ANALYSIS AND INTERPRETATION OF THE 1985 SEQUOIA TRANSPORT EXPERIMENT

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A report to the
California Air Resources Board

October, 1987

ARB Contract A6 082-32

TWIN PIPES

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ABSTRACT

An analysis and interpretation is presented of the 1985 Aerosol Transport and Characterization Program at Sequoia National Park, sponsored by the California Air Resources Board. Overall, it was found that the Program produced unique data sets and interesting new results relating particulate air quality and meteorology in the context of complex terrain. The major conclusion is that the meso-scale wind field, as modulated by synoptic-scale fluctuations, is the chief factor acting to cause variation in particulate concentrations in the Park. It is recommended that future work emphasize the following areas. (1) Three-dimensional structure of the meso-scale wind field in the southern Sierra foothills, with particular emphasis in the Fresno Eddy, the San Joaquin Valley nocturnal jet and the apparent convergence zone identified between Fresno and the Park. (2) Development of an objective synoptic typology to relate particulate concentration and composition to weather map features. (3) Application of modern numerical meso-scale wind field models the understanding of the complex wind field in the Park. In addition, it was recommended that in future measurement programs, greater effort be made to locate sites completely uneffected by local sources of pollutants.

INTRODUCTION

In this report, we present an analysis of the results of the 1985 Aerosol Transport and Characterization Program at Sequoia National Park, sponsored by the California Air Resources Board. Our objectives were to analyze and interpret each of the experiments which made up the overall program, select the most important results obtained and make recommendations for future work in the area. In addition, we have made a number of overall conclusions and recommendations.

On the whole, we have been most impressed with the work done by the groups involved in this study. The 1985 Sequoia program produced unique data sets and interesting new results. We feel that the ARB basically was well-served by its contractors.

Our major conclusion, which essentially mirrors that of the Principal Investigators involved in the program, is that the meso-scale wind field, as modulated by synoptic-scale fluctuations, is the chief factor acting to cause variation in particulate concentrations in Sequoia. We have concluded that further knowledge of the meso-scale structure of the atmosphere, relative to aerosol transport, in the vicinity of the Park is needed in order to understand the air quality problem in this area.

1. "Atmospheric Tracer Experiments Aimed at Characterizing the Transport and Dispersion of Airborne Pollutants in Sequoia and Kings Canyon National Parks". F.H. Shair, Principal Investigator.

Project Description.

The Cal Tech project, under the direction of F. H. Shair conducted tracer experiments designed to document the transport and dispersion properties of pollutant-laden air originating in the San Joaquin Valley and eventually impacting the area of Sequoia and Kings Canyon National Parks.

The Cal Tech group conducted four tracer experiments in July and August of 1985. The tracer material was sulfur hexaflouride gas (SF6) released as a continuous, ground-level source in the foothills of the Sierra Nevada Mountains to the southwest of the target area. Three releases were made from the Woodlake Fire Department and one from the Exeter City Hall. Three releases were made in the morning hours, between 7 and 11 AM. and one at night at 2 AM. The duration of the releases varied between 3 and 5 1/2 hours.

The resultant air concentration of SF6 was monitored by means of aircraft traverses and spirals, automobile traverses, a ground-level automatic sampler network and grab samples by project personnel camping at selected locations in the target area. No flight paths are shown for the aircraft. 720 1 hour samples were obtained from the automatic network, 300 grab samples were made during the airplane operation, 600 grab samples by the automobile teams and 200 grab samples from project camp sites. These data were reduced by means of the usual SF6 methodology.

In addition, at least two pibals were taken at Woodlake and some surface meteorological measurements were apparently made but no information is given regarding these.

Discussion of the Project Report

Data and results are presented in two documents:

(1) A two page project summary with 35 figures, 11 showing SF6 measurements made during the various tests. These figures are reproduced in the following pages. This document is essentially the visual part of a presentation given at the National Park Service/Air Resources Board Meeting on Acid Deposition, held at Sequoia National Park in January 1986.

(2) A data compilation, entitled "Brief Summary of Test 4", consisting of a three page description of measurement methodology and site locations, four major conclusions from the Cal Tech analysis and eight data appendices. Apparently all these data are from Test 4, held August 16-17,1985. The pages following show selected figures from the report.

In Document (2), the following-conclusions, which apparently pertain primarily to Test 4, are presented:

(1) Pollutants traveling from the south, which reach Exeter during the night, may significantly impact Sequoia National Park during the next day.

(2) The maximum impact of the above mentioned pollutants during the day is expected to be in the region northeast of Lake Kaweah.

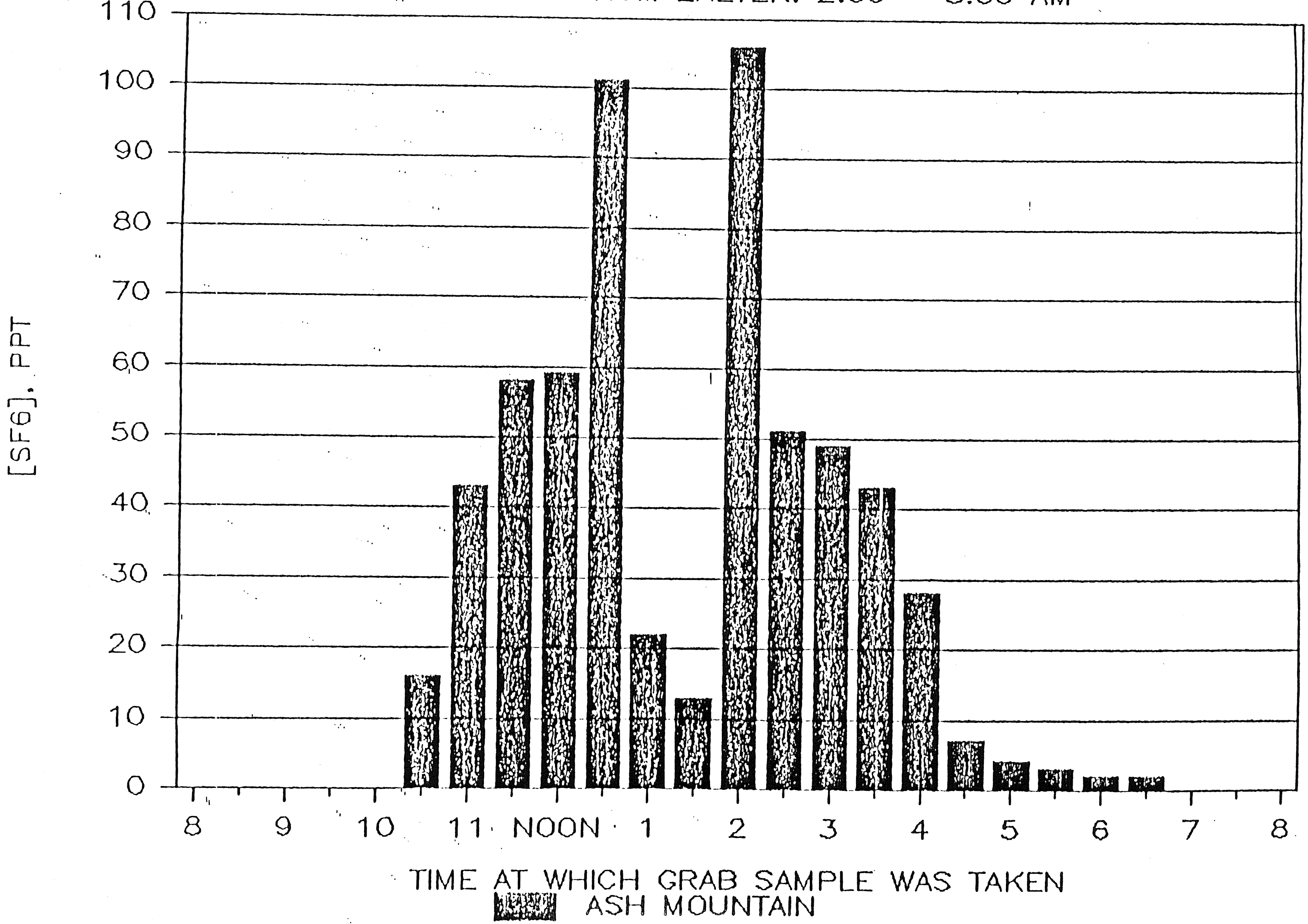
(3) The sampling site farthest from the release point was the Tablelands northeast of Emerald Lake. This site was 49 miles (79 km) from the release site. Twelve hours after the start of the release, the value of XU/Q at the Tablelands was 4.6×10^{-8} m^{-2}, stated to be "in close agreement with that estimated for the centerline of a Gaussian plume for B stability and a mixing depth of 4500 feet above ground level".

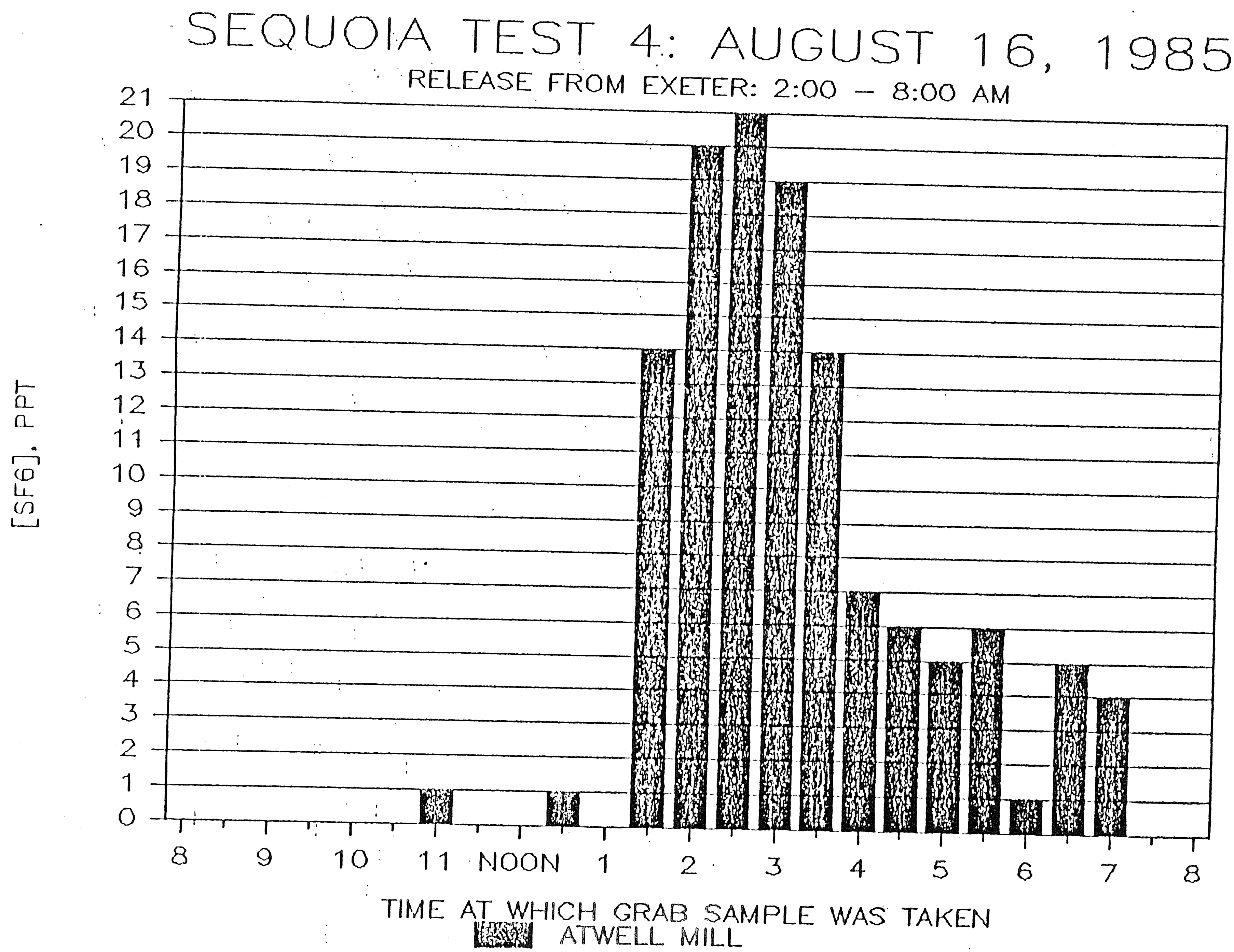
(4) Near the western edge of the park, the average concentrations in the downslope flow are about 10% of those in the preceding upslope flow.

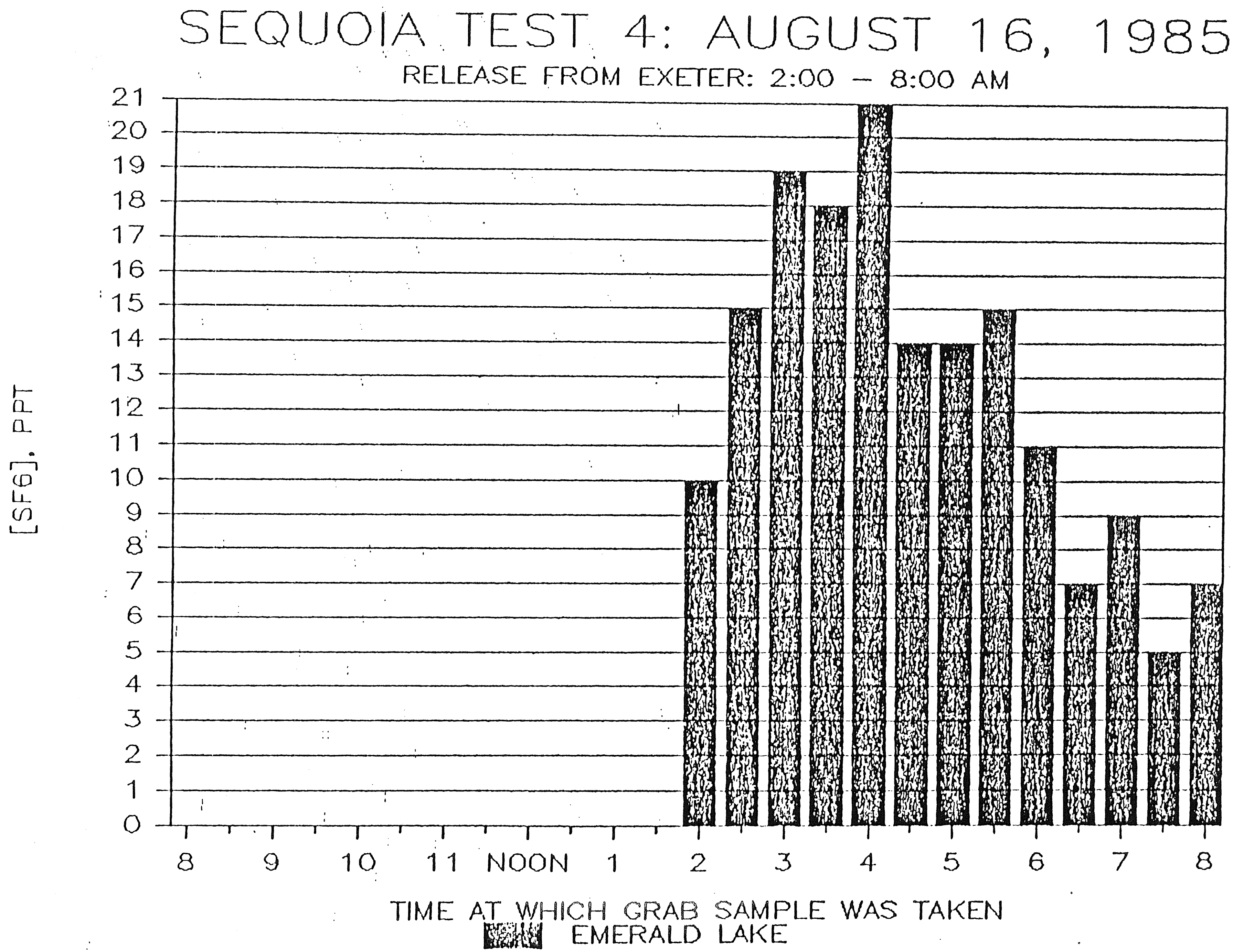
In Document (1), it is stated that airplane samples taken over Emerald Lake during a light rain "clearly indicate that pollutants transported upslope via the lower level air can mix with moisture transported via the upper level air" and that "the convective mixing associated with the rain also served to lower the tracer concentrations observed at Emerald Lake."

SEQUOIA TEST 4: AUGUST 16, 1985

RELEASE FROM EXETER: 2:00 – 8:00 AM




SEQUOIA TEST 4: AUGUST 16, 1985
RELEASE FROM EXETER: 2:00 – 8:00 AM
[SF6], PPT
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
8
9
10
11
NOON
1
2
3
4
5
6
7
8
TIME AT WHICH GRAB SAMPLE WAS TAKEN
ATWELL MILL


