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FIELD INVESTIGATIONS OF MECHANICAL DRAFT COOLING TOWER PLUMES

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FIELD INVESTIGATIONS OF MECHANICAL DRAFT COOLING TOWER PLUMES

by

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory (CERL).

The primary mission of the Corvallis laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lake systems; and the development of predictive models on the movement of pollutants in the biosphere.

This report describes field measurements of mechanical draft cooling tower plumes.

A. F. Bartsch
Director, CERL

ABSTRACT

Tethered kitoon (small blimp) sampling techniques were devised to measure the distribution of temperature and humidity in the invisible portion of power plant cooling tower plumes. Measurements were made on plumes from both single cell and multiple cell cooling towers under several conditions.

These measurements, together with data collected on the ambient meteorology and exit plume conditions, are particularly useful in moist plume modeling work.

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ACKNOWLEDGMENTS

Several persons and organizations contributed to this effort. Professor Ron West and students from the University of Colorado assisted in taking and reducing the data at the Comanche Power Plant. Other EPA employees who helped take the various plume measurements were Bruce Tichenor, Dave Slegal and Everett Quesnell. Environmental Systems Corporation measured the plume conditions at the exit of the single cell tower at Turkey Point, Florida. Duke Power Company personnel, Steve Apple, John Gaertner, Joe McHugh, and other employees helped set up the tests at Cliffside, North Carolina. The assistance of Florida Power and Light Company, Public Service Company of Colorado, and Duke Power Company are gratefully acknowledged.

SECTION 1

INTRODUCTION

A number of moist plume models are available to use in predicting cooling tower plume trajectories and dimensions. However, application of individual models provides significantly different results, and it is not certain which model is most valid and under which conditions. Part of the problem is the lack of complete sets of experimental data for model verification. Plume behavior depends on many factors, but much of the collected information is based on visual observations of chimney plumes. Often adequate source and background meteorological data are missing or uncertain. Numerical studies indicate that a given trajectory can be closely fitted in a variety of ways, depending upon what physical mechanisms are assumed to act on the plume. Therefore, it is also important to obtain information on the dimensions, dilution, and internal distribution of properties within the plume.

Several reports on other cooling tower plume studies have been published. One study correlates photographs of natural draft cooling tower plumes taken from an airplane with atmospheric scundings and power plant loadings (1). Helicopter measurements of vertical distributions of excess plume moisture in a natural draft cooling tower plume have been made at the Tennessee Valley Authority's Paradise Steam Plant (2). Aircraft measurements of horizontal temperature and moisture distributions of a multicell, mechanical draft cooling tower plume have shown that the typical bent-over plume model with its simplifying assumptions is limited in its application (3).

These data are of value in plume modeling, but more work needs to be done, particularly closer to the tower where most of the significant changes in the plume occur. Piloted aircraft sampling in this region is not only hazardous but uncertain because the speed of traverse of the aircraft is too fast relative to the time response of the instrument sensors. Also, it is difficult to get accurate position data.

A recognition of the inadequate field data on cooling tower plumes prompted the U. S. Environmental Protection Agency's Corvallis Environmental Research Laboratory to undertake a research effort to collect appropriate data from power plant cooling tower plumes. The research began with the development of a unique tethered kitoon sampling technique; three field studies were conducted and this report is the culmination of the project.

SECTION 2

SUMMARY AND CONCLUSIONS

The plumes from single and multiple cell cooling towers have been observed and sampled with respect to the temperature and humidity distributions. Corresponding ambient and efflux data were also taken.

When the site and atmospheric conditions are favorable the blimp/radiosonde sampling method described here will provide detailed plume data which can be used to verify various modeling techniques. Generally, a smooth traversing technique yields the most useful data. However, conditions at Cliffside necessitated point by point measurements. In comparing these data with model predictions one should base comparisons on a number of data points taken under similar conditions or within a relatively short time interval. The three-dimensional nature of the plume and the measurement location needs to be taken into account, and the location and time of the ambient measurements should be considered. Strong vortex mixing was observed in all plumes. This was evident both near the exit of the tower stack and, on a larger scale, in the curling of large scale plume puffs and the twisting of the sheet of cooling tower plumes.

At times, the downwind separation between puffs of plume material appeared more distinct than others. This is to be expected when the ambient wind speed fluctuates in direction and magnitude. However, measurements confirm that most of the plume dilution occurs relatively close to the stack exit.

SECTION 3

RECOMMENDATIONS

The simple radiosonde sampling technique could be improved by automatic data logging equipment which would store the information on tape in a format suitable for machine computation. This would eliminate much of the tedious hand transcription from strip charts. The dual theodolite tracking works well but is cumbersome and requires additional manpower. A tracking system which would automatically log the position of the radiosonde in three dimensions simultaneously with the other data would be quite helpful. If the data logging and reduction become automated, the whole cross section of the plume could be sampled in a relatively short time by using the lightweight radiosonde in a radio controlled, powered sailplane, like the larger units (e.g., 3 meter wingspan) available from model shops. More complete plume cross section data would be of considerable help to the modeler. However, it is essential that these traverses be made with very rapidly responding instrumentation.

Slow response instrumentation tends to eliminate the peaks and otherwise "smear" the data in time and space until significant aspects of the plume behavior, as well as cause and effect relationships, are obscured. It is important for model development and validation to distinguish between entrainment that is entwined into the plume in a steady wind and the apparent entrainment that results from the wind oscillating in direction and magnitude. It is recommended that more wind profile data be taken. Ideally, what is desired is a record of the local wind that a puff of plume material travels through from the time it leaves the stack until it is measured. The difficulties in making such measurement are recognized. However it might be accomplished by double theodolite balloon tracking or photographing vertical rocket smoke trails or other tracers introduced into the ambient. It is also recommended that some horizontal plume velocity measurements be made simultaneously with the wind measurements to ascertain how fast the plume acquires the horizontal velocity of the wind under various ratios of plume exit velocity to wind velocity.

SECTION 4

SAMPLING PROCEDURE

To circumvent sampling problems encountered by previous investigators and conform to project budget limitations, a new sampling technique (Figure 1) was developed using relatively inexpensive equipment. This sampling system allows measurement of plume temperature and humidity in the invisible or unsaturated portion of the plume. The following provides a description of the technique.

A lightweight (130 gram) temperature/humidity sensor coupled with a radiosonde is attached to the tail of a small blimp. This blimp is tethered by the cooling tower and allowed to "windvane" downwind. Thus the blimp and sensor are in the same vertical plane as the cooling tower plume. An operator positioned underneath the blimp traverses the blimp vertically through the plume by means of a second lightweight line hanging from the blimp.

Simultaneous sightings of the sensor from two theodolites placed at known locations are obtained. Temperature and humidity data transmitted from the radiosonde to the receiving station are continuously recorded. The exact time of the theodolite readings are noted on the recorder chart to enable subsequent coordination of position, temperature, and humidity.

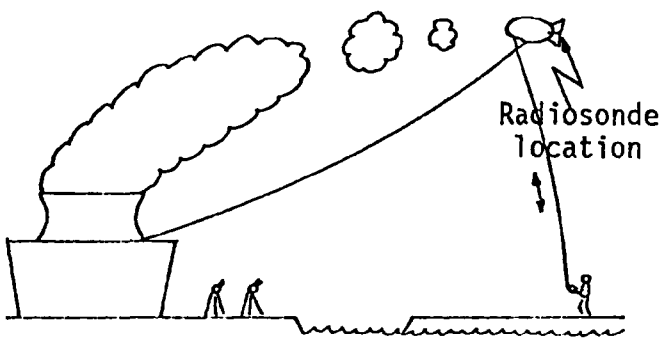

Figure 1. Plume sampling technique.

During field sampling, the sensor calibration was checked about every four hours. The temperature sensor was a small coated bead thermistor with an accuracy of ± 0.2°C and a time constant of approximately 2 seconds. The relative humidity sensor was a premium grade, carbon film hygristor with an accuracy of ± 2% and a time constant of 0.7 seconds. A new hygristor was installed at the start of each day and replaced whenever it appeared dirty.

Measurements using this system were made on plumes from the following sources:

(1) A single cell mechanical draft, salt water cooling tower located at Florida Power and Light Company's Turkey Point Plant.

(2) A ten cell cooling tower located at Public Service of Colorado's Comanche Power Plant near Pueblo, Colorado.

(3) Two, nine cell cooling towers at the Duke Power Plant at Cliffside, North Carolina.

SECTION 5

SINGLE CELL PLUME, FLORIDA

Data on the plume from a large single cell enables one to correlate basic plume behavior theory without the uncertainty of merging plumes. When the plume from the single cell, salt water cooling tower at Turkey Point was sampled, a complete set of tower effluent measurements including velocity, temperature, humidity, and particle size distribution were also being made by the Environmental Systems Corporation for EPA (4). Although the tower was only one cell, its size was comparable to the size of a single cell that could be used in a large multicell tower. The diameter was 8 meters and the air flow was about 422 cubic meters per second. Sampling at Turkey Point was fairly easy because the wind direction was relatively constant or changed slowly and the immediate area was free of high obstacles. There was fairly good access to the area beneath the plume. By using a small boat it was possible to sample over about half the surrounding area (180° sector). Most of the data are presented in Reference 5. Examples are shown here in Figures 2, 3, and 4.

The data collected were reduced to a series of plots which show the temperature and mixing ratio (grams of water per kilogram of air) as a function of the height above the ground. The data for each plot were obtained by pulling the blimp/radiosonde downward. The blimp actually traversed along a slight arc rather than a completely vertical line, so the distance given on the plot is an average distance from the tower.

To facilitate comparisons of the vertical atmospheric temperature gradient with the adiabatic or neutral temperature gradient (9.8°C/Km), the temperature profile is plotted between parallel lines whose slope is equal to 9.8°C/Km. Examination of the temperature profiles indicates that most of the data runs were made when the temperature gradient was near adiabatic.

Although relative humidity was the humidity parameter actually measured, it was deemed more appropriate to use the mixing ratio which, in a well-mixed environment, is nearly uniform and tends to remain constant throughout the day. The wind conditions at the site, together with the measured atmospheric gradient, indicated that for most of the data runs the atmosphere could be considered well-mixed. Therefore, an increase in mixing ratio is the result of an outside influence, in this case the cooling tower plume.

The data used to plot the curves shown were discrete points tabulated from a strip chart recorder. Approximately 50 data points were used for each vertical traverse, roughly 10 per minute. The data plots show the significant fluctuations, but not all the fluctuations that were recorded.

The dashed lines on the data plots are the results of a simple plume model which was developed to predict the trajectory and average plume properties assuming a circular plume cross section (6).

In addition to defining the plume, the profiles also provide ambient atmospheric background data on the temperature, stability and moisture content of the atmosphere. The blimp traverse was generally arranged so that the radiosonde was pulled from a position above the plume to a position underneath the plume. Thus the beginning and end of each traverse yielded ambient background data. Additional information is shown in Table 1.

TABLE 1

PERIPHERAL METEOROLOGICAL INFORMATION

Figures	2, 3, 4
Efflux temp. (°C)	30.0
Source height wind (m/sec)	5.4
Wind lapse (sec^{-1})	-0.011[a]
Surface press. (mb)	1030
Average horiz. distance to balloon (m)	125
Source type	single cell
Volumetric tower flow per cell (m^3/sec)	422
Cell diameter (m)	8.0
Location	Turkey Point Florida
Date	25 Feb 74

[a]Approx value from meterological tower 1 km away.

It is important to consider the variability of the ambient conditions at the time the plume measurements are made. For example, if the wind direction or speed changes during the time of the measurements, the plume cross section will appear to have a different width than it would have had if the conditions had remained constant. This type of plume spreading or dilution should be distinguished from that which occurs when the wind is steady.

As the questions involving plume prediction become more complex, it becomes necessary to examine the cross section of the plume in the vicinity of the stack. In a strong wind, the plume from a single cell may actually develop into two counter rotating vortex sheets. In this case, the greatest concentration peaks might be found in each single vortex and not in the center of the plume. Sampling becomes more difficult under these conditions because the balloon might tend to fly between the two vortex sheets. In this case, it would be desirable to also make several vertical traverses on each side of the plume center at essentially the same distance away from the

tower. The results of these side by side traverses would define the plume cross section.

The best results were obtained when the atmospheric conditions remained fairly constant during the time it took to make a traverse (i.e., about 5 minutes). However, when conditions are slightly variable, it is still possible to get data that approximate a steady state condition by averaging a composite profile from several short-term observations. As an example, the first and second runs on February 25, 1974, (Figure 2 and Figure 3), were made at the same downwind location under nearly the same environmental conditions. An average of these runs is shown in Figure 4. In this case there is relatively little difference. Ideally, these measurements should be taken simultaneously, but this would require extra equipment. An alternative would be to try to make several traverses before atmospheric conditions can change significantly.

The study at Turkey Point showed that under favorable meteorological conditions the blimp sampling technique could be used to obtain temperature and humidity distributions within the invisible part of the plume from a single cell tower. The next task was to apply a similar technique to a large multi-cell cooling tower.

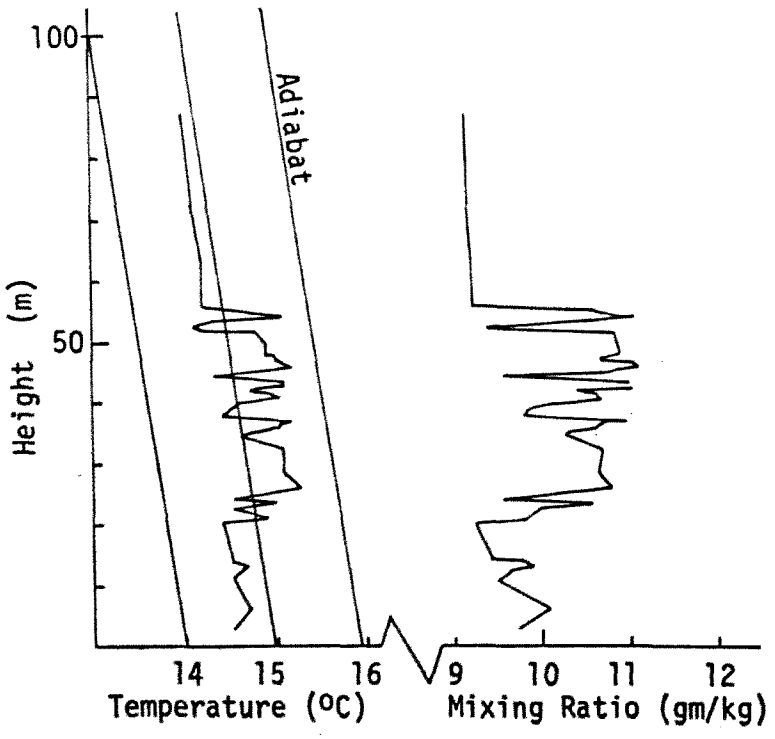

Figure 2. Single cell cooling tower plume profile. Run 1 (descent).

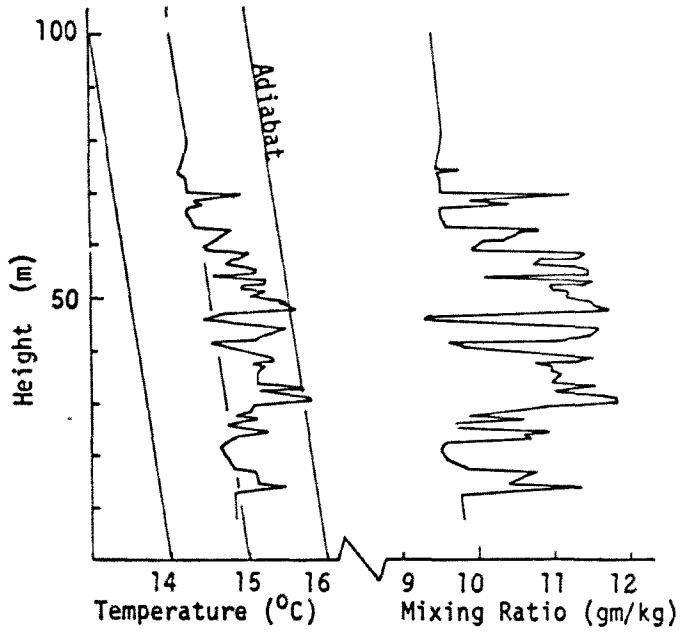

Figure 3. Single cell cooling tower plume profile. Run 2 (descent).

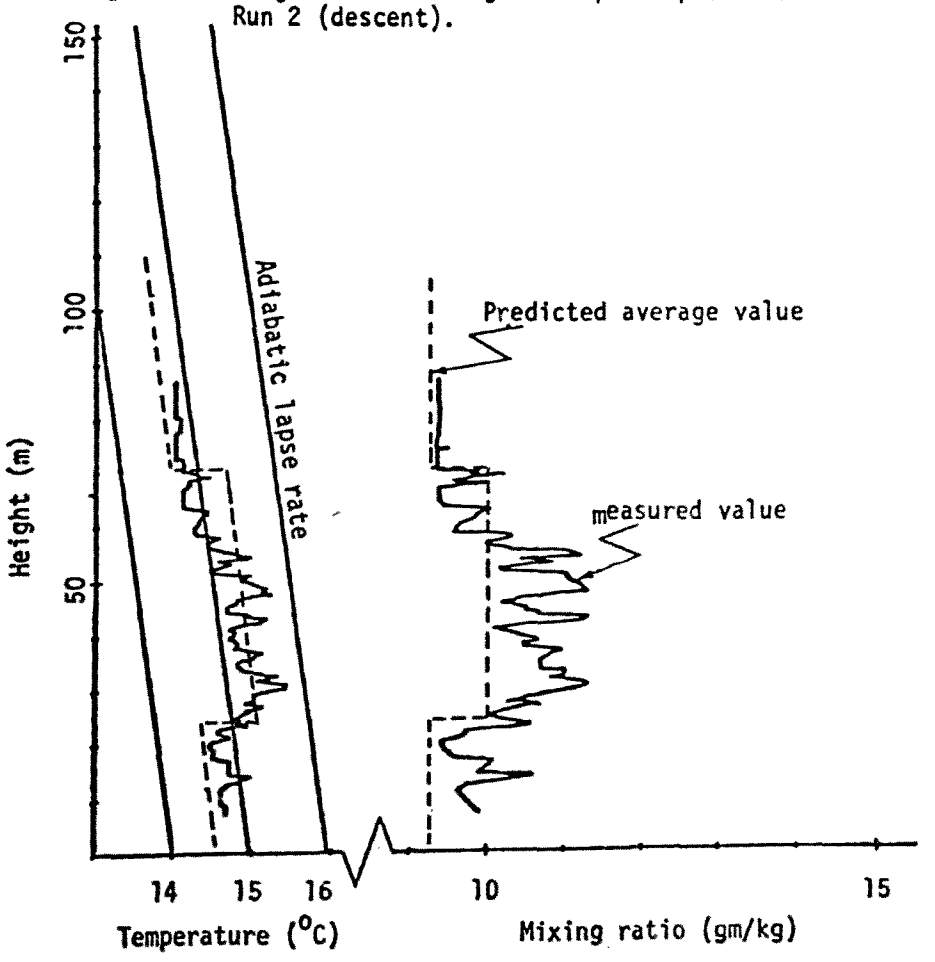

Figure 4. Single cell cooling tower plume profile. Average of Runs 1 and 2.

