EPA-600/7-78-059
April 1978

FIELD INVESTIGATION OF COOLING TOWER AND COOLING POND PLUMES

by

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Grant No. R802893

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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 plumes from a mechanical draft cooling tower and from a cooling pond.

A. F. Bartsch
Director, CERL

ABSTRACT

Measurements were made relating to the behavior of water-vapor plumes from forced-draft cooling towers and from cooling ponds. There were three categories of measurements. (1) Ambient weather data including temperature, humidity, wind speed and wind direction. These measurements were made with standard meteorological equipment. (2) Source data, including the temperature, mixing ratio and flowrate of the air leaving the cooling tower or cooling pond. Cooling-tower measurements were made with a traverse rig. Cooling-pond source data were estimated using correlations. (3) Water-vapor distribution in the atmosphere in the vicinity of the source, including temperature and mixing ratio of air above the ground at various locations with respect to source. These measurements were made with tethered-balloon-borne radio sondes.

Cooling-tower measurements were made at the Comanche Station of the Public Service Company of Colorado near Pueblo, Colorado. The Valmont Station of the Public Service Company of Colorado, near Boulder, Colorado was the site of the cooling-pond measurements.

The results are presented in graphical and tabular form. The reliability of the measured and calculated values is discussed. Cooling-tower results are not compared with predictive models. Cooling-pond results are compared with some methods of prediction. Significant features of cooling-tower and cooling-pond plumes are discussed.

This report was submitted in fulfillment of grant No. R802893 by University of Colorado under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from January 1974 to May 1975 and the data reduction was completed as of August 1976.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

MRI	-- Meteorological Research Incorporated
NCAR	-- National Center for Atmospheric Research
PSC	-- Public Service Company of Colorado

SYMBOLS

A	-- surface area of pond
C	-- psychrometric ratio, 0.47 mm Hg/°C
C_{pw}	-- heat capacity of water
$f(w)$	-- wind-speed function, defined in equation 13, in cal/m^2-s-mm Hg
H	-- humidity, g/m^3
h_a	-- specific enthalpy of air, j/kg dry air
H_a	-- absorbed sky radiation
H_b	-- back radiation
H_c	-- heat lost by convection and conduction
H_e	-- heat lost by evaporation
H_p	-- heat load added to pond
H_s	-- absorbed solar radiation
H_t	-- total surface heat exchange rate per unit surface area of pond
M	-- molecular weight of air
m_{da}	-- mass flowrate of dry air, kg/s
m_w	-- mass flowrate of water, kg/s
mr	-- mixing ratio, g water vapor/kg dry air
P	-- total pressure
p	-- partial pressure of water vapor
p^*_{sw}	-- vapor pressure of water in air saturated at wet-bulb temperature
R	-- universal gas constant
σ	-- Stephan-Boltzman constant
T	-- air dry-bulb temperature

T_{ref}	-- reference temperature, taken as 0°C
T_s	-- pond surface temperature
T_w	-- air wet-bulb temperature
T_{wa}	-- water temperature
u	-- wind speed, m/s

SUBSCRIPTS

in	-- refers to entering stream
out	-- refers to leaving stream

ACKNOWLEDGEMENTS

This project was conceived and initiated by M. D. Henderson and Dr. R. C. Johnson of the Department of Chemical Engineering, University of Colorado.

The U. S. Environmental Protection Agency sponsored the work. Dr. L. Winiarski of the Corvallis Environmental Research Laboratory was the Project Officer. His counsel and patience are much appreciated. Dr. B. Tichenor, W. E. Frick and Dr. Winiarski had major roles in the field study at Pueblo, Colorado. The sponsorship and assistance of the EPA is gratefully acknowledged.

The Public Service Company of Colorado (PSC) allowed the field studies to be made at their Valmont and Comanche Stations. They also made available pertinent data for these sites and plant operating conditions. George Greene and Dr. R. L. Pearson of PSC arranged for the on-site work. PSC personnel at Valmont and Comanche were most cooperative and helpful during the site studies. Dr. Loren Crow, Meteorology Consultant to PSC, supplied and reviewed Comanche weather data. Our great appreciation is hereby extended to PSC.

The National Center for Atmospheric Research (NCAR) loaned equipment for use in the field studies, trained University of Colorado personnel in equipment operation, and assisted in reduction of the Valmont data. Messrs. R. McBeth, D. Call and A. Morris were especially helpful. Without the assistance of NCAR, this work could not have been done.

Drs. R. C. Johnson and W. B. Krantz of the Chemical Engineering Department, University of Colorado, directed portions of this study. The field work was done by graduate student M. J. Gorman at Valmont and by former students Dr. J. W. Kaakinen, P. S. Stern and J. Frankel at Comanche.

SECTION 1

INTRODUCTION

The increasing use of electrical power has brought the United States into a period of rapid construction of new power-generating stations. The concern about requirements for environmental protection and the prediction of environmental impacts has heightened interest in the effects of projects such as power plants. All current-technology power plants dissipate more than half of the energy released from the fuel to a coolant, usually water, and thence to the surroundings. Most new power stations cool and recirculate the water to mitigate thermal pollution effects. The cooling devices in turn impact the environment. Most of the water-cooling systems discharge a large fraction of the heat by evaporation in the form of water vapor. This water vapor may condense in the atmosphere causing a plume which may be the most visible aspect of a power plant. The visible plume may touch the ground causing serious ground-fog problems. The water vapor and condensed water may affect local weather conditions.