SEQUOIA TEST 4: AUGUST 16, 1985
RELEASE FROM EXETER: 2:00 – 8:00 AM
[SF6], PPT
21
20
19
18
17
16
15
14
13
12
11
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9
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7
6
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2
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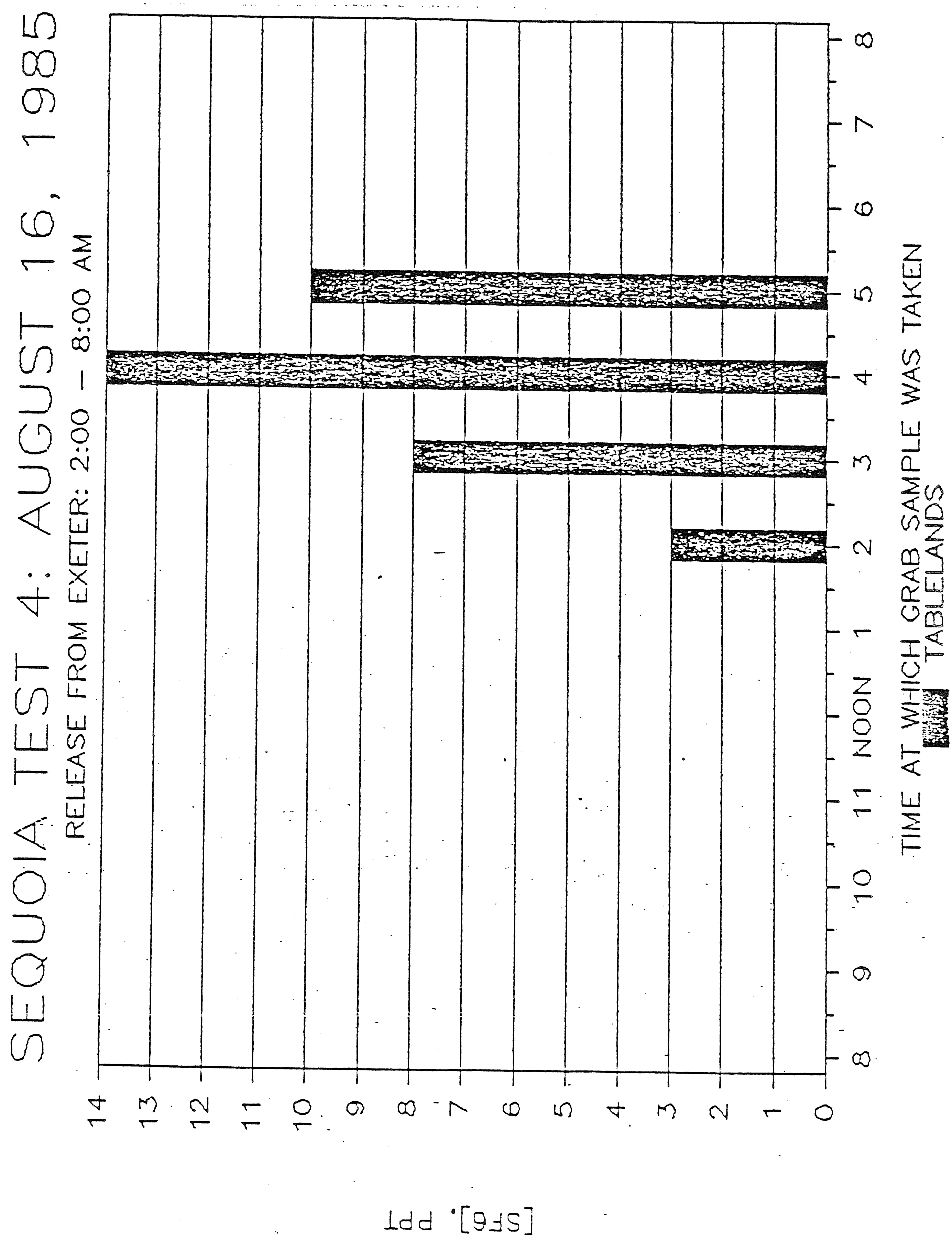
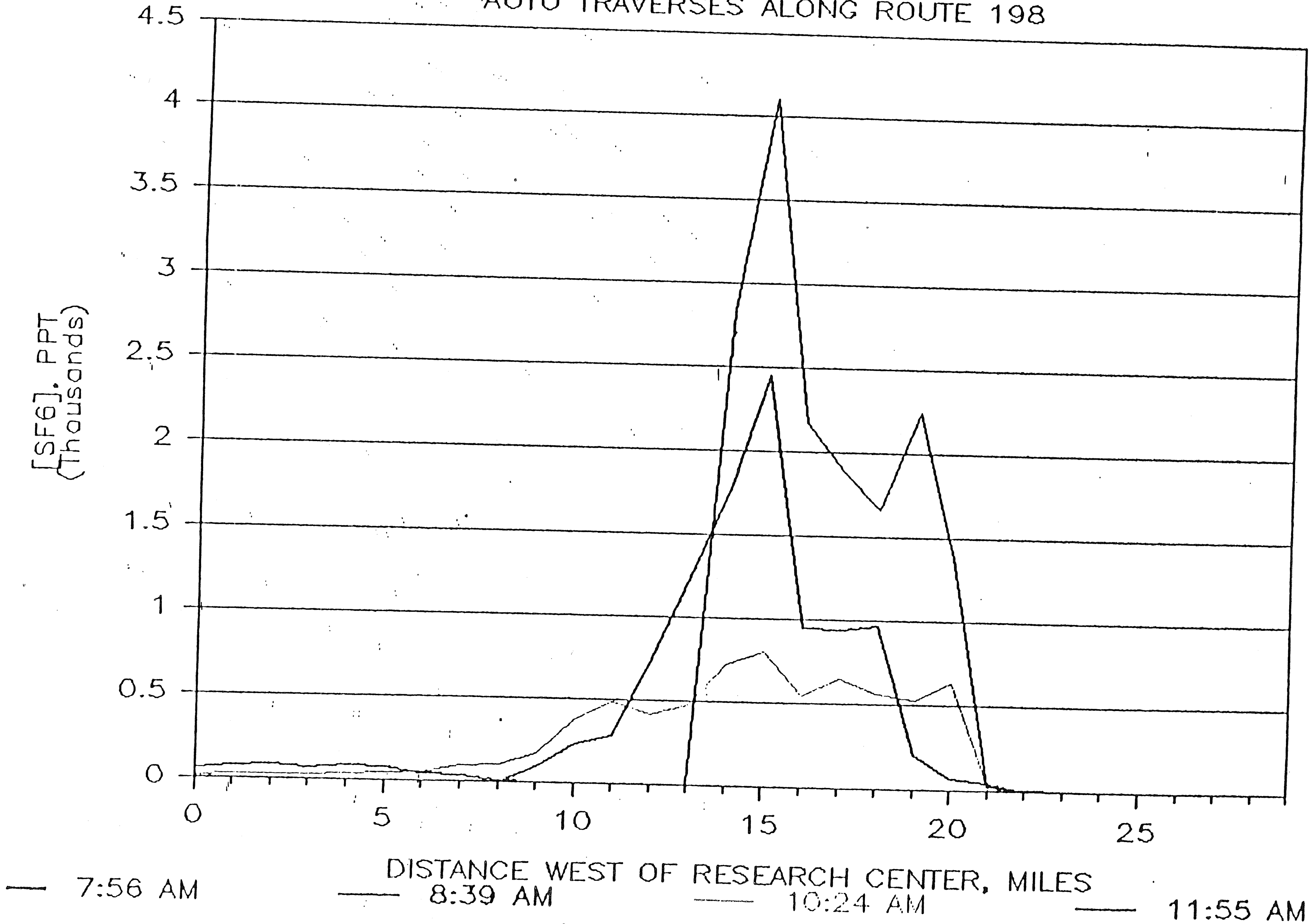
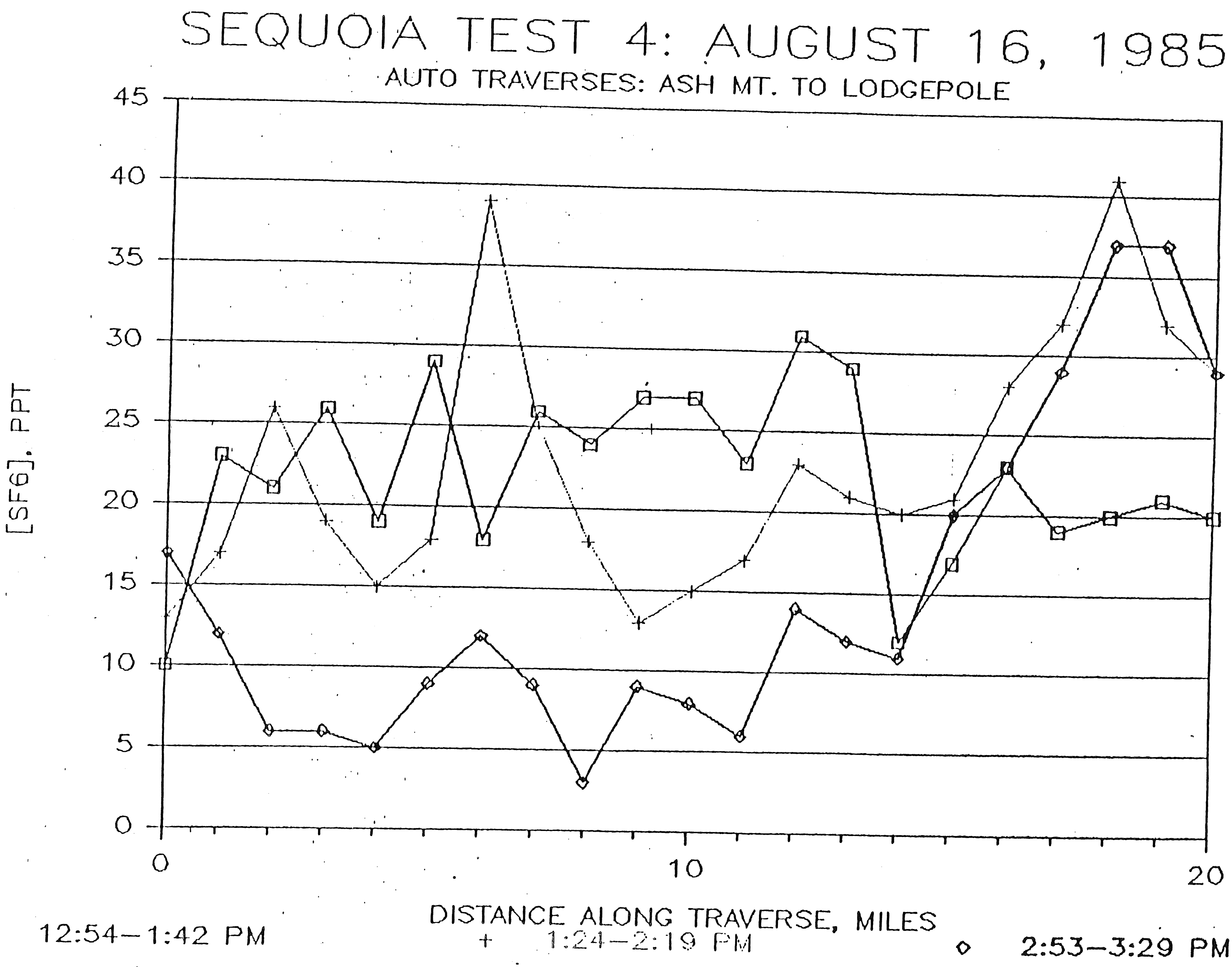
TIME AT WHICH GRAB SAMPLE WAS TAKEN
EMERALD LAKE


SEQUOIA TEST 4: AUGUST 16, 1985
RELEASE FROM EXETER: 2:00 – 8:00 AM
[SF6], PPT
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
8 9 10 11 NOON 1 2 3 4 5 6 7 8
TIME AT WHICH GRAB SAMPLE WAS TAKEN
TABLELANDS

SEQUOIA TEST 4: AUGUST 16, 1985

AUTO TRAVERSES ALONG ROUTE 198

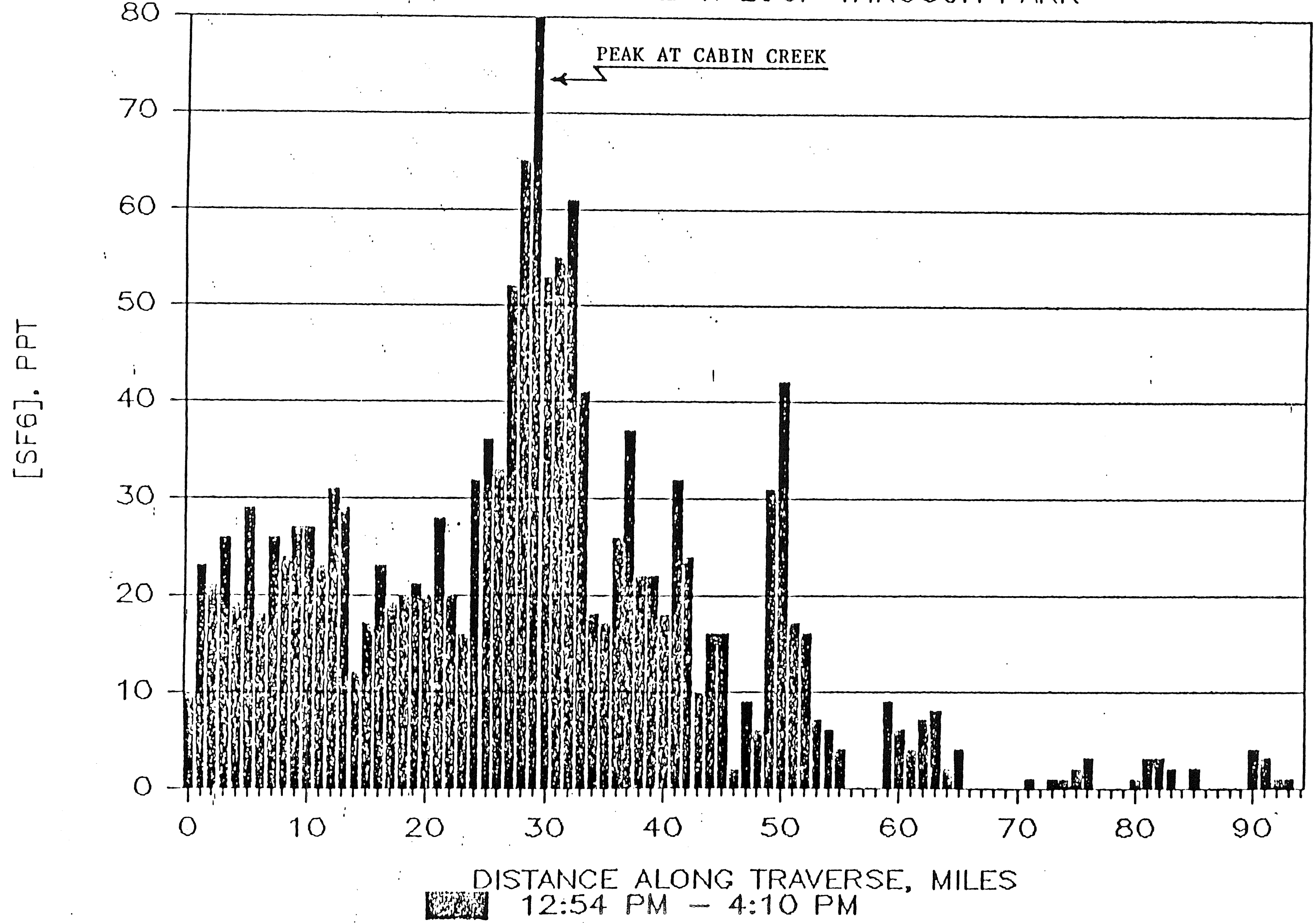




SEQUOIA TEST 4: AUGUST 16, 1985
AUTO TRAVERSES: ASH MT. TO LODGEPOLE
[SF6], PPT
45
40
35
30
25
20
15
10
5
0
0
10
20
DISTANCE ALONG TRAVERSE, MILES
12:54—1:42 PM
+ 1:24—2:19 PM
◇ 2:53—3:29 PM

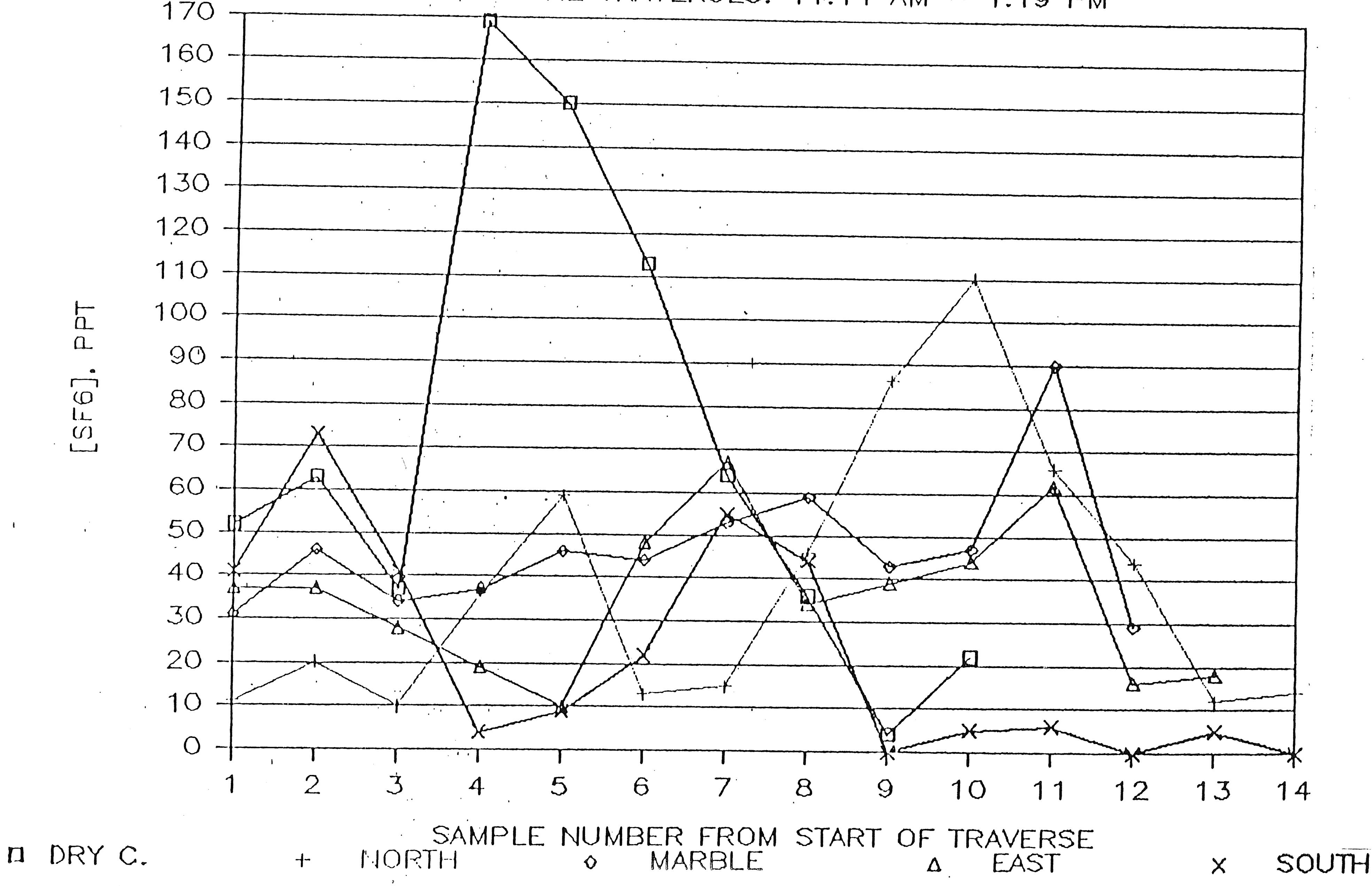
SEQUOIA TEST 4: AUGUST 16, 1985

AUTO TRAVERSE 4: LOOP THROUGH PARK



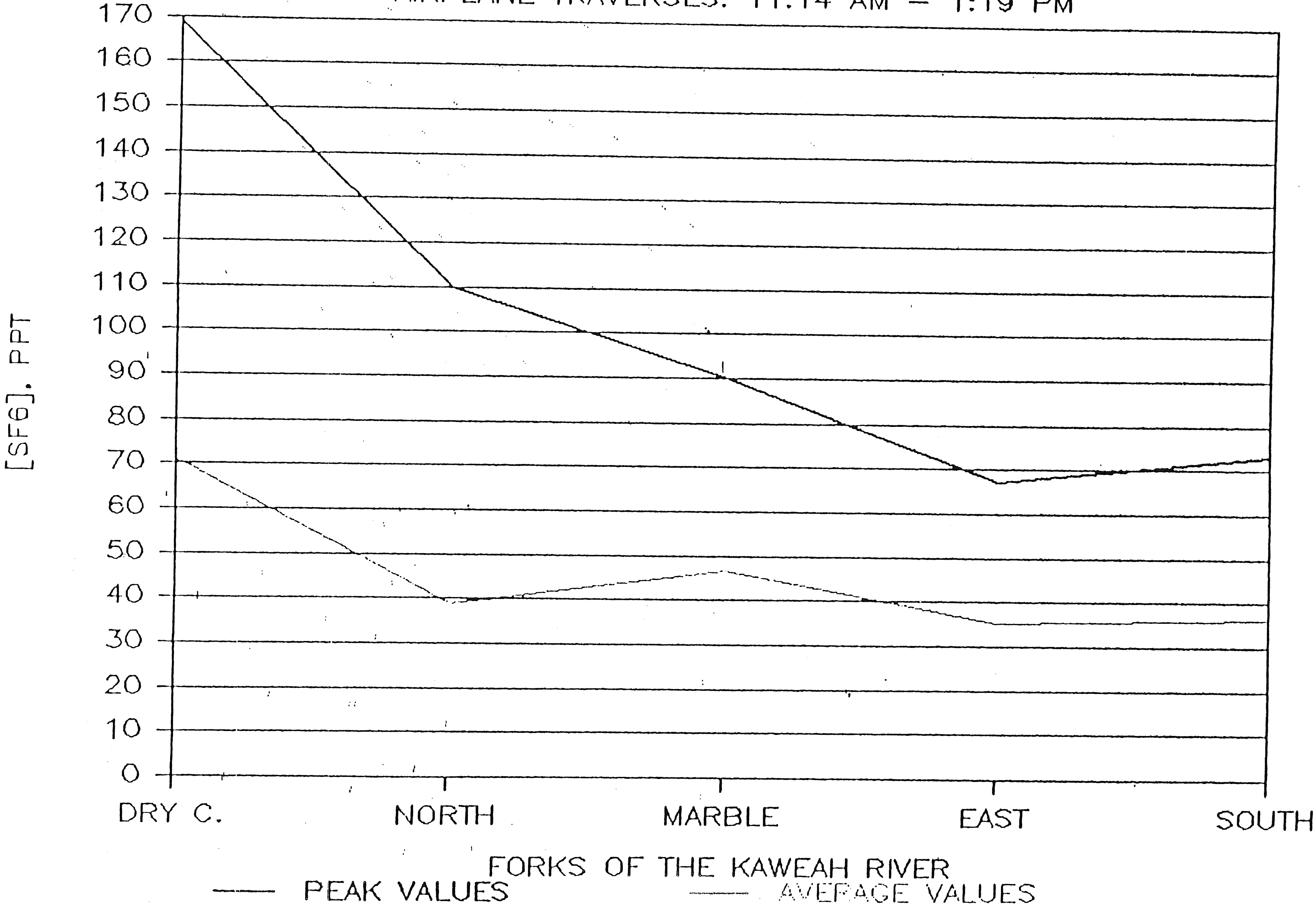
SEQUOIA TEST 4: AUGUST 16, 1985

AIRPLANE TRAVERSES: 11:14 AM – 1:19 PM



SEQUOIA TEST 4: AUGUST 16, 1985

AIRPLANE TRAVERSES: 11:14 AM – 1:19 PM



In Document (1), the author notes that the results of Test #4 show that the nocturnal southerlies flowing along the foothills, associated with the Fresno Eddy, persist until at least 7 AM. This is long enough to transport emissions from San Joaquin Valley oil fields to locations where they may then be transported into the Park by daytime upslope winds.

Also in Document (1), it is stated that the author has formulated a conceptual model, based on the interaction of the upper and lower flow regimes. No details are presented, however. It is stated that the model indicates that the southwest region of Sequoia will experience more damage than the northeastern region.

Recommendations and Suggestions for further work.

We wish to emphasize the importance of the synoptic context of the tracer experiments. Without such information, it is extremely difficult to interpret the tracer results. In addition, a comparative analysis of the entire set of four tracer experiments , taking into account the synoptic situation, would be a valuable contribution to the Sequoia program as well as to the current research literature.

There are additional analyses which could be done with the tracer data. These are not presented as deficiencies but as additional research topics. An obvious and probably valuable analysis with the Cal Tech data would be to do a detailed comparison with the data of the other three groups, especially the wind data of the Myrup-Flocchini group. An important question is whether or not the Davis wind data is sufficient to predict the displacement of the plume.

Looking toward the future, one key question for Sequoia research is how to represent the effect of mountain roughness in meso-scale or other numerical models. The conclusion that the plume from the Test 4 release behaved as a B stability Gaussian plume with a center line at 4500 feet above the surface is of considerable interest. It raises the questions of what the actual stability was and at what height was the centerline of the real plume. A simple recipe, perhaps in terms of an augmented centerline height or more unstable stability category, for adjusting Gaussian calculation for mountain conditions would be highly valuable if a reasonable degree of validity could be demonstrated. Presumably, the Cal Tech data set could be used for this purpose.

More sophisticated models, such as three-dimensional meso-scale airflow models require more detailed information regarding the distribution of dispersion parameters. It should be possible to fit the output of a diffusivity-based plume model to the Cal Tech data to obtain an optimum diffusivity diffusivity distribution. Diffusivities derived in this way could be compared to those obtained from flat terrain cases to obtain the "mountain effect".

A possibility also exists to use a mass-consistent wind flow model to obtain three-dimensional trajectories for source analysis. Such a technique may be the only feasible way to obtain three-dimensional trajectories.

Suggestions for further work fall into two categories, additional work on the present data set and improved tracer work in future experiments. With regard to the present tracer data set, we suggest the following: (1) The value of this information would be greatly increased if the Principal Investigator wrote a reasonably comprehensive final report. The two documents which have been provided to date are incomplete and poorly documented. They are not adequate to understand how these measurements were made. In addition, very little information is presented regarding three of the releases. (2) Specifically, the locations of all measurements should given precisely, including flight paths showing locations of grab samples and a map showing locations of all automatic samplers and surface grab samples. (3) The figures for document #1 are poorly drafted and annotated. This leaves much to be desired, especially considering that these figures are the only source of information for much of the experiment. At a bare minimum, the Principal Investigator should provide legible, well annotated versions of these figures. (4) Data equivalent to those given for Test 4 should be provided for the other three tests. (5) The diffusion data should be analyzed to obtain horizontal and vertical sigmas as a function of plume travel time. In addition, a more sophisticated analysis should be undertaken to obtain the effect of the mountainous terrain in Sequoia National Park on diffusivity of aerosols. It would be necessary to apply a three-dimensional meso-scale model to this problem. (6) The conceptual model, alluded to by the Principal Investigator in Document #1, should be supplied. (7) A study should be undertaken to make a detailed comparison between the tracer data and the measurements made by the other groups.