SECTION 6

MULTIPLE CELL PLUME, COLORADO

The next plume sampled was from a ten-cell cooling tower serving one of the 300 megawatt units of the Comanche Power Plant near Pueblo, Colorado. The diameter of each cell was about 10.2 meters and the volumetric air flow rate per cell was about 710 cubic meters per cell. The study was jointly conducted by EPA and University of Colorado.

The sampling at the Comanche Plant involved the use of two radiosondes on the same blimp. One radiosonde system was an experimental unit developed by the National Center for Atmospheric Research (NCAR) and operated by the University of Colorado personnel. This radiosonde had sensors for wet bulb and dry bulb temperature, wind speed, wind direction and pressure altitude which were multiplexed into one recorder giving single points for each parameter at 30 second intervals.

The EPA radiosonde was identical to the one used at Turkey Point and gave a continuous recording of temperature and humidity. It is advantageous to monitor a continuous graph of humidity and temperature during the traverse in order to determine when the sonde is in the plume. Vertical traverses through the plume were made with this dual sonde system.

Examples of the data acquired by this system are shown in Figures 5, 6 and 7 (6). Also shown are ambient temperature data taken from three temperature sensors which Public Service had installed on booms projecting out from the power plant chimney, plus a ground level measurement. It can be seen that these temperatures indicate a nearly adiabatic lapse rate and correlate well with the radiosonde measurements. The location of the traverse with respect to the cooling tower and the average wind direction is shown in Figure 6, the wind is coming from the east at about 45° to the tower axis. The blimp traverse was made nearly in line with the wind direction coming from the center of the tower. The apparent wind direction as indicated by the windvane on the NCAR sonde is also shown. Oscillations of the blimp, variations in the ambient wind direction, and internal plume motions all contributed to the direction indicated by this windvane. Therefore, it was difficult to make quantitative assessment of these wind data. However, the variation of the motion sensed by the windvane appeared to coincide with the plume location as indicated by the temperature and humidity sensor.

Other data runs are shown in Figures 8 through 21. These graphs were made using the 30-second internal temperature and altitude data from the NCAR/U. of C. radiosonde and the continuous humidity data from the EPA radiosonde. The location of each of these runs is shown in Figure 22.

(text continued on page 28)

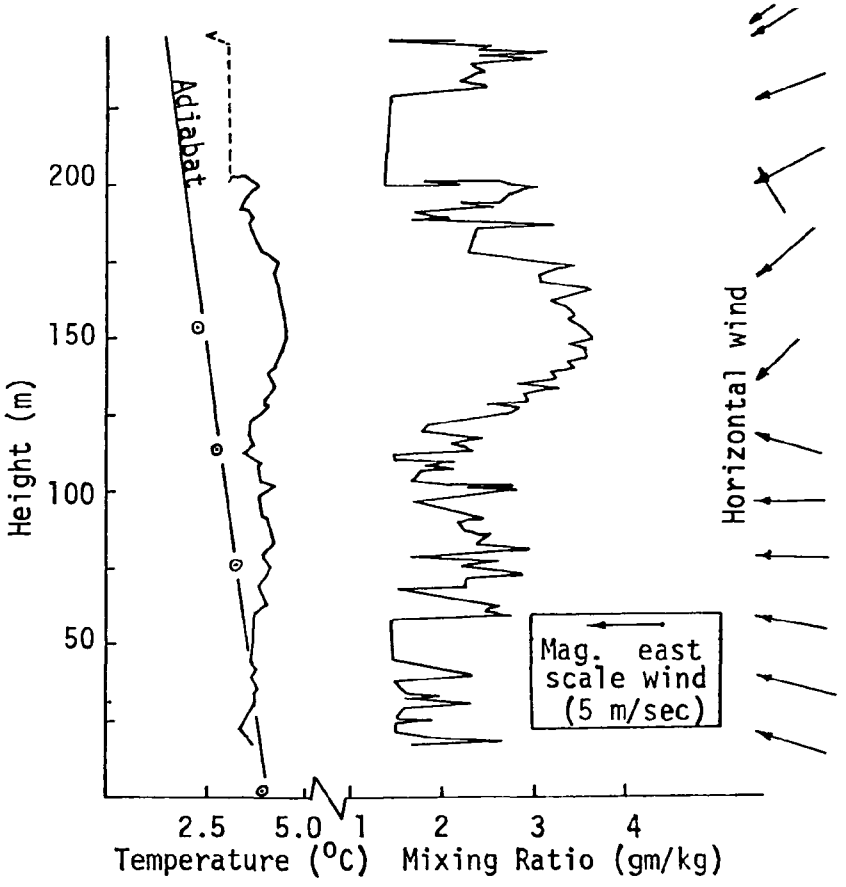

Figure 5. 10 cell cooling tower plume profile. Run 9C (ascent).

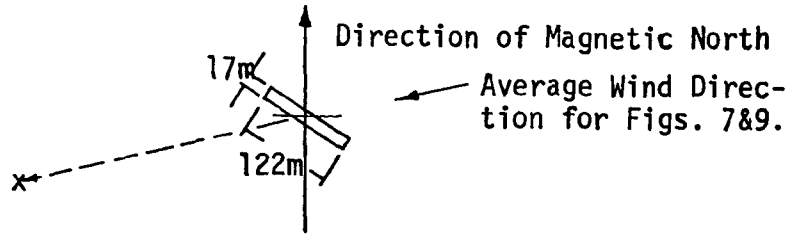

Figure 6. Approximate average balloon location (x) for Figures 7 and 9: 380 m from tower center.

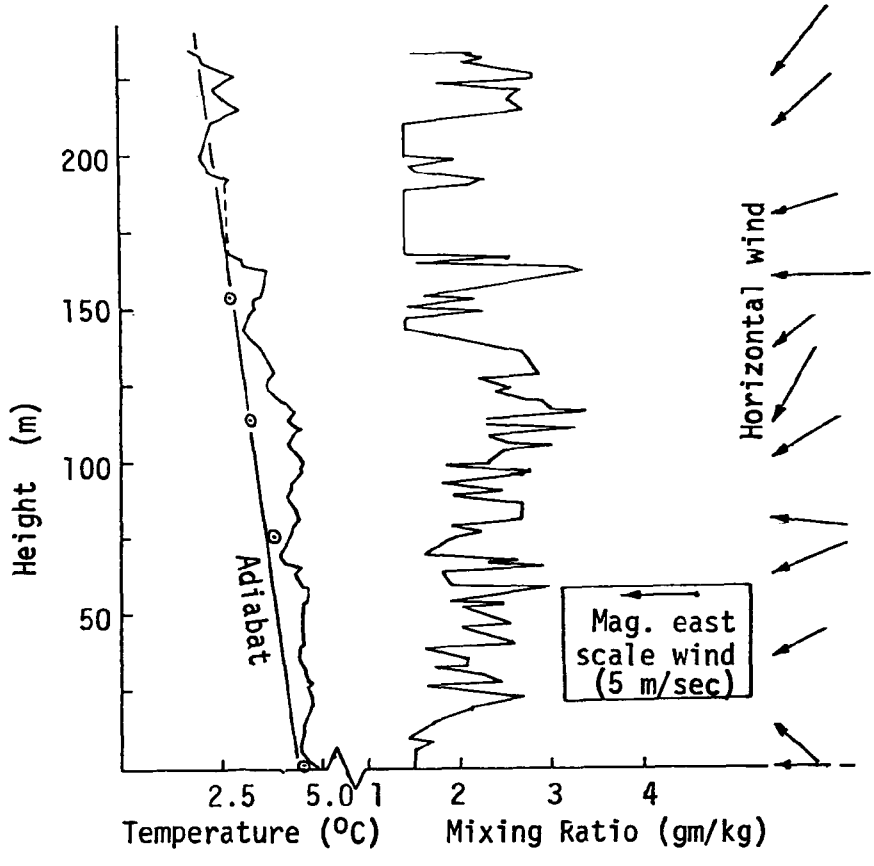

Figure 7. 10 cell cooling tower plume profile. Run 10C (descent).

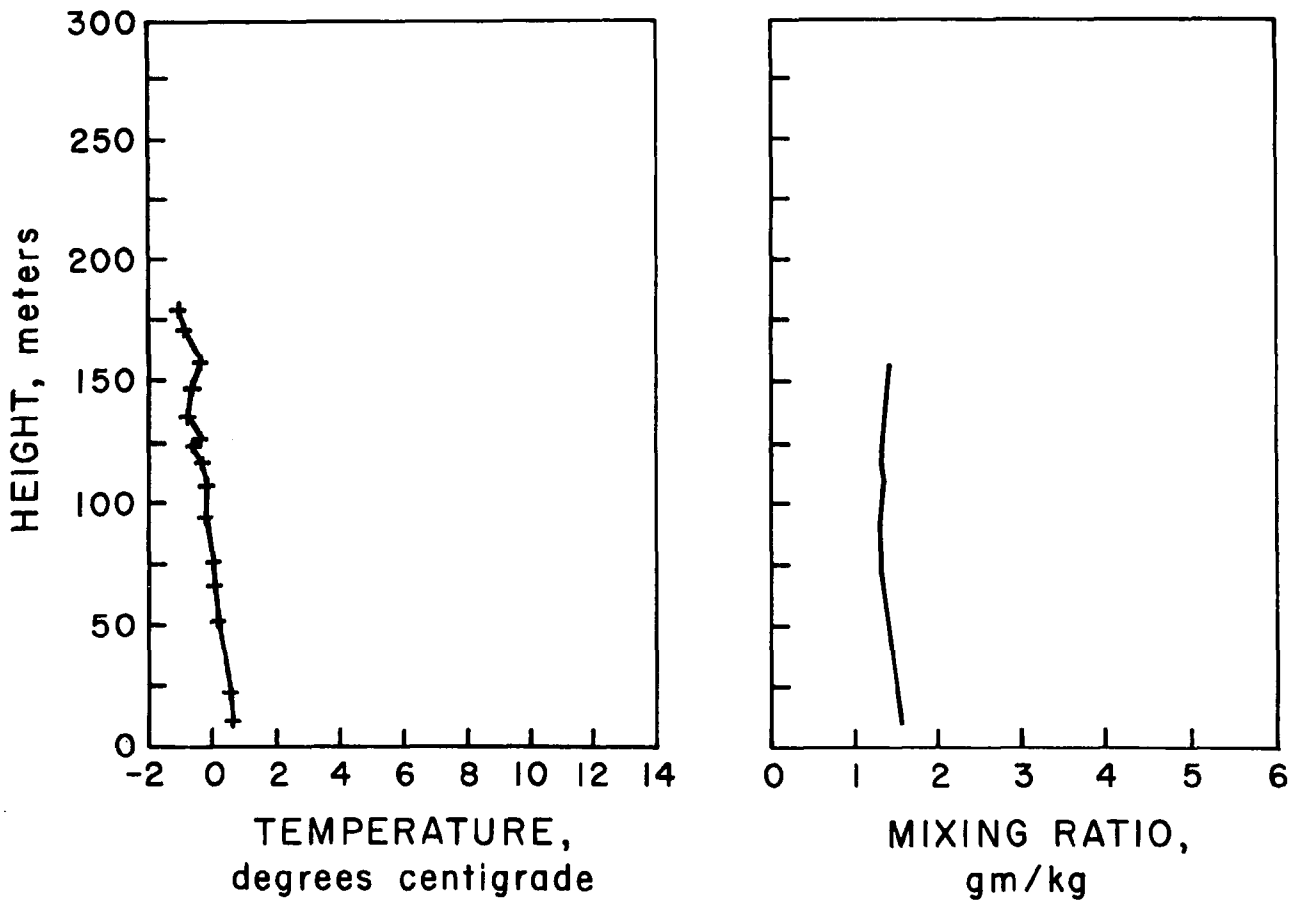

Figure 8. Run 4 on March 25, 1975 at 1030.

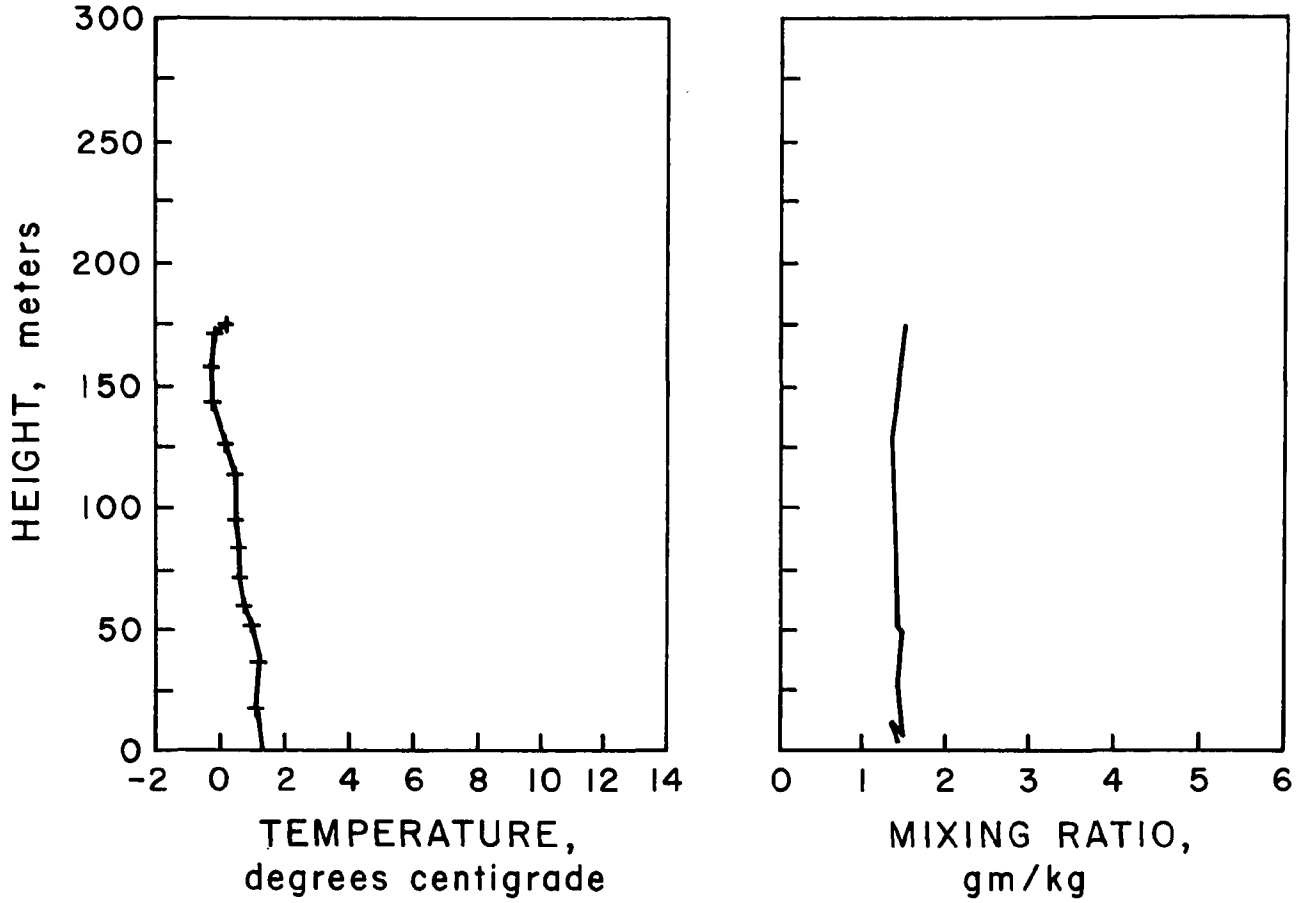

Figure 9. Run 6 on March 25, 1975 at 1052.

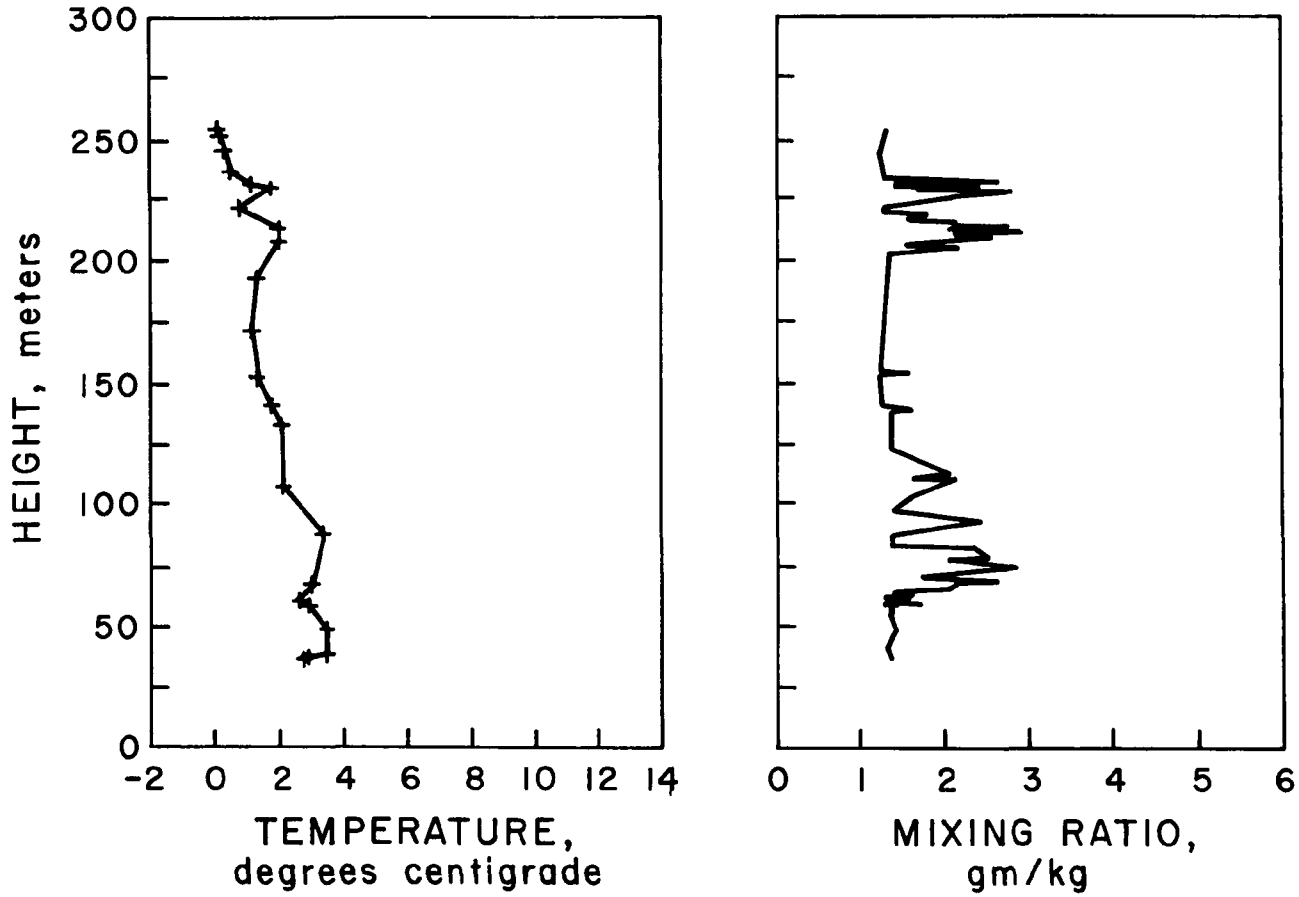

Figure 10. Run 7 on March 25, 1975 at 1125.