There have been a number of efforts to model and predict the fate of water vapor from natural- and forced-draft cooling towers and from cooling ponds. The efficacy of a modeling effort cannot be judged without field data on plume behavior. There has not been, however, a corresponding effort to obtain field data on water-vapor dispersion around cooling ponds and forced-draft cooling towers. There have been a limited number of visual and photographic measurements of fog plumes from cooling systems, a few ground level water-vapor-concentration measurements, and some laboratory simulations of plume behavior. Somewhat more work has been done around natural-draft cooling towers. In this situation, there is a distinct need for data on water-vapor concentrations in cooling-tower and cooling-pond plumes.

The work described in this report is part of the U.S. Environmental Protection Agency program to obtain field data on the behavior of plumes from forced-draft-cooling towers and from cooling-ponds. The results presented should be useful for testing predictive models of this behavior.

SECTION 2

CONCLUSIONS

1. The data necessary to determine plume behavior from forced-draft cooling towers and from cooling ponds can be obtained with existing equipment. In particular, the tethered-balloon-mounted temperature, humidity, wind-speed and wind-direction radio sonde is an effective tool for obtaining water-vapor profiles at wind speeds of less than 10 m/s.

2. Characterization of water-vapor-emission rates is fairly difficult. This is especially true for cooling ponds where the emission rate must be estimated and no independent checks are available. A method was developed whereby water-vapor-efflux rates from a forced-draft cooling tower can be estimated from the plant power load once the tower characteristics have been determined.

3. A complete set of data for one day of operation of a cooling tower has been obtained and is presented. These data include: ambient conditions; water-vapor-efflux rates, temperatures and mixing ratios; and a number of water-vapor profiles at various locations with respect to the tower. Partial sets of data are presented for five other days.

4. Ambient data, estimated water evaporation and water-vapor profiles have been obtained and presented on portions of six days for a cooling pond.

5. Some significant features of cooling-tower and cooling-pond plumes which must be reflected in any models have been identified.

6. The results presented should be useful for testing plume-behavior models.

SECTION 3

RECOMMENDATIONS

As a result of this study the following are recommended:

1. Some modifications of the NCAR-type sonde are desirable for water-vapor-profile work. Continuous readings from the sensors, especially of temperature, would be useful. A simpler, more reliable humidity sensor is highly desired. Easier and more reliable methods of sonde-location measurement are needed.

2. Simultaneous, three-dimensional, water-vapor profiles should be obtained. This would require simultaneous flight of at least two and preferably three, balloons and sondes.

3. The correlation of source-water-vapor efflux with plant load and other variables should be established prior to water-vapor-profile measurement.

4. More data, especially three-dimensional profiles and profiles under a wider variety of ambient conditions, are necessary before definitive tests can be made of predictive models.

SECTION 4

EXPERIMENTAL PLAN

Cooling-tower measurements were made at the Comanche Station of the Public Service Company of Colorado (PSC) at Pueblo, Colorado in March, 1975. Cooling-pond measurements were made during March and April, 1974 at the Valmont Station of the PSC near Boulder, Colorado.

COOLING TOWER

The Comanche Station of the PSC is located about 6.5 km south of Pueblo, Colorado, about 9.5 km southwest of the Pueblo Memorial Airport, at an elevation of about 1,470 m. The Station had one 350 MW, coal-fired unit on line at the time of the measurements. Figure 1 is a portion of the plot plan of the Comanche Station.

The cooling tower at Comanche, was a Marley, double-cross-flow, Model 6616-4-10. The tower contained ten cells. The overall length of the tower was 122 m (400 ft); the overall width was 22.2 m (72.7 ft). The tower was oriented with the long axis southeast. The base of the tower was located at 1,471.5 m (4,827.7 ft) elevation. The fan deck was 12.6 m (41.3 ft) above the base, and the tops of the fan cylinders were at 18.1 m above the base. Pertinent dimensions and design specifications of the tower are given in Table 1. In normal operation, water was circulated at the maximum rate and the fans were run at maximum throughput.

TABLE 1. COMANCHE COOLING TOWER SPECIFICATIONS

Type	Marley Model 6616-4-10
Number of Cells	10
Fan cylinder height above tower base	18.1 m
Fan cylinder diameter at top	9.24 m
Fan diameter	8.53 m
Design air flow rate per cell (At design air density - 0.943 kg/m^3)	749.5 m^3/s
Design water flow rate	9.026 m^3/s
Fan brake-power	139.7 kW