In future tracer experiments in the Sequoia area, we recommend the following: (1) The experiment should be designed to investigate the effect of the major meso-scale flow features of the San Joaquin Valley-Sierra system. In particular, the rôles of the Fresno Eddy, the San Joaquin

Nocturnal Jet and the nocturnal Sierra drainage winds were not well described by the 1985 experiment. This is not a criticism, but future experiments should be specifically designed to clarify those processes not covered in the 1985 study. (2) Aircraft soundings should be made in conjunction with future tracer experiments. (3) The experiment should be planned so as to obtain releases under contrasting synoptic situations.

2. "Transport of Atmospheric Aerosols Above the Sierra Nevada Slopes". L.O. Myrup and R.G. Flocchini, Principal Investigators.

Project Description

The general objective of the Myrup/Flocchini portion of the Sequoia program was to document boundary-layer transport of aerosol pollution into the Park area. To accomplish this, four measurement programs were carried out: (1) Tethersonde profiles of temperature, humidity and wind velocity. (2) Tethered balloon measurements of aerosol concentration profiles. (3) Pibal wind measurements at three sites in the Park. (4) Measurement of surface meteorological parameters at the pibal winds sites.

The three measurement sites were chosen to be representative of low, intermediate and high elevations within the study area. The lower site was located 30 m above and 125 m northwest of Park Headquarters at Ash Mountain at an elevation of 560 m. The intermediate elevation site was located in Wolverton Meadow, 1.5 km southwest of the Lodgepole Campground and 1 km from the General's Highway at an elevation of 2222 m. The upper site was located at Emerald Lake, 3.5 km east of the Lodgepole Campground along the Marble Fork at 2719 m elevation. Pibals and surface weather stations were operated at all three sites. The two tethered balloon operations were conducted only at the intermediate site. The characteristics of the sites are summarized in the accompanying table (Table 2 from author's report).

The tethersonde apparatus was operated two to three times a day to obtain boundary-layer profiles of temperature, humidity and wind velocity. The sensor package achieved heights above the surface between 250 and 550m with an average value of approximately 350m. An effort was made to obtain soundings for both stable and unstable conditions. Four soundings were made between the hours of 6 and 12 PDT, 13 between 12 and 18 PDT, 4 between 18 and 24 PDT and 2 between 24 and 6 PDT. Representative soundings obtained with the tethersonde system are shown in the accompanying figures.

The tethered balloon aerosol sampling device is a recently developed system (Flocchini (1984,1986); the Sequoia program was the first it was operated in field conditions. Sampling units, consisting of batteries and

	EMERALD LAKE	WOLVERTON	ASH MOUNTAIN	FRESNO STATE
Longitude	118.68	118.73	118.83	119.75
Latitude	36.62	36.60	36.50	36.93
Township	15S	15S	16S	13S
Range	30S	30E	29E	20E
Section	24W	29NE	33E	5SE
Elevation (m msl)	2719	2222	560	100
Height Above Valley Floor (m)	10	200	50	0
Up/Down Valley (degrees)	90/270	080/260	020/210	135/315
Valley Floor Width (m)	250	100	125	100 km
Ridge Height (m msl)	3400 SE 3400 NNW	2750 SE 2450 NW	1900 E 1080 W 1600 NW	1200 W 4000 E 2000 SE
Ridge Height Above Site (m)	767 SE 767 NNW	528 SE 228 NW	1340 E 520 W 1040 NW	1100 W 3900 E 1900 SE
Distance Ridge To Ridge (km)	S N-S	10.9 NNW-SSE	7.4 NW-SE	200 SW-NE
Valley Floor Slope (%)	S	6	7.5	~0
Upslope/Downslope (degrees)	150/130	135/315	300/120	090/270
Slope Inclination (%)	18	10	23	

TABLE 2: TOPOGRAPHIC FEATURES

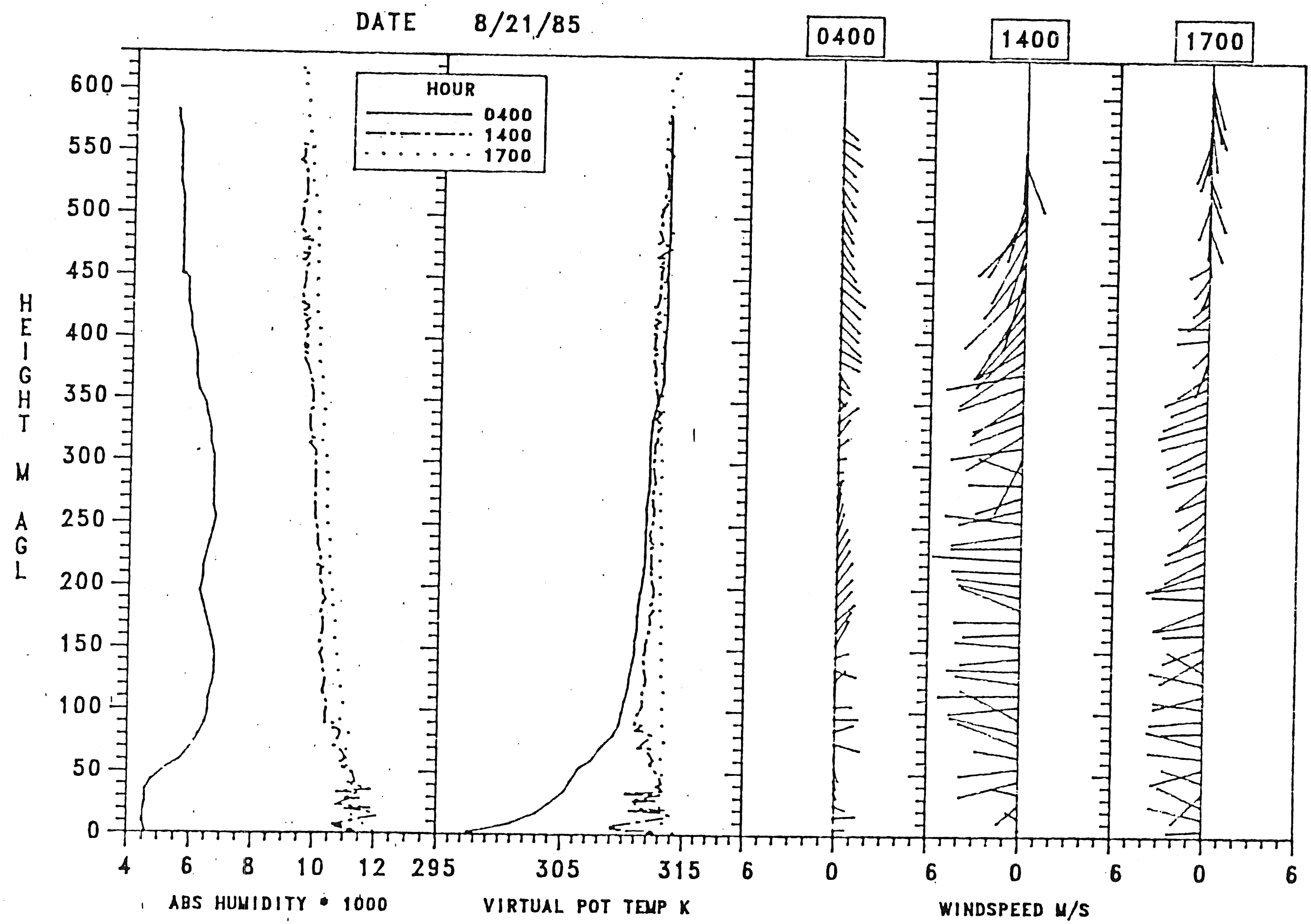


Figure 14: Tethersonde profile for August 21, 1985, at 0400, 1400 and 1700 PDT for Wolverton.

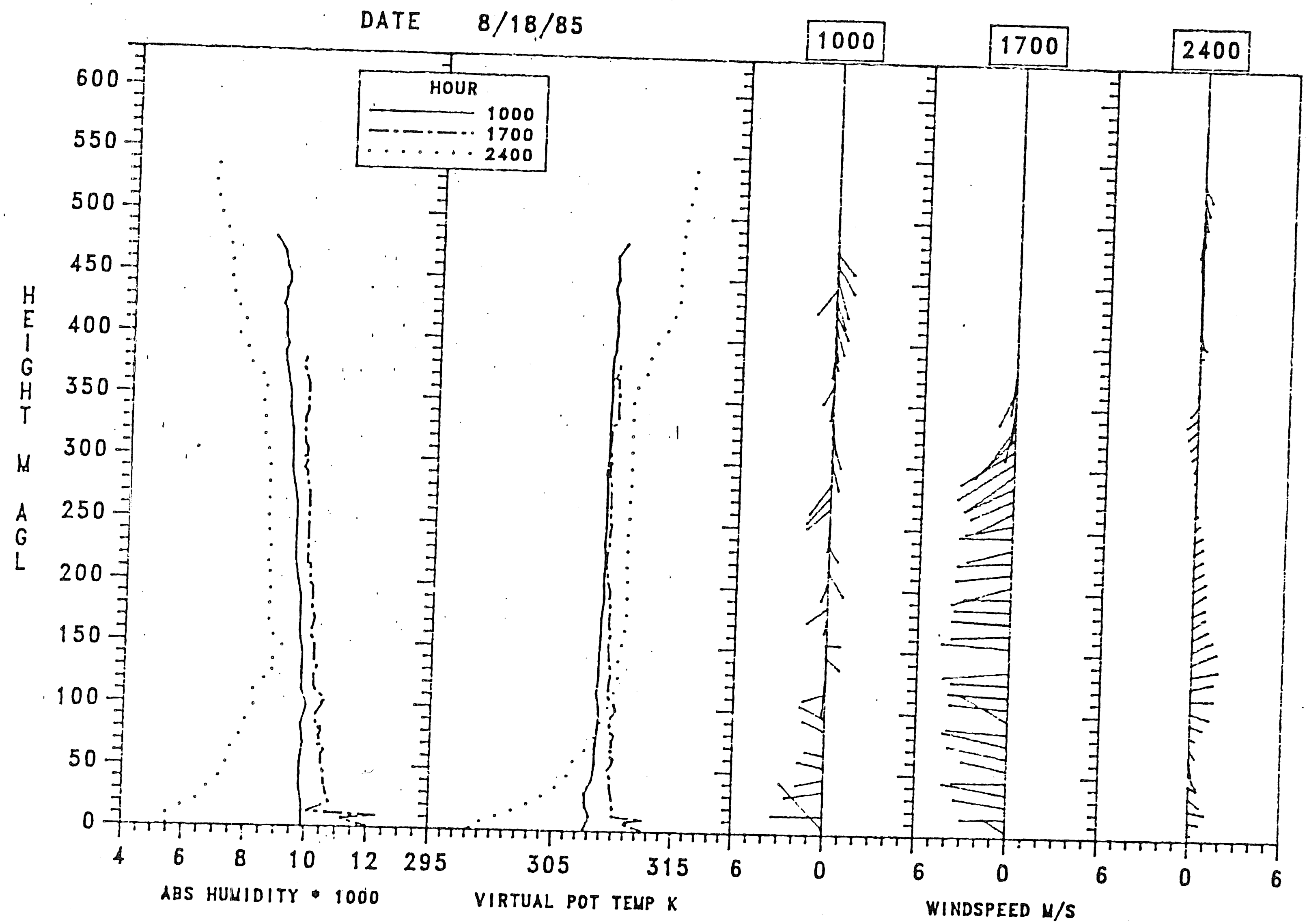


Figure 11: Tethersonde profile for August 18, 1985, at 1000, 1700 and 2400 PDT for Wolverton.

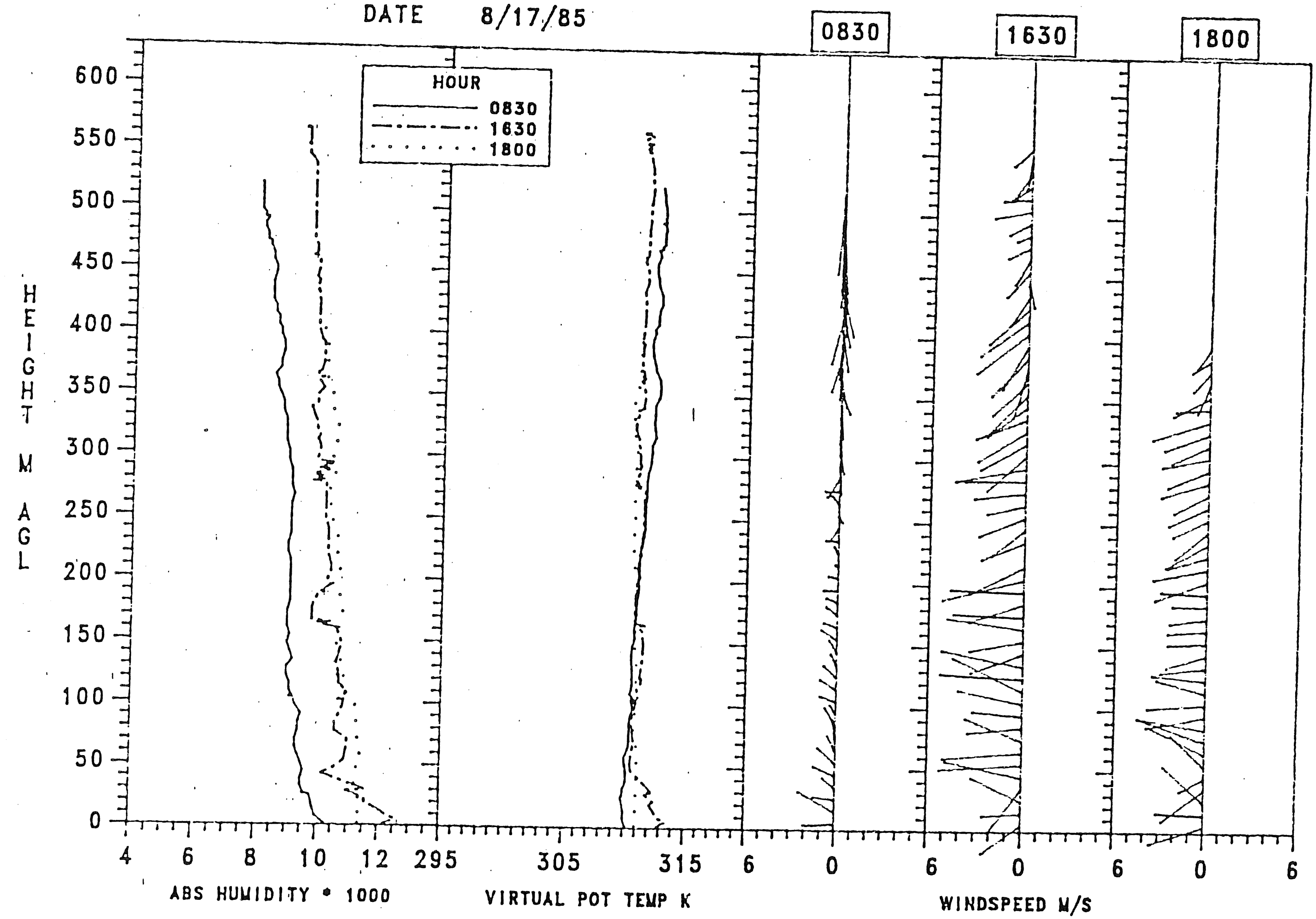


Figure 10: Tethersonde profile for August 17, 1985, at 0830, 1630 and 1800 PDT for Wolverton.

filter cassette assemblage, were suspended at 50,100, 150, 200 and 250 m above the ground. The filter cassette is similar to the two stage stacked filter design described by Cahill, et al (1979). For the coarse mode 8.0 micron coated nuclepore filters were used. For the fine mode, 3.0 micron teflon filters were used.

The aerosol samplers were run from one to two hours, which allowed consistent detection of major elements whereas minor elements, such as lead and vanadium, were frequently below the detection limits of the PIXE (Cahill 1976, Flocchini 1976) technique of elemental analysis. A new analytic technique, proton elastic scattering, was employed for elemental hydrogen. In addition, the filters were analyzed for gravimetric mass and carbon soot. The errors for the various analysis techniques were stated to range from 4 % for sulfur to 10 - 15% for copper, lead and bromine. The accompanying table shows values of aluminum, silicon, potassium and carbon-soot, averaged over all profiles taken between August 13 - 22.

The tethered balloon aerosol sampling system had a high failure rate (>30%) during the month of July, primarily due to battery explosions. The accompanying figures show representative aerosol profiles.

Single theodolite pibals were obtained at all three sites four times a day, including 2 at night on 50% of the observation days. Theodolite readings were made at 90 m height increments. The soundings generally extended to at least an elevation of 5 km MSL. The data is somewhat incomplete in July due to equipment problems. The Sequoia pibals are augmented by those made in Fresno by the Fresno State Group. Pibals were taken in Fresno 4 times a day at approximately the same times as in Sequoia.

Surface meteorological measurements were also made at the three pibal sites. Temperature and humidity were measured at heights of 2 and 5 m at Wolverton Meadow and Emerald Lake and at 7 and 10 meters at Ash Mountain.

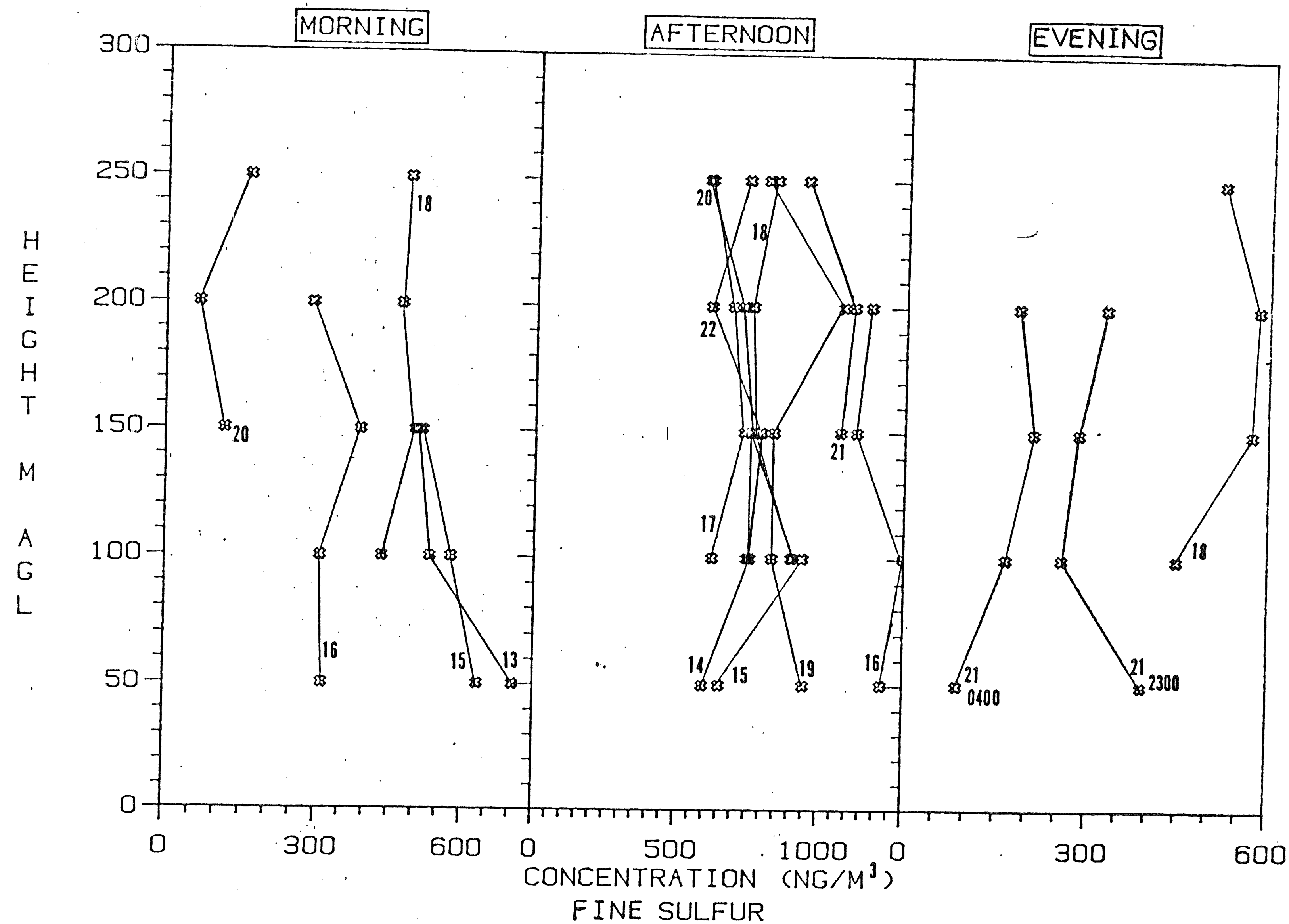


Figure 32: Individual fine aerosol concentration profiles for sulfur.

