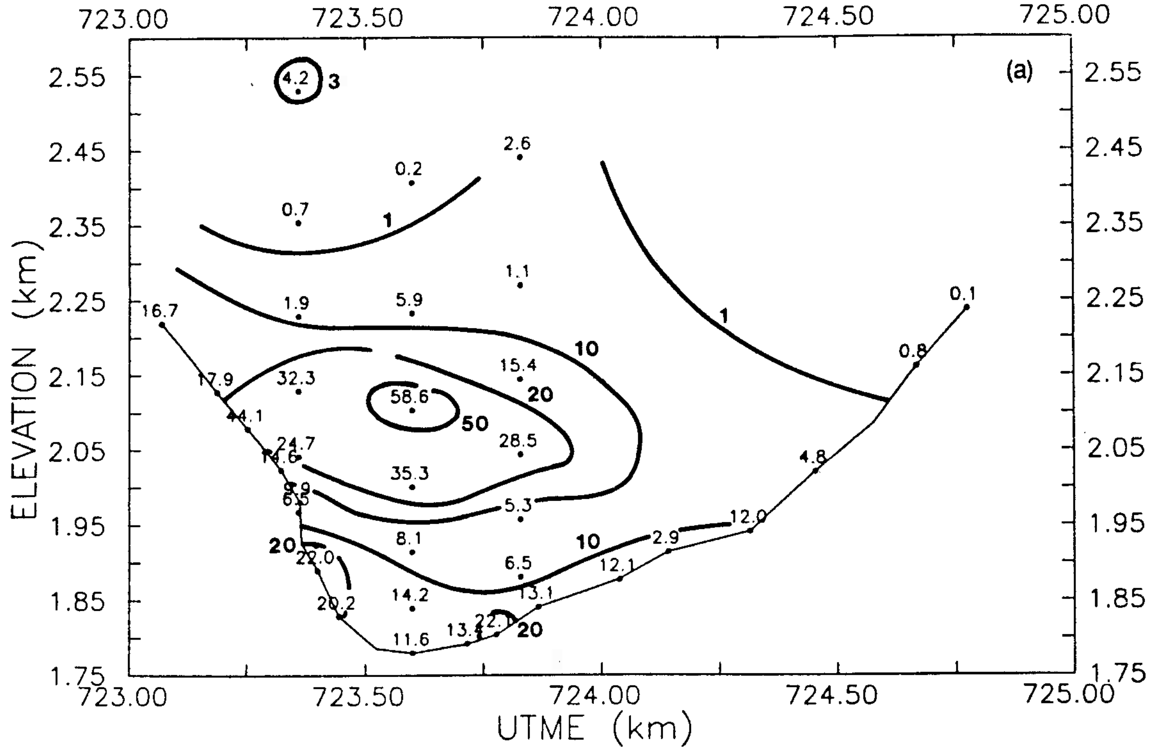


Figure 9-D

Test 4, 09/30/84, 0700 MST, PP3



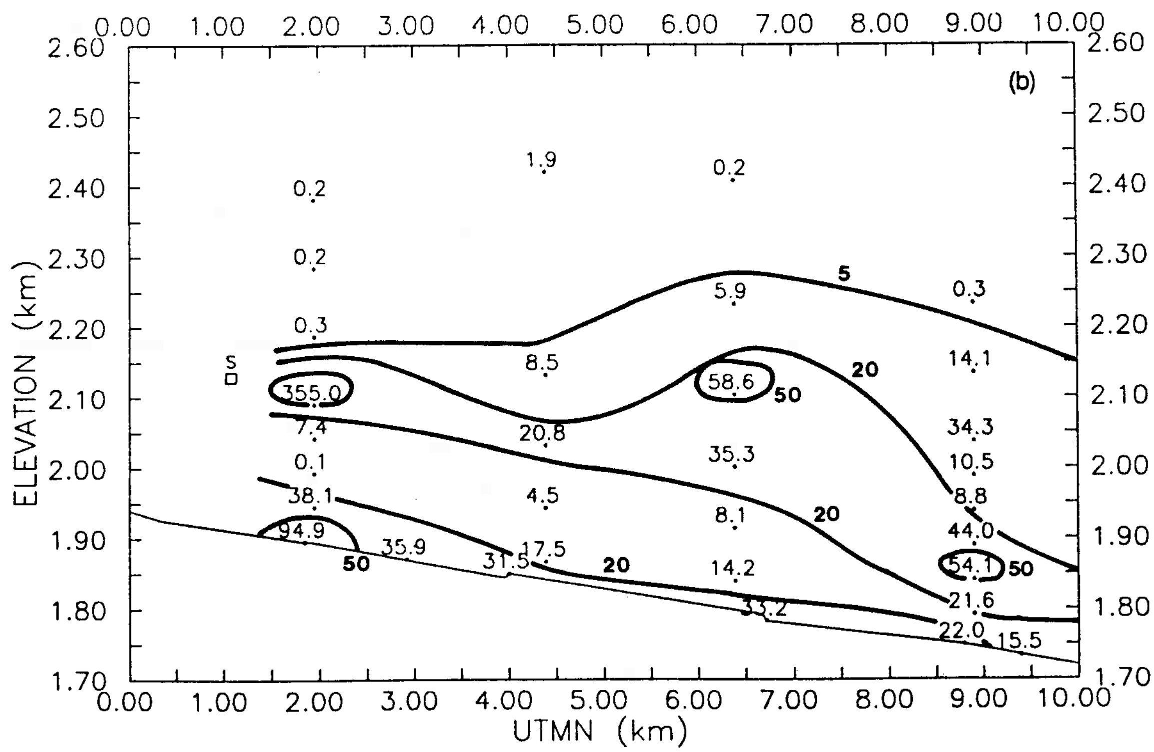


Figure 9-E

Test 4, 09/30/84, 0830 MST, PP3

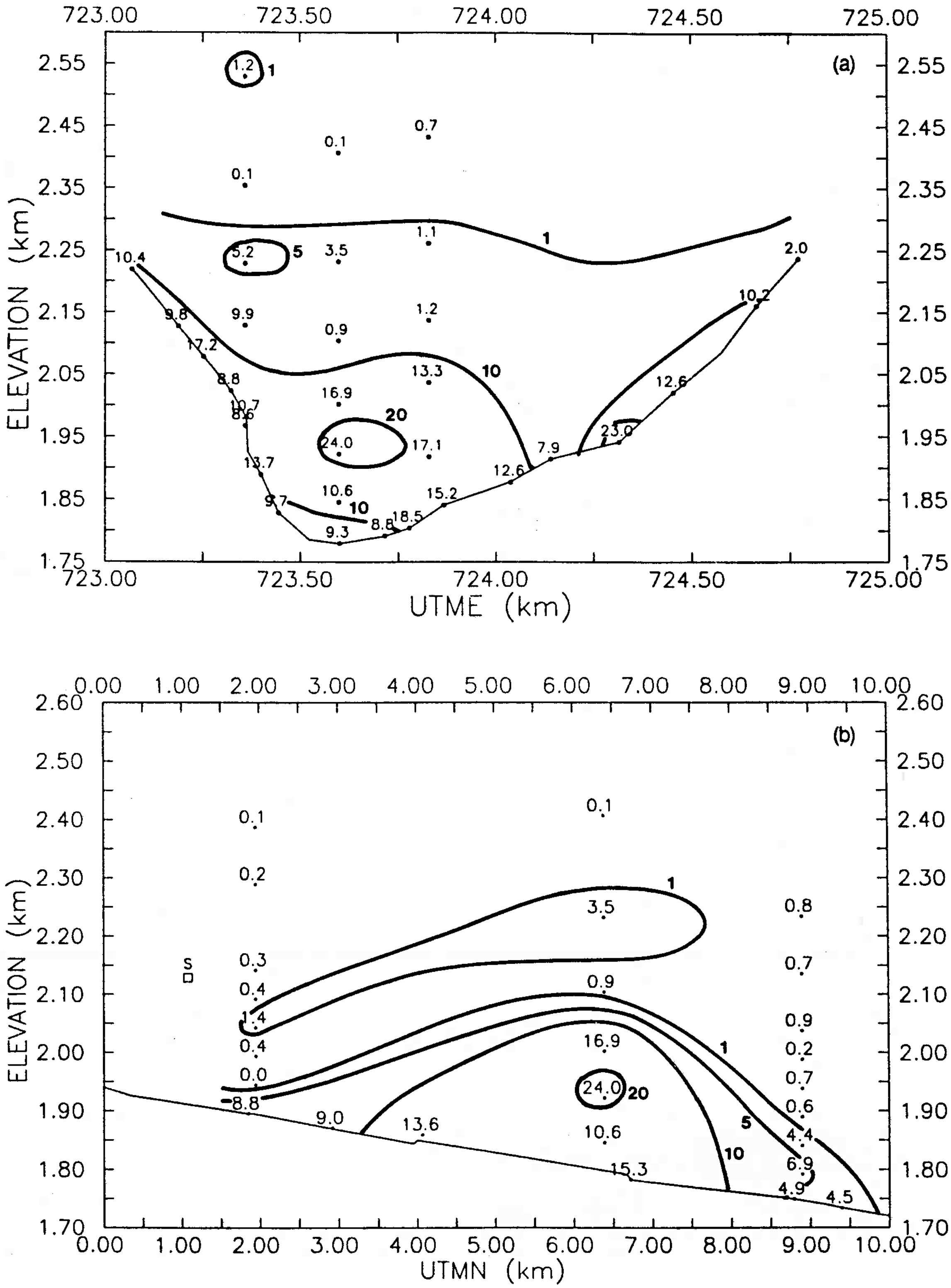


Figure 9-F

Test 4, 09/30/84, 1000 MST, PP3

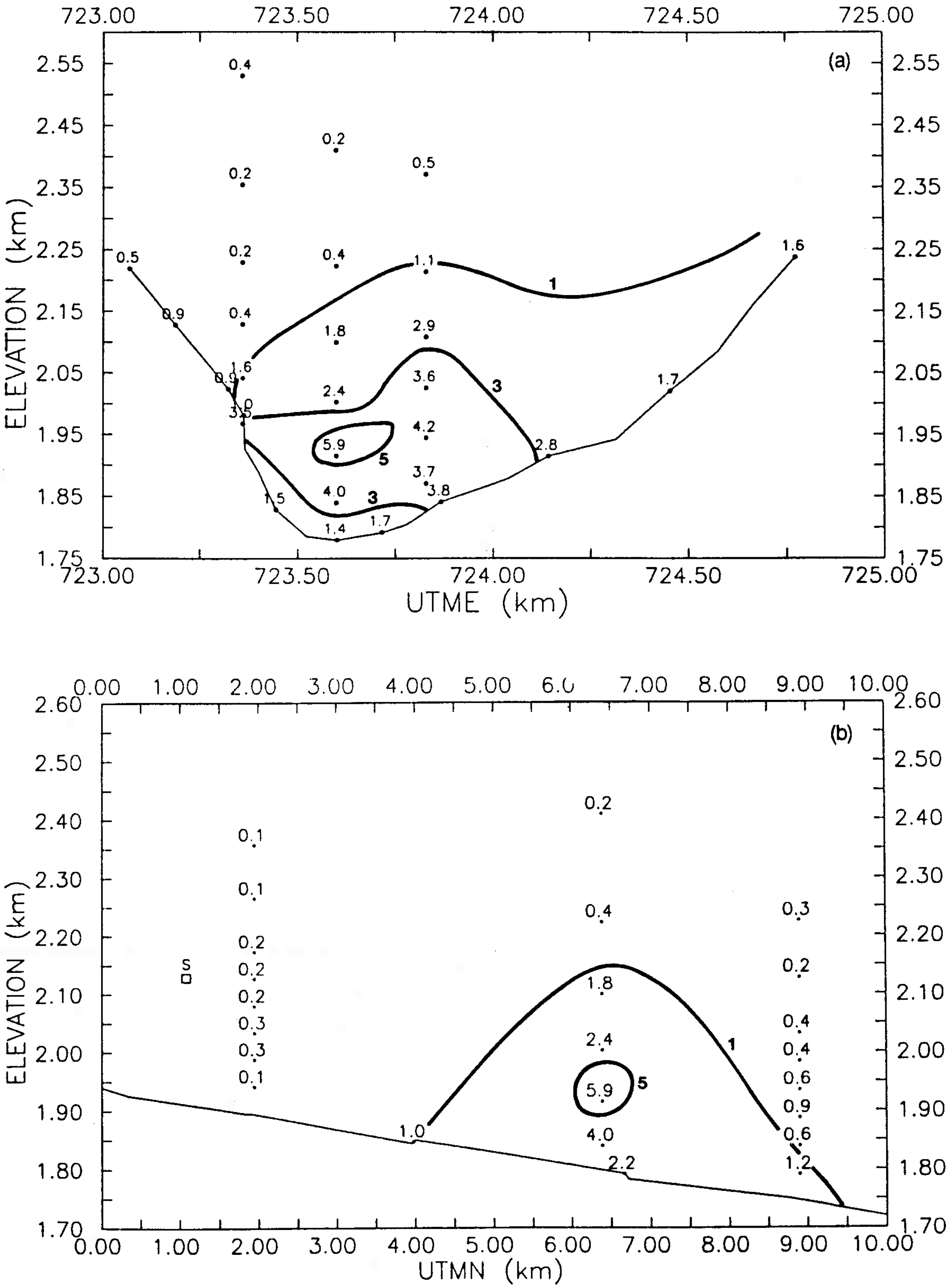


Figure 9-G

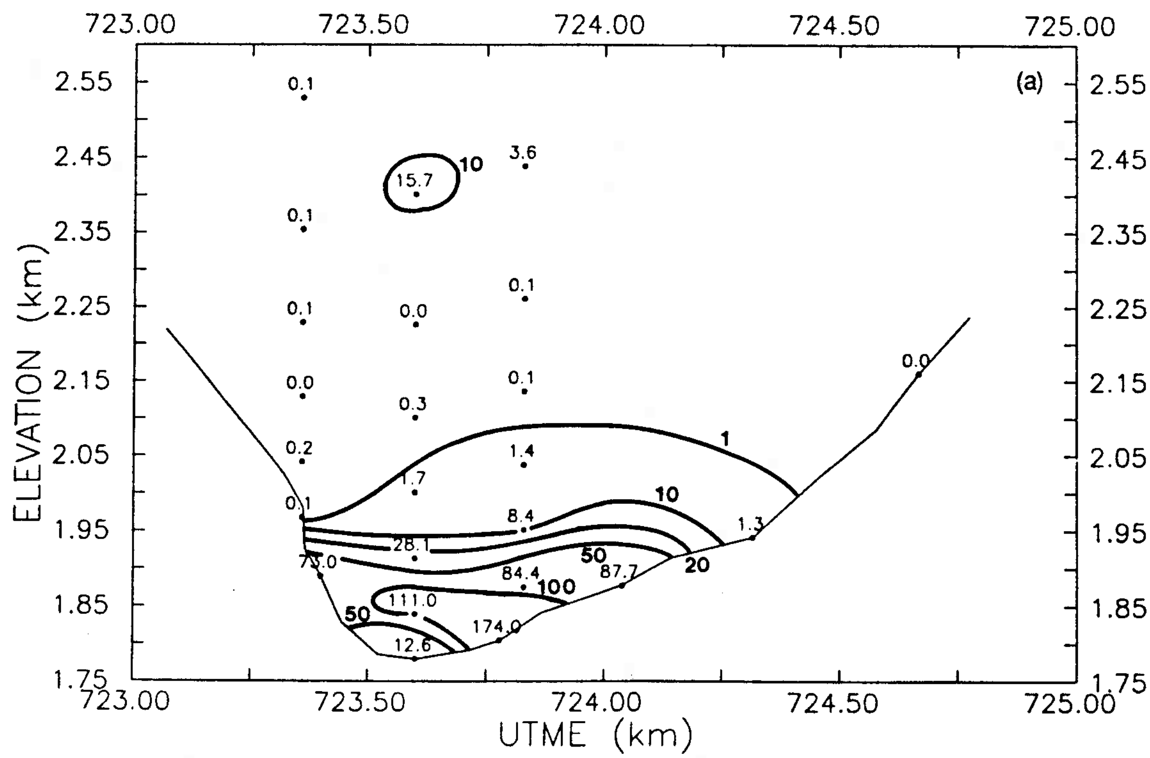
The post-sunrise concentration isopleths (Figs. 10-E to 10-G) across arc 1 demonstrate the effects of the cross-valley circulations resulting from the differential heating of the valley sidewalls, and the upslope winds on the sunlit western sidewall. The tracer at the bottom of the canyon was advected by the cross-valley winds towards the heated sidewall, and carried up the wall by the slope winds and ventilated out of the valley. As the depth of the upslope flow increased with time, the nocturnal plume was entrained into it and fumigated to the surface of the wall. This process increased concentrations at higher elevations on the western sidewall. As the entire valley floor was exposed to the sunshine by 1000 MST, the resulting convective mixing made the concentrations fairly uniform across the valley cross-section.