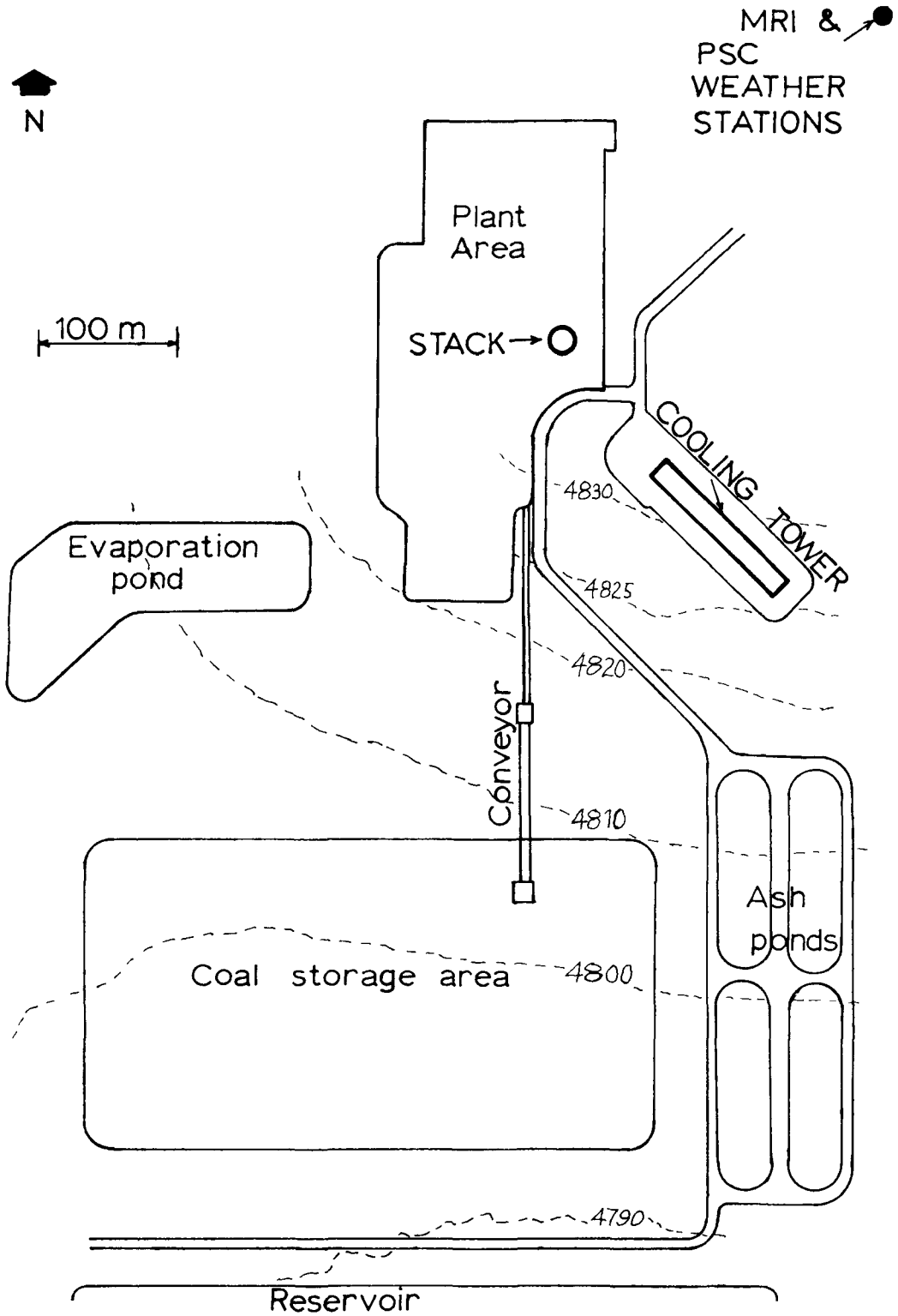

Figure 1. Portion of Comanche Plot Plan.

Measurements

The overall plan was to determine the ambient atmospheric conditions, the rate of evaporation from the cooling tower and water-vapor profiles in the atmosphere near the source. The determination of each of these types of information is described in detail below.

Ambient Conditions --

It was desired to know the ambient-air temperature and water-vapor content and the wind speed and wind direction.

There were several sources for ambient data at the Comanche site. PSC had a weather station located about 350 m north of the cooling tower, as marked in Figure 1, where temperature and relative humidity were measured at 1.5 m above the ground and recorded on a hydrothermograph with a seven-day chart. Wind speed and direction were measured at 10 m height and recorded. This station was operated for PSC by Loren W. Crow, Consulting Meteorologist, Denver, Colorado and access to the records was obtained with PSC permission and the cooperation of Dr. Crow.

A Meteorological Research, Inc. (MRI) weather station about 10 m north of the PSC weather station. The MRI station recorded temperature, wind speed and wind direction at 2 m height. A hydrothermograph with a one-day chart was placed adjacent to the PSC hydrograph. Both the MRI station and the hydrothermograph were obtained on loan from the National Center for Atmospheric Research (NCAR), Boulder, Colorado. Both had been calibrated in the NCAR Laboratory. The temperature sensor on the hydrothermograph was recalibrated on-site after two days operation after it was found to be reading erroneously. The PSC and MRI temperature charts had smallest scale divisions of 2°F (1.1°C) and 10°F (5.6°C), respectively, and readings were estimated to the nearest 0.5°F (0.28°C) and 1°F (0.56°C), respectively. These values are reported to the nearest 0.1°C as converted, but the resolution is at best ±0.5°C and ±1°C, respectively. The NCAR hydrothermograph scale had smallest divisions of 1°C and values were estimated to the nearest 0.1°C, but the resolution is ±0.5°C.