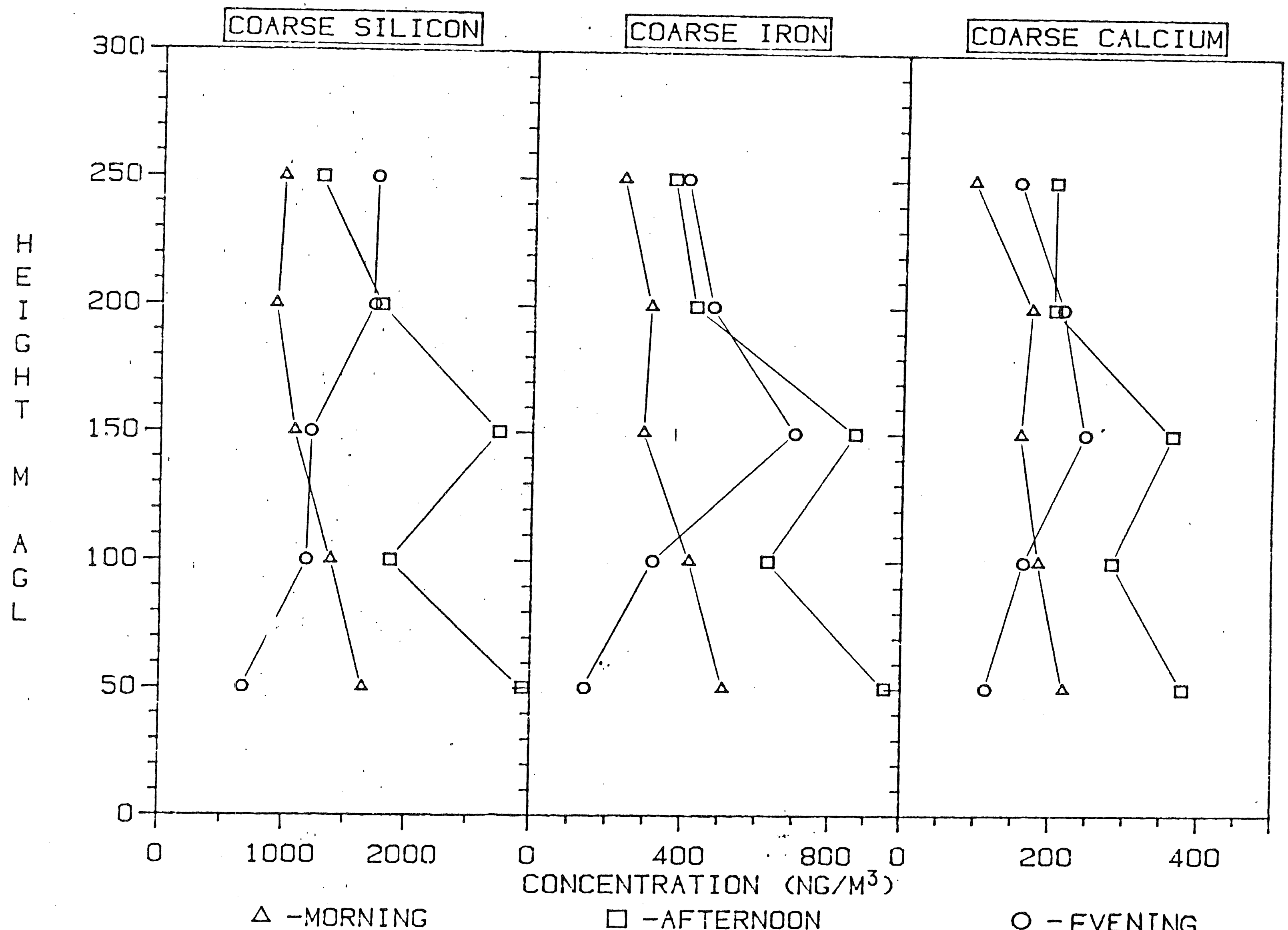


Figure 31: Average coarse aerosol concentration profiles for silicon, iron and calcium.

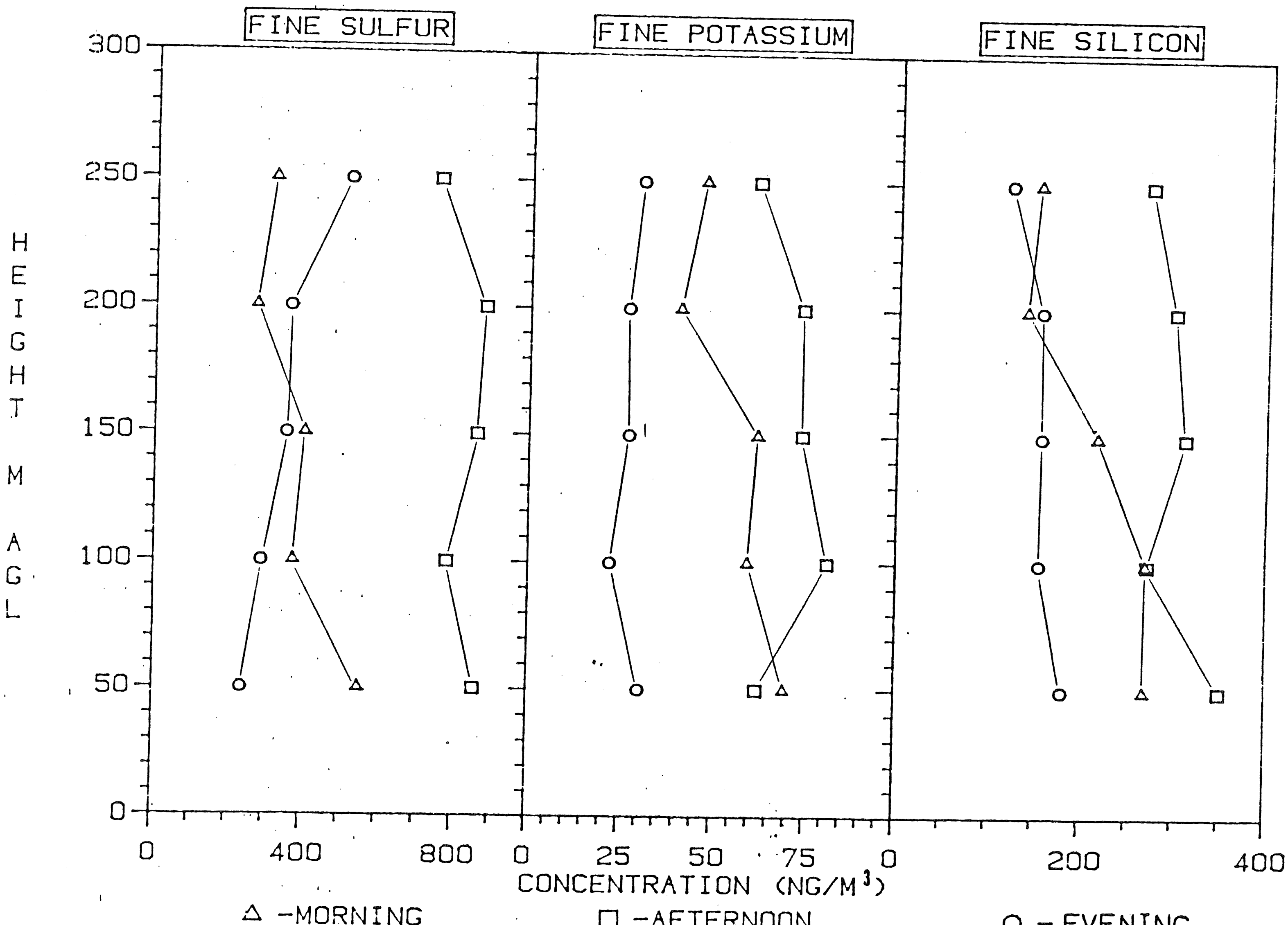


Figure 30: Average fine aerosol concentration profiles for sulfur, potassium and silicon.

Discussion of the Project Report

The results of this project are presented in a report which consists of 31 pages of text and three appendices which provide measurement and data processing details. In addition, a data appendix is included which contains listings of all tethersonde data, hodographs of the tethersonde winds, plots of the tethered balloon aerosol profiles, pipal wind profiles and plots of the surface meteorological data.

Analysis of the tethersonde data showed that, in most cases, boundary-layer thickness exceeded the vertical extent of the soundings. This is a significant limitation on the tethersonde information since it means that the data cannot be put in a non-dimensional form. Without boundary-layer thickness it will be more difficult to compare these results with flat terrain cases available in the literature.

The authors did compute a bulk Richardson number for a fixed delta z, i.e.,

$$Rb = \frac{g}{T} \frac{\Delta\theta \, \Delta Z}{\bar{U}^2}$$

where ΔZ is the lower 200 m, $\Delta\theta$ is the potential temperature difference and Ubar is the average windspeed over this interval. The average bulk Richardson number for various times of the day is shown below.

Period	Time (PDT)	Average R_b
Afternoon	3-17	-0.68
Late Afternoon	18-20	+88.83
Night	21-07	+223.30
Morning	08-12	+43.46

The values were not converted in equivalent values of the quantity, h/L, as would be desirable, because h was not known, as mentioned above. However, this analysis does reveal a reasonable distribution of stability in the data. In addition, the fact that the average stability for the entire morning period is positive may be a significant finding for air quality modeling of the Park region.

The local influence of Wolverton Meadow was apparent in the soundings, especially in the morning hours where a shallow surface inversion can often be identified. In most cases, the air above this surface inversion was neutrally stratified. Presumably, the stratification of the upper air is more representative of regional stability. These results suggest that there are special problems in determining representative stability during the morning hours. The same is probably true at night although there is nothing in the data to demonstrate it.

The authors present individual and composite hodographs for periods corresponding to the average bulk Richardson numbers, given above. In general, the hodographs show considerable separation by Richardson number. These diagrams, given in dimensional form since the information necessary for a non-dimensional presentation was not available, indicate little or no shear for the afternoon cases. Considerable directional shear is apparent in the stable periods, as would be expected. However, interpretation of these diagrams is difficult since heights are not unambiguously shown. The data points are not connected or height-coded in any way.

The tethered-balloon aerosol profiles reveal a complex structure that makes generalizations difficult. One result is clear: almost all aerosol concentrations are higher in the afternoon hours than in the morning or nighttime hours. This is particularly true for fine sulfur but also holds for fine silicon and potassium and coarse iron, silicon, and calcium. Another striking feature of of the aerosol profiles is the "nocturnal gradient" observed for coarse silicon, iron and calcium. For these elements, concentration almost always increases with height at night over the lower 100 m. This behavior was not observed for the fine aerosols. Presumably, this type of profile reflects surface removal processes which affect coarse but not fine particles. The accompanying diagrams show aerosol profiles averaged for morning, afternoon and night conditions.

The flux diagrams show that the afternoon upslope fluxes of the various elements are generally larger than the nocturnal downslope fluxes. This generalization is particularly true in the case of fine sulfur. However, for some elements, such as fine and coarse silicon, fine and coarse mass and others, there is less upslope/downslope separation indicated. The direction of the daytime flux is predominantly from the west while at night direction is highly variable. The accompanying diagrams illustrate the behavior of the flux quantity discussed above.

The pibal wind measurements show that the upslope/downslope regime at Ash Mountain is deeper and more intense than at the upper stations. In the afternoon and evening hours, this may be due to the influence of the meso-scale northwesterlies which sweep through the San Joaquin Valley in these hours. Strong convergence in the wind field is indicated by the pibals at Fresno and Ash Mountain during the nightime hours. The authors suggest that the observed convergence may result in the formation of a "smog front" sometime in the future. The accompanying diagram shows a pibal-winds cross-section from Fresno to Emerald Lake illustrating the convergence zone.

The pibal measurements show three superimposed wind regimes: (1) A lower, boundary-layer upslope/downslope diurnal regime. (2) The San Joaquin Valley meso-scale diurnal circulation, including such features as the Fresno Eddy and the northwesterly nocturnal jet. (3) Large-scale, low frequency fluctuations associated with the passage of synoptic disturbances.

The following conclusions are either stated by the authors or are implicit in their discussion.

(1) When averaged over the entire observation period, the concentration of all fine elements is higher in the afternoon than it is in the nighttime or morning hours. For these aerosols, there is no evidence of a systematic nocturnal maximum, as reported by Cahill.

(2) The concentration of some of the coarse elements, including silicon, iron and calcium, shows a strong tendency to increase upward in the lower 200 m during the nighttime hours.

(3) The fluxes of most elements also show larger values during the afternoon upslope period in comparison with other times of the day.

(4) The flux of certain of the elements, such as fine and coarse silicon and fine mass, shows less of an upslope/downslope contrast.

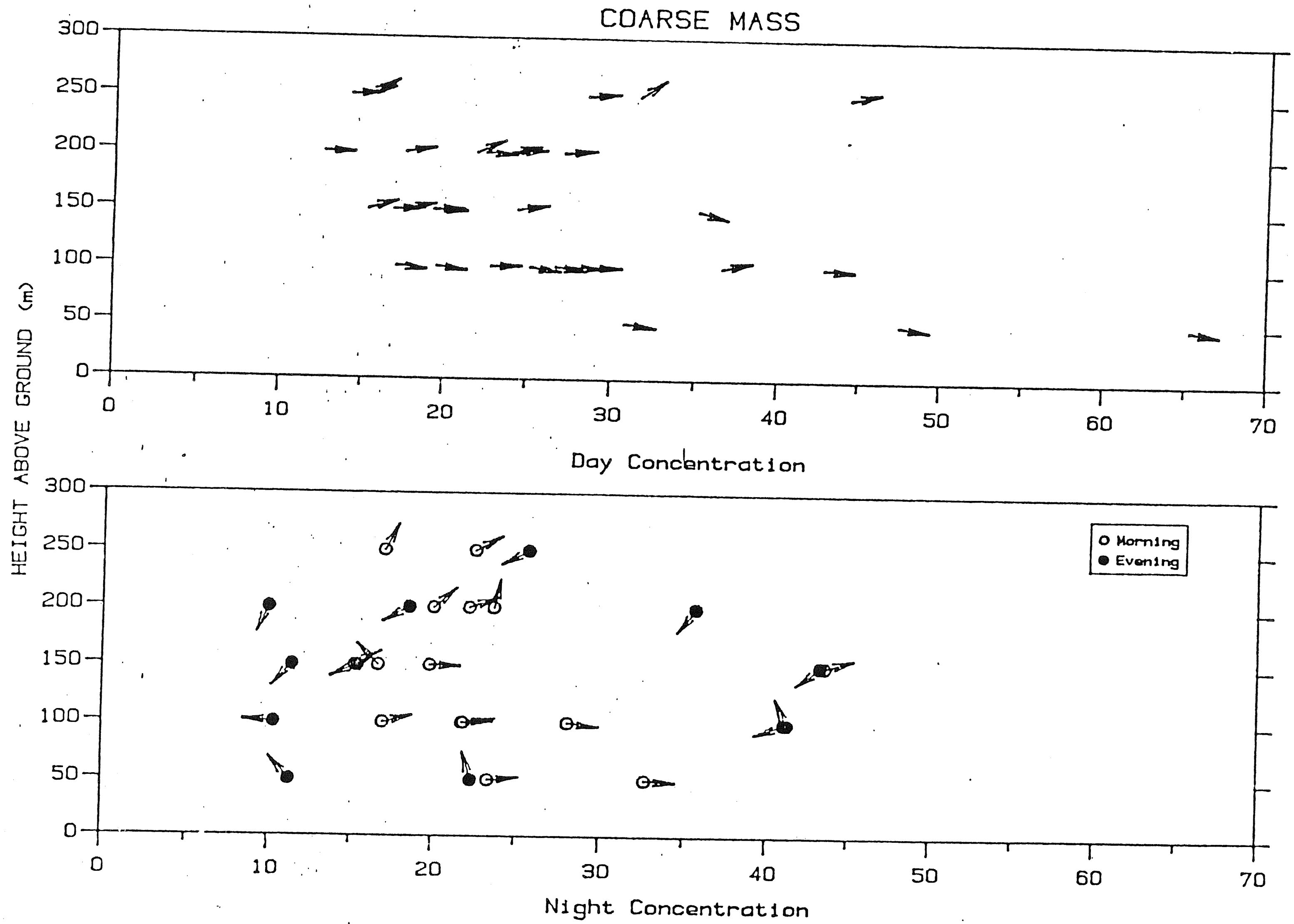


Figure 35: Scatter plot of coarse mass aerosol concentration profiles.

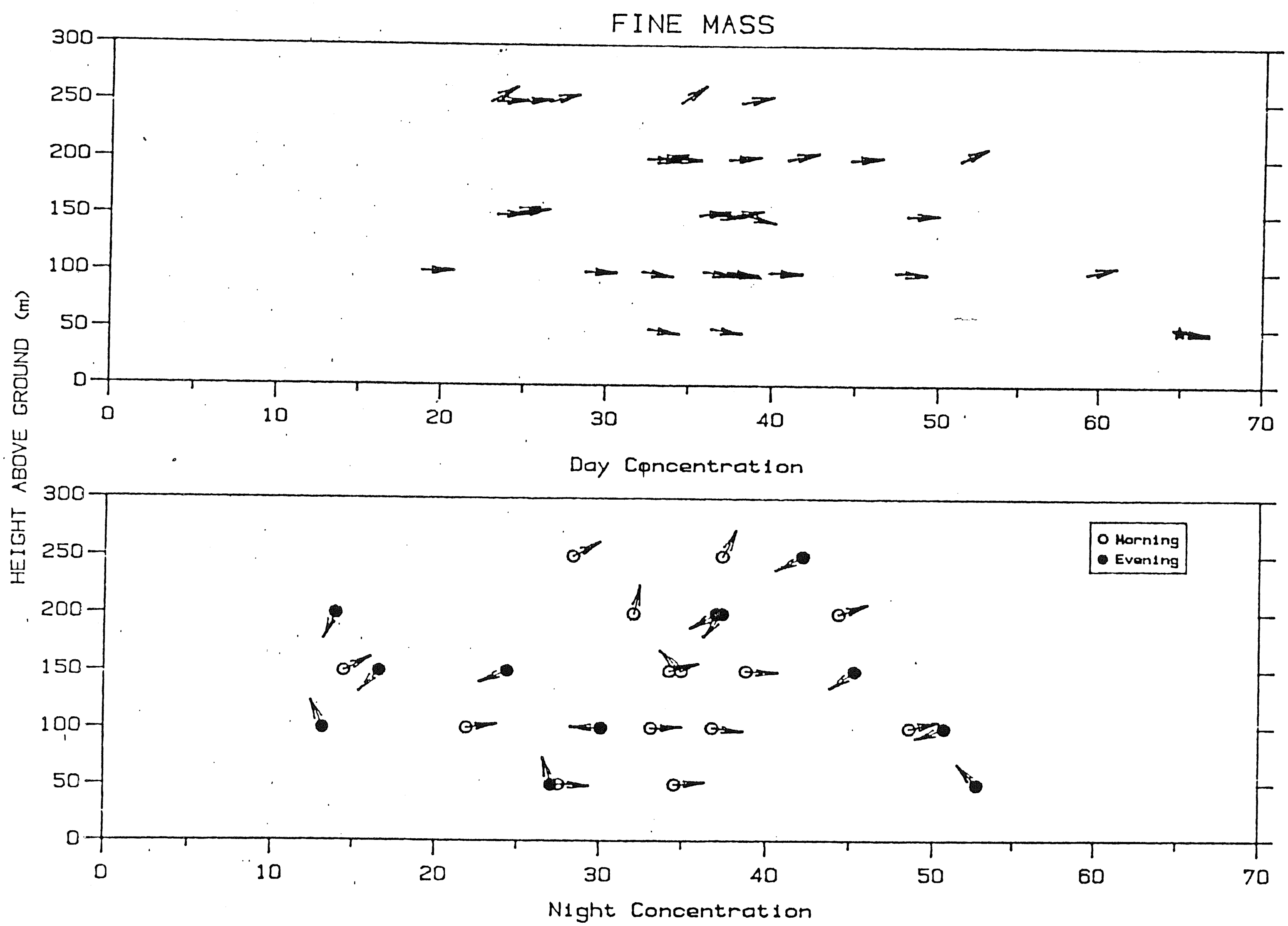


Figure 40: Scatter plot of fine mass aerosol concentration profiles.

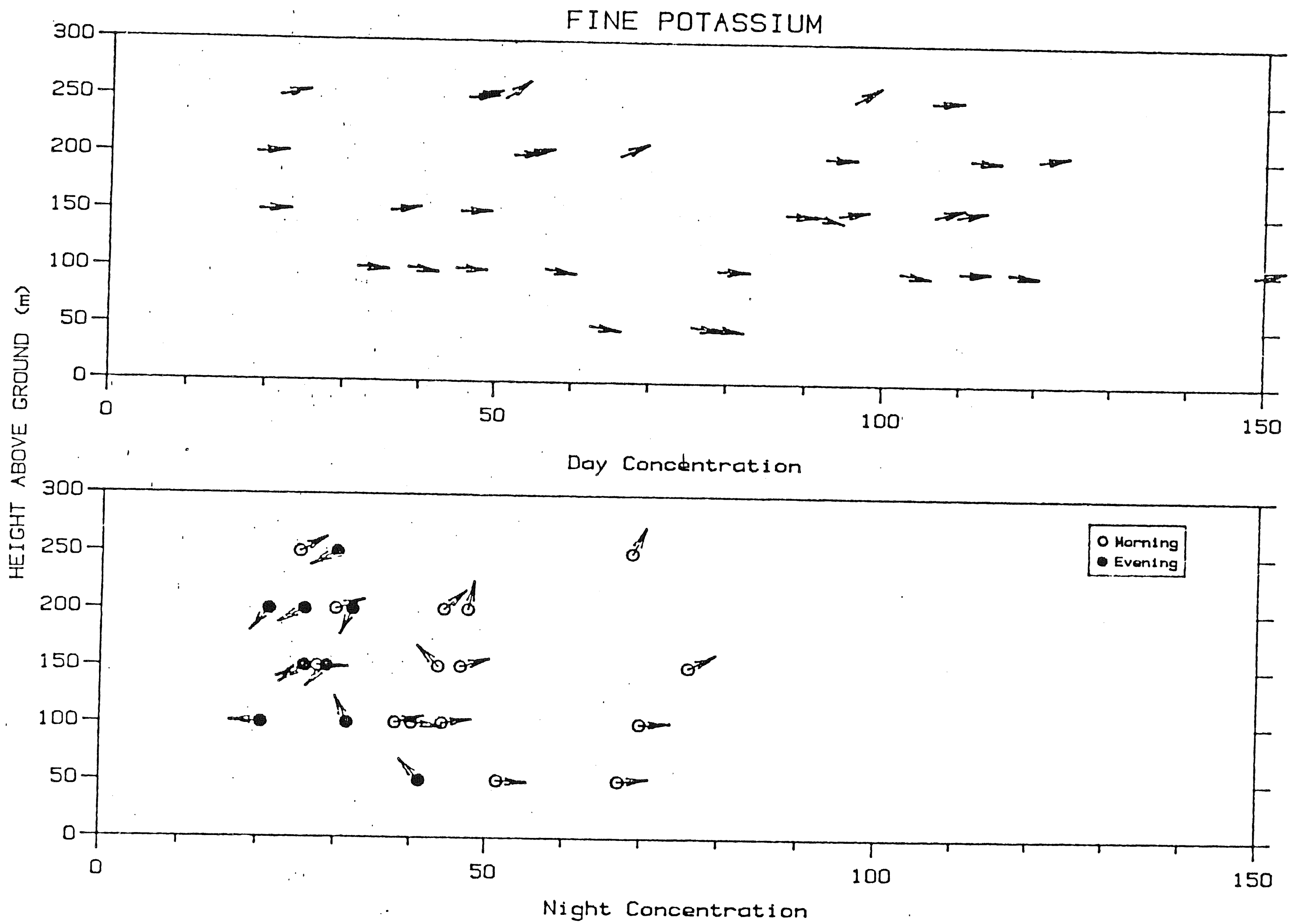


Figure 41: Scatter plot of fine potassium aerosol concentration profiles.