Tracer concentration distributions along the valley-axis are shown in the lower panels (b) of Figs. 10-A to 10-G. The drainage winds were fairly strong and, therefore, the tracer was distributed over a longer downvalley distance than was the case on 26 September. The tracer plume depth varied from 100 to 300 m above the ground, depending on the distance from the source. Maximum surface concentrations for each time period were observed within 3 km from the source, and ranged up to about 500 $p\ell/\ell$. The concentration isopleths after sunrise (Figs. 10-E to 10-G) suggest undercutting of the drainage flow by the reversal of the surface wind to up-valley direction, starting near the mouth of the valley. This factor, together with the upslope winds on the sunny western sidewall, led to the rapid decrease in concentrations near the surface. At 0830 MST, the plume inside the valley was separated into two parts: the usual surface plume, and an elevated plume segment near the source.

3.3 Temporal Variation of Peak Concentrations

The temporal variation of peak tracer concentration on each of the three arcs was analyzed to study tracer transport and ventilation in Brush Creek Valley. Peak surface concentrations were observed at or near the same receptor location on each arc for the two tracer experiments analyzed here. Figure 11(a) shows the peak relative concentrations at the surface on each arc, averaged over the two elevated-release experiments; the results averaged over the two surface-release experiments are shown in Fig. 11(b). The peak relative concentrations for the elevated releases were about half of those for ground releases. Arc 3 (which was closest to the release site) consistently registered the highest concentration levels for elevated as well as ground releases. As expected, arc 1 had the lowest initial concentrations, which increased rapidly during the first two hours after the release began. For the elevated release, the maximum concentrations were recorded at about 0500 MST. For the ground release, the concentrations remained relatively constant during the period 0200 to 0800 MST. After 0500 MST, the peak concentrations at arc 1 were larger than those at arc 2. The concentrations rapidly declined after the occurrence of sunshine on the valley floor. By 0900 MST, arc 1 had the largest concentrations of the three arcs.

Test 4, 09/30/84, 0100 MST, PP2



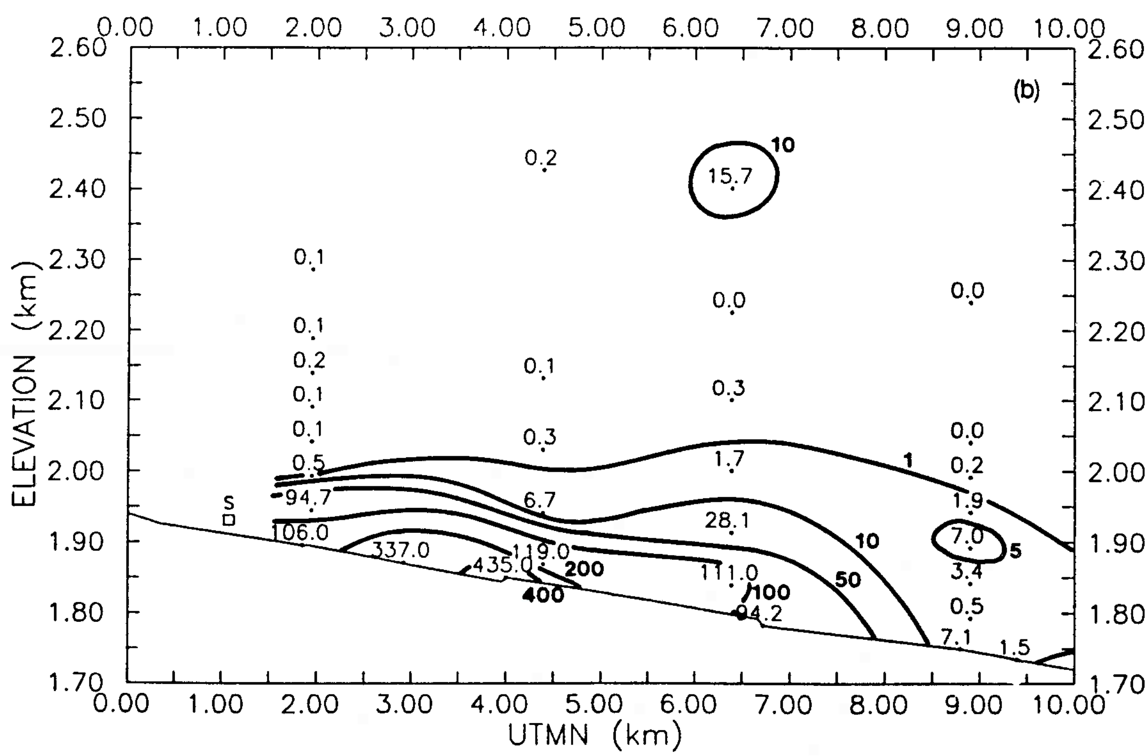
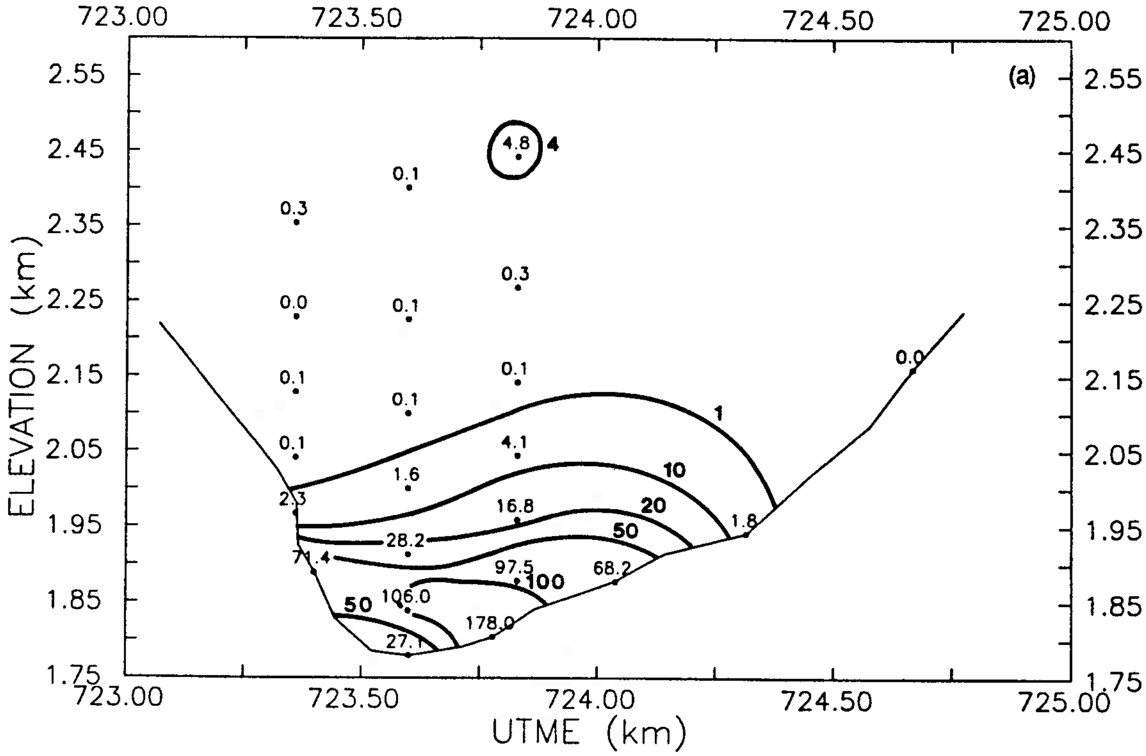