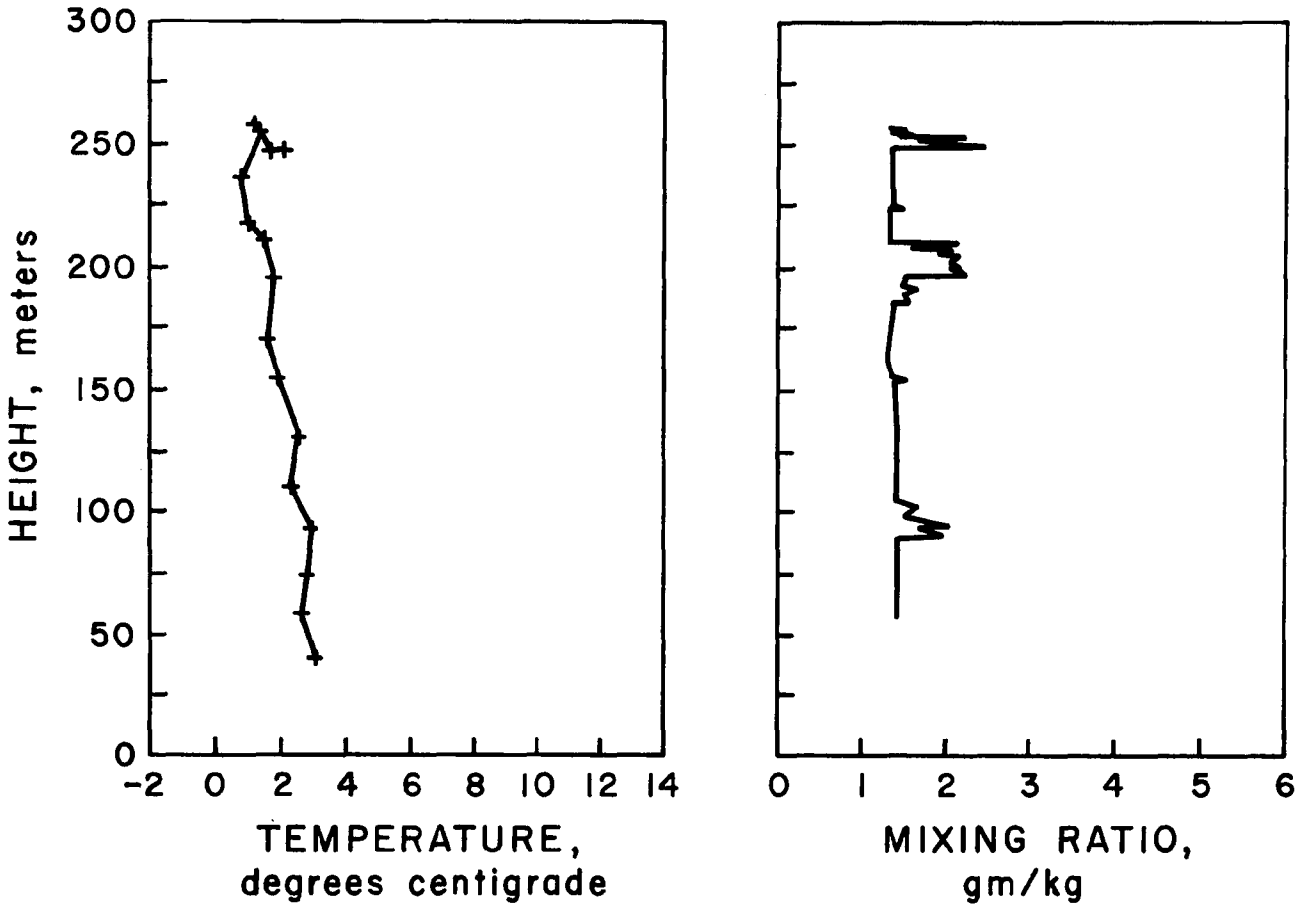

Figure 11. Run 7p on March 25, 1975 at 1134.

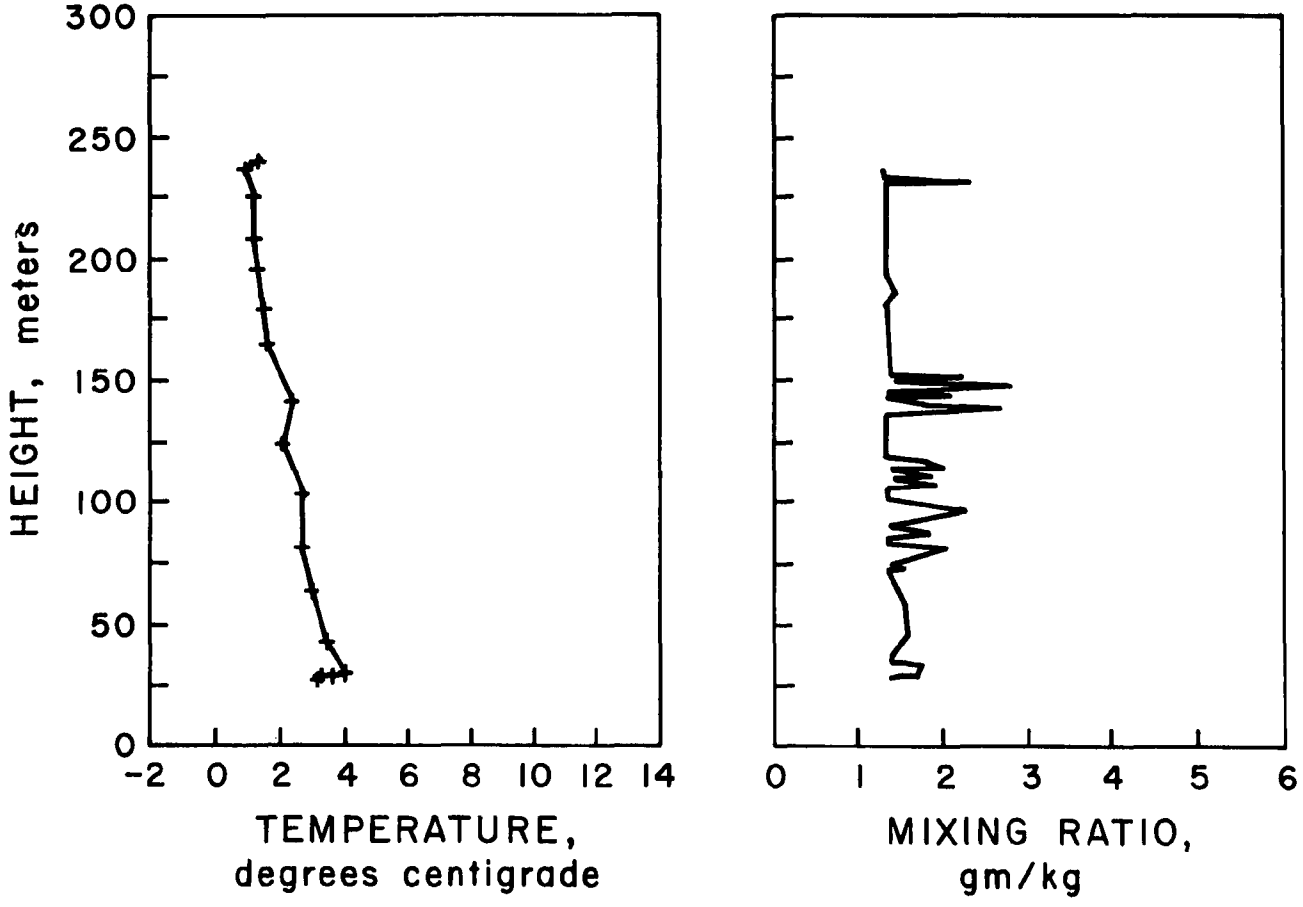

Figure 12. Run 8 on March 25, 1975 at 1146.

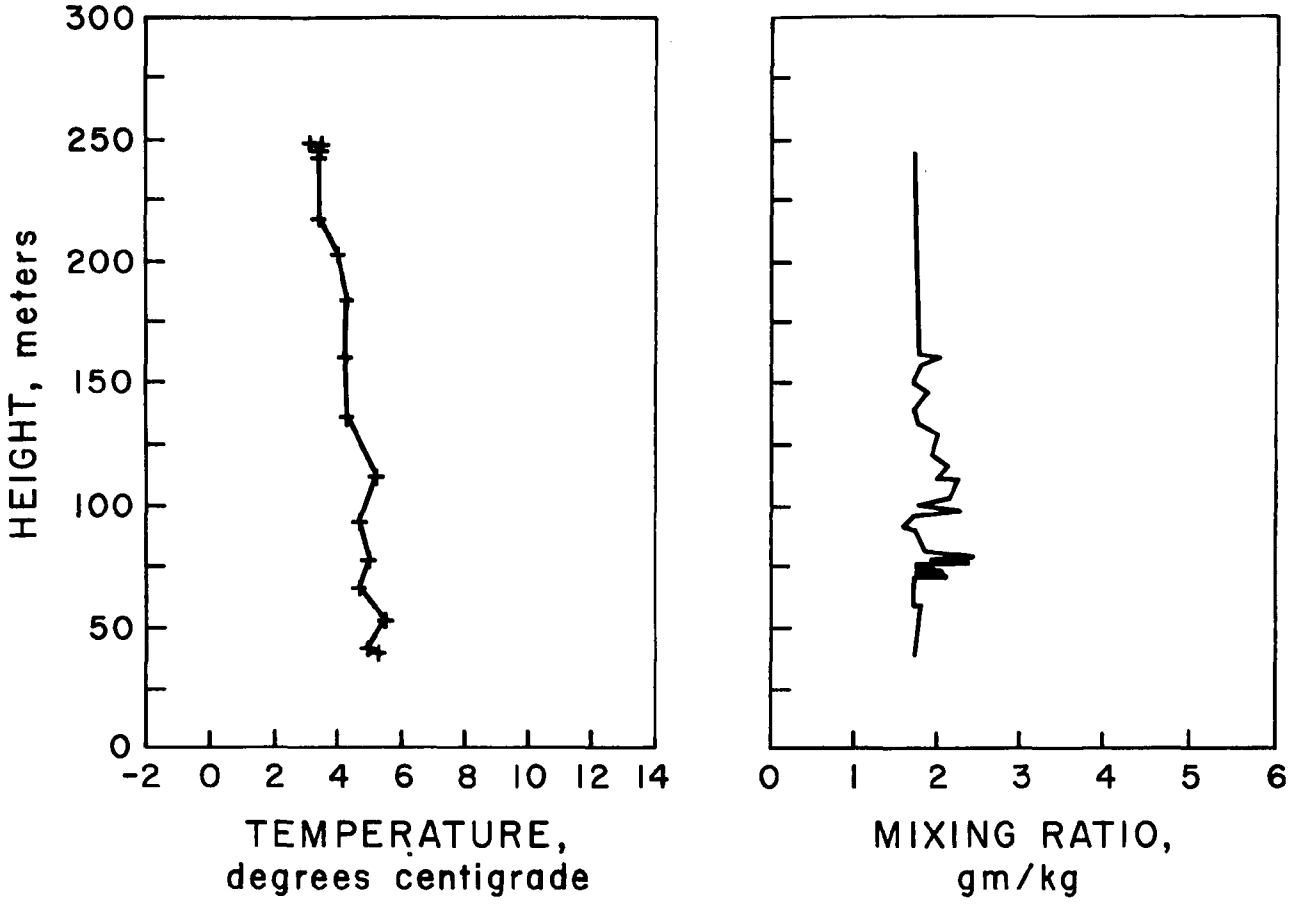

Figure 13. Run 11 on March 25, 1975 at 1302.

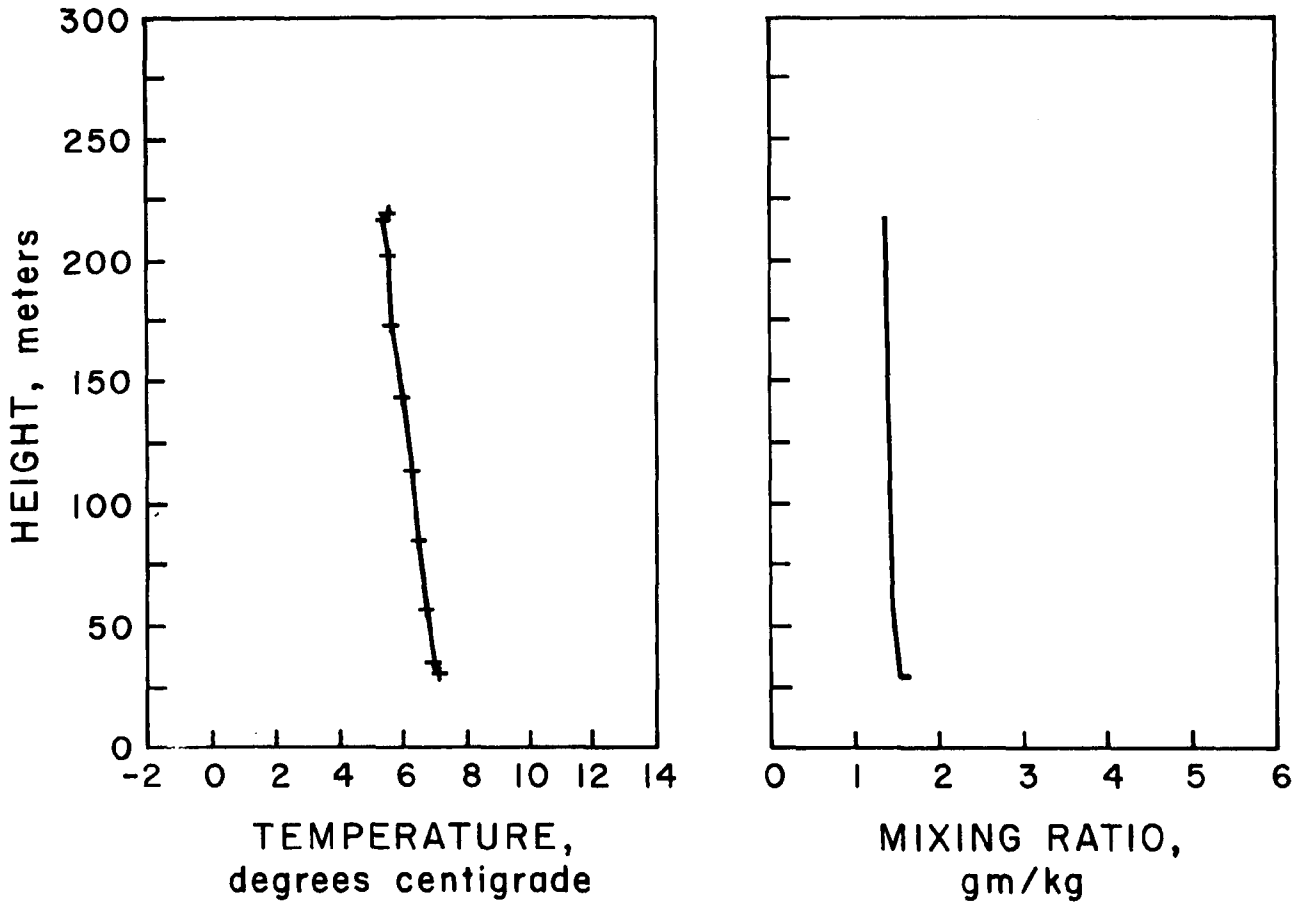

Figure 14. Run 15 on March 25, 1975 at 1441.