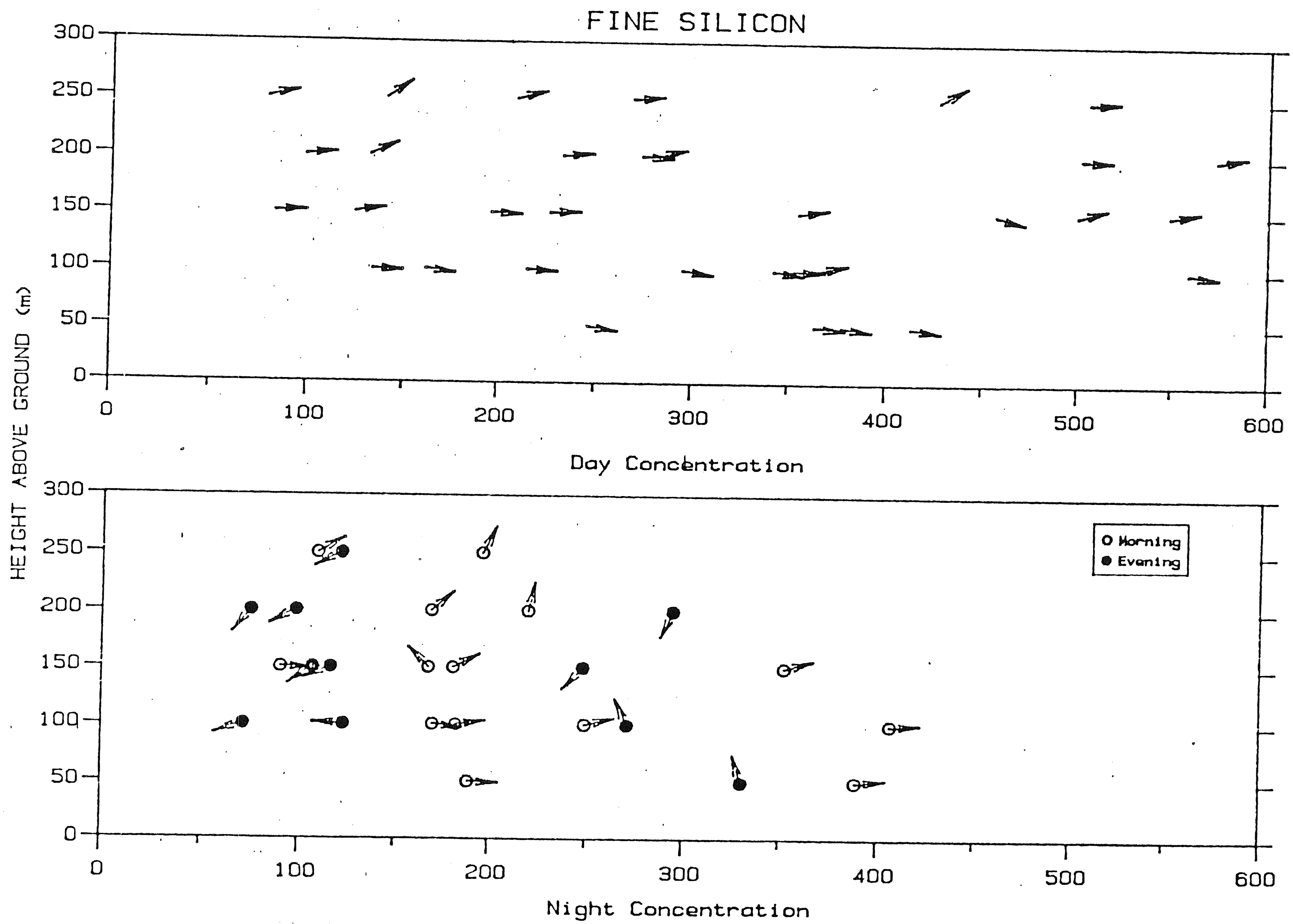


Figure 42: Scatter plot of fine silicon aerosol concentration profiles.

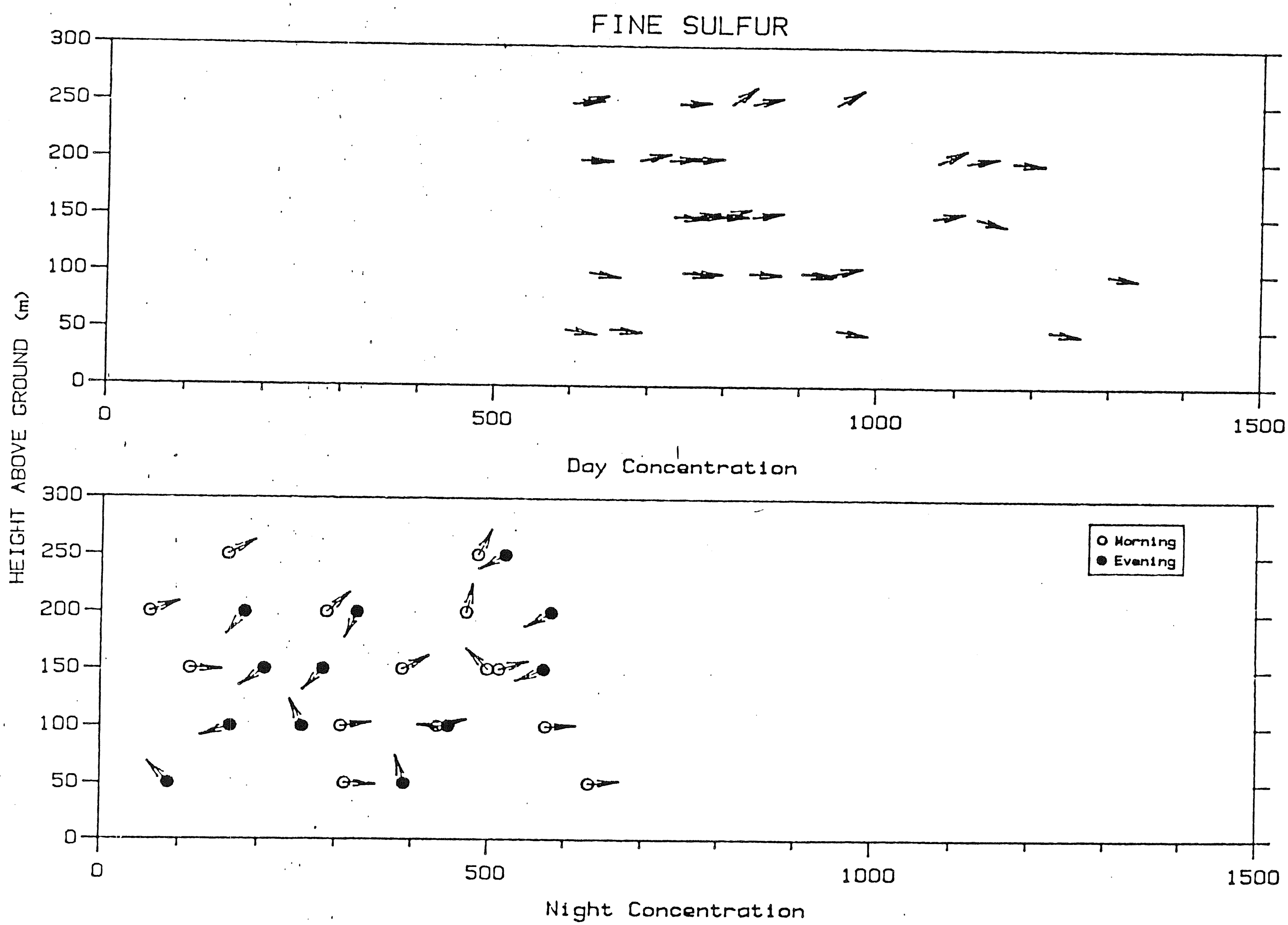


Figure 43: Scatter plot of fine sulfur aerosol concentration profiles.

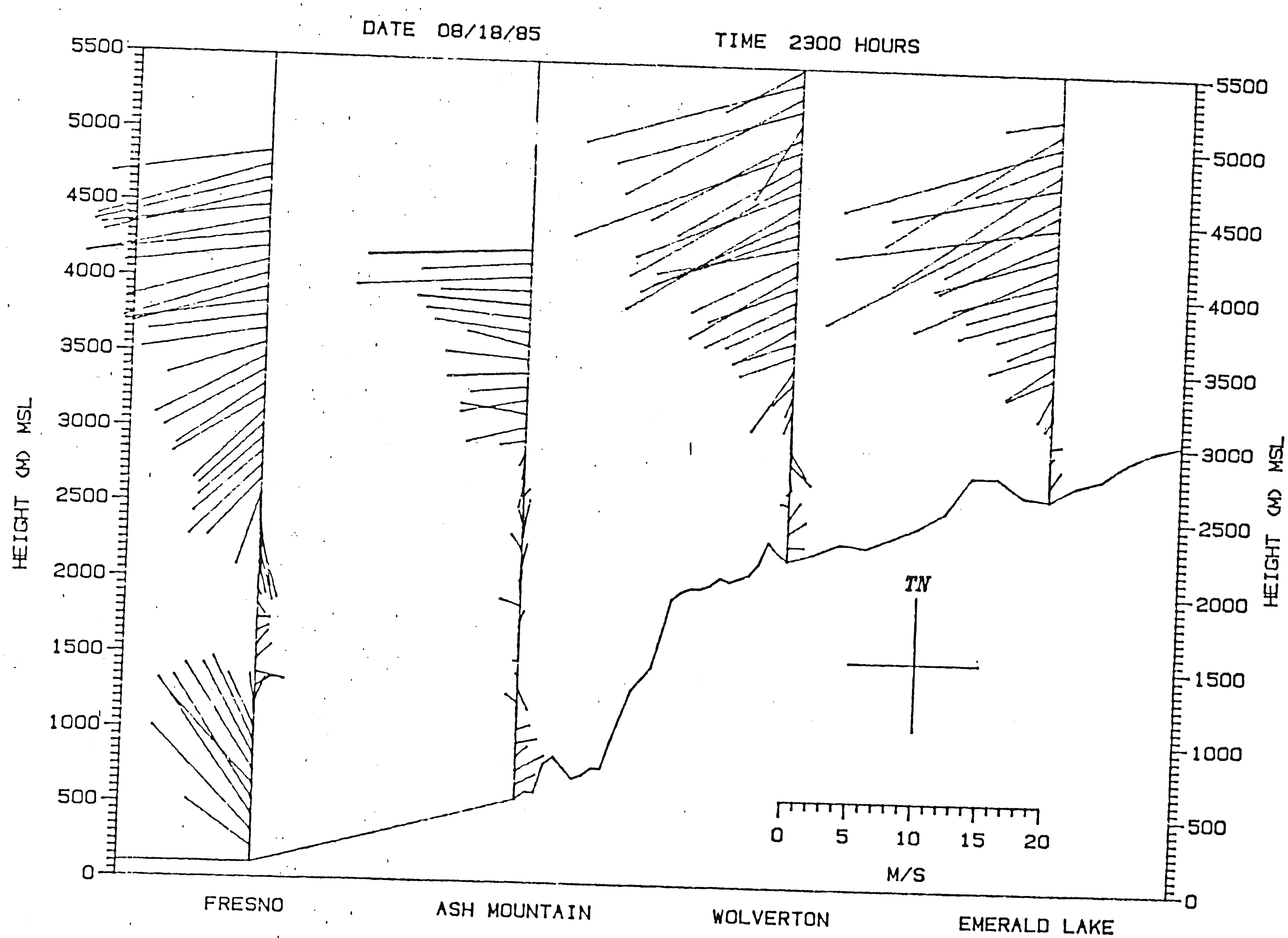


Figure 31: Pilot balloon wind profiles for August 18th, 1985, at 2300 PDT.

(5) The potential for "smog front" phenomena seems to exist in the lower regions of the Park, due to convergence in the meso-scale wind field.

(6) The upslope/downslope boundary-layer, meso-scale and large-scale winds seem to interact in a complex fashion to produce the observed aerosol transport.

<u>Recommendations and Suggestions for further work</u>

Perhaps the major shortcoming of the Myrup/Flocchini operation was the fact that the tethersonde ascents did not normally include the entire boundary-layer. This was due to the height limitations of the tethersonde system. Without information on the boundary-layer thickness, it is not possible to present the boundary-layer measurements in non-dimensional coordinates. Had it been possible to non-dimensionalize these data, the research objective of identifying the "mountain effect" would have been easier since the mountain data could have been compared with flat terrain data in the same coordinates. However, it should still be possible to develop a useful method of non-dimensionalizing the boundary-layer data and this should be an important objective in future work with the 1985 data. This would allow presenting the important hodographs in a more comprehensible and useful manner.

In future transport experiments in the Sierra Nevada region, they would be important to obtain soundings that include the entire boundary-layer. This could be done with an instrumented aircraft with sufficient power to operate at high elevation.

The value of the aerosol profile data would be greatly enhanced if it were obtained in conjunction with three-dimensional meso-scale trajectories. It may be that the complex nature of the meteorology in this region will require a network of aerosol profiles in order to assess the relative influence of sources within and outside of the Park.

In future experiments, we recommend a more integrated approach to the meteorology of the region. This would include observation periods in various synoptic situations, estimation of three-dimensional meso-scale trajectories and measurement of the entire boundary-layer. Further work with the aerosol profile system is recommended in close conjunction with tracer and trajectory studies.

There are related questions concerning the relation between synoptic events and the Central Valley and Sequoia region meso-scale systems. How does the Fresno eddy respond to passing synoptic systems? There is no information concerning this question in the literature although it may be a key factor in forecasting pollution events. The behavior of the polluted layer in the Central Valley as synoptic-scale troughs approach from the west may a significant factor in the pollution meteorology of the Sierras. It would be expected that the field of low-level convergence, normally found in advance of such structure, would act to deepen the pollution-containing boundary-layer. Thus even if winds were not appropriate to transport pollution into the Park region, the deepening polluted layer could still engulf at least the lower portions of the Park.

The authors suggest that since pronounced horizontal convergence exists in the wind field between Fresno and Ash Mountain, "smog fronts" may form in this region sometime in the future. Perhaps these already exist. This should be investigated in the near future.

3. "PARTICULATE MONITORING FOR ACID DEPOSITION RESEARCH AT SEQUOIA NATIONAL PARK". T.A. Cahill, Principal Investigator.

Project Description

A study was made of particles and meteorology at Sequoia National Park. Data were collected at Ash Mountain (elevation 2000 ft.), Giant Forest (elevation 6400 ft.), and Emerald Lake (elevation 9260 ft.) from June to October 1985. The particles were collected with four types of samplers. The Solar Powered Aerosol Sampling Impaction (SPASI) unit was deployed at Ash Mountain and Emerald Lake. This unit collects particles in the range .25 to 3.0 micrometers and is capable of 8 hour time resolution. A National Park Service stacked filter unit (SFU) was utilized at all three sites. This unit collects particles in two size regimes: .1 to 2.5 micrometers and 2.5 to 15 micrometers. The samples are collected for 3 days. A Davis rotating-drum universal size-cut monitoring (DRUM) sampler was located at Giant Forest. This unit is capable of 4 hour time resolution and collects particles in 8 size regimes. An Air Resources Board virtual impactor (VI) was also located at the Giant Forest site. This unit has size cuts similar to the stacked filter unit. The collected samples were analyzed for a variety of parameters, including mass hydrogen, carbon (soot), and elements sodium and heavier. A summary of collection and analysis is taken from the Cahill report (Table 2.2).

The objectives of the study stated by the investigators were:

1. To characterize the particulate composition of fine particles by determining the concentration of all elements from hydrogen through lead.

2. To determine what material is available for wet and dry deposition by measuring particulate concentrations by element and size.

3. To determine how particulate concentrations vary with time as the meteorology changes. This will be viewed by elemental species and particle size.

4. To determine the extent of transport of particulate pollutants from the San Joaquin Valley by comparing elemental concentrations measured at three elevations with sufficient time resolution to look at transport.

5. To provide convenient time plots and other visual representations of

particulate concentrations to concurrent projects on the effects of wet and dry deposition and to studies dealing with meteorology and gasses.

Discussion of the Project Report

The project report is contained in a 57 page document plus four appendices. The report is dense with information and explanatory hypotheses. The three-page project summary is particularly well done and informative.

The authors present evidence that fine sulfur concentrations at Sequoia National Park are consistent with the large-scale distribution of sulfur aerosols through the western United States. Figures 3.1 and 3.2 taken from the author's report illustrate this argument. This fact has a number of implications. Since, on the average, sulfur concentration is highest in the southern portion of this region, it is to be expected that southerly winds would bring higher concentrations at Sequoia. The observed high correlation in fine sulfur concentration at Yosemite and Sequoia as demonstrated in figure 3.3 is interpreted as reflecting the large-scale nature of synoptic fluctuations which dominate the variance. Elemental particle concentration fluctuations apparently driven by synoptic variation are illustrated in Figures 3.6-3.9 and 3.13 again taken from the authors report. We agree in the overall assessment of the importance of synoptic forcing. However, it is likely that specific meso-scale features such as the Fresno eddy or the San Joaquin nocturnal jet are directly responsible for modulation of mountain aerosol concentrations. How synoptic systems interact with the mesoscale to influence transport into the Sierras is poorly understood.

The overall importance of the diurnal upslope/downslope wind system in affecting particulate concentrations in the Park is discussed in the Cahill report and agrees, in general, with the Myrup/Flocchini report. Figures 3.15-3.20,3.23 and 3.24 illustrate the diurnal variation in meteorological parameters, and to a lesser degree in concentrations. However, the Cahill group interpretation of their measurements as showing that "Night time downflow wind usually contains more sulfur than daytime upslope winds" seems to be in direct disagreement with the measurements of the Myrup/Flocchini group. It appears from the figures included in the report that isolated nocturnal peaks in fine sulfur do indeed occur in the Park. The origin and significance of the nocturnal fine sulfur peaks is of interest. Since the higher regions of the Park have considerably lower concentrations of fine sulfur and all other aerosol, downslope winds would

Table 2.2: SAMPLERS AND MEASURED VARIABLES BY SITE

Site Sampler	Size Range	Time Resolution	Analyzable Samples	Samples Analyzed by Method PIXE	Mass	LIPM	PESA	FAST
Giant Forest (6400 ft)								
DRUM	9.6-15um	4 hour	672	168	0	0	0	0
	4.8-9.6um	4 hour	672	168	0	0	0	0
	2.4-4.8um	4 hour	672	168	0	0	0	0
	1.2-2.4um	4 hour	672	336	0	0	0	0
	0.6-1.2um	4 hour	672	336	0	0	0	0
	0.10-0.6um	4 hour	672	672	0	0	0	0
	0.088-0.10um	4 hour	672	168	0	0	0	0
SFU	0-2.5um	24 hour	112	112	112	112	112	70
	2.5-15um	24 hour	112	112	112	0	0	0
VI	0-2.5um	24 hour	112	16	112	112	16	0
	2.5-15um	24 hour	112	16	112	0	16	0
Ash Mountain (2000 ft)								
SPASI	.25-3um	8 hour	340	340	0	0	0	0
SFU	0-2.5um	3 day	32	32	32	32	32	20
	2.5-15um	3 day	32	32	32	0	0	0
Emerald Lake (9260 ft)								
SPASI	.25-3um	8 hour	340	340	0	0	0	0
SFU	0-2.5um	7 day	16	16	16	16	16	10
	2.5-15um	7 day	16	16	16	0	0	0
Total (actual)			5700	3000	400	250	275	0

Figure 3.1 Fine mass (Dp <2.5 µm), concentrations and percent of fine mass as ammonium sulfate, soil, soot and remaining mass, at NPS sites, averaged over a two year period, 1983 to 1985. These data represent samples taken over more than 80% of all hours.