Figure 10. Observed concentrations (in $p\ell/\ell$) of PP2 tracer in Brush Creek Valley for the surface release in Test 4. Concentration isopleths are shown for valley cross sections (a) along arc 1, and (b) along valley axis at a given time (start of sampling period). Figs. 10-A to 10-G present these plots 90 min apart starting from 0100 MST.

Test 4, 09/30/84, 0230 MST, PP2



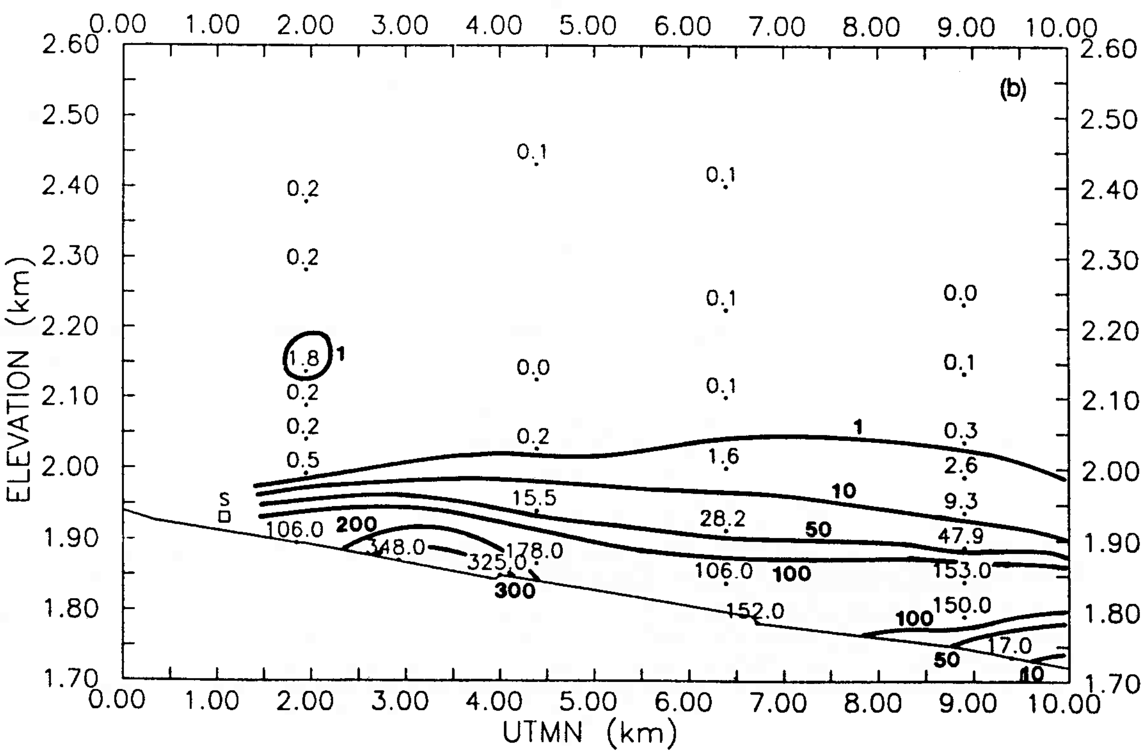


Figure 10-B

Test 4, 09/30/84, 0400 MST, PP2

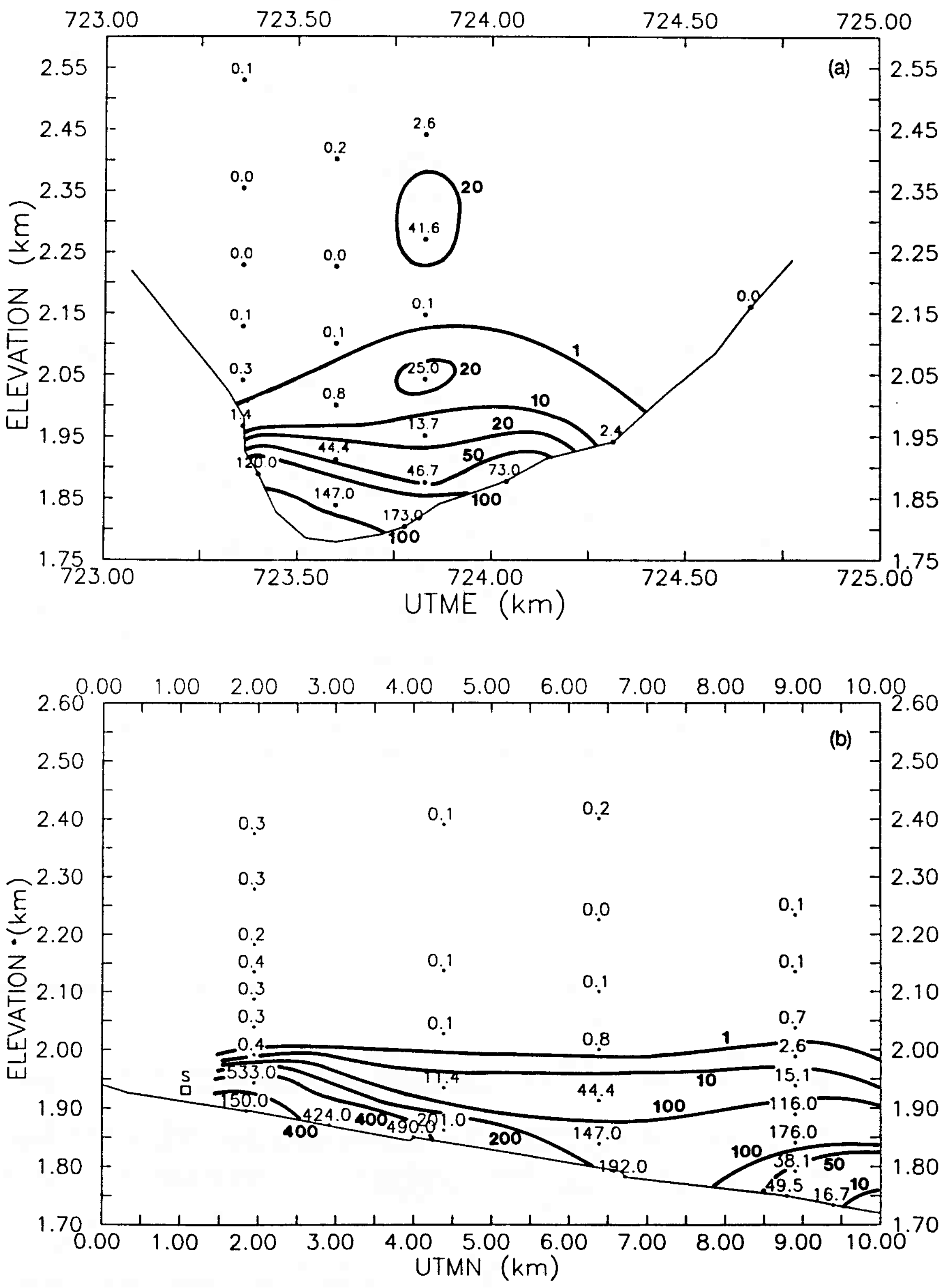


Figure 10-C

Test 4, 09/30/84, 0530 MST, PP2