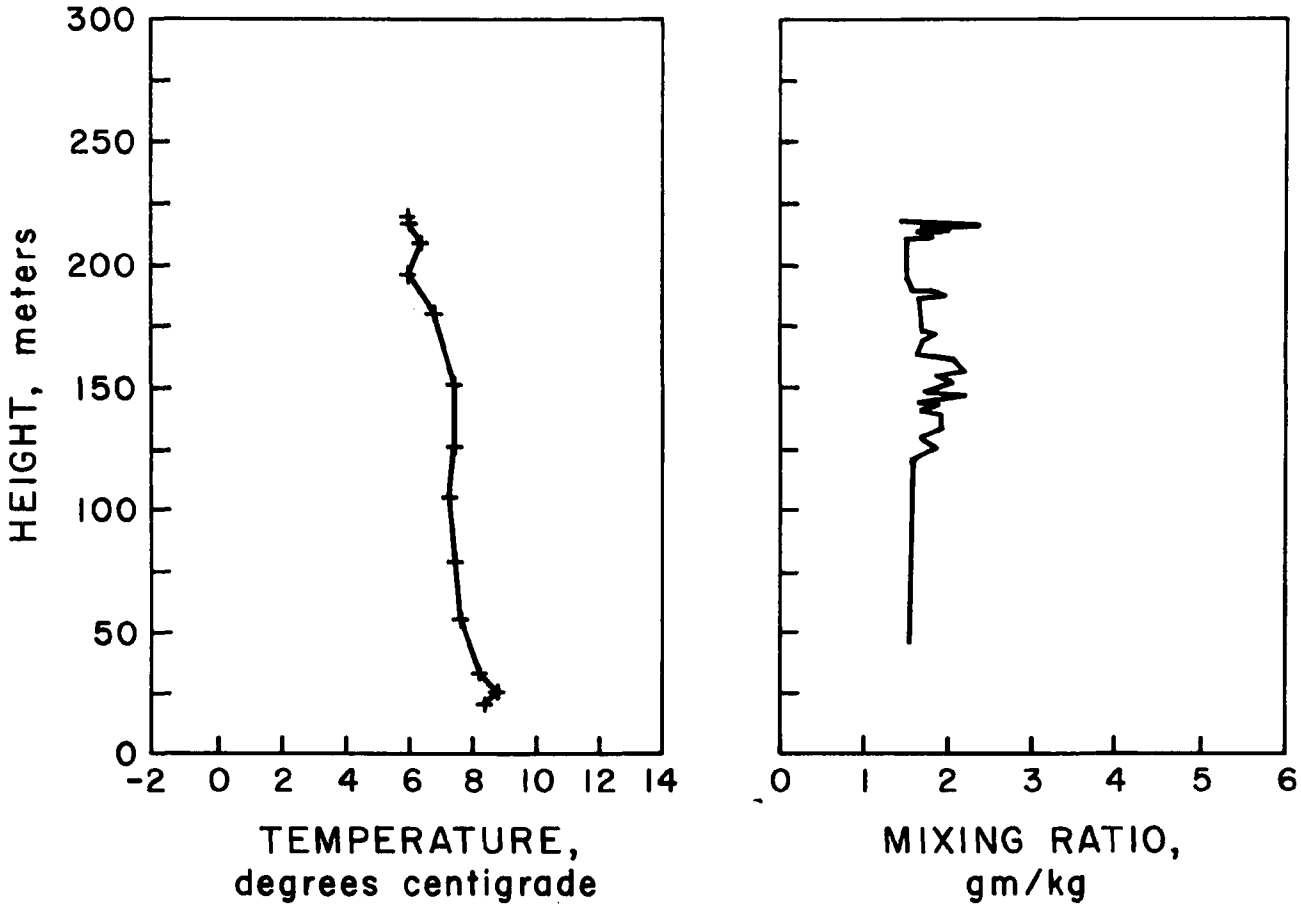

Figure 15. Run 16 on March 25, 1975 at 1455.

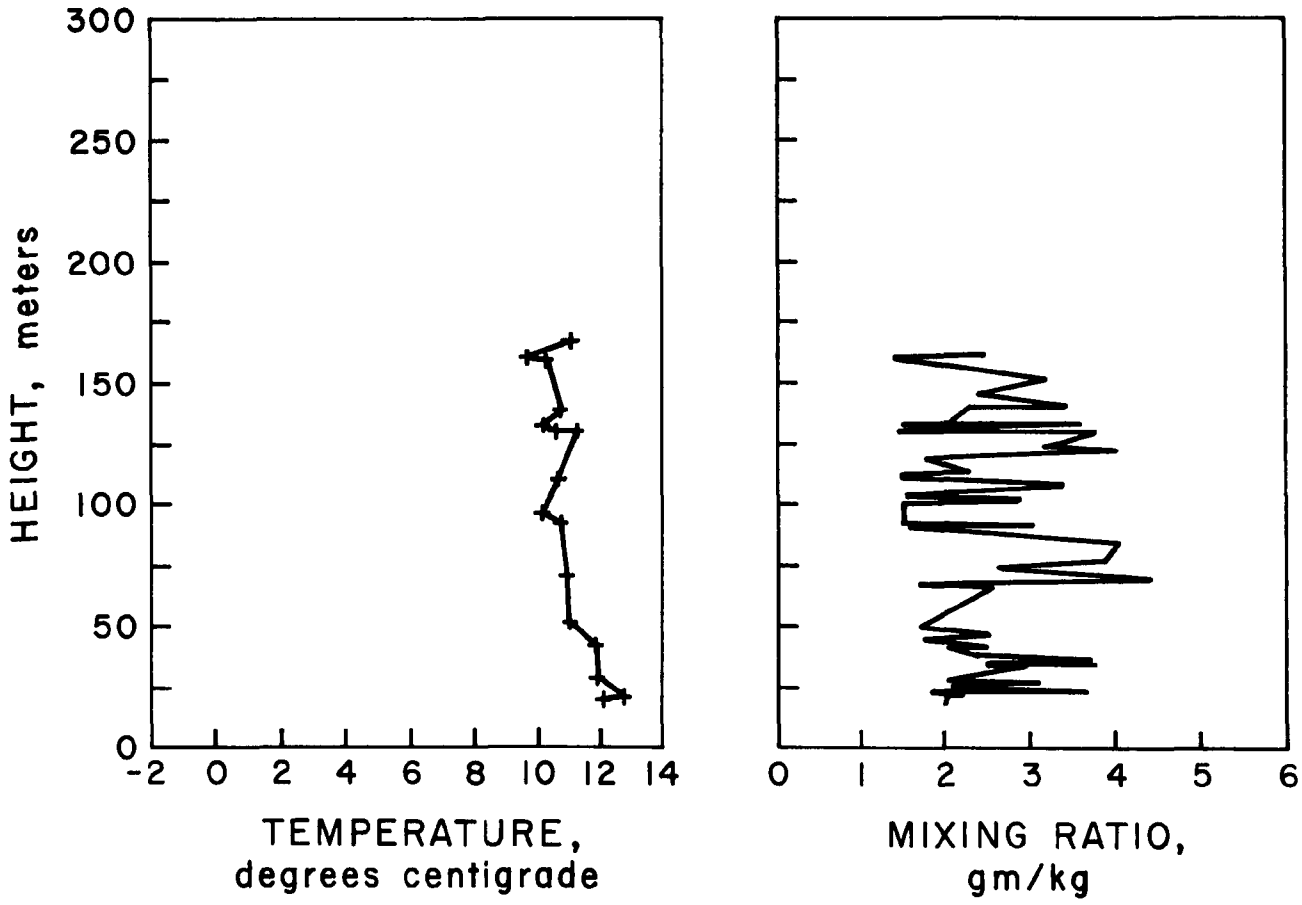

Figure 16. Run 17 on March 25, 1975 at 1624.

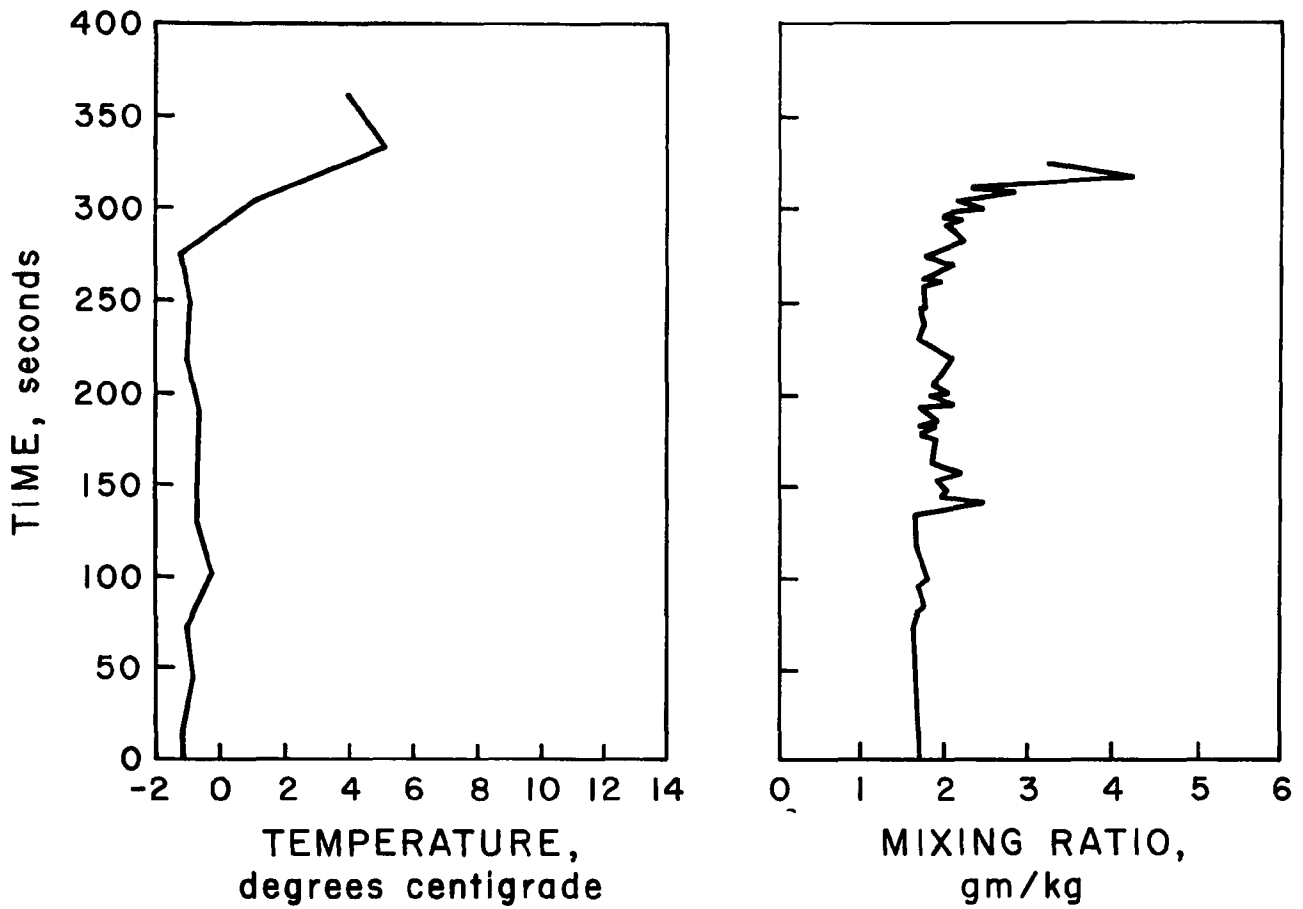

Figure 17. Run 3 on March 25, 1975 at 0930. Horizontal traverse at about 95 meter elevation, moving north toward cooling tower.

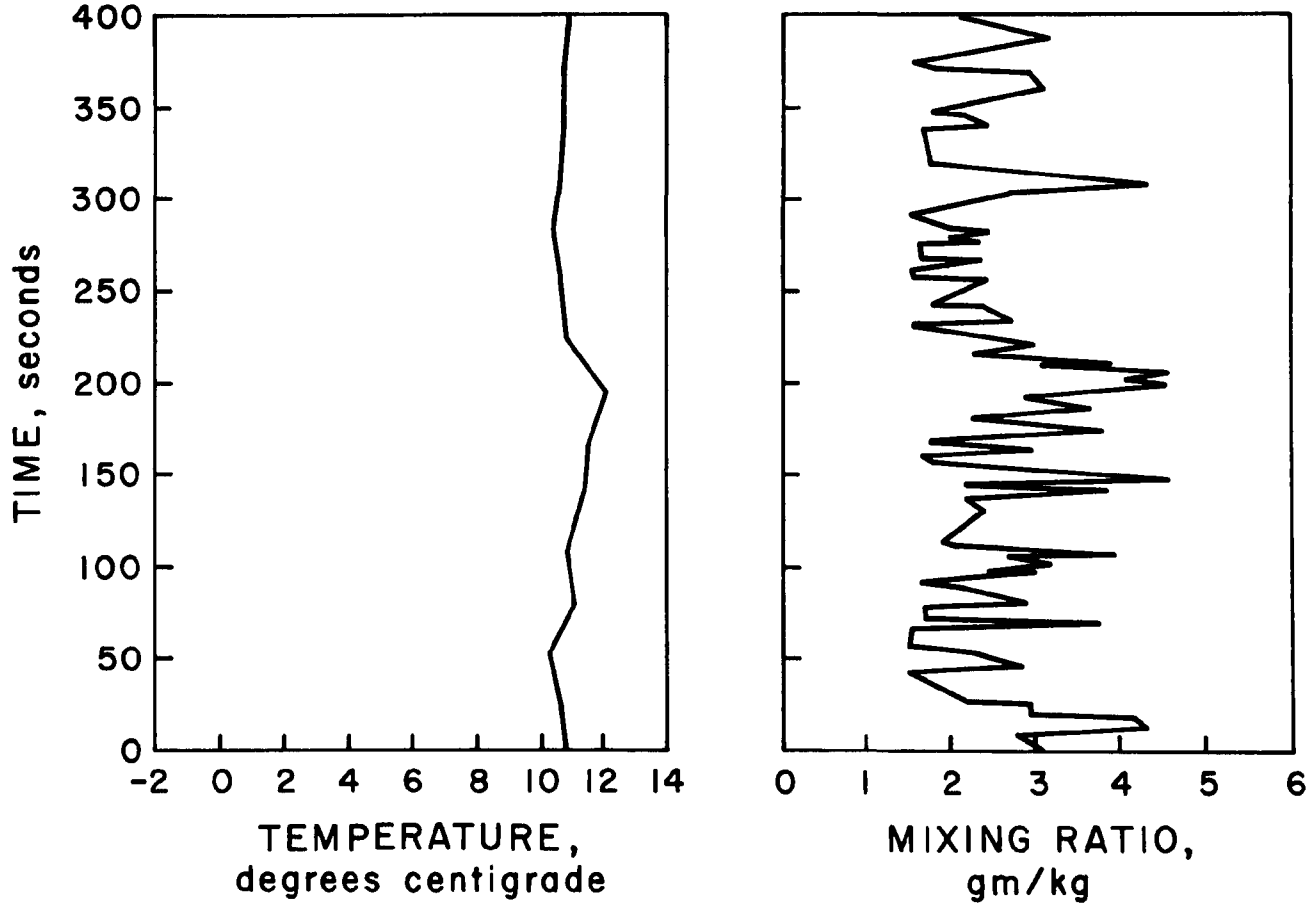

Figure 18. Run 18 on March 25, 1975 at 1636. Horizontal traverse at about 95 meter elevation, moving east to west.

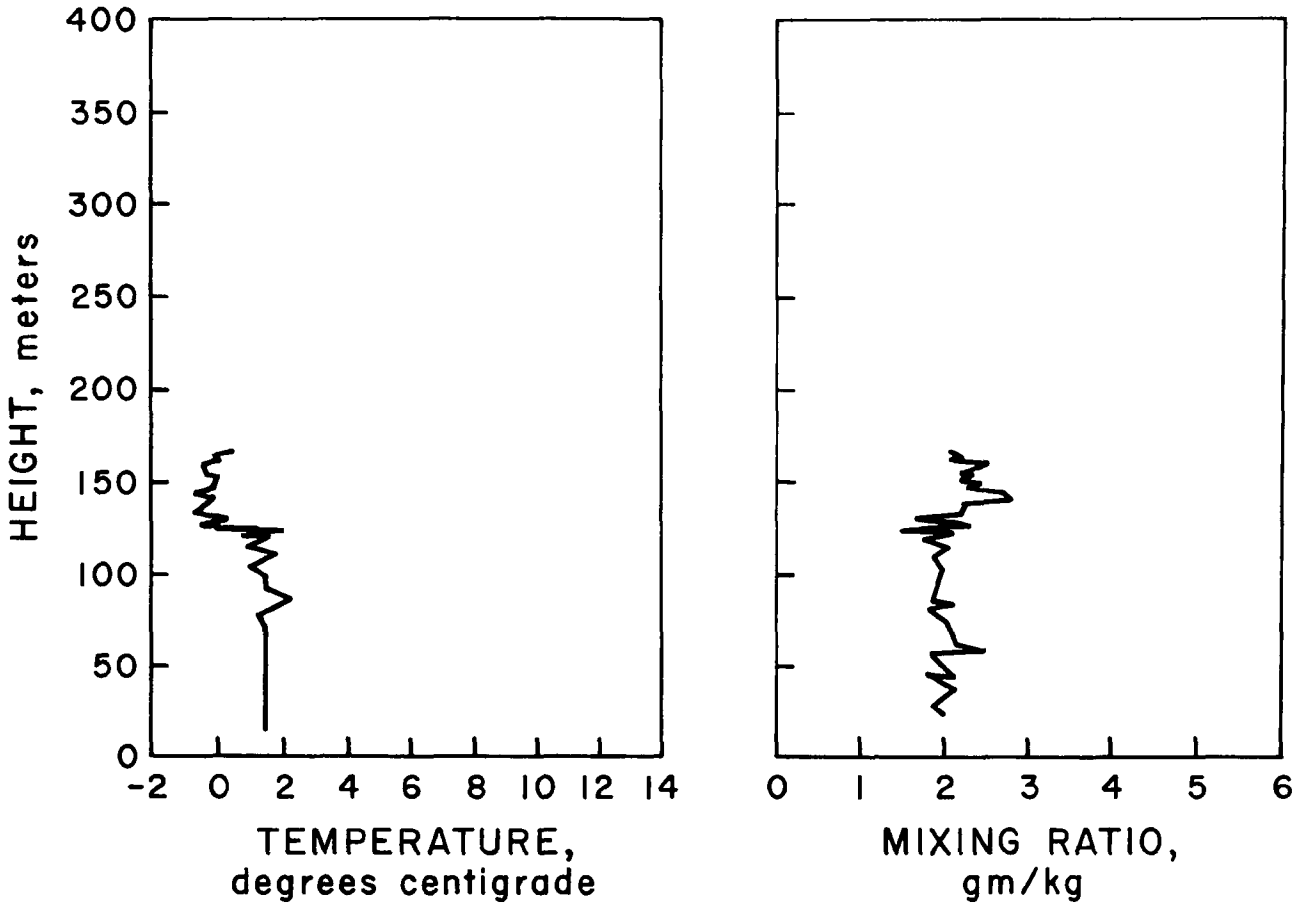

Figure 19. Run 30 on March 26, 1975 at 0936.