Both the PSC and MRI wind-speed sensors recorded wind-run. The wind speed was obtained by dividing wind-run by elapsed time. Wind-run was taken between half hours, so the hourly values are an average from the half-hour before to the half-hour after the hour.

A solarimeter on loan from and calibrated by NCAR was used to measure total insolation. The solarimeter usually was located at the PSC ground station, but occasionally was placed near the base of the cooling tower.

Temperatures were measured on probes extending from the plant stack at heights of 76, 112 and 152 m. These temperatures were recorded and access to these records was obtained with the cooperation of Crow. These values were read to the nearest 0.5°F and converted to the nearest 0.1°C. At times the wet- and dry-bulb temperatures near the cooling tower base were measured with an Assman, aspirated psychrometer. This instrument was calibrated at the University of Colorado and could be read to the nearest 0.1°C.

The ambient pressure was measured and recorded occasionally. The normal atmospheric pressure at Pueblo is about 665 mm Hg.

Source Measurements --

The rate of water vapor emission from the source is an essential value in any plume modeling work. In an effort to determine source values, studies were conducted on the water-vapor-emission rates from the cooling tower.

It was desired to determine the volumetric flow rate, the water vapor content and the temperature of the air being discharged from the cooling tower. A rig was built to make the necessary measurements. The rig consisted of a 5 cm diameter aluminum pipe, 6 m long. On one end of the pipe were mounted a Gill propeller anemometer and two YSI, bead thermistors, one dry and one wick-wetted. The thermistors were mounted in a 2.5-cm-diameter aluminum tube which was aspirated, and the electronics were mounted externally. The thermistor set-up was on loan from NCAR and was identical to that on the balloon sonde described later. Wiring from these instruments passed via a multi-wire cable through the center of the pipe and thence to a digital voltmeter (DVM) and a recorder on the cooling-tower fan deck. The signal from the anemometer was recorded while those from the thermistors were manually read on the DVM and recorded.

Scaffolding was erected adjacent to the fan cylinder of the fifth cell from the northwest corner of the tower. Two scaffolds were erected on opposite sides of the fan cylinder -- approximately the north-northwest and south-southeast sides. A complete diameter traverse could be made by moving the pipe and instruments from the wall to near the center of the cylinder from each side. Readings were taken on only the one cell of the tower because the scaffolding was required. Readings were taken at five or six "equal-area points" on each radius.

Water temperatures frequently were measured in the inlet pipe and at various points in the distribution system on the top of the cooling tower and in the bottom collection basin and outlet of the tower with a metal thermometer supplied and calibrated by PSC (the calibration was checked against the Assman thermometer). The thermometer had 2°F divisions and was read to the nearest 0.5°F (0.3°C). Also, PSC personnel read and recorded the temperatures at the condenser inlet and outlet to the nearest 0.5°F (0.3°C), several times daily and they made available those values. Hourly values of the plant load were obtained from PSC records. The circulating water flowrate was obtained from the capacity of the circulating pumps in the condenser-feed line and was not measured.

The inlet-water temperature was found to be the same at all locations in the tower. The outlet-water temperature was the same within 1°F at the two ends of the tower. Values of water temperatures read at the cooling tower tended to be 1 to 2°F lower than corresponding values read by PSC personnel at the condenser inlet and outlet. However, the change in water temperature agreed within 1°F (0.5°C) as measured by PSC and by our team. PSC water temperature values have been used almost exclusively in the analysis of the cooling tower because PSC had a more complete set of values, especially at the times when balloon flights were being made.

Near the end of the measurement program it was discovered that the signals from the wet and dry thermistors on the cooling-tower probe were not good and one set of readings was taken at the edge of the fan cylinder with the Assman psychrometer. Also, the exit-air-temperature records taken early in the program were lost when blown away by the wind. So, very few data on the exit-air temperature were available.

Balloon Sonde Measurements --

Measurements of conditions in the atmosphere -- wind speed and direction, pressure, and wet- and dry-bulb temperature -- were made with the NCAR Boundary-Layer Profile (BP) system. The BP system used at Comanche is described below. Advanced systems of this type are now commercially available.

The sensors were calibrated by NCAR in their laboratory. The thermistor readings were checked in the field against the Assman psychrometer and gave excellent agreement.

The system consisted of a balloon, winch, telemetry package and ground station. The balloon was a Follmer Model 115, dirigible-shaped with three inflated stabilizer fins. Its length was 4.9 m, maximum diameter 1.4 m, and total displacement 3.7 m -- the largest permitted without special FAA waiver. The balloon was constructed of 2 mil polyethylene and had an internal dilation system to permit a 760 m elevation change. Net static lift at sea level was 1.8 kg. Using 100 lb-test nylon cord for tether, a 935 g telemetry package could be lifted to 610 m in calm conditions and to less than 245 m in 9 m/s winds. The winch was developed at NCAR and consisted of a drum with level wind, driven directly from a half-inch, heavy-duty drill. An SCR speed controller permitted smooth control of the line at speeds from .3 to 3 m/s. A line footage indicator aided in determining balloon-ascent characteristics.