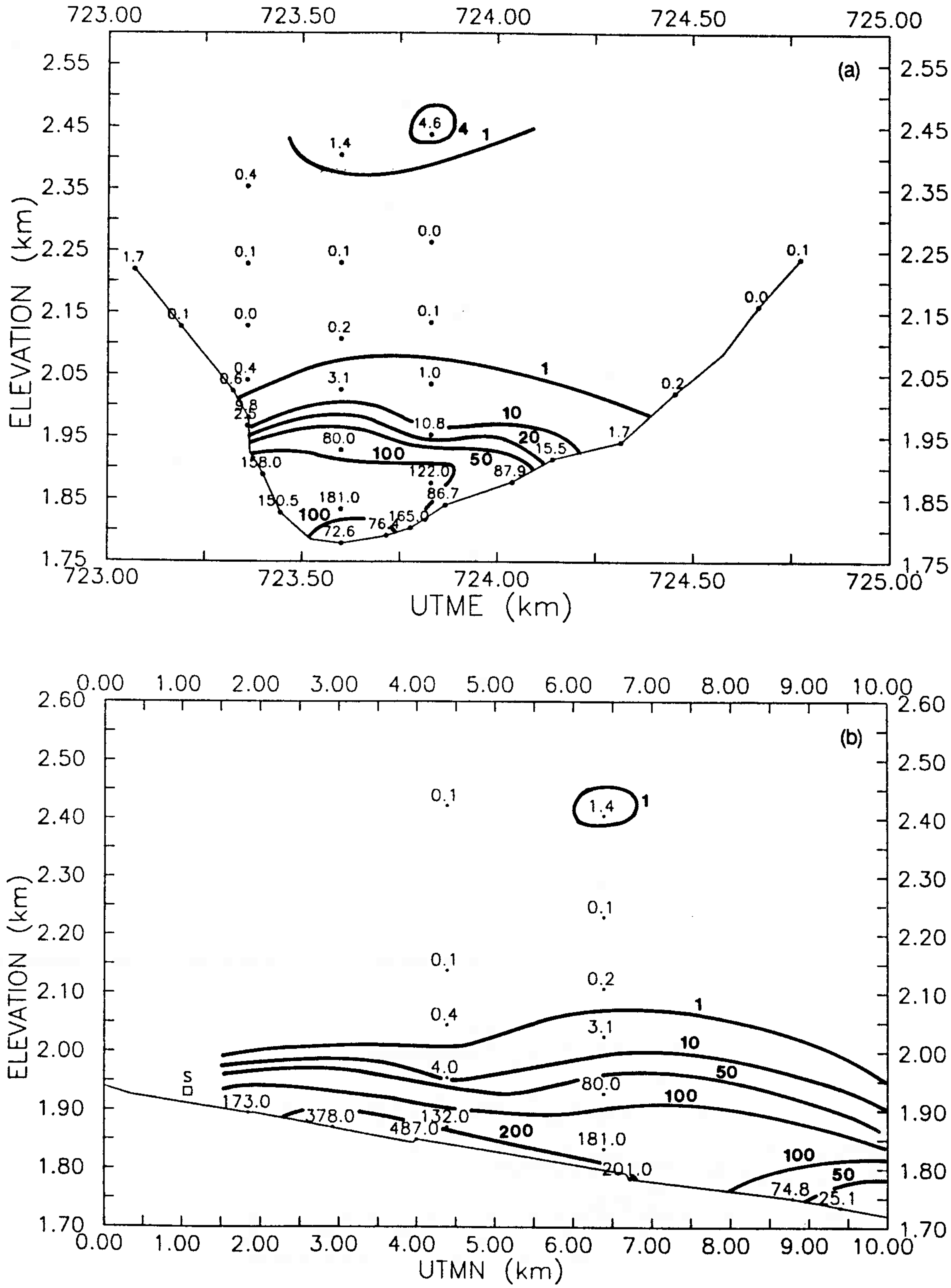


Figure 10-D

Test 4, 09/30/84, 0700 MST, PP2

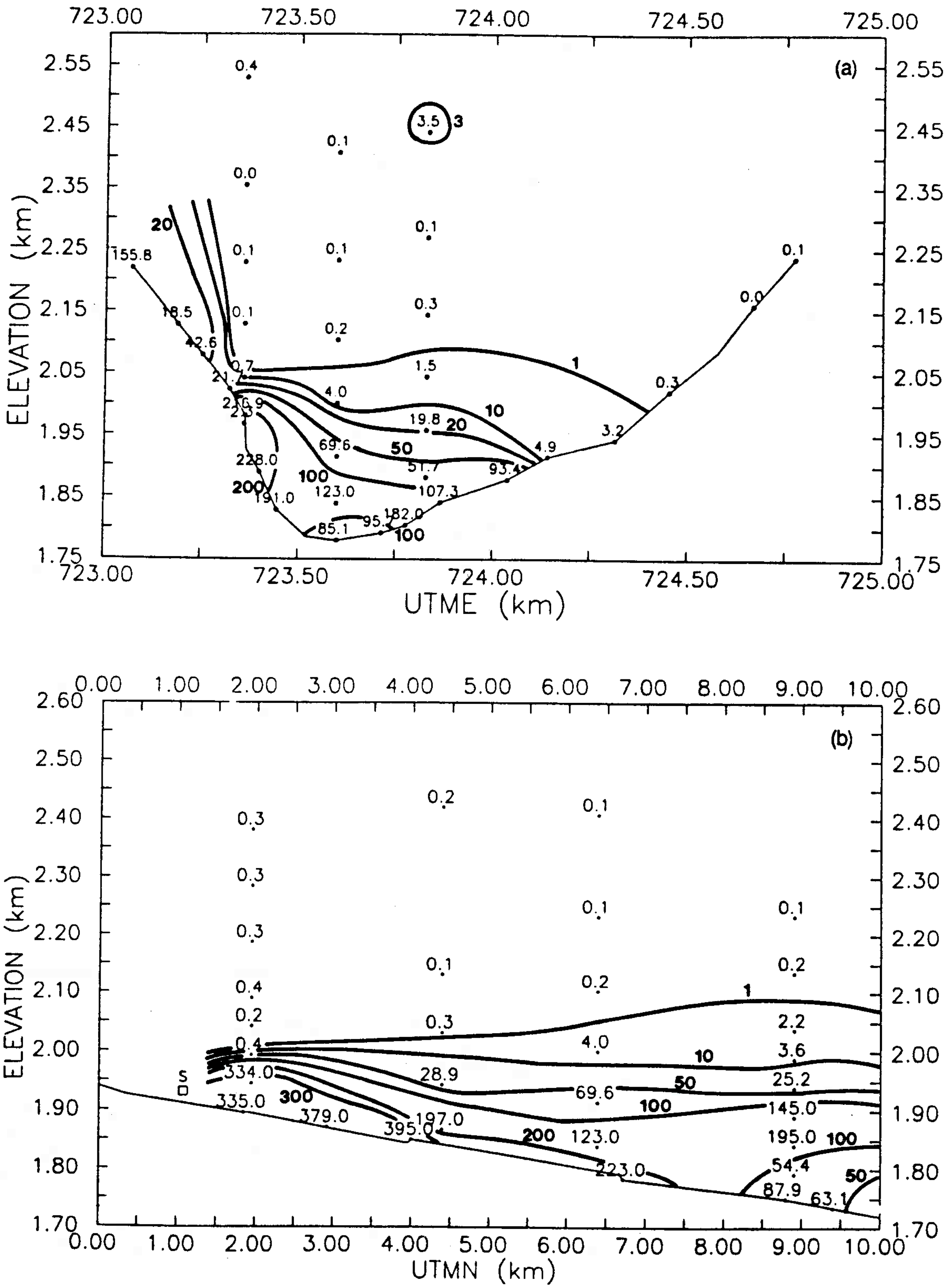


Figure 10-E

Test 4, 09/30/84, 0830 MST, PP2

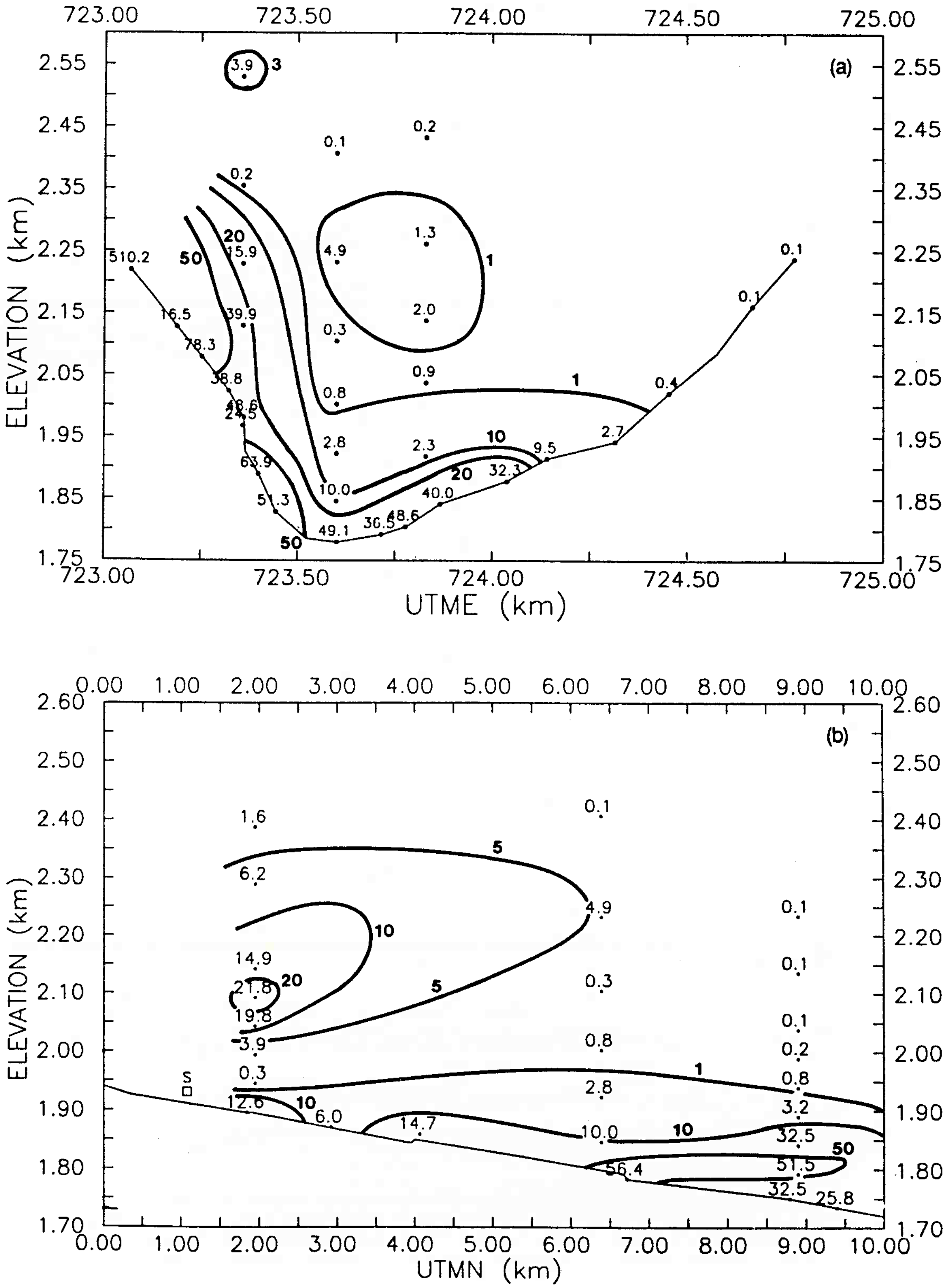
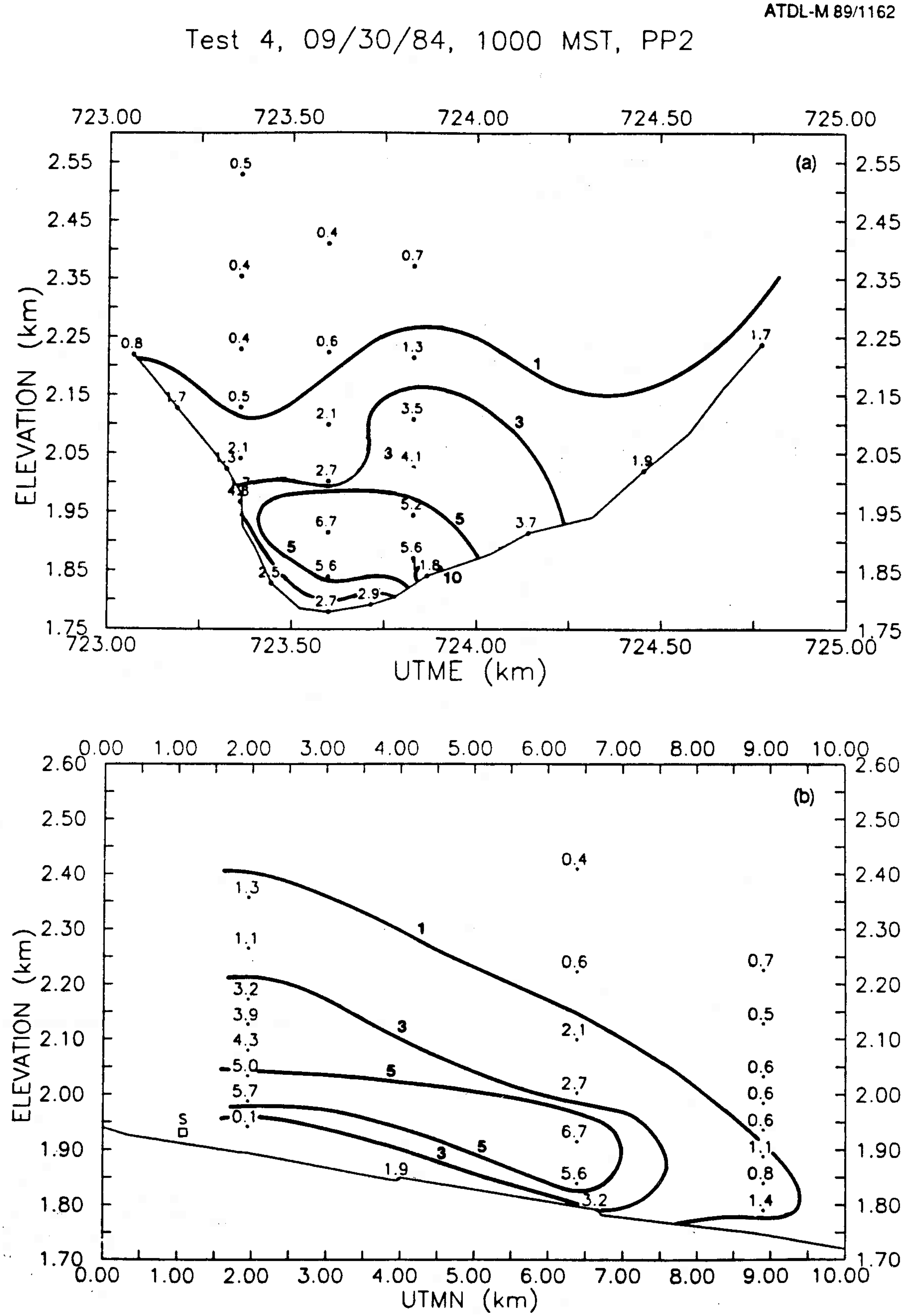