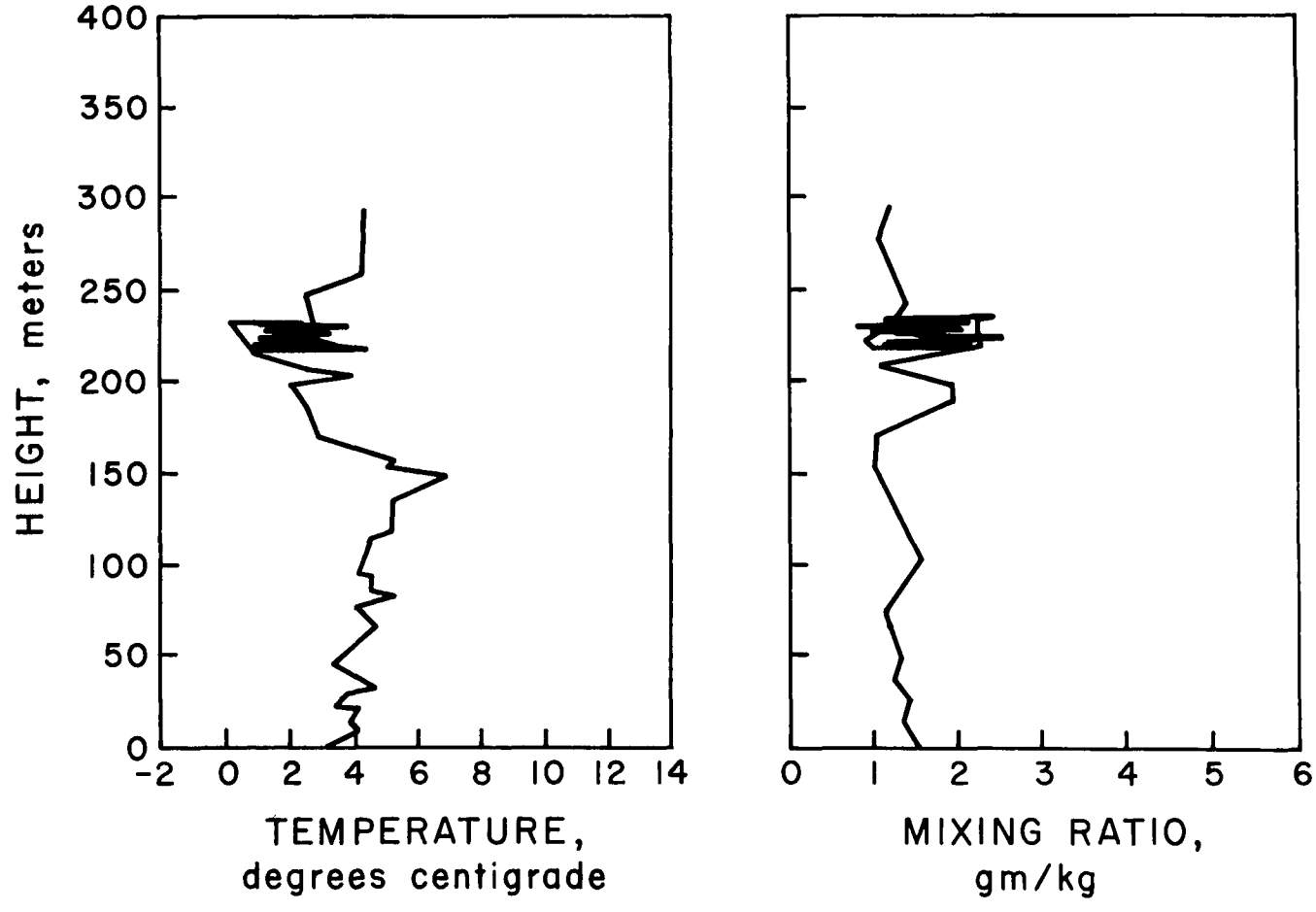

Figure 20. Run 31 on March 26, 1975 at 1003.

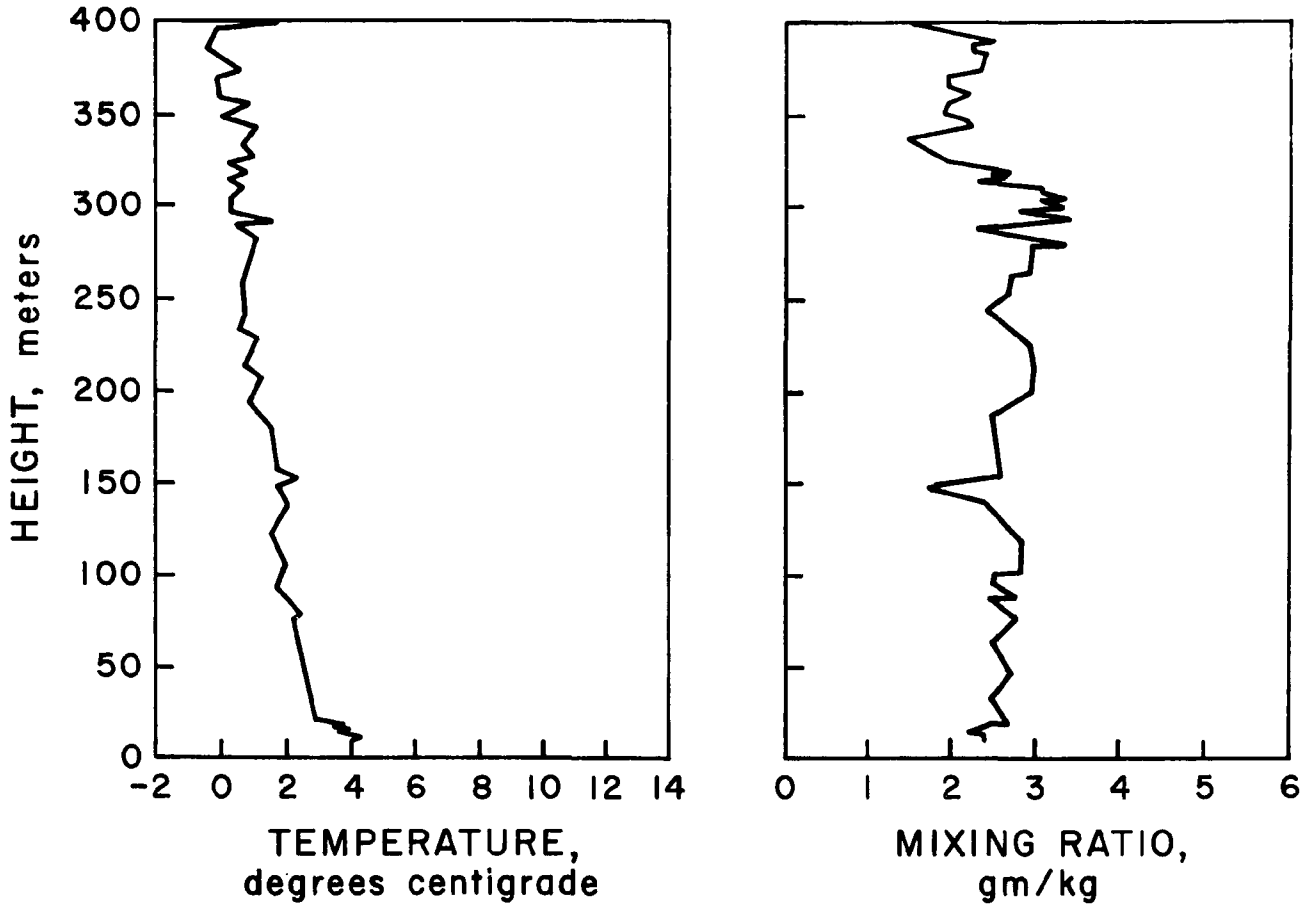

Figure 21. Run 32 on March 26, 1975 at 1030.

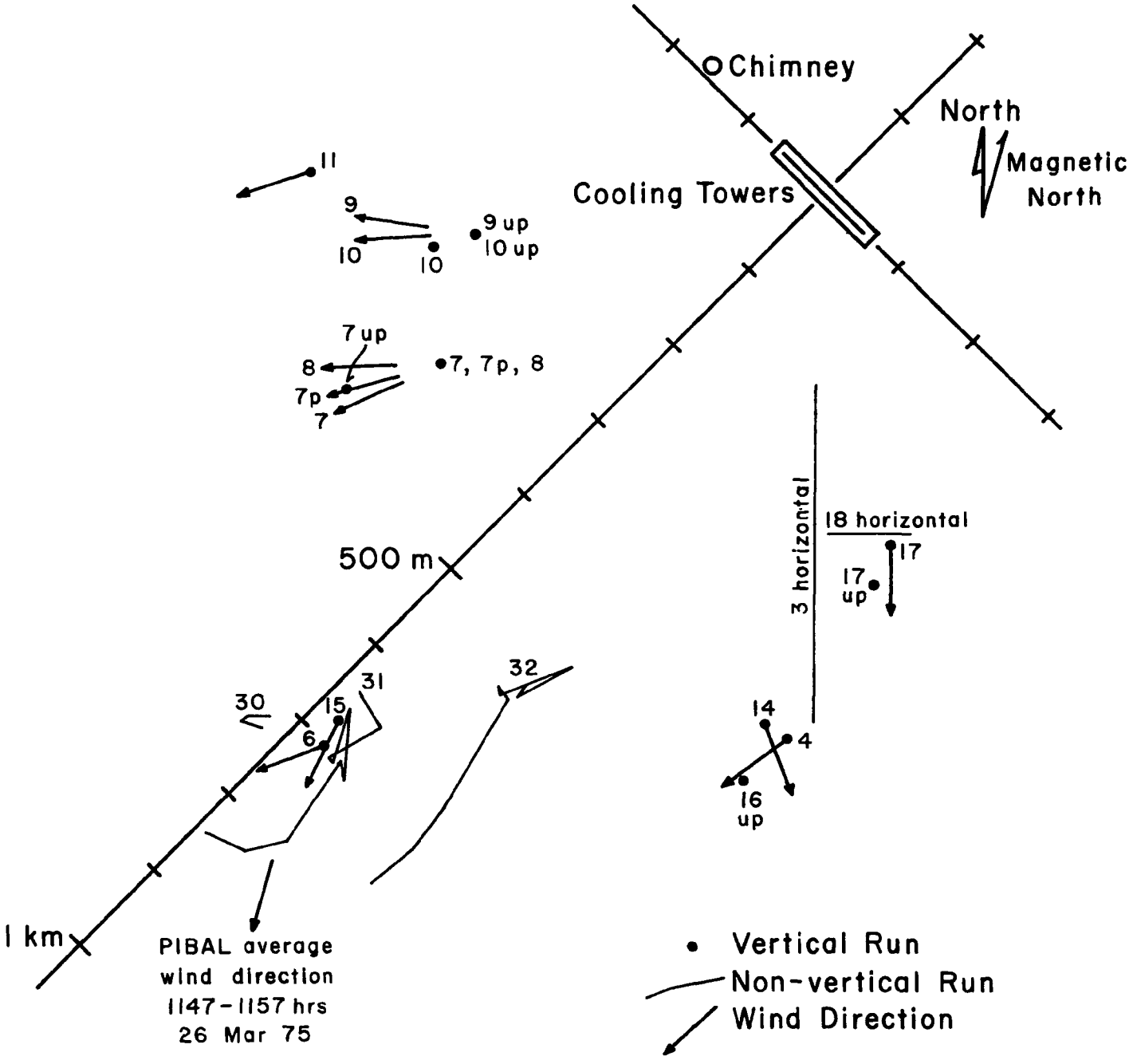

Figure 22. Map of Comanche plant showing run location and wind direction.

Although it is difficult to find any plume activity in several of the runs, they provide valuable ambient background data. To a lesser extent, even if the location of the plume is not known, it is of interest for the modeler to know that the plume is definitely not in a certain area. The plume model can be checked to see if it predicts a plume in this area.

Background and source data were collected and compiled by West (5). The measured velocity distribution across the cooling tower stack is shown in Figure 23. There is good reproducibility of the velocity. Unfortunately, the temperature probe malfunctioned. However, a few glass thermometer measurements were available. West (5) prepared preliminary estimates of the cooling tower efflux which are given in Table 2.

The meteorological data are given in Tables 3 and 4. An interpretive key follows the tables.

In analyzing the radiosonde data, one curious thing to note on the vertical traverse runs is that the plume seems to have peak concentrations at two different elevations. The upper peak is fairly consistant at about 225 meter elevation. It is not known if this is significant. One hypothesis is that the upper peak may be part of the plume from the smoke stack. Another hypothesis is that the sheet formed from the ten cooling tower plumes has curled up on the edges and twisted, the curling being analogous to the twin vortices of a single cell plume previously discussed. These are only tentative hypotheses and more study is required for a definitive answer.

It would be desirable to monitor the internal plume motions by some means, possibly with a tracer. On one occasion when small visible packets of plume moisture persisted for a considerable distance, these plume cloud puffs were observed rotating or spiraling around the axis of the plume over one-half mile downwind. The cause of this motion is not certain, but it may be related to an early twisting of the line of plumes as they emerge from the tower cells in a wind that is blowing at a slight angle to the line of tower cells. This low level twisting brings down the edge of the plume which results in more recirculation of plume moisture back into the downwind cells. However, the manner in which the plumes merge and the resulting cross section significantly affects the entrainment and hence the plume trajectory. More study should be devoted to understanding this phenomenon.

The Comanche field study yielded plume data on a large mechanical draft tower in a relatively dry climate. However, it was also desired to obtain data on large mechanical draft systems in a more humid environment. Therefore, another field study was set up in cooperation with meteorologists from Duke Power Company to sample the cooling tower plume from their power plant near Cliffside, North Carolina.

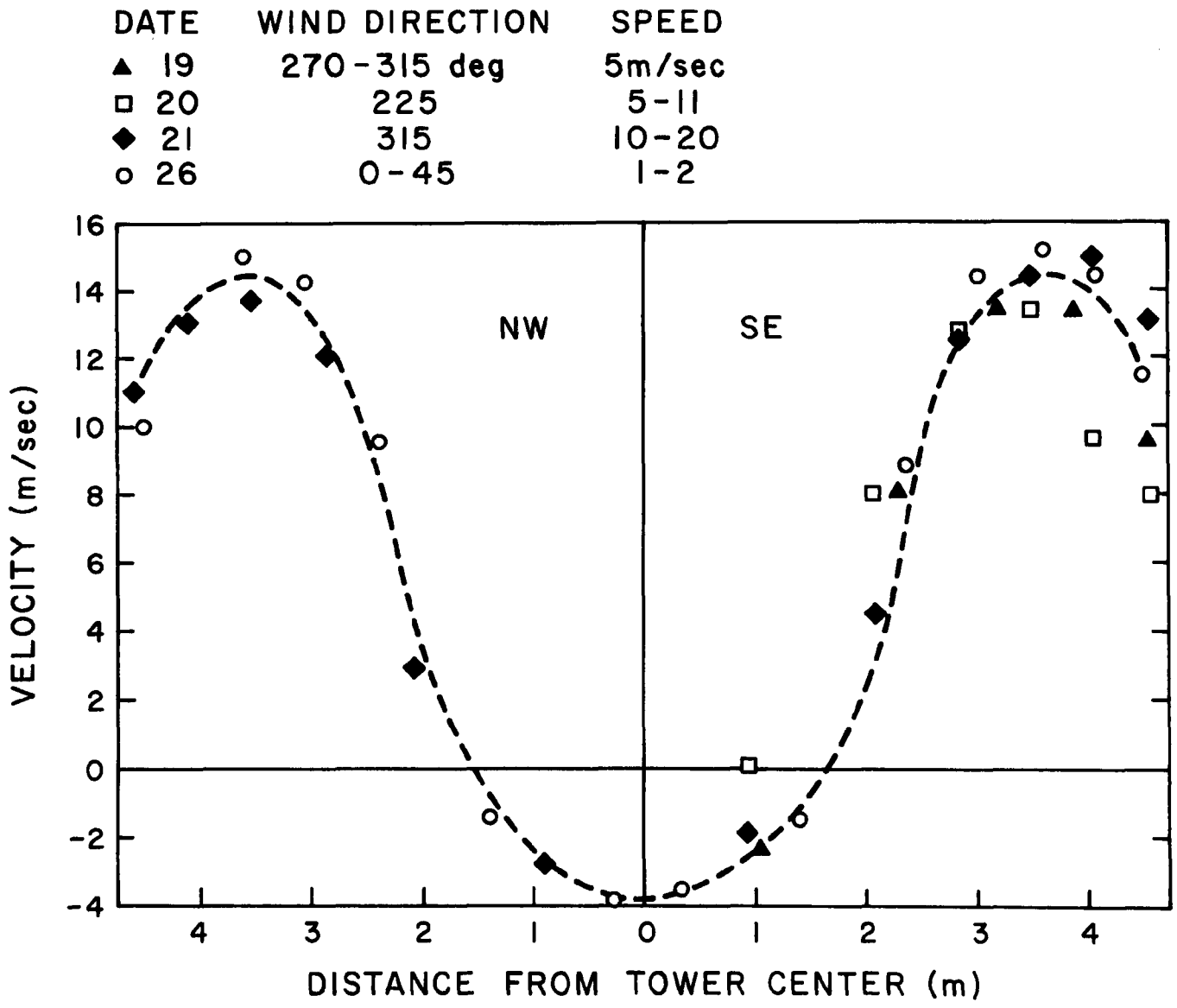

Figure 23. Velocity profiles of cooling tower cell at Comanche power plant, March 1975.