Figure 2 depicts the telemetry package -- blocks (1) through (15) -- and the ground station -- blocks (16) through (19). The telemetry package used NiCd batteries as power supply. A precision regulator provided +6 and -6 V for the telemetry system and sensors. Pressure was measured by an aneroid cell whose output was linearized by a linear voltage differential transformer. Both dry- and wet-bulb temperatures were detected by YSI bead thermistors whose outputs were linearized. The two thermistors were shielded in a tube at the top of the telemetry package and were aspirated by a tiny D.C. motor and fan. The wet-bulb thermistor was wetted by a tissue wick leading to a small water reservoir. Wind was detected by a 3-cup anemometer with two small attached magnets that closed a reed switch twice for each cup revolution; the linearizer converted the frequency of switch closures to a D.C. voltage. Wind direction was determined by a compass (not shown) which was clamped to a calibrated resistor for each reading.

The linearized sensor outputs, in the range 0-100 mV, and a sync pulse were fed to a time multiplexer. The sync-pulse amplitude was determined by an internal 100 mV reference signal and therefore represented full-scale-sensor output. Each data frame from the multiplexer consisted of a full-scale-sync-pulse followed by a zero reference and then seven pairs of data

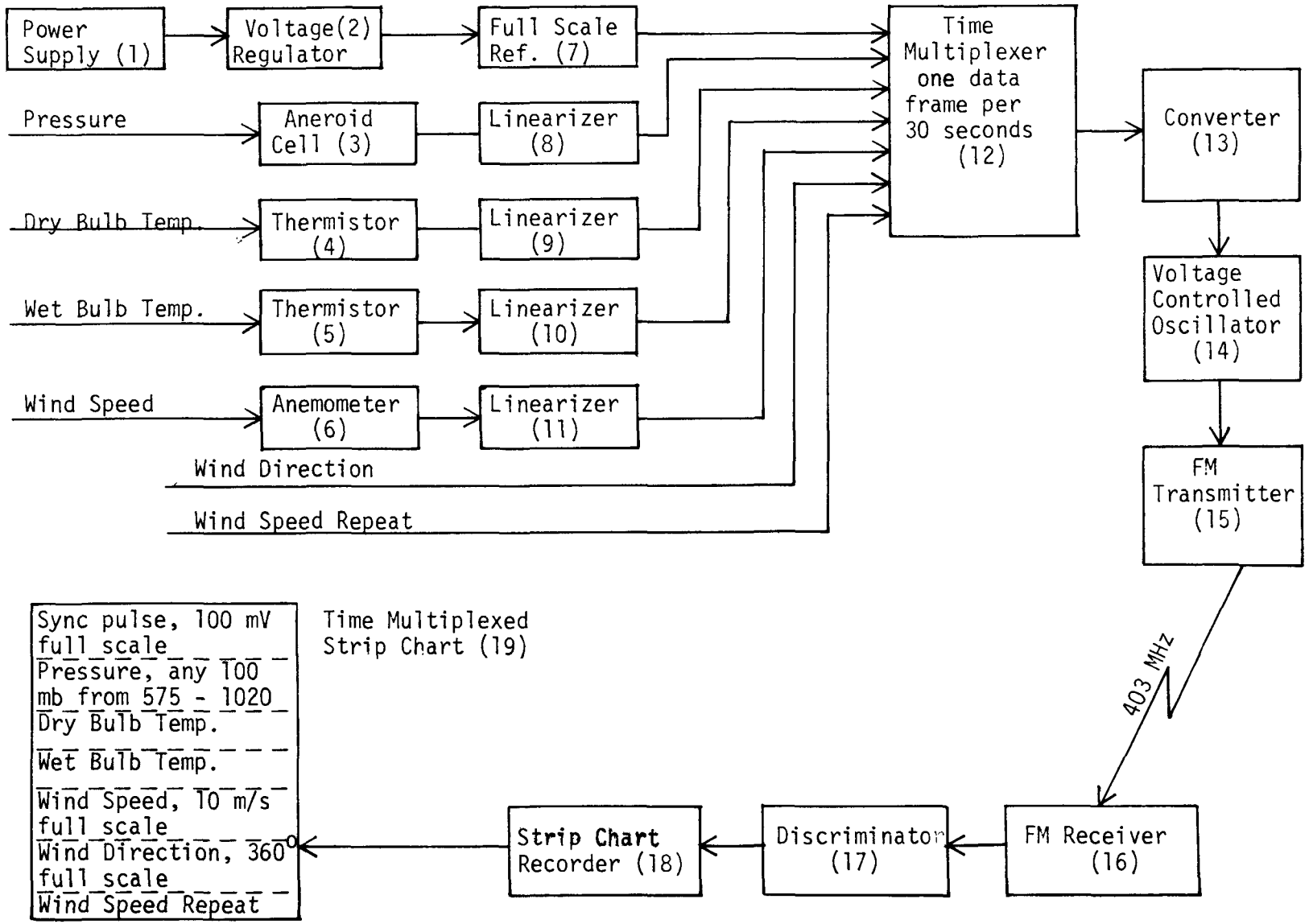

Figure 2. Block diagram of NCAR Boundary Profile System.

pulses and zero references. Output from the multiplexer was converted to a voltage output in the range 0 to 1.5 V. A voltage-controlled oscillator operating on IRIG channel 8 (3 kHz ± 7.5%) converted the 0 to 1.5 V signals linearly to the audio tone necessary for telemetry transmission. An FM radio transmitter operated at 403 mHz and delivered a nominal power of 50 mW to a pair of crossed-dipole antennas fed 90° out of phase, thus providing circular polarization.