Figure 10-F



Test 4, 09/30/84, 1000 MST, PP2
(a)
UTME (km)
ELEVATION (km)
(b)
UTMN (km)
ELEVATION (km)

Figure 10-G

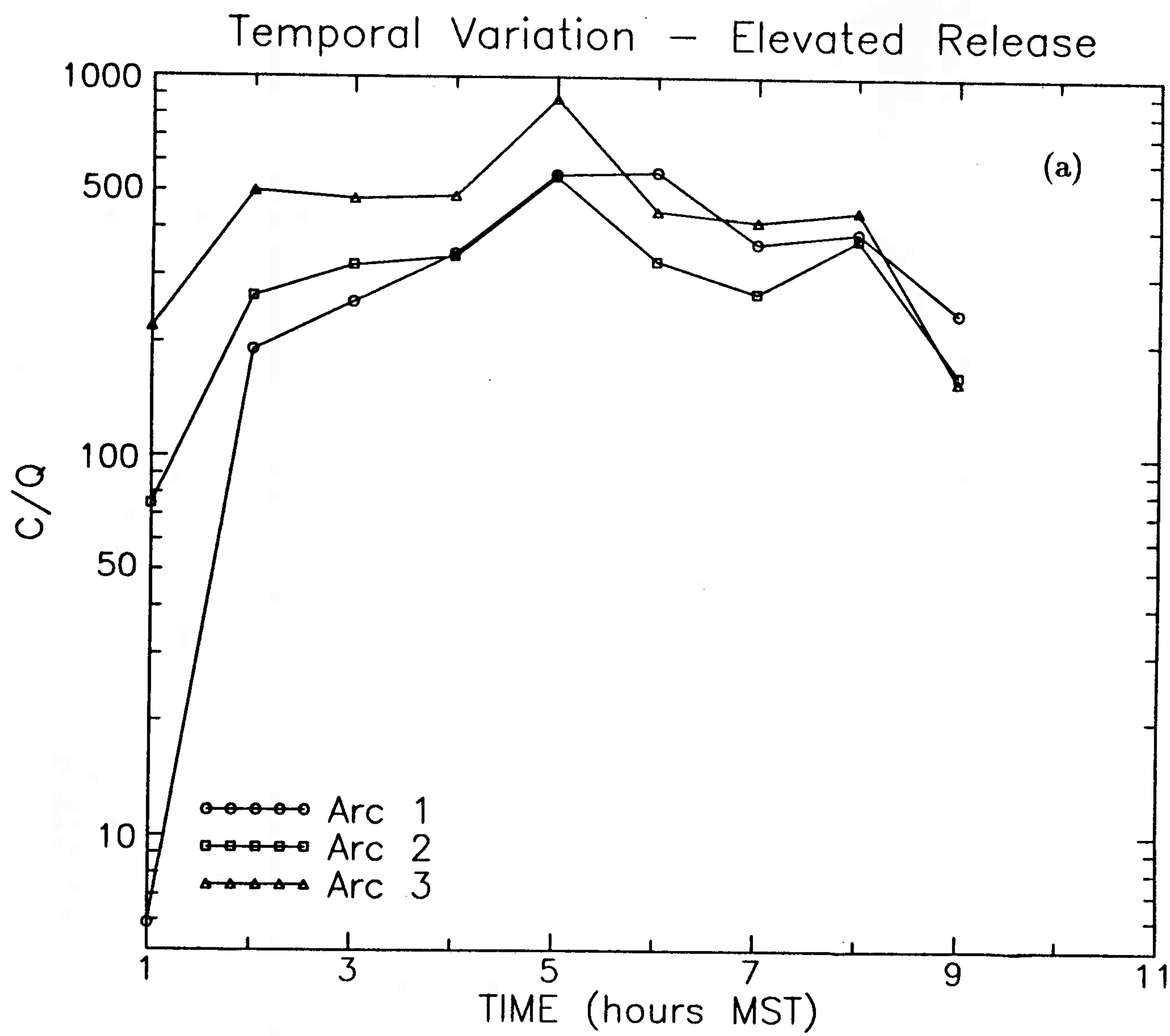


Figure 11. Temporal variations of peak relative surface concentrations, C/Q, on each arc: (a) averaged over the elevated-release experiments in Tests 2 and 4, and (b) averaged over the surface-release experiments in Tests 2 and 4.