TABLE 2. COOLING TOWER EFFLUX (Reference 5)

DAY '75	TIME MDT	EFFLUX TEMP. °C	EFFLUX MIXING RATIO g/Kg	TOTAL WATER VAPOR RATE 10^5 g/sec	PLANT LOAD, MW
3/25	0600	13.5	11.1	0.829	171
	0900	22.4	19.7	1.413	332
	1000	22.8	20.3	1.453	336
	1100	23.5	21.1	1.505	336
	1300	24.4	22.4	1.590	336
	1400	25.0	23.2	1.641	338
	1500	25.2	23.5	1.660	336
	1600	25.4	23.8	1.680	327
	1700	25.6	24.1	1.699	327
	1800	25.3	23.7	1.680	328
	1900	25.1	23.4	1.654	330
	2200	24.5	22.6	1.603	330
3/26	0600	23.4	21.0	1.498	330
	0900	21.3	18.5	1.335	282
	1000	21.4	18.6	1.333	283
	1200	23.3	20.9	1.492	285
	1300	24.0	21.8	1.550	283
	1400	24.6	22.7	1.602	285
	1500	27.0	26.4	1.846	340
	1700	26.6	25.6	1.794	338

STACK TRAVERSE RESULTS

1. Area Average Velocity = 10.2 m/s

Area Per Stack = 70.0 m^2

2. Volumetric Gas Flow Rate

Measured = 1.516×10^6 Ft^3/Min - Stack

= 715 m^3/sec - Stack

Design = 1.588×10^6 Ft^3/Min - Stack

Total For Column (10 Stacks)

= 1.52×10^7 Ft^3/Min

= 7150 m^3/s

TABLE 3. AMBIENT DATA AT COMANCHE POWER PLANT, MARCH 25, 1975

RUN	ACTUAL	TIME	TEMP. AT GROUND, °C				TEMP. ALOFT, °C			LAPSE RATE °C/100m		WIND SPEED, m/s		WIND DIRECTION		REL. HUMIDITY, %			ISOLATION
NO.	RUN TIME	MDT	a	b	c	d	76m	112m	152m	76-112m	112-152m	b	c	b	c	a	b	d	cal/cm^2-HR
		0700		-6.1	-6.4	-3.0	-0.7	-1.2	-2.0	-1.4	-2.0	1.8	1.3	320	330±30		51	54	
		0730			-6.4			-1.7	-2.0		-0.7								
		0800		-5.8	-5.3			-1.7	-2.0		-0.7	0.9	1.2	290	280±30		50		
3C	0836	0830			-3.6		-0.8	-2.5	-2.9	-4.7	-1.0								
		0900		-3.3	-2.2		0.0	-2.2	-2.5	-6.1	-0.7	0.9	1.3	30	30±40		47		34
		0930			-1.0		+0.9	-0.5	-1.3	-3.9	-2.0								
		1000		-0.8	-0.8		1.3	-1.1	-1.7	-6.7	-1.5	1.8	2.0	0	30±40		44		28
4C	1030-36																		
5C	1041-50	1030			0.0		0.9	-0.4	-0.8	-3.6	-1.0								
6C	53-1100	1100		+0.6	+1.6		2.1	+0.8	+0.4	-3.6	-1.0	1.8	2.2	40	40±40		42		50
7C,7p	1125-34																		
		1130	5.9		3.3		2.3	1.8	1.3	-1.4	-1.2					35			
8C[1]	1146-55																		
		1200	4.0	2.6	3.3		2.8	2.3	1.7	-1.4	-1.5	3.1	2.9	90	70±30	36	39		22
9C	1211-20																		
10C	1224-31	1230	4.4		4.4		3.7	3.2	2.7	-1.4	-1.2					36			
11C	1302-05	1300	5.4	4.4	5.6		5.0	4.3	3.5	-1.9	-2.0	2.2	2.3	80	60±40	36	37		30
12C	1328-33	1330	6.2		6.1		5.5	5.0	4.4	-1.4	-1.5					35			
13C	1346-51																		
		1400	7.1	6.4	6.7		8.0	6.7	6.1	-3.6	-1.5	0.9	1.4	30	0-V	34	34		34
	NEW																		
14C	HYZRISTOR	1430	8.2		7.8	8.0	8.6	7.0	6.4	-4.4	-1.5					33		28	
15C	1441-49																		
16C	1455-1501	1500	8.9	8.1	7.8		8.9	7.8	7.8	-3.0	0.0	1.8	2.2	340	320±40	32	31		36
		1530	10.7		10.5		10.5	9.7	8.9	-2.2	-2.0					30			
17C	1624-32	1600	11.0	10.3	10.5		11.7	9.7	8.9	-5.5	-2.0	3.1	3.3	20	0±30	25	28		12
18C	1636-45	1630	11.8		10.5		11.1	10.0	9.4	-3.0	-1.5					28			
19C	1651-57																		
		1700	11.8	11.0	11.1		10.5	10.0	9.4	-1.4	-1.5	4.9	4.7	320	300±30	28	27		14
		1730	11.1		10.5		10.0	9.5	9.0	-1.4	-1.2					28			
		1800	10.6	10.0	10.0		9.8	9.3	8.9	-1.4	-1.0	6.2	4.8	290	280±10	28	27		4
		1830	10.0		9.0		9.5	9.1	8.5	-1.1	-1.5					28			
		1900	9.7	8.8	8.5		9.6	8.8	8.3	-2.2	-1.2	7.1	5.4	280	280±10	28	27		

a - Data from NCAR Hydrothermograph

b - Data from PSCo Hydrothermograph or wind tower (10m)

c - Data from Meteorological Research Inc. (MRI) ground station (wind@3m)

d - Data from Assman Psychrometer or metal thermometer near base of cooling tower

TABLE 4. AMBIENT DATA AT COMANCHE POWER PLANT, MARCH 26, 1975

RUN	ACTUAL	TIME	TEMP. AT GROUND, °C				TEMP. ALOFT, °C			LAPSE RATE °C/100m		WIND SPEED, m/s		WIND DIRECTION		REL. HUMIDITY, %			ISOLATION
NO.	RUN TIME	MDT	a	b	c	d	76m	112m	152m	76-112m	112-152m	b	c	b	c	a	b	d	cal/cm^2-HR
		0800	-2.0	-3.1	-3.2			-2.3	-2.8		-1.2	4.0	3.8	10	10±10		82		
		0830	-1.5		-2.2			-2.1	-2.7		-1.5				10±20				
		0900	-0.8	-2.2	-1.1			-1.6	-2.3		-1.7	4.0	3.2	30	40±30		78		
30	0936-45	0930	0.0		0.0	+2.0		-1.6	-2.1		-1.2				50±30	52		55	
31	1003-14	1000	+1.1	+0.1	+0.6			-0.4	-0.7		-0.7	3.1	2.5	40	50±30	56	74		54
32	1030-41	1030	2.0		1.7		3.7	+0.7	0.0	-8.3	-1.7				20±30	54			
3B	1057-1108	1100	3.7	2.2	4.5	5.5*	4.4	2.2	+1.5	-6.1	-1.7	1.8	1.8	40	0±90	50	61		
		1130	5.1		6.1		5.9	4.2	2.7	-4.7	-3.7				0 HV	47			
		1200	6.9	5.6	7.2		6.8	5.3	4.5	-4.2	-2.0	1.3	1.7	0	0 HV	43	56		
		1230	7.8		11.1	11.5*	8.6	6.9	6.1	-4.7	-2.0				30±40	39			
		1300	9.6	8.6	10.0	7.5	8.6	7.8	7.6	-2.2	-0.5	1.8	2.0	0	30±60	37	50	63	
		1330	10.9		11.7		10.0	8.9	8.3	-3.0	-1.5				70±90	34			
		1400	12.2	10.2	13.9		12.0	11.3	10.7	-1.9	-1.5	2.2	2.6	90	90 HV	32	35		
		1430	12.0		12.8		13.0	12.8	12.4	-0.6	-1.0				120±90	31			
		1500	14.0	13.3	15.3		13.5	13.0	12.4	-1.4	-1.5	2.7	2.8	110	70±60	28	29		
		1530	14.1		14.4		14.6	13.9	13.3	-1.9	-1.5				190±40	28			
		1600	14.8	14.2	15.0		14.5	13.5	12.8	-2.8	-1.7	4.9	3.7	210	190±40	28	30		
		1630	13.8		13.3		13.5	12.5	11.9	-2.8	-1.5				270±60	28			
		1700	11.3	12.8			11.2	10.0	10.7	-3.3	+1.7	7.6		270		36	39		

*metal thermometer

a - Data from NCAR Hydrothermograph

b.- Data from PSCo Hydrothermograph or wind tower (10m)

c - Data from Meteorological Research Inc. (MRI) ground station (wind@3m)

d - Data from Assman Psychrometer or metal thermometer near base of cooling tower

KEY TO TABLES 3 AND 4

Blank--No data for indicated time.

Temperatures Aloft--Temperatures from sensors on Public Service Co. (PSC) Stack at 76,112 and 152 meter heights.

Wind Speeds--Designation such as 3.1 G 10.7 indicates 3.1 meters/sec. mean, gusts to 10.7 meters/sec. Meteorological Research Institute (MRI) values are averaged over one hour period.

Wind Direction--0° North, 90° East, 180° South, 270° West. PSC values are hourly mean. MRI values are hourly mean; HV means highly variable, direction varied up to 360° in one hour. V means direction varied up to 180° in 1 hour; ± indicates approximate range of variation.

Temperatures at Ground--

a - Data from NCAR Hydrothermograph
b - Data from PSCo Hydrothermograph or wind tower (10m)
c - Data from Meteorological Research Inc. (MRI) Ground Station (wind @ 3m)
d - Data from Assman Psychrometer or Metal Thermometer near base of cooling tower.

SECTION 7

MULTIPLE CELL PLUME, NORTH CAROLINA

The tower plume sampled here came from one of the two, nine cell mechanical draft towers located at Duke Power Company's Cliffside plant. The individual stack diameter was about 10 meters and the exit plume velocity was about 10.4 meters per second. The power plant output varied between 300 and 575 megawatts.

The meteorological conditions prevailing during the sampling runs at the Cliffside Power Plant were significantly different from the conditions at either the Turkey Point or the Comanche tests. During most of this study period the winds at the Cliffside Power Plant were so light that the plume rose nearly vertically. When the plume did bend, it was often too high to use a smooth traversing technique. In this case, the blimp/radiosonde was used to make point measurements in and around the plume in the vicinity of the tower. Plans called for use of a three-man crew, with sensor positions determined by a single theodolite and a new radiosonde which included a pressure altimeter. Unfortunately, the altimeter malfunctioned, so again it was necessary to use two theodolites for accurate position. Most of the data points in the appendix were taken this way. The location of the cooling towers and coordinate system adopted is shown in Figure 24. The origin of the coordinate system is at the center of cooling tower B at the level of the stack rim. All of the data collected have been reduced according to this coordinate scheme. The volume of the data and its three-dimensional nature preclude its being shown in Figure 24. Instead, these data are presented in the appendix.

Meteorologists and engineers from Duke Power Company made wind measurements at two elevations. The lower level wind was measured at about the same elevation as the base of the cooling tower but located across the river. This sensor measured total feet of wind run. The upper level anemometer was located on a water tower approximately 50 meters above the top of the cooling tower stacks. Unfortunately, problems developed with this upper level wind sensor and some of the data were uncertain. However, the wind often was very light, almost calm. As expected, under these conditions, the wind did not establish a very definitive direction.

Duke Power Company also provided measurements of the cooling towers and plant operating conditions (Table 5).

A special sampling run was conducted at the Cliffside towers to determine the conditions of the plume relatively close to the stack exit. These measurements were taken about 46 meters above the tower cells by using

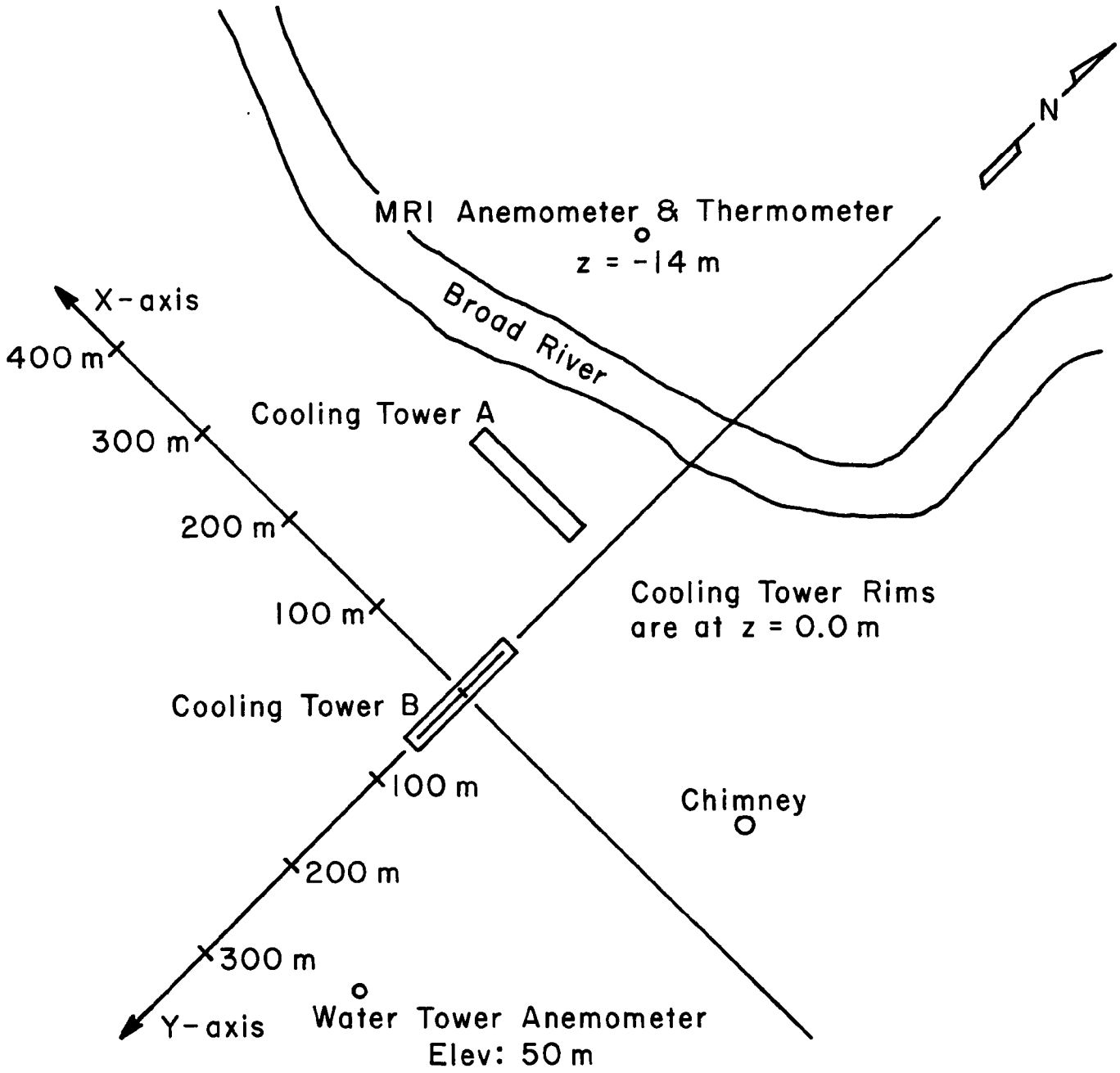

Figure 24. Cliffside coordinate system.

TABLE 5. CLIFFSIDE POWER PLANT DATA

Date 1975	Start Time	Stop Time	Average Generated Megawatts	Tower A Water Temp. in °C	Tower B Water Temp. in °C	Tower A Water Temp. in °C	Tower B Water Temp. in °C	Tower A Water Flow 10^6 Kg/hr	Tower B Water Flow 10^6 Kg/hr
Oct. 30	1337	1628	575	33.2	33.1	20.4	20.2	25.8	23.8
Oct. 31	1325	1559	575	32.1	32.1	19.3	19.4	25.6	24.2
Nov. 1	1247	1534	315	22.2	22.6	15.1	14.9	26.5	24.5
Nov. 3	0946	1201	325	25.0	25.3	17.3	17.7	26.3	24.3
Nov. 3	1428	1600	322	25.8	26.1	18.6	18.4	26.2	23.5
Nov. 4	0921	1221	303	25.6	25.8	18.5	18.5	26.2	24.1
Nov. 4	1411	1619	303	26.6	26.9	19.6	19.7	26.1	23.4
Nov. 5	0908	1246	387	29.1	29.3	20.2	20.4	26.0	23.9
Nov. 5	1403	1618	395	30.4	30.7	21.6	21.6	25.9	23.0

two tethers on either side of the tower. The position was determined by sighting with a single theodolite and noting which cell the blimp was above. The results of these close-in measurements are as follows:

Time 1255-1302, 1 November 1975
Average Plume Temperature 17.0°C
Ambient Dry Bulb Temperature 15.3
Ambient Humidity 30%
Average exit velocity 10.4 m/sec
Plume Efflux Temperature 25.5°C
Wind Speed (MRI) 2.36 m/sec
Wind Direction (MRI) 200°

The field observations at Cliffside showed how the plume from a mechanical draft tower behaved under relatively light, almost calm wind conditions. In this case, the thickness of the plume cross section perpendicular to the tower axis remained narrower than the plume width parallel to the tower axis for a distance of over 500 meters. However, if the wind speed did pick up at an oblique angle to the lower axis there was a tendency for the edge of this two-dimensional plume sheet to fold over.

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APPENDIX A

EXPLANATION OF TABLE A-1

The data from the Cliffside Cooling Towers are organized in Table A-1 as follows: Column 1 indicates the date of the run, either the end of October or the beginning of November in 1975; Columns 2, 3, 4, are, respectively, the x, y, z, coordinate locations of the balloon and radiosonde. Column 5 is the number of seconds elapsed since the beginning of the particular sampling run. The presence of the number 1 in column 6 signifies that the balloon was judged to have gone into the plume. The data were examined for a period of approximately a 10-second interval before and after the position indicated. Column 7 is the average temperature over this period. Columns 8, 9, 10 are the average, maximum, and minimum relative humidity, respectively. This must be considered in using the data, particularly close to the tower where the blimp could move in and out of the plume within this time interval. Column 11 is the actual time. The presence of the numeral 1 in column 12 indicates the start of a run. Columns 13, 14, 15 are, respectively, the wind direction in degrees, the wind speed in meters per second, and temperature in degrees centigrade recorded by the MRI Station located across the Broad River in Figure 24. When available, the data in Column 16 and 17 are, respectively, the relative humidity calculated onsite using a sling psychrometer and the tower efflux velocity. Interspaced in the table are the wind direction/speed from the top of the water tower, the plume efflux temperatures of designated cells on Tower B, on-site temperatures and a few relevant comments.