The telemetry signal was received at the ground receiver by a helical antenna. The receiver output was fed to a discriminator that converted audio frequency to an output in the range ±1 to ±2.5 V and thence to an Esterline Angus model S 601-S Speed Servo strip chart recorder.

The NCAR balloon had stable flight characteristics at low wind speeds. At speeds above about 10 m/s, however, roll of the balloon tended to swing the instrument package wildly and safe flights could not be made.

The radio-receiving station was set up at a convenient location, and constant communications were maintained between the crew with hand-held CB-radio units.

Frequent high winds at Comanche limited the data-taking to one flight on March 20 and nineteen flights on March 25. During the last 16 runs on March 25, the EPA radio sonde was also attached to the NCAR balloon. Late on the day of March 25, 1975, the tether line snapped and the balloon and sondes were irretrievably lost.

A sample pulse-record of the sonde data is shown in Figure 3. Each data frame lasted thirty seconds and consisted of: the full-scale sync-pulse followed by pressure, wind speed, dry-bulb temperature, wet-bulb temperature, wind direction and, again, wind speed pulses. Each sensor-signal pulse lasted for about 1.5 s.

The sonde data from Pueblo were hand-reduced to the corresponding physical readings. Baseline drift was not a serious problem, when some drift did occur it was compensated as readings were taken off the recorder chart. A template was constructed for each variable so that pulse heights were read off of the strip chart as physical values.

The pressure-sensor reading was a relative value, i.e., full-scale on the recorder chart corresponded to a pressure change of 100 millibar (mb). At a fixed atmospheric pressure, pressure decreases with altitude by 1 mb per 10 m, hence the change in pressure as the balloon ascended or descended could be used to determine its height. There were 50 scale divisions on the recorder-chart paper, so each division corresponded to a 2 mb change in pressure or 20 m change in height. Values were read to the nearest 0.5 mb (5 m), so the precision of the height determinations is approximately ±5 m. The absolute pressure at the sonde was determined by setting the sonde reading equal to the absolute pressure read with the altimeter at times when the sonde was at ground level. Due to variations in ground level, there is approximately ±0.5 mb (5 m) error in the absolute height so determined. This, combined with the relative error, suggests that overall there was about ±10 m uncertainty in

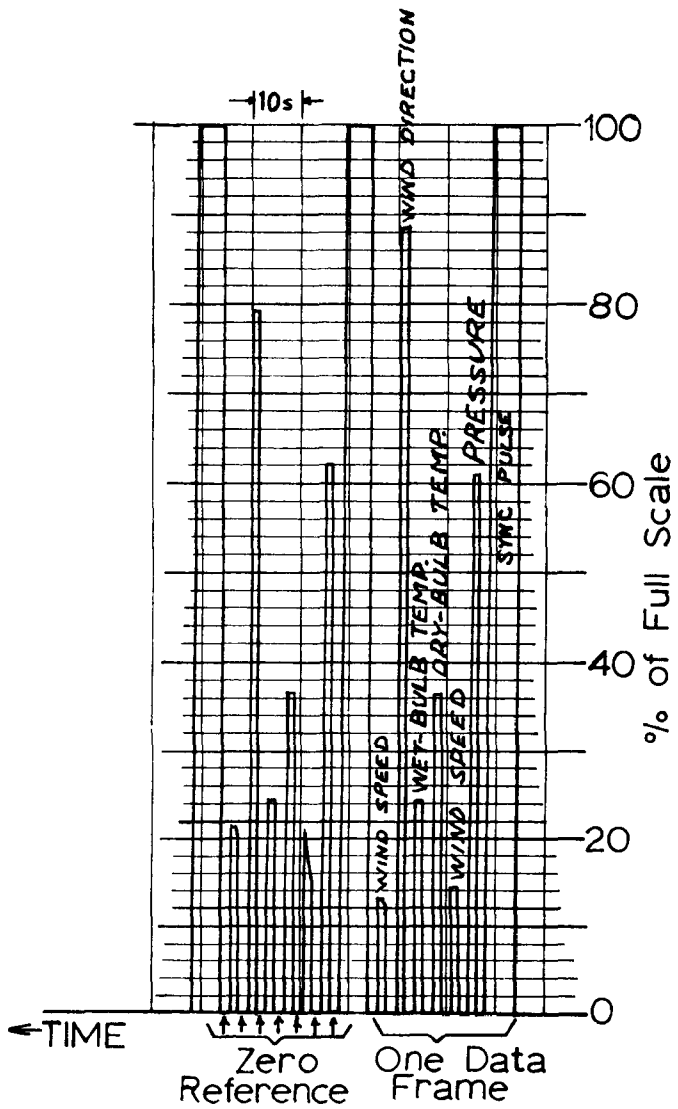

Figure 3. Sample recorder trace from NCAR sonde.