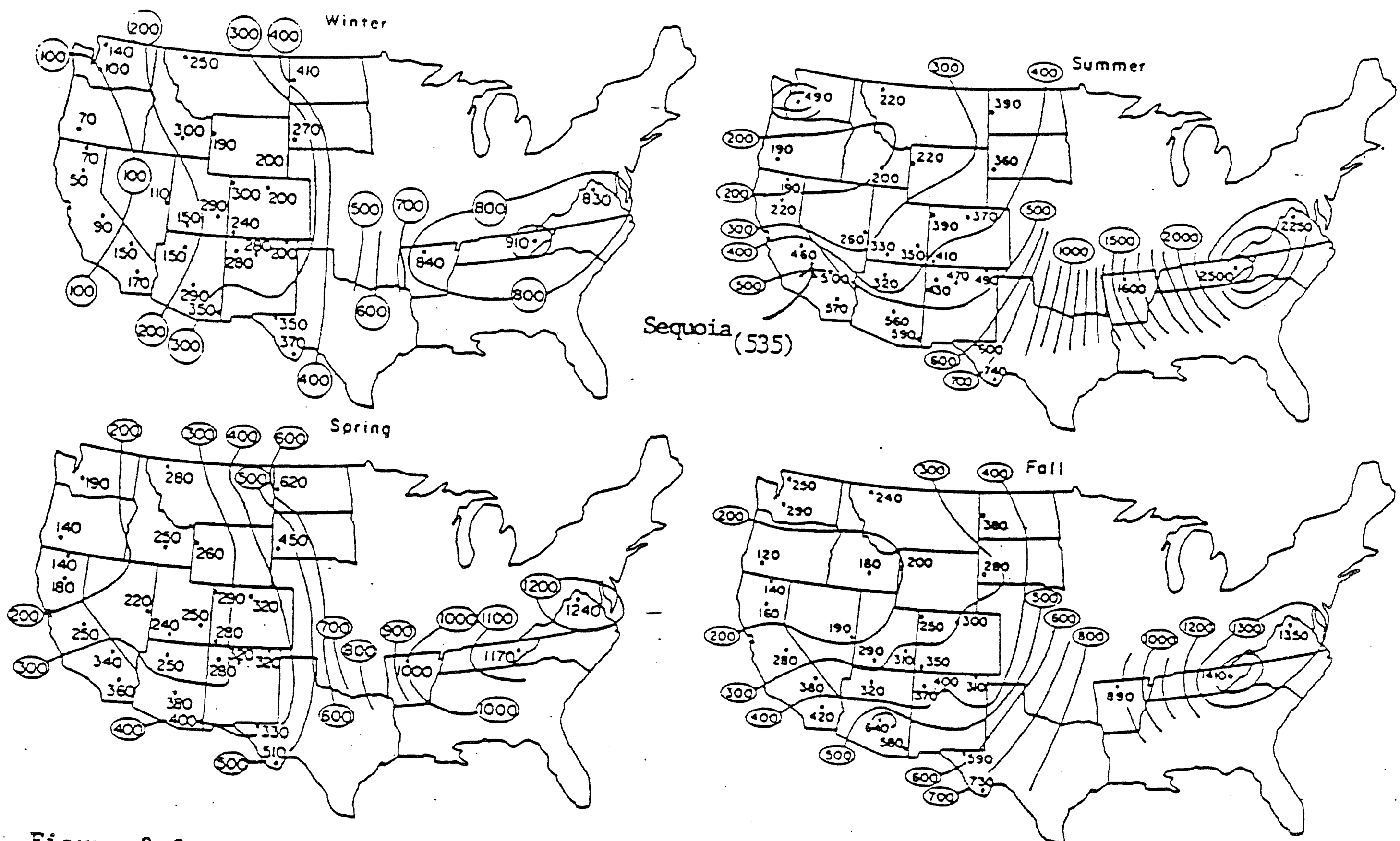


Figure 3.2 Concentration of fine sulfur at NPS sites averaged by season. Note that the value at Sequoia, summer, 1985, of 535 ng/m^3, is similar to other California sites, supporting a regional interpretation of sulfur concentrations.

Figure 3.3 Comparison of fine sulfur at Sequoia and Yosemite

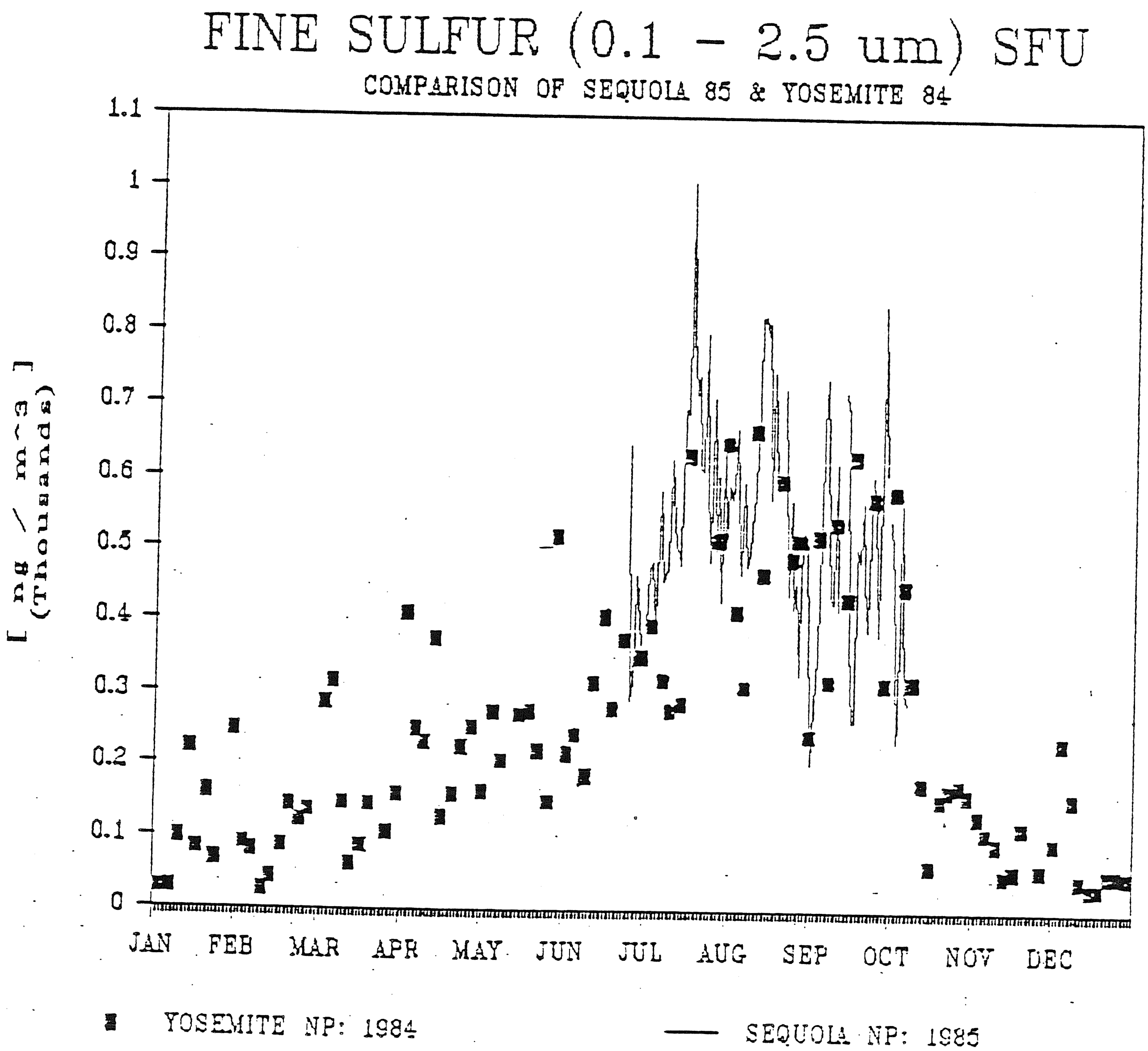


Figure 3.4 Sulfur comparison at two Sierra sites, summer 1985.

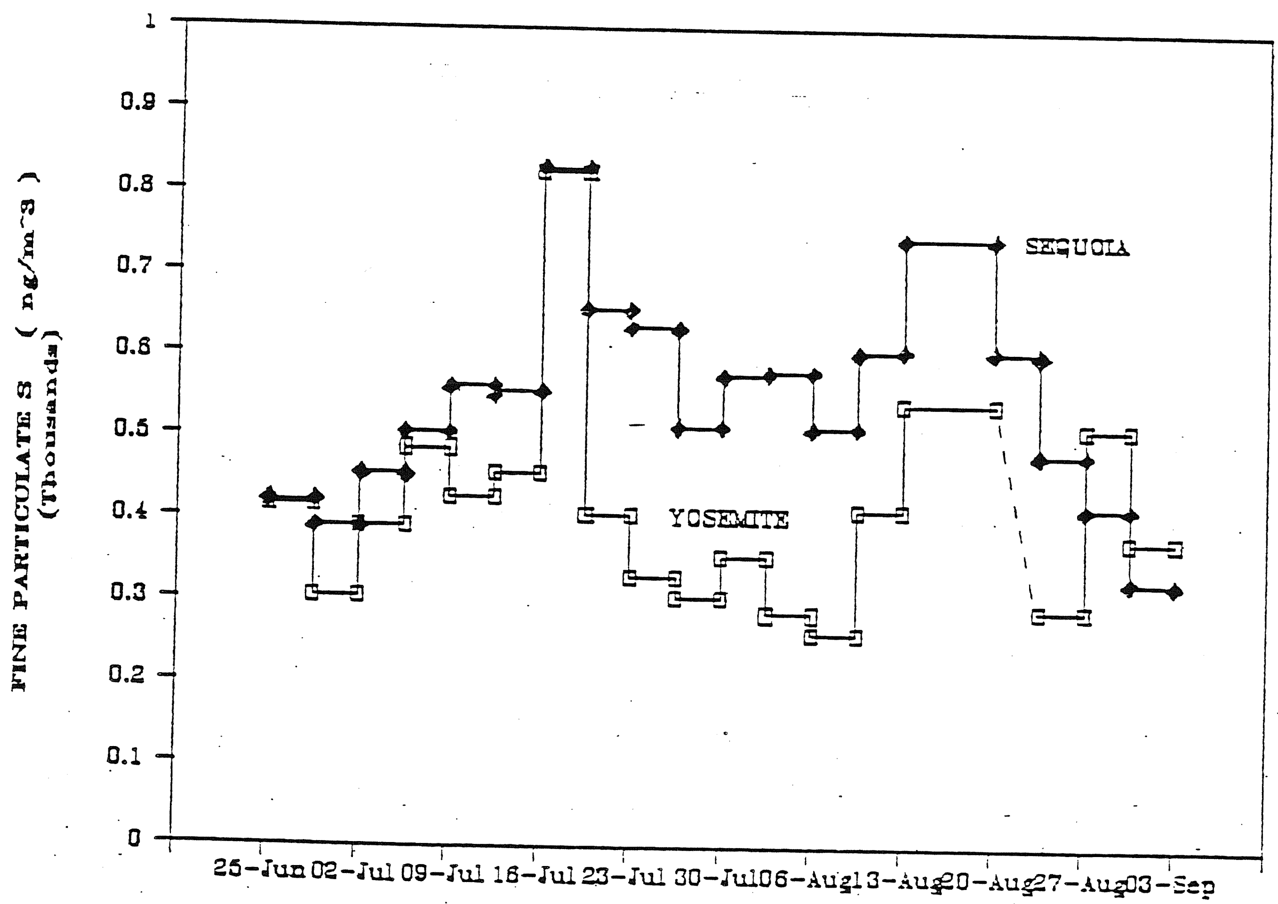


Figure 3.6 Daily coarse mass at Giant Forest

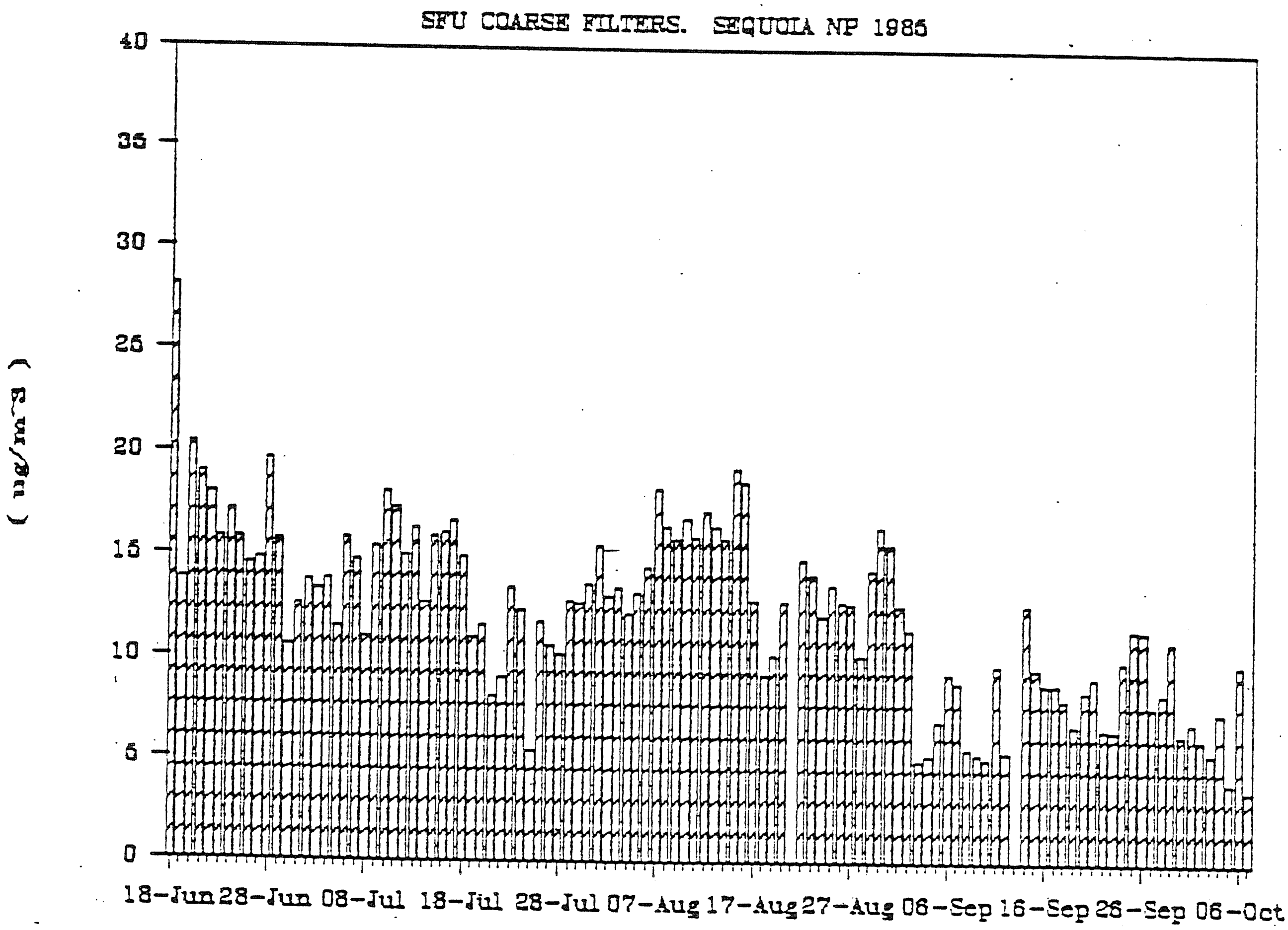


Figure 3.7 Daily fine mass at Giant Forest

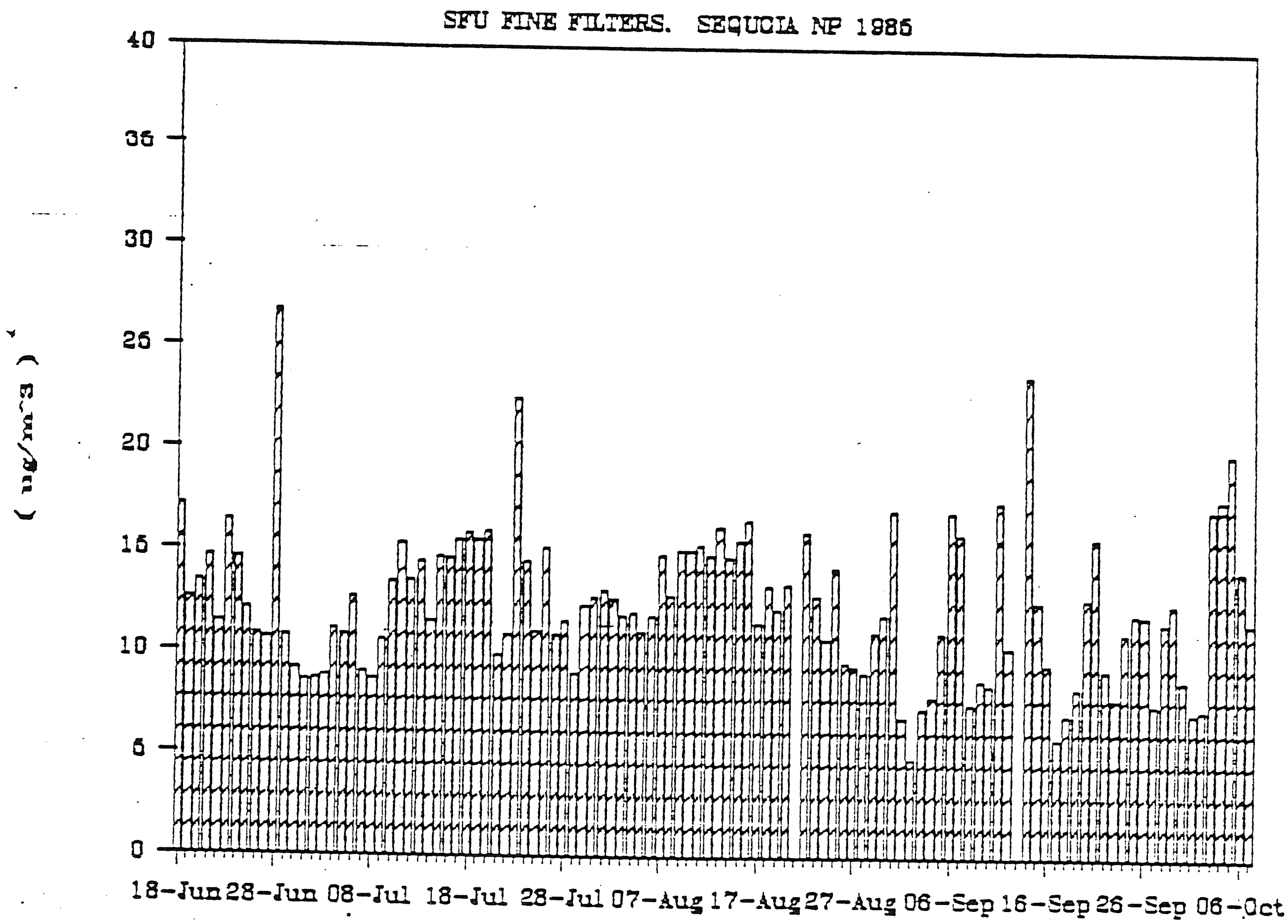
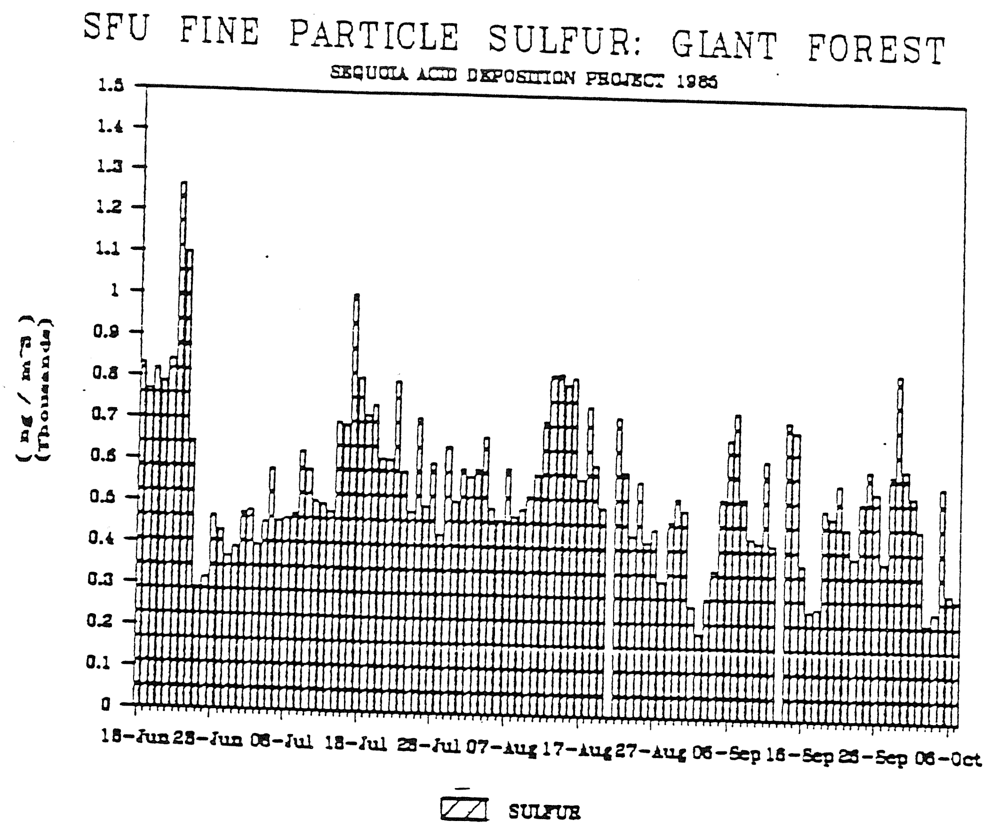