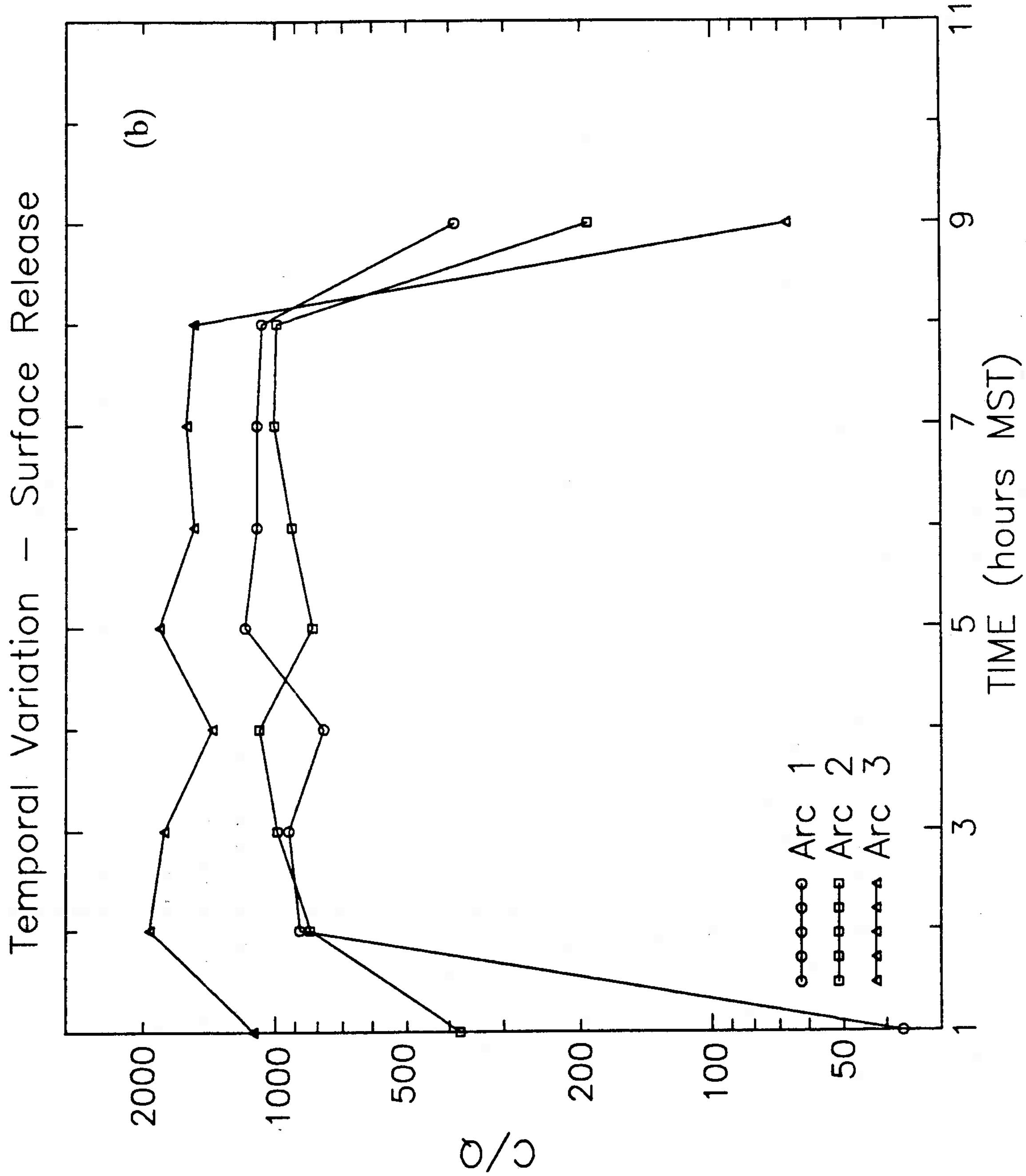

Temporal Variation – Surface Release
(b)
C/O
2000
1000
500
200
100
50
1
3
5
7
9
11
TIME (hours MST)
Arc 1
Arc 2
Arc 3

Figure 11(b)

4. CONCLUSIONS

During the early morning hours, for both elevated and surface releases, maximum concentrations were observed on the lower part of the eastern sidewall, because of the horizontal curvature of the valley. For elevated releases, high concentrations were observed at the surface very close to the release location, providing evidence for strong subsidence over the center of the valley. The tracer plume was generally confined within the 400 m deep drainage layer. However, significant concentrations were sometimes observed above the drainage layer. Barr and Orgill (1989) postulated the occurrence of internal buoyancy waves and rotors in the drainage flow. Stone and Hoard (1989) presented evidence for low-frequency fluctuations in the Brush Creek drainage flow caused by the waves. Several early-morning isopleths of tracer concentrations presented in this report display oscillatory behavior typical of the wave phenomena.

Following sunrise, adverse along-valley pressure gradients, turbulent entrainment of air from above the drainage layer, and surface warming reduced the established valley drainage. The plume moved towards the sunlit side of the valley and the tracer was transported up the heated western sidewall starting at 0700 MST. As Orgill (1989) noted, brief periods of fumigation of the plume, which resulted from the development of the convective boundary layer and onset of up-valley winds after 0700 MST, kept concentrations relatively high in the lower part of the valley until the up-valley winds were well-established after 0830 MST.

Gudiksen and Shearer (1989) suggested that upslope transport along the western wall was the main process by which the tracer was cleared from the Brush Creek Valley during the early periods after sunrise. It is likely that the heating and shading of the steep western and eastern sidewalls, respectively, after sunrise led to local circulations which played an important role in venting the tracer out of the valley by exchanging mass with air above. These circulations seemed to consist of cross-valley advection, as postulated by Whiteman (1989), as well as vortices resulting from the rising warm air near the heated west wall and compensatory sinking of cold air near the shaded east wall. As the sunlight spread to the bottom and eastern wall of the valley, the cross-sectional contours for both tracers showed evidence of the roll-vortex circulation and of periodic reversals in valley flow direction. The latter feature, which was precursor to the typical daytime up-valley flow regime, advected some of the tracer back up the valley. During these morning transition periods, low concentrations were observed in all experiments at the samplers located on both Skinner Ridge and Brush Mountain. A few samplers located in the neighboring Carr Creek and Clear Creek Valleys registered no concentrations, thus indicating that there was no mass transfer from Brush Creek Valley into the adjacent valleys.

The plume characteristics were quite sensitive to the tracer-release height in relation to the height of the nocturnal drainage jet. For the surface release, the plume was narrower and confined to the lower part of the valley, and displayed a well-defined leading edge typical of a gravity current on an incline. For the elevated release, the location of the tracer plume centerline could not be discerned from the concentration isopleths. This was especially true for the PP3 release of 26 September. Observed PP3 concentrations peaked a short distance from the source as the elevated plume was apparently transported by subsidence and diffused by turbulence to the surface. Subsequently, as the Brush Creek flow drained into Roan Creek, ground-level concentrations decreased sharply with downwind distance as in the surface release case. The effect of the tributary (Pack Canyon) flow on the transport and dispersion of tracers in the valley is not well understood.

Shearer (1990) calculated the horizontal and vertical plume dispersion coefficients from the hourly tracer concentrations (averaged over the period 0100 to 0600 MST) observed at arc 1 in Brush Creek Valley during the 1984 ASCOT tracer experiments. The σ_y coefficients estimated by him for both the PP2 and PP3 plumes were substantially smaller than the Pasquill-Gifford (P-G) σ_y value for class F stability. This indicates that the tracer plume had grown wide enough to fill the valley by the time it arrived at arc 1, and its lateral diffusion was restricted by the presence of the sidewalls. The estimated σ_z was larger than the P-G class F value, suggesting that the vertical plume spread was not affected. On the other hand, analysis by Rao and Schaub (1990) of turbulence data obtained by Doppler sodars and tower-mounted instruments located along the valley-axis in Brush Creek showed that the observed hourly-average standard deviations σ_θ and σ_ϕ of horizontal and vertical wind directions were much larger than those generally observed over flat terrain during nighttime stable conditions. This suggests that the tracer plume would have spread much wider laterally, were it not for the restriction imposed by the valley sidewalls. It is necessary to account for this feature in models of tracer dispersion in valleys (see, *e.g.,* Rao *et al.*, 1989).

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