fixing the height from the pressure. With this in mind, the hand-reduced values of sonde altitude were estimated from the pressure data as follows. The absolute pressure was established by interpolation of pressures measured with the altimeter. Not all flights were started at ground level, so the sonde pressure at ground level at the time closest the flight time was set equal to the interpolated ground-level barometric pressure. Other pressure readings from the sonde were then converted to absolute-pressure values. The height above ground level at any time was then determined as 10 m for each mb difference in pressure from ground level. These heights were plotted versus time and a smooth curve drawn through these points. Heights were read from the curve to the nearest 5 m. Generally the data points fit a smooth curve to well within ±5 m, but occasionally there were pressure fluctuations corresponding to as much as ±10 m height which could have been due to actual bouncing of the balloon or due to erroneous signals or reading of the signals. In these cases, the smoothed curve was used. It is estimated that the elevation values are within ±10 m of the true values and that the absolute pressures are within ±1 mb (0.76 mm Hg) of the true pressures.

The balloon location was determined independently with theodolites. Two theodolites were in fixed, known positions relative to each other and to the cooling tower. The operators tracked the balloon and, on a given signal, stopped tracking and read the elevation and inclination angles. From these values the distance of the balloon from the cooling tower, and its height, were calculated. The height values so determined usually agreed within ±10 m with those determined from the pressure. Sometimes these values did not agree so well, but this was found to be due to poor time synchronization of the readings. When the time sync was adjusted, agreement was quite good. Thus the height values reported should be good to within ±10 m and the relative heights in any given flight should be good to within ±5 m.

Except for wind speed, all sensors gave essentially a constant reading for the 1.5 s of the recorded pulse. The wind-speed reading often changed during a single 1.5-s pulse, however, sometimes by as much as a factor of 2. This was due to fast changes in the wind speed and the rapid response of the anemometer. When this occurred, an average of the wind speed during the pulse was read and recorded. Full scale on the recorder chart was 10 m/s in wind velocity, so each scale division was 0.2 m/s. Values were read to the nearest 0.1 m/s, but when the wind speed was changing, the average was probably only accurate to ±0.2 m/s.

Full scale on the chart equalled 360° in wind direction, so each chart division corresponded to 7.2°. Values were read to the nearest 3° and the resolution error is about ±5°. Directions are relative to magnetic north (= 0° = 360°).

Full scale on the chart corresponded to 25°C of temperature. Each scale division was 0.5°C. Different temperature ranges were available via a selector switch on the sonde. Temperature values were read with great care to the nearest 0.1°C, and the resolution error is considered to be 0.1°C. Both the wet-bulb temperature and the difference between the wet- and dry-bulb are important in the calculation of humidity. Since the temperatures were read in pairs, in exactly the same way, it is believed that the uncertainty in the

temperature difference is also ±0.1°C.

The mixing ratio, mr, g of water vapor per kg of dry air, was calculated from the formula (1),

$$mr = (622\ p)/(P - p) \tag{1}$$

The water-vapor partial pressure, p, in mm Hg, is given by (2)

$$p = p^*_{sw} - 0.00066\ (1 + 0.00115\ T_w)\ \ (P)\ (T - T_w) \tag{2}$$

Values of the saturation vapor pressure of water were obtained from the Handbook of Chemistry and Physics (3).

Errors in the calculated mixing ratios result from errors in the absolute value of the wet-bulb temperature and from errors in the difference between the wet- and dry-bulb temperatures. At 0°C an error of 0.1°C in the wet-bulb temperature, if the temperature difference is correct, results in a 1.4 percent error in the saturation mixing ratio. An error of 0.1°C in the temperature difference, if the wet-bulb temperature is correct, causes an error of about 1 percent in the saturation mixing ratio. The percentage error increases as the relative humidity decreases. For example, at 0°C, 30 percent relative humidity, the mixing-ratio errors due to a 0.1°C temperature or temperature difference error are about 5 and 20 percent, respectively. It is estimated that the mixing ratio values determined by wet- and dry-bulb thermometry should be within ±10 percent of the correct values for the conditions of this work. Changes in mixing ratio during a single flight should be well within this range.

COOLING POND

Cooling-pond measurements were made at the Valmont Station of PSC, located about 3 km east of Boulder, Colorado at an elevation of about 1,600 m. There was one 185 MW, coal- and gas-fired unit operating at Valmont during the measurement period. Figure 4 is a map of the vicinity of the Valmont Station. Water cooling is accomplished by cooling ponds. There are three lakes at Valmont, but during the measurement period only two, Leggett Owen Reservoir and Hillcrest Lake, were in the cooling loop. Water was not circulated through the larger Valmont Lake. The hot water was discharged into Owen Reservoir and the cool water was taken from Hillcrest Lake. The elevation at the lakes' surface is about 1,593 m.