Figure 3.8 Daily fine sulfur at Giant Forest



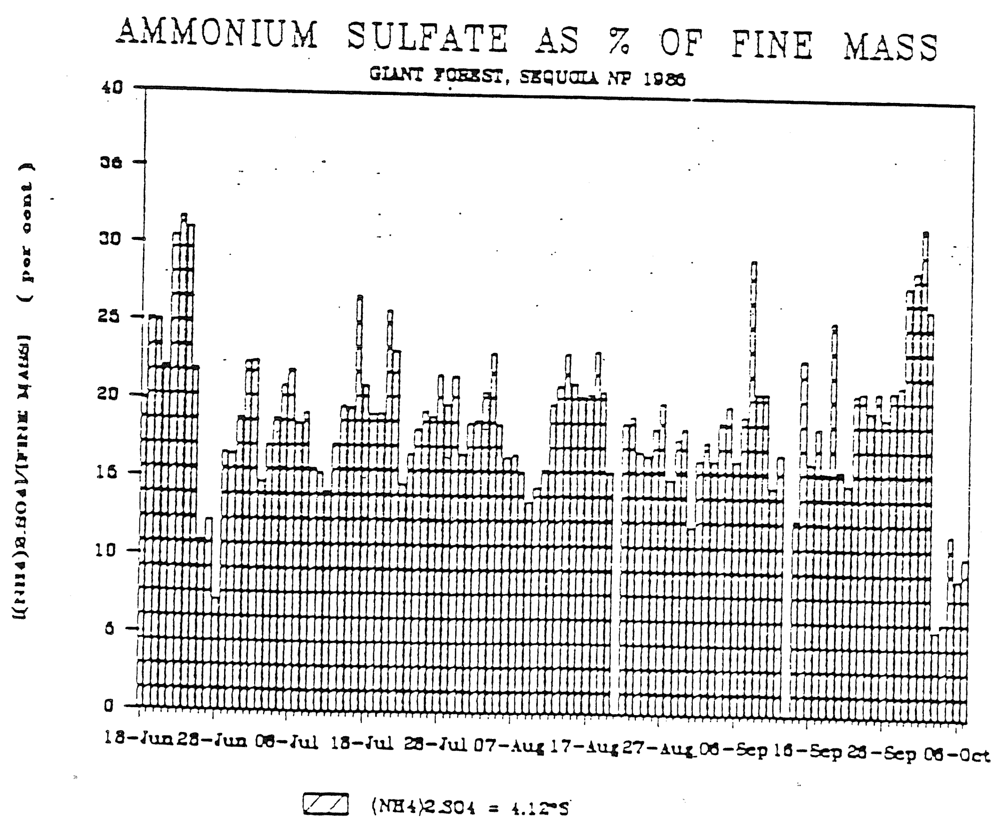
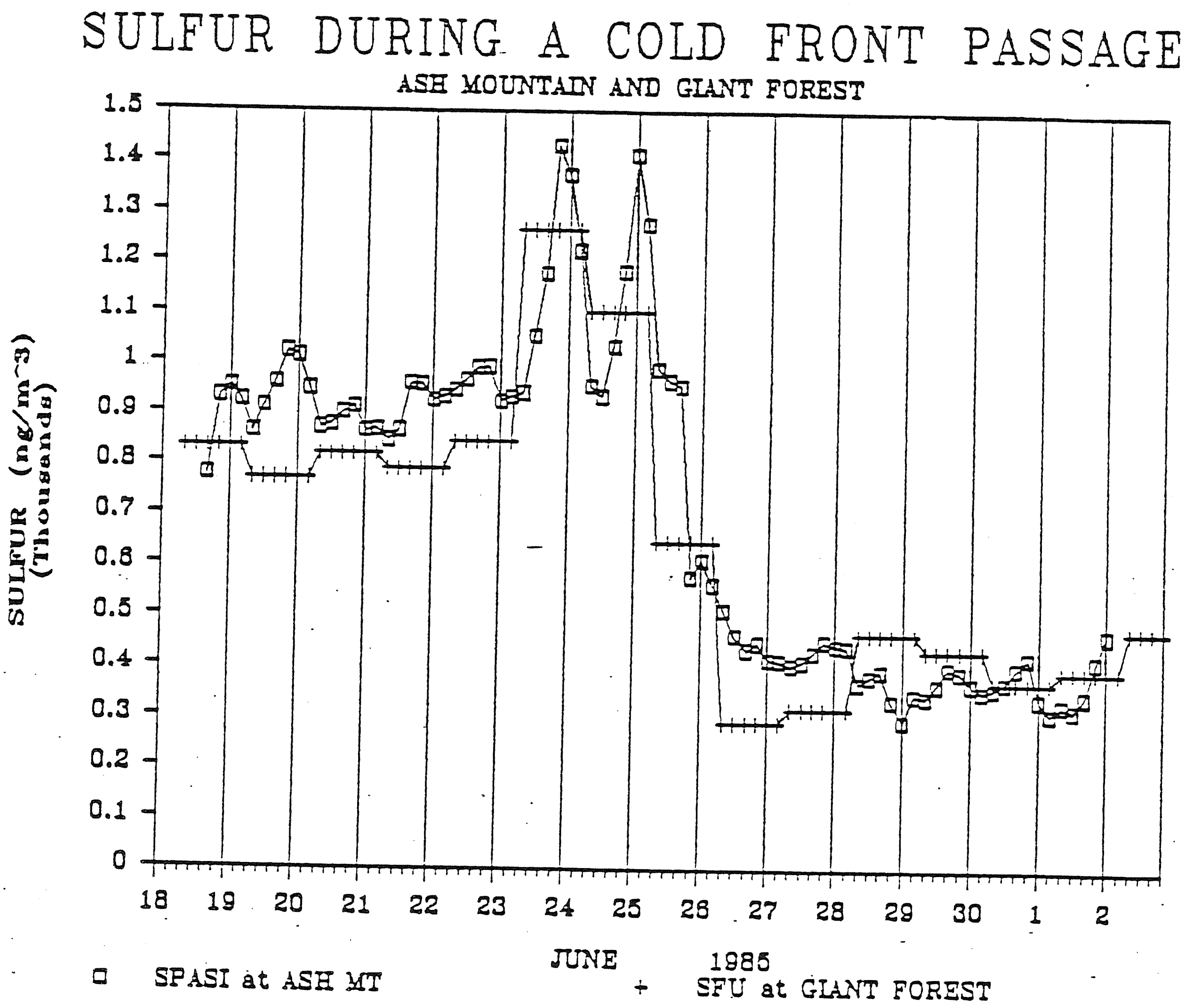


Figure 3.13 Fine sulfur at Giant Forest and Ash Mountain, June 1985



Spasi sampler results represent the sum of the DRUM stage (0.25 <d <3.0μm) and the afterfilter (d <0.25μm) SFU results are for the fine filter (d <2.5μm).

Figure 3.15 Mean diurnal wind speed at Mid-Elevation Station, Sequoia NP September 1985

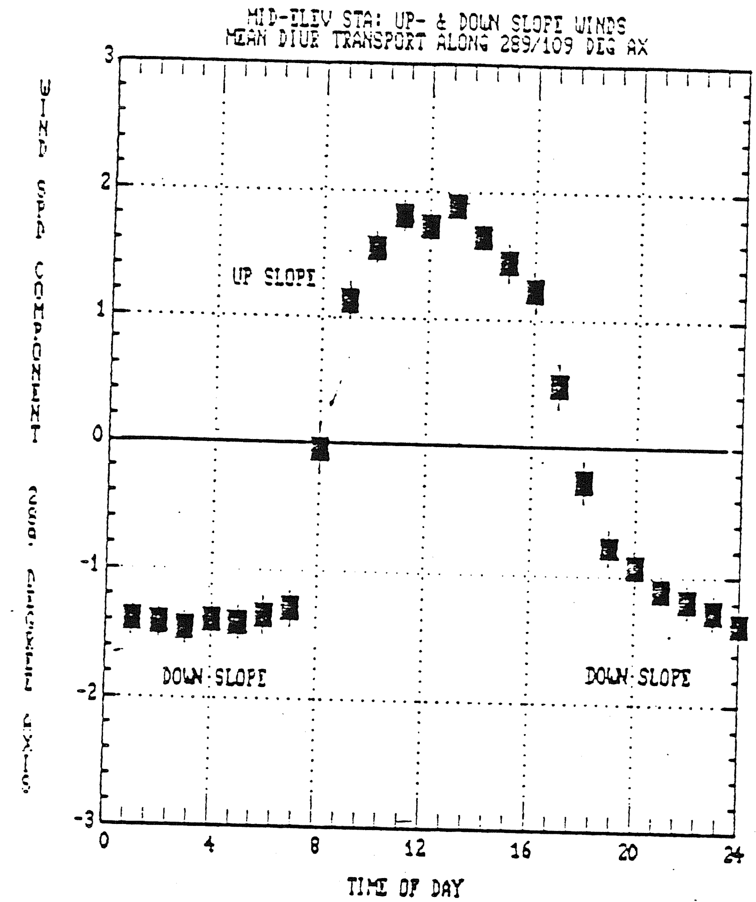


Figure 3.16 Hourly wind speeds at Elk Creek, Sequoia NP, August 1985

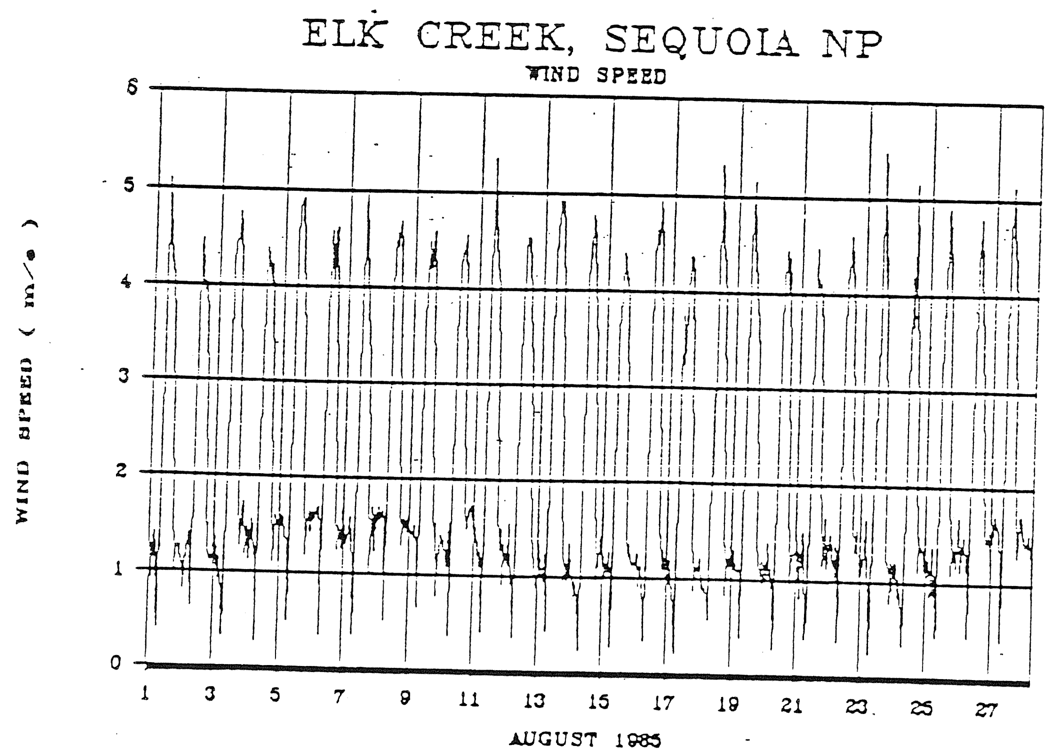


Figure 3.17 Diurnal wind directions at Elk Creek, Sequoia NP, July 1985

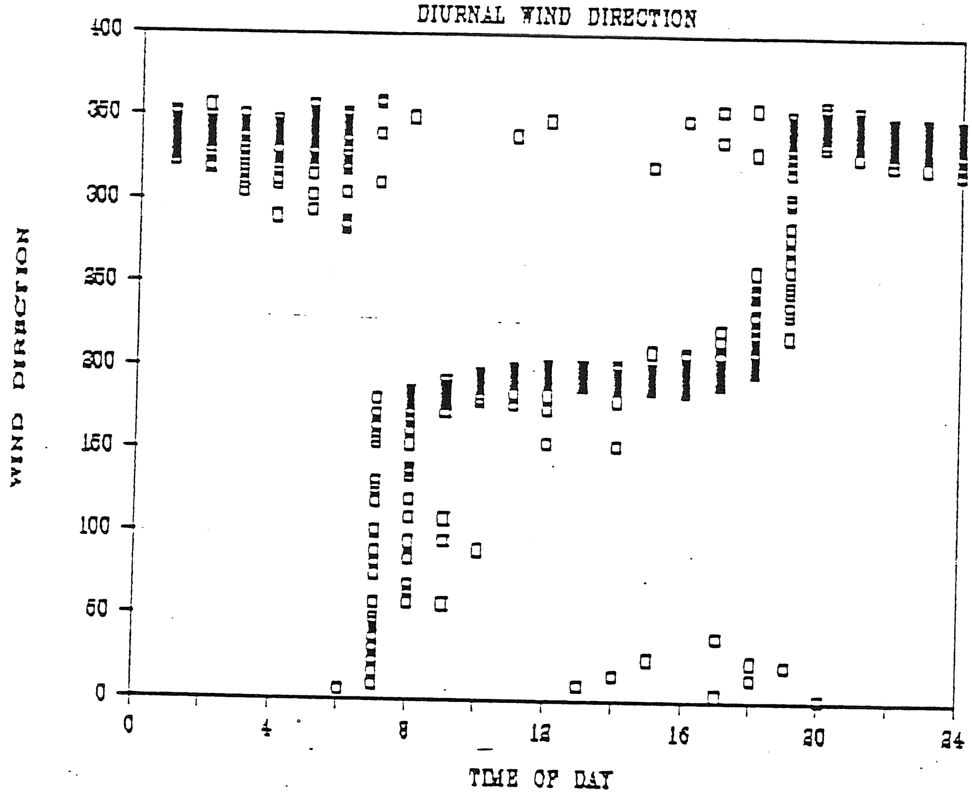


Figure 3.18 Diurnal wind directions at Elk Creek, Sequoia NP, August 1985

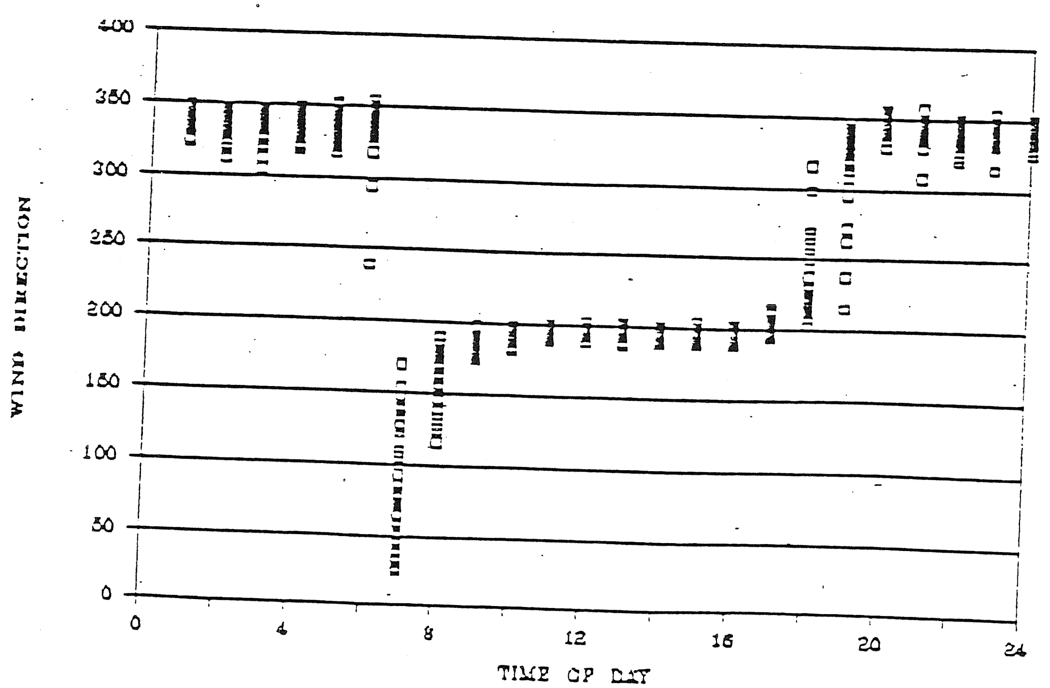


Figure 3.19 Sulfur concentrations, 0,55 to 0.10μm at Giant Forest, August 198

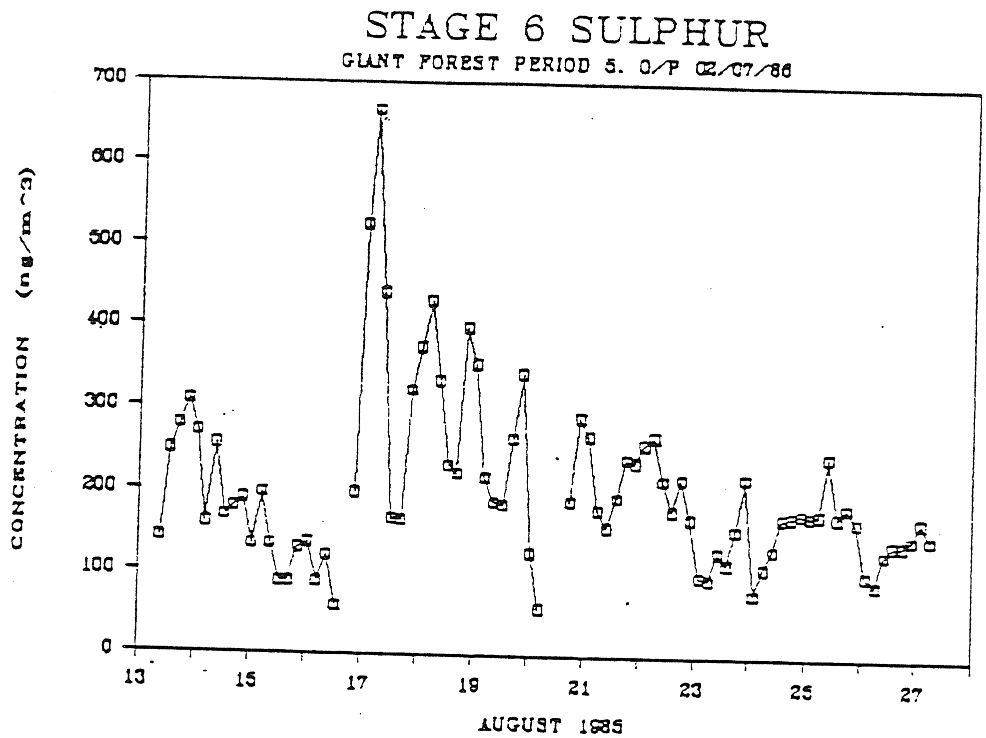
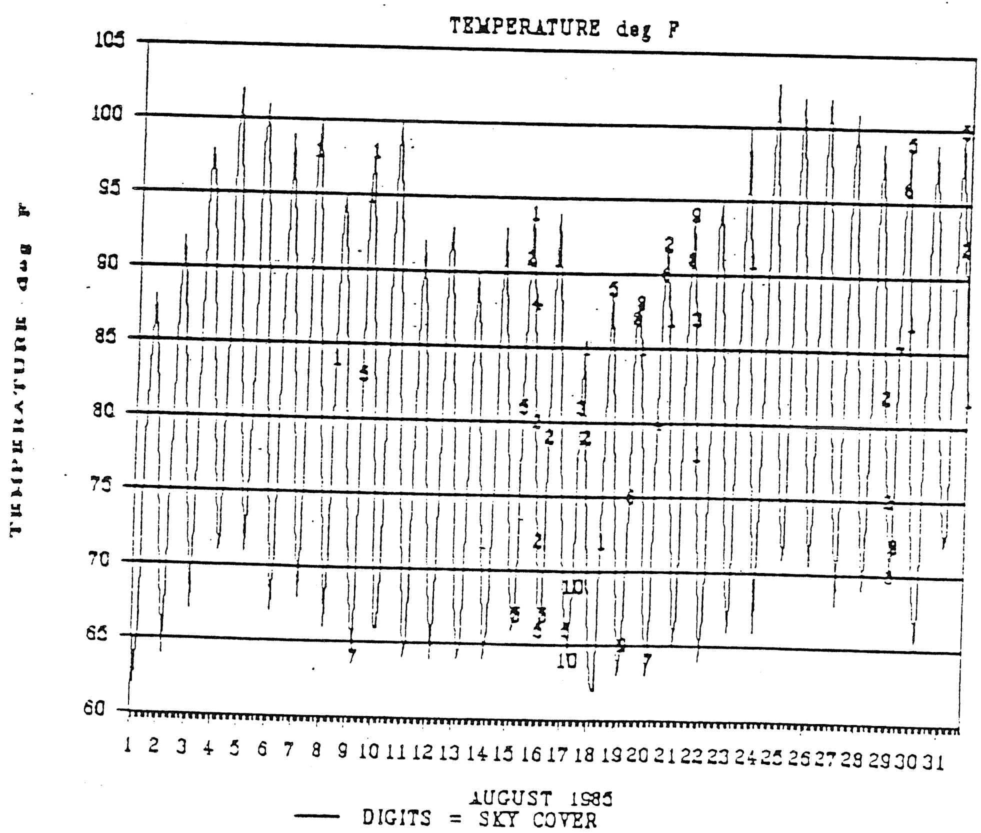


Figure 3.20 Three-hourly temperature and cloud cover at Fresno Airport, August 198



be expected to reflect the origin and similarly show low concentrations, as is indicated by the Myrup/Flocchini averaged measurements. Occasional nocturnal maxima suggest some kind of second-order counter-gradient process, possibly involving the three-dimensional meso-scale wind system.

Cahill et al present a synoptic typology supposed to relate synoptic pattern and aerosol type:

a) Western, synoptic; high in N, Cl, Na; low in H,S (across San Joaquin Valley)

b) Inland low pressure; moderate N, high S, H, Ni; (wind from south, east; from Bakersfield and the California/Arizona desert)

c) Northern synoptic; lowest N, S, high H, particulate Na, Cl (pH rises in storm) (from the North Pacific)

Very little information is given to support these conclusions. As they now stand the descriptors are insufficient to use the typology on a specific weather map. It should be remembered that the inland low pressure exists on virtually every summertime weather chart. Does this mean that all days belong to category b)? We feel that Cahill's scheme is a first step but much work remains to be done before such an approach can be useful. What is needed is a typology based on a statistical analysis of trajectories. It may be necessary to take into account vertical motion since the vertical gradients of aerosol concentration are much larger than the horizontal.