TABLE A-1. CLIFFSIDE PLUME DATA

Date Oct/Nov	Coordinates of Balloon Sightings X	Y	Z	Run Time (sec)	In Plume = 1	Mean Temp (°C)	Mean Humidity (%)	Max Humidity (%)	Min Humidity (%)	Actual Time	Start Run = 1	Wind Dir. (deg)	Wind Speed (m/sec)	MRI Temp (°C)	Ambient Humidity (%)	Efflux Vel. (m/sec)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
30	100	110	45	3	1	19.2	20	46	16		1	010	3.0	18.3		
	125	32	48	102	1	19.9	56	58	54							
	177	4	66	145	1	20.2	18	33	15							
	260	30	39	187	1	20.7	17	24	15	1424						
	166	61	141	13	0	18.6	16	16	16	1430	1	350	3.0	18.3		
	155	29	114	83	0	18.6	16	16	16							
	136	7	61	170	1	19.2	18	26	16							
	140	4	27	230	1	20.8	40	65	20							
	137	-22	2	241	1	21.1	36	38	35							
	-277	234	382	84	0	17.6	16	16	16	1530	1	350	3.0	18.0		
	163	17	54	148	1	18.8	20	38	15							
	135	0	48	179	1	19.4	35	50	18							
	128	-15	39	239	1	19.4	26	62	20							
	128	-23	2	270	1	19.0	22	32	18							
	202	93	103	0	0	16.2	17	17	17	1540	1	340	3.4	17.3		
	202	62	95	52	1	16.2	20	47	15							
	196	48	78	81	0	16.0	15	15	15							
	201	25	66	126	1	16.6	28	42	15							
31				WATER TOWER WIND 280/MISSING												
31	182	-11	101	4	0	16.7	17	17	17	1405	1	030	2.0	13.3		
	186	-52	48	97	0	14.5	18	18	18							
				WATER TOWER WIND 325/MISSING												
	174	-76	106	15	0	13.5	17	17	17	1445	1	060	1.8	13.3		
	131	-104	180	90	1	14.4	20	37	17							
	278	-368	265	145	1	14.4	19	33	17							
	139	-72	25	185	1	16.3	22	38	17							
	131	-67	0	210	1	16.6	25	32	21							

TABLE A-1. (continued)

Date Oct/Nov	Coordinates of Balloon Sightings (X)	(Y)	(Z)	Run Time (sec)	In Plume = 1	Mean Temp (°C)	Mean Humidity (%)	Max Humidity (%)	Min Humidity (%)	Actual Time	Start Run = 1	Wind Dir. (deg)	Wind Speed (m/sec)	MRI Temp (°C)	Ambient Humidity (%)	Efflux Vel. (m/sec)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
				WATER TOWER WIND 355/MISSING												
	142	-85	22	32	1	15.5	33	47	20		1	030	1.9	13.3		
	118	0	-25	145	0	13.7	17	17	17							
	176	-67	138	145	0	13.7	17	17	17							
	216	-122	146	187	1	14.5	17	23	15							
	241	-148	180	221	0	13.3	17	17	17							
	200	-119	176	268	0	13.0	17	17	17							
	267	-172	190	306	0	12.7	17	17	17	1455						
1				1010 CELLS 2,3,5,9: 27, 27, 28, 28 DEG												
				WATER TOWER WIND 010/MISSING												
1	-101	-222	168	0	0	13.3	42	42	42	1445	1	180	2.6	18.0		
	-82	-212	155	50	0	13.1	42	42	42							
	-20	-203	152	106	1	13.5	42	49	40							
	-24	-168	128	151	1	12.7	64	75	55							
	-13	-158	118	188	1	13.2	58	63	55							
				WATER TOWER WIND 060/MISSING												
3	-140	-59	168	52	1	13.5	69	72	66	1035	1	190	1.8	15.2	64	10.6
	-125	-47	141	101	1	13.6	72	74	69							
	-104	-109	82	188	1	14.0	67	69	66							
				WATER TOWER WIND 045/MISSING												
	-157	-53	247	82	1	12.9	68	73	66	1045	1	220	1.8	15.7		
	-119	-56	204	136	1	13.6	66	71	65							
	-111	-29	169	184	1	13.8	69	71	68							
	-110	-60	128	221	1	14.3	68	71	67							
	-97	-55	102	259	1	14.6	66	73	64							
				WATER TOWER WIND 050/MISSING												
	-74	-96	195	136	0	16.5	63	64	63	1050	1	240	1.8	16.2		
	-147	-97	254	192	1	16.0	65	66	64							
	-193	-128	205	247	1	14.8	68	72	66							
				WATER TOWER WIND VRB/MISSING												
	-149	-47	285	0	1	13.8	67	72	64	1055	1	270	1.7	16.9		
	-126	-10	292	275	1	14.2	65	68	65							

PIBAL 0

TABLE A-1. (continued)

Date Oct/Nov	Coordinates of Balloon Sightings (X)	(Y)	(Z)	Run Time (sec)	In Plume = 1	Mean Temp (°C)	Mean Humidity (%)	Max Humidity (%)	Min Humidity (%)	Actual Time	Start Run = 1	Wind Dir. (deg)	Wind Speed (m/sec)	MRI Temp (°C)	Ambient Humidity (%)	Efflux Vel. (m/sec)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
				WATER TOWER WIND VRB/MISSING												
	-230	-75	390	194	0	14.2	61	61	60	1110	1	270	1.1	18.3		
	-249	-33	402	246	0	14.1	61	61	59							
	-282	-16	407	308	0	14.3	58	58	58							
	-235	-6	401	378	1	14.0	61	61	60							
	-182	-28	355	438	1	14.0	63	64	62							
	-184	-42	291	483	0	14.7	64	64	64							
	-124	-7	257	526	1	15.0	67	72	64							
				WATER TOWER WIND VRB/MISSING												
	-212	-134	388	44	1	14.7	66	71	64	1125	1	280	1.5	19.0		
				BEGIN TIME APPROX. THEO. RELEVELED												
	-163	-179	391	191	0	15.2	64	64	64							
	-174	-145	368	256	0	15.6	64	64	64							
	-215	-69	340	318	1	15.7	64	66	64							
	-72	-45	359	375	1	15.5	65	72	59							
	-476	-100	610	456	0	15.9	63	63	63							
				WATER TOWER WIND 040/MISSING												
	-167	-112	410	0	1	15.2	68	68	68	1148	1	190	1.5	20.6		
	-83	-150	396	84	1	15.0	66	67	65							
	-55	-134	377	140	1	15.6	65	67	63							
	-35	-133	344	173	0	17.9	58	60	57							
	-167	-510	526	221	0	18.8	56	58	55							
	-101	-79	294	270	1	16.5	66	69	64							
	-96	-73	250	313	1	16.9	68	74	64							
	-98	-26	180	455	1	17.1	63	66	61							
				WATER TOWER WIND 045/MISSING												
				ON SITE TEMP 24.2												
	-39	-194	283	406	1	20.9	58	59	58	1349	1	230	1.3	24.0	39	
	-55	-204	275	468	1	21.9	57	58	57							
	-82	-103	265	529	1	20.8	58	61	57							
	-70	-128	234	574	0	19.7	59	60	59							
	-22	-182	164	633	1	21.2	56	58	56							
	-21	-93	155	678	0	21.6	56	56	56							
	-64	-94	97	747	1	22.1	58	61	56							

TABLE A-1. (continued)

Date Oct/Nov	Coordinates of Balloon (X Y Z)			Run Time (sec)	In Plume = 1	Mean Temp (°C)	Mean Humidity (%)	Max Humidity (%)	Min Humidity (%)	Actual Time	Start Run = 1	Wind Dir. (deg)	Wind Speed (m/sec)	MRI Temp (°C)	Ambient Humidity (%)	Efflux Vel. (m/sec)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
				WATER TOWER WIND 345/MISSING												
	17	-101	81	29	0	21.4	55	56	55	1357	1	220	1.3	24.5		
	-17	-150	115	82	0	24.0	55	56	55							
	-20	-167	166	127	0	24.7	55	56	55							
	-33	-177	196	161	0	24.2	55	56	55							
	-65	-221	250	204	0	22.4	56	56	56							
	-99	-229	264	248	0	20.7	57	57	57							
	-234	-554	446	297	0	20.0	57	57	57							
				1430 CELLS 1-9: 26.0,26.0,25.4,25.7,26.4,26.4,26.0, 26.0,26.0												
				WATER TOWER WIND 350/MISSING												
	-55	-180	235	123	0	20.7	55	55	55	1425	1	170	1.3	25.2		
	-99	-254	286	195	0	20.8	55	55	55							
	-193	-441	392	229	0	21.2	55	55	55							
	-81	-180	255	269	0	21.4	56	56	56							
	-84	-212	215	303	0	21.5	55	55	55							
	-41	-116	191	347	1	21.7	55	56	55							
	-55	-187	179	381	0	22.2	54	54	54							
	-66	-157	150	413	0	22.0	55	55	55							
	-57	-159	124	462	1	22.0	57	61	56							
	-57	-151	100	498	1	22.0	58	64	56							
	-49	-88	73	539	1	21.9	59	66	55							
	-36	-79	42	592	1	22.0	64	69	56							
	-75	-67	42	670	1	22.0	58	62	56							
				WATER TOWER WIND 350/MISSING												
	-142	-159	230	89	1	18.7	59	61	58	1510	1	180	1.2	24.5		10.6
	-173	-120	263	147	1	19.5	58	59	58							
	-122	-48	197	229	1	18.8	58	59	58							
	-213	-127	324	292	0	18.6	58	58	58							
	-96	-73	333	360	0	18.2	58	58	58							
	-72	-113	254	422	0	19.2	57	57	57							
	-51	-49	212	485	0	20.0	56	56	56							
	-41	-30	161	554	0	21.2	56	56	56							
	-37	-49	109	598	0	21.7	55	55	55							
	-23	-10	85	632	0	22.0	55	55	55							
	-31	-17	75	684	1	22.7	63	66	60							
4				1015 REL HUM 54, ON SITE TEMP 21.0												

TABLE A-1 (continued)

Date Oct/Nov	Coordinates of Balloon Sightings (X)	(Y)	(Z)	Run Time (sec)	In Plume = 1	Mean Temp (°C)	Mean Humidity (%)	Max Humidity (%)	Min Humidity (%)	Actual Time	Start Run = 1	Wind Dir. (deg)	Wind Speed (m/sec)	MRI Temp (°C)	Ambient Humidity (%)	Efflux Vel. (m/sec)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	1030	CELLS 1-9:		25.0,26.0,26.5,26.0,27.0,27.0,26.0,26.0,27.0												
4	20	146	29	77	0	20.7	55	55	55	1100	1	210	1.2	23.0		10.6
	24	123	58	127	0	20.1	55	55	55							
	17	105	76	177	0	20.0	55	55	55							
	10	87	118	267	0	20.1	55	55	55							
	-11	76	145	315	0	20.0	55	55	55							
	-118	40	168	382	0	20.7	55	55	55							
	-148	9	159	429	1	20.7	57	58	57							
	-116	26	372	716	1	17.9	64	67	62							
	-134	29	380	756	0	17.6	61	61	60							
	-136	22	375	795	0	17.5	59	59	59							
	-155	11	328	834	1	17.5	60	62	59							
	-195	-78	286	898	0	18.7	58	58	58							
	-162	-131	286	991	0	19.4	57	57	57							
	-125	-105	333	1056	0	18.7	58	58	58							
	-104	-73	417	1142	0	17.9	59	59	59							
	-60	-99	360	1278	1	18.1	60	61	60							
	-55	-110	351	1413	1	18.1	59	62	58							
	-41	-207	290	1480	1	18.5	57	59	56							
	-86	-195	260	1537	0	19.0	56	57	56							
	-113	-149	258	1619	0	18.5	57	57	57							
	-167	-106	256	1714	1	18.7	58	61	56							
	-193	-72	263	1839	0	19.0	56	56	56							
	-219	-18	267	1981	0	19.5	55	55	55							
	-99	-35	317	2050	1	19.0	58	60	56							
	-199	74	178	382	0	20.7	55	55	55	1135	1	250	1.2	23.3		
				TIME	APPROX											
	-222	-8	175	494	1	20.7	56	60	54							
	-178	-34	226	547	1	20.7	56	59	55							
	16	-31	293	618	1	18.8	56	58	55							
	-34	-30	348	736	1	18.6	60	63	57							
	27	166	4	868	0	17.5	58	58	56	1150						
	-155	44	323	940	0	18.4	57	57	57							
	-206	-46	245	1039	0	20.9	54	54	54							
	-170	-53	254	1095	1	20.1	56	57	55							
	-14	-20	302	1155	1	18.9	58	61	57							
	23	-6	280	1245	0	19.3	57	57	57							
	4	-42	274	1297	1	19.9	60	58	57							
	-47	-78	362	1347	1	19.8	58	60	57							
	-96	-12	444	1426	0	18.2	59	59	59							

TABLE A-1. (continued)

Date Oct/Nov	Coordinates of Balloon Sightings (X)	(Y)	(Z)	Run Time (sec)	In Plume = 1	Mean Temp (°C)	Mean Humidity (%)	Max Humidity (%)	Min Humidity (%)	Actual Time	Start Run = 1	Wind Dir. (deg)	Wind Speed (m/sec)	MRI Temp (°C)	Ambient Humidity (%)	Efflux Vel. (m/sec)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
PIBAL 1																
				1300 ON SITE TEMP 26.1												
				WATER TOWER WIND 230/2.9												
				1230 CELLS 1, 2,5,9: 26.2, 27.0, 28.0, 28.0												
	155	237	87	107	1	20.8	55	57	54	1314	1	300	.9	25.2	41	
	130	173	102	156	1	21.2	56	56	56							
	107	81	89	212	0	21.4	55	55	55							
	89	30	73	252	0	21.7	55	55	55							
	98	2	45	286	1	21.9	55	57	55							
	115	-20	26	317	0	22.3	55	55	55	1320						
				WATER TOWER WIND 225/1.1												
				WATER TOWER WIND 195/2.2												
	63	133	125	54	0	22.8	55	55	55	1322	1	300	.9	25.2		
				TIME APPROX												
	57	229	172	910	0	22.8	56	56	56							
	69	283	140	147	0	22.5	54	54	54							
				WATER TOWER WIND 315/1.3												
	340	-55	221	6	0	22.7	51	51	51	1403	1	360	1.0	26.1		
	179	48	322	85	0	21.1	55	56	55							
	445	-23	255	283	0	21.2	53	53	53							
	451	-36	258	342	0	21.8	52	52	52							
	489	-40	269	388	0	21.9	53	53	53							
	513	-33	290	438	0	21.9	53	53	53							
	519	-11	207	493	0	22.4	54	54	54							
	589	-27	304	616	0	21.2	55	55	54							
	510	-2	419	716	0	20.8	54	54	54							
	253	-11	250	799	0	21.4	54	55	54							
	214	-17	222	848	0	21.7	54	54	54							
PIBAL 2																
				WATER TOWER WIND 360/1.6												
	218	-235	224	30	1	22.6	54	56	53	1445	1	090	1.0	26.1		
				TIME APPROX												

TABLE A-1. (continued)

Date Oct/Nov	Coordinates of Balloon Sightings (X Y Z)	Run Time (sec)	In Plume = 1	Mean Temp (°C)	Mean Humidity (%)	Max Humidity (%)	Min Humidity (%)	Actual Time	Start Run = 1	Wind Dir. (deg)	Wind Speed (m/sec)	MRI Temp (°C)	Ambient Humidity (%)	Efflux Vel.(m/sec)
1	2 3 4	5	6	7	8	9	10	11	12	13	14	15	16	17
	235-228 239	229	1	22.3	52	56	51							
	202-241 290	370	0	22.2	55	55	54							
	223-273 222	408	0	22.5	51	52	50							
	244-301 173	462	1	22.7	53	56	51							
	109-157 346	531	1	21.0	55	58	53							
	143-232 384	567	0	21.7	54	55	54							
	134-257 361	660	1	22.6	52	59	51							
	135-262 352	702	0	22.3	51	52	51							
	169-354 324	762	0	23.5	52	52	52							
	158-309 386	847	0	22.2	51	51	51							
	171-340 369	894	0	22.5	51	51	51							
	135-221 410	939	1	20.7	58	60	55							
	150-210 384	982	1	20.7	56	57	54							
	127-303 445	1016	1	20.7	56	57	56							
	150-352 459	1062	0	20.6	54	55	54							
	154-421 485	1102	0	20.2	55	56	55							
	171-446 490	1141	1	20.7	55	56	54							
	164-387 607	1175	0	20.7	54	54	53							
	136-341 411	1258	0	21.0	54	54	54							
	146-339 374	1295	0	20.7	54	54	54							
	127-331 293	1356	1	21.4	59	65	54							
	95-306 284	1389	1	21.5	57	58	56							
	73-297 238	1431	1	21.8	58	62	57							
	84-217 262	1481	1	21.2	59	66	56							
	138-167 210	1533	1	21.5	55	58	54							
	114-111 193	1591	0	21.7	54	54	54							
	270-266 247	1640	1	22.0	61	63	56							
		WATER TOWER WIND 345/2.2												
	278-158 196	1686	1	27.2	62	63	60	1514	1	80	.9	25.2		
	394-390 402	7	1	18.7	59	60	58							
	813 -01326	51	1	18.8	57	58	56							
	314-320 486	81	0	19.3	55	56	55							
	299-291 361	118	0	20.2	54	54	54							
	240-232 242	154	0	20.7	55	55	55							
	214-199 182	190	0	21.1	55	55	55							
	210-179 149	236	1	21.2	57	61	55							

TABLE A-1. (continued)

Date Oct/Nov	Coordinates of Balloon Sightings (X Y Z)	Run Time (sec)	In Plume = 1	Mean Temp (°C)	Mean Humidity (%)	Max Humidity (%)	Min Humidity (%)	Actual Time	Start Run = 1	Wind Dir. (deg)	Wind Speed (m/sec)	MRI Temp (°C)	Ambient Humidity (%)	Efflux Vel.(m/sec)
1	2 3 4	5	6	7	8	9	10	11	12	13	14	15	16	17
	220-221 211	270	1	21.1	57	63	55							
	207-202 216	303	1	21.1	58	67	55							
	160-194 234	347	1	21.5	56	58	55							
	152-204 198	385	0	22.8	52	52	52							
	184-136 137	427	0	23.9	52	52	52							
	244-284 147	470	6	24.0	50	51	49							
	228-276 213	521	0	24.7	51	51	51							
	160-217 292	596	1	22.7	52	55	50							
	186-279 298	630	0	23.1	51	51	51							
	207-325 326	662	0	23.3	50	50	50							
	239-365 377	708	0	23.6	51	51	51							
	232-395 332	744	0	24.6	50	50	50							
	241-389 345	781	0	22.8	51	51	51							
	222-391 333	815	0	22.7	51	51	51							
	169-349 298	859	0	23.2	50	50	50							
	163-347 260	897	0	23.8	50	50	50							
	157-318 236	931	0	23.4	50	50	50							
	140-285 229	965	0	23.0	51	51	51							
	134-258 225	994	0	22.9	51	51	51							
	130-239 185	1037	1	23.6	51	54	50	1535						
		WATER TOWER WIND 310/2.5												
		WATER TOWER WIND 025/2.2												
	217 -0 741	31	1	21.7	55	59	53	1540	1	120	.9	24.7		
	72-196 232	92	1	21.7	58	64	54							
	78-212 224	130	1	21.8	58	65	55							
	74-230 239	162	1	21.6	56	65	55							
	82-242 235	207	0	21.2	54	54	54							
	72-284 204	275	1	20.7	56	54	57							
	51-283 205	338	1	22.0	55	61	53							
	55-286 175	404	1	22.8	55	55	54							
	54-189 219	469	1	21.6	59	61	55							
	87-276 218	523	1	21.9	55	56	54							
	70-224 243	566	1	21.2	55	58	55							

TABLE A-1. (continued)

Date Oct/Nov	Coordinates of Balloon Sightings (X)	(Y)	(Z)	Run Time (sec)	In Plume = 1	Mean Temp (°C)	Mean Humidity (%)	Max Humidity (%)	Min Humidity (%)	Actual Time	Start Run = 1	Wind Dir. (deg)	Wind Speed (m/sec)	MRI Temp (°C)	Ambient Humidity (%)	Efflux Vel. (m/sec)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	98	-273	154	40	1	21.9	59	64	56		1	080	.9	24.1		
	76	-204	144	182	0	21.7	54	54	54							
	86	-195	119	139	1	22.0	56	59	54							
	83	-195	86	207	1	22.2	59	60	57							
	88	-128	88	267	1	22.2	59	61	58							
	131	-167	91	389	1	22.0	66	67	65							
5	0930 REL HUM 70. HYGRISTOR CALIBRATED TO SLING PSYCHROMETER															
				WATER TOWER WIND 025/2.7												
5	-30	-27	248	265	1	12.5	73	74	72	1027	1	270	.7	20.5		10.5
	1	33	205	324	1	12.3	75	80	72							
	33	34	240	374	1	12.4	74	77	71							
	-61	-1	262	427	1	12.3	83	86	81							
	-71	-21	257	468	1	12.8	80	83	76							
	-106	-7	229	516	1	12.8	77	77	76							
	-145	5	203	589	0	13.5	71	71	71							
	-142	65	184	663	0	13.8	77	77	76							
	-111	128	155	768	0	14.3	69	69	69							
	-124	145	103	858	0	14.3	69	69	69							
	-78	124	53	917	0	13.2	71	71	71							
	-27	89	68	1020	0	13.3	71	71	71							
	33	56	150	28	1	12.6	68	70	68	1042	1	360	1.1	22.2		
	19	49	153	74	1	13.4	71	74	68							
	20	64	215	133	1	13.3	68	72	67							
	-48	71	258	209	1	13.3	76	78	75							
	-8	80	244	273	1	13.0	77	83	73							
	-23	103	245	317	1	12.7	77	79	76							
	-20	121	227	366	1	12.9	74	75	72							
	-1	132	324	404	0	13.2	72	72	72							
	66	155	176	481	0	13.6	70	70	70							
	69	154	268	542	0	13.8	68	68	68							
	27	166	4	33	0	16.0	62	63	61	1054	1	030	1.0	24.1		
	36	98	172	116	0	21.4	59	59	59							
	16	78	167	170	0	21.7	60	60	60							

TABLE A-1. (continued)

Date Oct/Nov	Coordinates of Balloon Sightings X	Y	Z	Run Time (sec)	In Plume = 1	Mean Temp (°C)	Mean Humidity (%)	Max Humidity (%)	Min Humidity (%)	Actual Time	Start Run = 1	Wind Dir. (deg)	Wind Speed (m/sec)	MRI Temp (°C)	Ambient Humidity (%)	Efflux Vel.(m/sec)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	-63	26	185	225	1	17.5	65	67	63							
	-14	53	167	274	1	16.7	68	75	66							
	-23	-40	189	317	1	15.3	71	77	67							
	-31	20	169	370	1	14.8	73	78	71							
	7	-67	186	432	1	14.8	65	68	63							
	38	-57	178	515	1	15.8	65	71	62							
	-7	-31	191	571	1	15.2	69	72	66							
	-26	-9	186	642	1	15.1	66	69	65							
	-9	6	190	683	1	15.5	70	75	67							
	26	41	192	723	1	15.8	65	68	64							
	30	48	169	784	1	15.9	64	69	63							
	4	63	179	824	0	15.7	64	64	64							
	11	46	156	861	1	15.0	66	75	65							
	12	24	143	900	1	16.3	65	68	63							
PIBAL 3																
				1230	CELLS 7, 9: 31.0, 31.0											
	-90	-32	33	2	0	23.6	59	59	59	1242	1	030	1.4	26.8	42	
	-86	-68	41	32	0	23.5	59	59	59							
	-72	-67	57	82	0	24.5	59	59	59							
	-73	-53	72	132	0	24.5	59	59	59							
	-33	-58	61	169	0	23.8	59	59	59							
	1	-80	64	205	0	24.8	58	58	58							
	1	-73	74	245	0	24.6	58	58	58							
	12	-74	62	276	0	23.6	59	59	59							
	17	-72	72	309	1	23.8	60	64	59							
	28	-14	155	344	0	23.1	61	61	61							
	81	-8	155	402	1	21.1	60	64	59							
	37	48	113	448	0	21.4	59	59	59							
	27	44	116	510	0	21.3	60	61	59							
	6	9	104	562	0	18.4	63	63	63							
	27	12	80	630	0	19.3	62	62	62							
	8	-16	78	677	0	19.7	61	61	61							
	27	-48	82	754	1	19.0	61	63	60							
	42	-27	79	805	1	20.6	62	65	60							

TABLE A-1. (continued)

Date Oct/Nov	Coordinates of Balloon Sightings (X)	(Y)	(Z)	Run Time (sec)	In Plume = 1	Mean Temp (°C)	Mean Humidity (%)	Max Humidity (%)	Min Humidity (%)	Actual Time	Start Run = 1	Wind Dir. (deg)	Wind Speed (m/sec)	MRI Temp (°C)	Ambient Humidity (%)	Efflux Vel. (m/sec)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	26	16	56	79	0	18.7	63	63	63	1300	1	360	1.2	26.8		
	-8	10	34	142	0	18.6	63	64	62							
	-2	7	24	199	1	21.5	64	69	61							
	-10	8	45	248	1	21.5	63	67	61							
	20	14	93	304	1	20.7	64	71	62							
	58	10	118	339	0	18.9	61	62	61							
	77	5	122	376	1	20.1	61	61	60							
	72	-3	99	411	1	21.5	61	63	60							
	90	-8	71	444	1	21.3	61	62	60							
	38	-23	89	495	0	21.6	60	60	60							
	43	-41	98	573	0	22.2	60	60	60							
	48	-14	95	624	1	21.7	60	65	60							
	45	-9	77	660	1	21.9	63	68	60							
	18	-8	76	709	1	23.0	61	62	60							
	10	-22	111	752	0	22.0	60	60	60							
	64	-21	129	797	0	20.5	60	60	60							
	73	-13	132	835	0	20.9	60	60	60							
	69	-14	159	891	0	20.5	60	60	60							
	14	-3	134	936	0	20.5	60	60	60							
	65	6	103	972	0	19.8	60	60	60							
	17	19	96	1010	0	19.8	61	61	61							
	16	26	79	1049	0	19.1	62	62	62							
	46	39	68	1208	0	19.0	63	63	63							
	74	20	67	8	0	18.7	63	63	63	1322	1	070	1.5	27.2		
	14	-11	107	66	1	18.8	64	72	62							
	50	-26	135	113	1	18.3	63	67	61							
	94	-37	77	151	1	20.8	63	65	62							
	70	-37	104	217	1	20.1	63	67	61							
	45	-38	106	309	0	20.5	61	61	61							
	63	-35	104	362	1	20.2	62	65	61							
	73	-25	78	407	1	20.7	65	71	62							
	32	-11	79	446	1	19.3	65	76	62							
	11	-6	88	486	1	19.0	64	68	62							
	40	5	65	539	1	20.6	65	72	61							
	45	12	89	560	1	20.8	67	73	64							

TABLE A-1. (continued)

Date Oct/Nov	Coordinates of Balloon Sightings X	Y	Z	Run Time (sec)	In Plume = 1	Mean Temp (°C)	Mean Humidity (%)	Max Humidity (%)	Min Humidity (%)	Actual Time	Start Run = 1	Wind Dir. (deg)	Wind Speed (m/sec)	MRI Temp (°C)	Ambient Humidity (%)	Efflux Vel. (m/sec)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	139	61	234	11	1	17.8	64	66	64	1335	1	045	1.2	27.2		
	101	-26	158	48	1	17.8	63	65	63							
	31	-36	154	116	0	17.9	62	63	62							
	-3	-74	150	172	1	18.2	65	72	63							
	17	-104	124	217	1	19.8	63	66	60							
	-14	-49	212	247	0	21.2	62	62	61							
	30	-74	196	285	1	20.7	64	69	61							
	75	-93	177	323	1	21.1	62	64	61							
	105	-55	164	362	0	21.6	60	60	60							
	101	-41	134	393	0	21.8	60	60	60							
	81	-42	98	440	0	21.2	60	60	60							
	49	13	93	481	1	22.1	61	65	59							
	41	15	85	562	0	21.8	60	60	60							
	35	5	95	614	0	20.5	62	62	62							
	6	-7	110	652	1	18.7	67	73	62							
	40	-16	89	705	0	19.1	62	62	62							
	43	-5	111	747	1	21.2	62	66	60							
	65	6	85	824	1	19.7	62	65	62							
	41	4	60	889	0	18.0	63	63	63							
	23	3	63	910	1	17.6	65	72	62							
				1403	ON SITE	TEMP	29.0									
	-35	-81	58	181	1	24.2	64	66	62		1	360	1.4	27.2	42	
	-4	-67	73	260	1	22.0	63	65	62							
	-12	-53	89	314	0	23.8	63	63	63							
	14	-89	61	362	1	23.0	64	66	63							
	11	-70	77	403	0	22.3	63	63	63							
	12	-33	81	449	0	22.9	63	63	63							
	18	-8	75	486	0	23.0	63	63	63							
	44	2	51	531	0	22.9	63	63	63							
	45	21	45	579	0	21.8	63	63	63							
	31	28	48	611	1	21.6	64	72	63							
	23	34	29	637	1	22.0	65	67	63							
	65	7	33	692	0	20.7	65	65	65	1425						

TABLE A-1. (continued)

Date Oct/Nov	Coordinates of Balloon Sightings X	Y	Z	Run Time (sec)	In Plume = 1	Mean Temp (°C)	Mean Humidity (%)	Max Humidity (%)	Min Humidity (%)	Actual Time	Start Run = 1	Wind Dir. (deg)	Wind Speed (m/sec)	MRI Temp (°C)	Ambient Humidity (%)	Efflux Vel. (m/sec)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	17	-75	85	16	0	22.0	61	61	61	1439	1	030	1.2	28.0		
	-24	-5	102	72	0	23.3	61	61	61							
	27	20	83	134	1	21.5	64	70	61							
	16	-42	172	177	0	22.0	61	61	61							
	-13	-46	85	208	1	22.7	63	65	61							
	-6	-24	84	239	0	22.5	61	61	61							
	26	-40	78	277	0	22.2	61	61	61							
	18	-57	53	320	1	21.3	61	64	61							
	-3	-49	52	349	1	21.3	62	65	61							
	-1	-44	47	387	1	21.7	61	65	61							
	-10	-35	38	430	1	21.7	61	66	61							
	-9	-28	40	469	1	22.3	61	63	61							
	16	-26	34	512	1	22.2	65	71	61							
	9	-17	44	546	1	22.3	64	71	61							
	29	-21	61	592	1	22.0	65	72	61							
	33	-13	88	626	1	21.8	65	72	61							
	39	-6	72	664	1	21.5	63	69	62							
	26	-10	94	749	0	20.6	62	62	62							
	42	-5	73	796	0	19.9	63	63	63							
	40	-9	84	857	1	19.9	64	68	62							
	53	-10	90	909	1	19.6	64	68	62							
	52	-8	78	944	1	20.0	62	64	62							
	44	-0	81	976	0	19.8	62	62	62							
	45	4	69	1011	1	19.8	63	68	62							
	45	8	55	1044	1	20.6	65	69	62							
	34	6	45	1078	1	20.0	67	72	63							
	29	2	50	1116	1	19.9	65	71	63							
	14	9	61	9999	0	19.6	64	64	64							
	149	-66	197	166	1	22.9	65	69	64	1535	1	050	1.5	27.3		
	155	-70	174	220	0	18.0	64	64	64							
	140	-109	249	280	0	19.6	61	61	61							
	154	-112	212	415	0	19.0	62	62	62							
	143	-124	204	454	0	19.5	61	61	61							
	128	-115	201	495	0	20.7	61	61	61							
	131	-120	180	527	0	21.2	61	61	61							
	121	-89	215	600	0	20.5	61	61	61							
	114	-108	202	666	0	19.5	61	61	61							
	136	-116	203	744	1	20.2	62	63	62							

TABLE A-1. (continued)

Date Oct/Nov	Coordinates of Balloon X	Y	Z	Sightings	Run Time (sec)	In Plume = 1	Mean Temp (°C)	Mean Humidity (%)	Max Humidity (%)	Min Humidity (%)	Actual Time	Start Run = 1	Wind Dir. (deg)	Wind Speed (m/sec)	MRI Temp (°C)	Ambient Humidity (%)	Efflux Vel. (m/sec)
1	2	3	4		5	6	7	8	9	10	11	12	13	14	15	16	17
	94	-166		220	33	1	19.7	63	65	62	1549	1	030	1.1	26.8		
	94	-215		167	79	0	20.0	62	62	62							
	93	-205		222	131	1	19.0	64	66	63							
	87	-206		162	168	1	19.2	63	65	62							
	60	-197		151	202	1	19.5	63	65	62							
	60	-192		133	243	1	19.2	63	66	63							
	40	-133		182	292	0	18.8	63	63	63							
	49	-136		151	337	1	18.6	64	67	63							
	63	-89		176	389	1	18.5	64	68	64							
	87	-82		154	441	1	18.5	67	71	64							
	129	-71		133	494	1	18.2	66	71	64							
	122	-62		139	536	0	18.1	64	64	64							
	122	-50		151	645	0	17.7	64	64	64							
	124	-77		99	752	1	17.9	64	67	64							
	121	-76		101	799	1	18.0	65	68	64							
	110	-77		108	838	1	18.1	70	73	64							
	57	-109		159	890	1	17.7	67	73	64							
6					1110	ON SITE TEMP 25.6, REL HUM 54											
6	93	-88		197	617	1	18.0	62	63	59	1145	1	045	1.2	25.6		
	-6	-158		187	696	1	17.4	63	65	61							
	182	-154		246	27	1	17.3	60	61	59		1	060	2.5	25.6		
	131	-102		171	117	1	17.5	60	61	59							
	121	-62		136	181	1	18.3	58	64	58							
	101	-74		116	242	1	18.9	59	62	58							
	61	-48		74	535	1	19.6	61	68	56							
	-13	-61		72	591	1	19.9	60	64	58							
	111	3		155	760	1	19.2	57	59	56	1213						
					1237	ON SITE TEMP 26.5, REL HUM 47											
	-27	-113		163	330	1	17.9	61	70	59		1	130	1.9	25.7		
	-30	-107		176	406	0	17.5	61	61	61							
	-16	-143		149	444	0	17.5	60	60	60							
	2	-174		86	498	1	18.3	61	63	60							
	-18	-60		184	556	1	18.1	61	66	59							

TABLE A-1. (concluded)

Date Oct/Nov	Coordinates of Balloon Sightings X	Y	Z	Run Time (sec)	In Plume = 1	Mean Temp (°C)	Mean Humidity (%)	Max Humidity (%)	Min Humidity (%)	Actual Time	Start Run = 1	Wind Dir. (deg)	Wind Speed (m/sec)	MRI Temp (°C)	Ambient Humidity (%)	Efflux Vel. (m/sec)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	52	-77	169	609	0	19.1	63	64	62							
	83	-77	185	647	0	18.7	57	57	57							
	95	-104	171	740	0	18.3	57	57	57							
	75	-95	192	788	0	17.9	58	58	58							
	81	-133	194	834	0	17.3	58	58	58							
	74	-146	189	884	0	17.4	59	59	59							
	68	-169	199	930	0	17.3	59	59	59	1250						
	17	-206	215	4	0	17.7	63	63	63	1252	1	100	1.7	25.7		
	17	-206	194	128	1	17.1	64	68	62							
	53	-209	173	172	0	17.2	61	61	61							
	53	-221	162	239	0	17.1	61	61	61							
	63	-116	218	284	0	16.7	61	61	61							
	56	-101	222	334	0	16.5	61	61	61							
	80	-129	196	371	0	16.6	61	61	61							
	67	-124	185	409	0	16.4	62	62	62							
	38	-64	225	451	0	16.5	62	62	62							
	57	-128	158	494	0	16.6	62	62	62							
	53	-127	140	533	0	16.6	62	62	62							
	53	-102	141	568	0	16.8	62	62	62							
	49	-107	128	616	1	17.0	64	75	62							
	43	-122	110	655	1	16.4	65	73	63							
	3	-103	167	719	0	16.3	63	63	63							
	25	-108	159	798	0	16.3	63	63	63							
	-16	-71	193	875	0	16.2	63	63	63							
	89	-99	153	921	0	16.0	64	64	64							
	91	-79	180	960	0	16.0	64	64	64							
	101	-87	168	1014	0	16.0	63	63	63							
	106	-89	160	1082	0	16.2	63	63	63							
	129	-76	124	1136	0	16.5	62	62	62							
	127	-89	120	1225	1	16.3	63	65	63							
	45	-182	157	1296	0	16.4	62	62	62							
	10	-98	191	1371	0	16.6	61	61	60							
	64	-51	197	1437	0	16.4	62	62	62							
	60	-10	215	1470	0	16.6	61	61	60							
	38	-37	218	1518	0	17.3	58	59	58							
	53	-86	200	1561	0	18.0	58	58	58							

1445 TOWER EXIT VELOCITY 35.0
1330 CELLS 1, 2, 7, 9: 29.0, 30.5, 31.0, 31.5

TABLE A-2. RELEASED BALLOON COORDINATES VERSUS TIME

Run Time (sec)	Coordinates of Balloon Sightings X	Y	Z
PIBAL 0			
30	11	180	46
90	139	168	131
150	-29	134	211
210	-149	42	277
240	-189	2	252
270	-417	-91	395
300	-584	-128	455
330	-749	-141	489
PIBAL 1			
15	25	185	37
60	53	223	166
90	102	256	300
120	91	253	374
150	79	234	432
180	50	250	546
210	64	278	725
240	82	343	884
270	82	414	981
300	98	416	934
PIBAL 2			
30	130	-102	27
60	142	-159	45
90	190	-212	95
120	221	-256	127
150	253	-331	160
180	269	-404	199
PIBAL 3			
30	2	164	35
90	-24	155	90
120	-26	159	136
150	-14	161	161
180	13	148	185
210	32	176	238

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

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		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Lawrence D. Winiarski and Walter F. Frick		8. PERFORMING ORGANIZATION REPORT NO.
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16. ABSTRACT

Tethered Kitoon (small blimp) sampling techniques were devised to measure the distribution of temperature and humidity in the invisible portion of power plant cooling tower plumes from both single cell and multiple cell cooling towers under several conditions.

These measurements, together with data collected on the ambient meteorology and exit plume conditions, are particularly useful in moist plume modeling work.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
cooling towers, plumes plume computer programs plumes trajectories plumes cooling towers plumes, thermal analysis plumes, atmospheric diffusion		Field 14 group 13I+

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