The major conclusions as stated by the investigators are as follows:

1. Particulate matter concentrations are somewhat higher at Giant Forest than at Yosemite . Both sites have levels much higher than Lassen, Lava Beds, and Crater Lake.

2. Summer sulfur values at the Giant Forest site show considerable correlation with values at Yosemite during the summer period.

3. Particulate matter concentrations are more highly variable in time than local surface meteorology.

4. The fall-off of concentrations from Ash Mountain to Giant Forest is approximately 25%. Significant correlations exist in time between these two sites. Figure 3.5 taken from the submitted report shows the sulfur concentration.

5. Further reductions in concentrations occur going from Giant Forest to Emerald Lake and in addition time correlations appear to decrease by late summer. Refer again to Figure 3.5.

6. Night time downflow wind usually contains more sulfur than daytime upflow winds. Night time peaks in sulfur occur at Emerald Lake and Giant Forest. Figures 3.19 and 3.23 depict the sulfur concentrations as a function of time.

7. Factor analysis of the Giant Forest data indicate that both urban and industrial sources exist for sulfur at Giant Forest. Tables 4.1 and 4.2 taken from the investigators report are a summary of the analyses.

8. Potassium , a smoke tracer, reaches maxima when the wind changes direction. The short duration peaks indicate a local source.

9. Interesting patterns are seen in rainfall/ particulate comparisons, separating summer storms into categories that vary according to synoptic meteorology. Specifically, the largest excess hydrogen ion and sulfur values in rainfall were associated with inland low pressure systems bringing air from the south and east.

Figure 3.5 SFU fine sulfur at 3 elevations in Sequoia NP

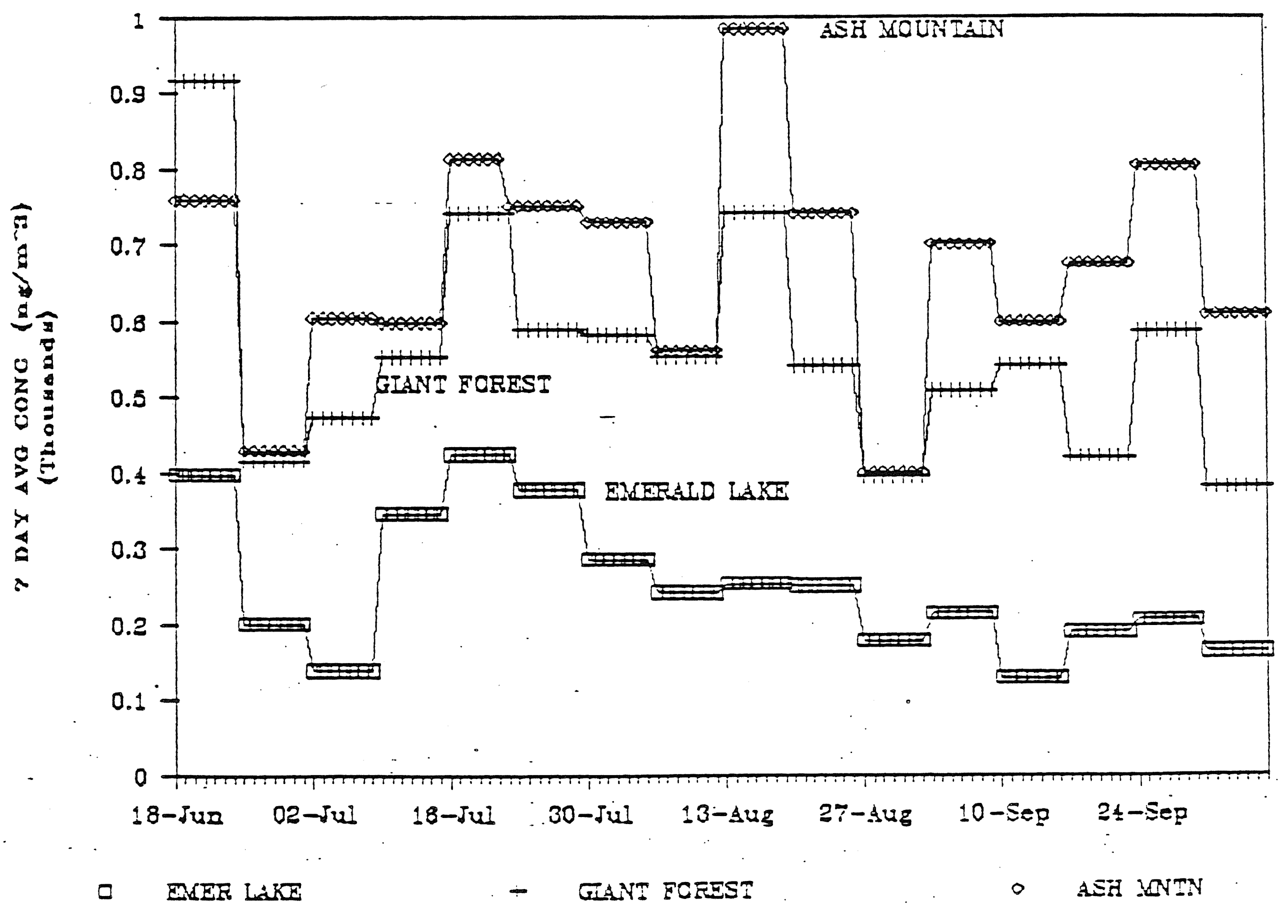


Figure 3.23 Fine particulate sulfur (SPASI) at Emerald Lake, July and August 1985

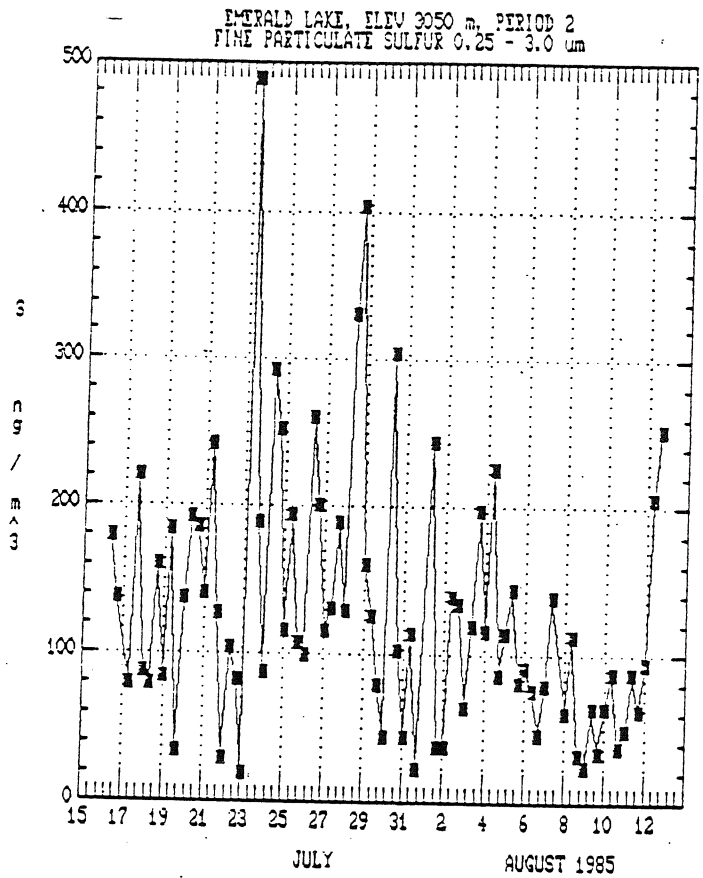


Figure 3.24 Fine potassium (SPASI) at Emerald Lake, July and August 1985

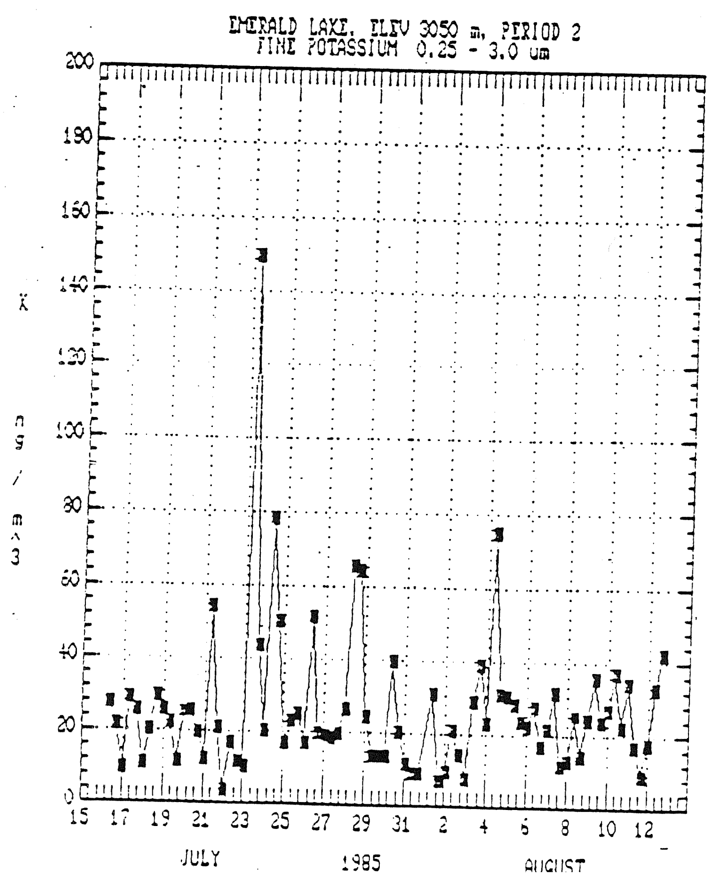


Table 4.1 Correlation matrix of elemental concentrations at Giant Forest (6-25-85 through 11-7-85). Sampler: SFU (fine stage; 0.1-2.5um); 24-hr samples

ELEMENTS	Al	Si	S	K	Ca	Ti	Mn	Fe	Ni	Zn	Br	Pb
Al	1.00	0.89	0.13	0.36	0.92	0.81	0.66	0.91	0.15	0.38	0.64	0.48
Si	0.89	1.00	0.07	0.33	0.90	0.88	0.69	0.99	0.17	0.42	0.65	0.47
S			1.00	-0.18	-0.01	-0.13	0.05	0.10	0.38	-0.02	0.34	0.47
K				1.00	0.54	0.31	0.19	0.32	0.21	0.13	0.15	0.11
Ca	0.92	0.90		0.54	1.00	0.81	0.60	0.89	0.12	0.34	0.56	0.31
Ti	0.81	0.88			0.81	1.00	0.65	0.87	0.03	0.30	0.51	0.28
Mn	0.66	0.69			0.60	0.65	1.00	0.69	-0.07	0.51	0.42	0.46
Fe	0.91	0.99			0.89	0.87	0.69	1.00	0.20	0.41	0.65	0.48
Ni									1.00	0.13	0.19	0.40
Zn							0.51			1.00	0.42	0.49
Br	0.64	0.65	0.34		0.56	0.51	0.42	0.65		0.42	1.00	0.61
Pb	0.48	0.47	0.47				0.46	0.48	0.40	0.49	0.61	1.00

Correlations between fine elemental species at Giant Forest are shown in Table 4.1. Very high correlations (>0.89) exist between silicon and other soil-derived elements (Al, Ca, Ti, and Fe). High correlations exist between Si and Mn(0.69) as expected, but a low correlation exists for K (0.33). We interpret this as evidence of fine smoke at this site, as K occurs also as a smoke tracer. The correlation of Si with Br is based on few observations, and can probably be discounted. Sulfur correlates well with nothing at all, as might be expected at a site dominated by secondary, not primary, aerosols, but the modest correlations of sulfur with Ni (0.38), Br (0.34) and Pb (0.47) are suggestive of its anthropogenic origins, including fuel oil.

Initially five factors were selected and rotated using the EQUIMAX rotation. In addition, two, three, four and six factors have been extracted to investigate how the variation separates as one examines the correlations in finer detail. The final Equimax rotated factor matrix for 5 factors is displayed in Table 4.2.

Table 4.2 Equimax rotated factor scores for Giant Forest fine SFU data

ELEMENT	FACTOR 1	FACTOR 2	FACTOR 3	FACTOR 4	FACTOR 5
Al	0.59	0.60			
Si	0.79				
S					0.67
K				0.77	
Ca	0.60	0.47		0.60	
Ti	0.75				
Mn		0.48	0.56		
Fe	0.79				
Ni					0.65
Zn			0.68		
Br			0.39		0.38
Pb			0.58		0.58

The most significant factor scores have been retained in each column.

FACTOR 1: Al, Si, Ca, Ti, Fe is derived from CRUSTAL material. Samples of local soil were collected at each of the sites, then resuspended and sampled in the laboratory. Results are presented in Table 4.3.
FACTOR 2: Al, Ca, and Mn. May be a local soil high in aluminum.
FACTOR 3: Zn, Mn, Pb and Br. Pb and Br indicate source associated with automobile traffic, and hence either a valley source or local traffic. The source of Zn and Mn is not known, although the correlation coefficients put most Mn in soil.
FACTOR 4: K and Ca. This K may be derived from wood burning, or alternatively from biogenic emissions from the forest. The association with Ca is unexpected.
FACTOR 5: S, Ni, Pb and Br. This signature is an unambiguous indicator of valley pollution, either local or in the southern San Joaquin, carrying evidence of oil burning and automotive exhaust fumes.

Silicon and potassium time plots are presented in Figures 4.1 and 4.2, as key indicator elements for Factor 1 (CRUSTAL) and Factor 4 (POTASSIUM). A similar time plot of S, as an indicator for Factor 5 (VALLEY POLLUTION) was shown earlier as Figure 3.8.

TABLE 4.3: SEQUOIA ELEMENTAL PROFILES* SFU FINE STAGE SOIL AEROSOL PROFILE %

SITE	Mg	Al	Si	K	Ca	Ti	Mn	Fe
AM1		27.8	47.6	3.6	2.4	1.4	0.24	16.6
AM2		23.8	46.7	4.0	2.9	1.3	0.37	20.1
GF1	4.1	20.3	57.1	3.9	1.5	1.1	0.05	11.6
GF2	4.8	27.0	49.7	3.3	3.4	1.0	0.27	10.3
EL1	7.0	20.4	54.2	4.2	1.0	0.9	0.20	11.8
EL2	4.5	24.8	54.7	3.6	0.8	0.8	0.24	10.4
SFU COARSE STAGE (2.5 - 15 um), SOIL AEROSOL PROFILE %								
AM1		28.9	47.5	4.0	2.5	1.1		15.6
AM2		26.6	47.5	4.5	3.1	1.3	0.19	16.4
GF1		21.2	59.2	4.2	2.8	1.2		11.4
GF2		26.3	52.7	4.2	4.3	0.9	0.22	9.0
EL1		22.8	59.1	5.0	1.8	0.9		10.4
EL2		26.8	58.1	4.0	1.5	0.7	0.18	8.7

* Soil samples seived and then resuspended in the laboratory as aerosols
AM=Ash Mountain; GF=Giant Forest; EL=Emerald Lake

Recommendations

1. Particulate and meteorological data should be collected at the same location. A careful match should be made between the effect to be studied and the resolution of the measured parameters. For example, 8 hour resolution may be sufficient for transport back calculations but insufficient to look at upslope transport.

2. Experiments should be designed to examine the specific meso-scale features identified in these reports as playing a critical role in the transport of particulate pollution to the Sequoia National Park. These would include the upslope-downslope wind system, the Fresno eddy and the Nocturnal jet.

3. The sulfur concentration could be examined in light of other meteorological parameters such as mixing height in the valley or delta p at appropriate sites.

4. This is a complex system and cannot be looked at by studying one parameter at a time. The complete meteorological system as a whole must be studied.

5. The authors do not show the results of the VARIMAX rotations but show only EQUIMAX rotations. This is unfortunate since VARIMAX is the most widely used technique in factor analysis. In order to compare with other results in this area, varimax results should also be presented. The use of principal components is only an aid in interpreting the data. The factors and correlations shown here do indicate an association between sulfur and nickel. The factor also includes lead and bromine which indicates the air mass probably originated from the local area. There is no differentiation of data as day or night and we think further conclusions would warrant supporting data.

6. The details of the potassium analysis should be shown.

7. Although the Myrup/Flocchini, Cahill and Shair reports contain an unprecedented amount of meteorological and transport information, important questions remain unanswered. For instance, it appears that the Fresno Eddy may play a major role in transporting pollution into the Sequoia region from the south. Is this a simple transport process, operating "down-the-gradient" or are there more subtle, three-dimensional

and counter-gradient processes at work? The present data set is not sufficient to answer this question.

4. OVERALL COMMENTS AND RECCOMMENDATIONS

In the discussions above and in what follows in this section we have made a number of observations. Many of these center on the need for more coordination of the measurements. Some pertain to important measurements which were not made or were inadequately made. This is always true in large programs involving several cooperating research groups and institutions. In the context of such efforts, the 1985 Sequoia program was a great success. Unique data were obtained and important new insights were achieved concerning transport processes in this region. But even excellent programs can be improved. Furthermore, the 1985 program has raised a number of questions which will require further study.

After reviewing the project reports, we are left with the strong impression that the role of meso-scale wind circulations is central to the problem of understanding particulate air quality in the Sequoia National Park. The meso-system in this region is unusually complex and is poorly understood. The structure of the Fresno Eddy and its response to changing synoptic conditions is largely unknown. The list of scientific literature on the Eddy is very short. Yet it appears that southerly flows, associated with the Fresno Eddy, may be the main mechanism transporting aerosols and gas phase pollutants from the southern San Joaquin Valley to the southern Sierra Nevada . The three-dimensional structure of the Eddy is particularly important in this regard.

There is no generally accepted theory to explain the formation and behavior of the Fresno Eddy. To our knowledge, there is no published theory at all. One of us (LOM) has developed a simple theory, based on the principle of conservation of potentional vorticity, which seems to explain a number of observed properties of the Eddy. In this theory, a wave is forced in the northwesterly flow along the foothills of the Sierra by variation in depth of the boundary-layer associated with the slope of the mountains. Such waves are called depth-effect Rossby waves or topographic waves in the fluid dynamics literature (Greenspan, 1968; Pedlosky, 1979). The downwind trough in this wave is predicted to form close to the observed location of the Fresno Eddy. In addition to correctly specifying the location of the Eddy, the theory predicts the "wavelength" or position of the eddy to be proportional to the square root of the product of mean wind speed times boundary-layer depth. This prediction has not been studied and might be examined in future transport studies in the San Joaquin Valley. Another possibility is that the Eddy reflects an internal Kelvin wave, also forced by the presence of the Sierra as eastern boundary of the northwesterly Valley flow, but not depending on the depth of the boundary-layer. Kelvin Waves also require substantial stability to prevent the wave energy from escaping in the vertical. Internal Kelvin waves have apparently been observed in the marine layer along the coast of California (Dorman, 1985) and may be a factor in the meteorology of the San Joaquin/Sierra Nevada region.

We recommend that the Fresno Eddy receive additional theoretical study.

It has been suggested, by more than one investigator, that the widespread application of ammonium nitrate fertilizer in the Central Valley may be the main source of nitrate aerosol in the Sequoia region. Feedlots may also be an important source. In either case, the specific pathways and processes involved are largely unknown. It is also an area where abundant expertise and information exists in the agricultural research community. We suggest that this important area may be an excellent topic for future cooperative studies, involving soil scientists, plant nutritionists, and meteorologists.

Specific comments and recommendations follow.

(1) We recommend a comprehensive study of the meso-scale wind field in the southern San Joaquin Valley and adjacent foothills and its role in transporting pollutants from the Valley to the southern Sierra Nevada. This would have to include measurement of the three-dimensional winds, boundary-layer structure, tracer studies, aerosol profiles, relation to synoptic conditions, verification of the potential vorticity theory for the Fresno Eddy referred to above, study of the nocturnal jet and its role in transporting pollutants from the north. This study would lay more emphasis on circulation and processes, especially the Fresno Eddy, in the Valley and its fringes than did the 1985 program. The foothill convergence zone and its possible importance in creating "smog fronts" and the possible importance of the nocturnal jet to Sierra air quality would receive special emphasis. This comprehensive study should be directed by a meteorologist with broad experience with micro-, meso- and synoptic-scale meteorology.

(2) We recommend that the synoptic typology outlined by Cahill be extended and put on a firm basis. We suggest synoptic-meso trajectories would be the most effective basis for such a typology.

(3) We recommend that consideration be given to the application of modern meso-scale models to the problem of understanding the complex wind system in the Sequoia region. This might include use of a mass-

consistent model to reconstruct the three-dimensional wind field and associated trajectories. Another possibility would be to use a dynamics-based model to study the Fresno Eddy and its response to external conditions. In the immediate future, consideration should be given to analysis of the 1985 data set for the purpose of obtaining diffusivities appropriate for representing the rough terrain of the Sierra Nevada .

(4) The specific role of thunderstorms in transporting ions to the Sierra from source regions to the south should be the subject of a special study. This study would make heavy use of satellite imagery. At the first stage, a thunderstorm study would emphasize the 1985 case in order to make use of the Sequoia program data set.

(5) In future transport studies, more attention should be given to selecting measurement sites completely unaffected by local sources of pollutants. We have the impression that convenience was the dominant criterion for selecting some of the 1985 sites. All instrumentation should be located at the sites selected. This includes meteorological, particulate, and gas samplers. This would avoid some of the difficulty in data interpretation.

(6) The following specific research topics should be pursued: (1) Spatial correlation of aerosol species, using the technique of principal components analysis, throughout the Sierra Nevada . (2) The question of how isolated nocturnal maxima form and their possible significance should be studied.

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