Ambient Conditions

At Valmont only the MRI weather station was available for measurements of ambient temperature, wind speed and wind direction. Ambient humidity was determined from frequent readings with the Assman Psychrometer. Ambient pressure was also read at various times. There were no corroborating ambient measurements in the Valmont program, except for readings from the balloon sonde when it was outside the influence of the ponds. Insolation was not measured at Valmont.

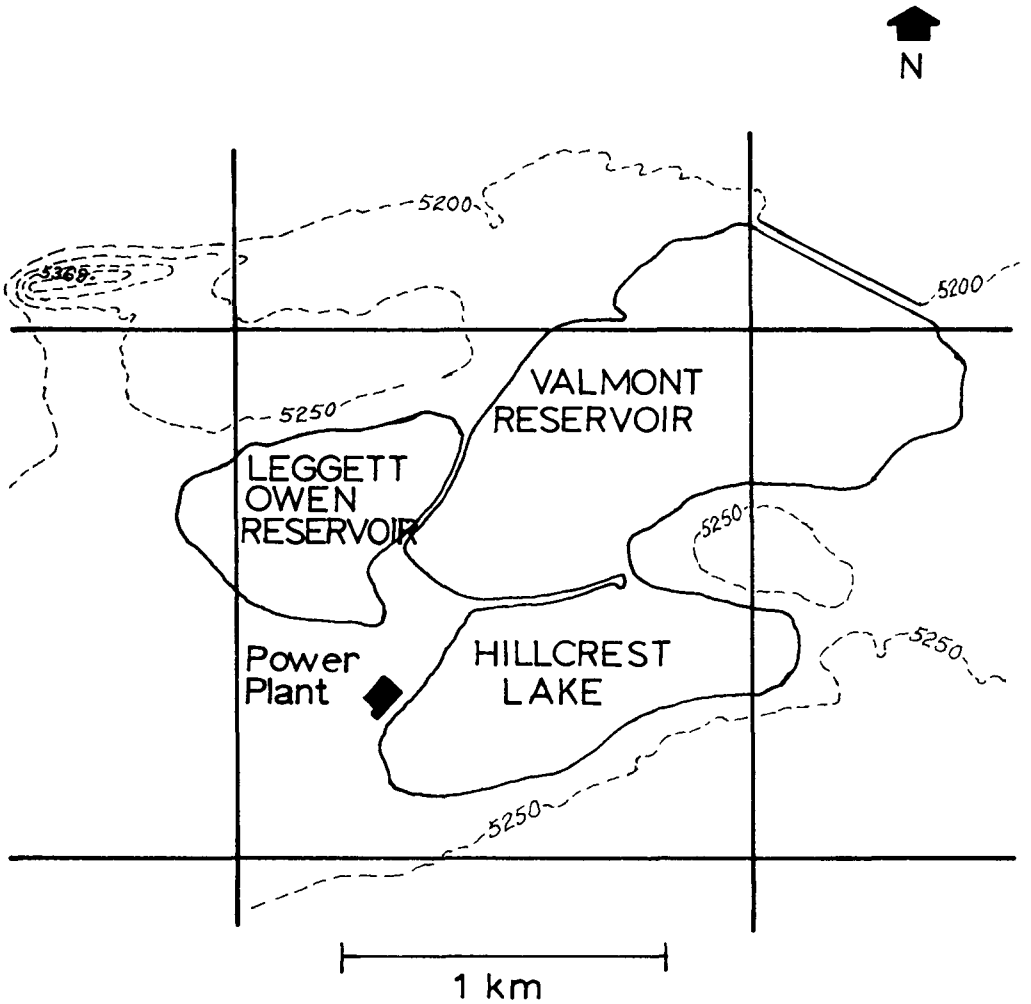

Figure 4. Valmont site map.

Source Data

No direct measurements were made of the water conditions in the cooling ponds at Valmont. Water-vapor-source data consisted of condenser-inlet and outlet temperatures and water flowrates recorded and furnished by PSC. The temperature-difference values should be accurate to within ±0.5°C. The uncertainty in the water flowrates is not known.

Balloon Sonde Measurements

The BP system used at Valmont was identical to that described above for Comanche, except that it did not include a wind-direction sensor. The sonde data collected at Valmont were reduced on the NCAR-computer system.

The data reduction procedures and calculation methods were as described above as follows. For machine reduction, pulse heights and time were read from the chart via a Bendix Datagrid and processed on a digital computer. At Valmont, balloon flights were made at marked locations whose positions were later fixed with a theodolite. The computer reduction of the pressure (height) data did not smooth the values as did the hand-reduction. However, for pressure and the other variables, when the rate-of-change of the variable appeared smooth, not all points were read and an internal interpolation routine was used.

SECTION 5

COOLING TOWER RESULTS

Measured values, reduction of these values and the results obtained, and the reliability of these results are presented in this section.

AMBIENT DATA

Reliable data on the ambient atmospheric conditions are essential in any effort to model the behavior of plumes injected into the atmosphere. At Comanche there were at least two sources of each ambient measurement (except insolation) so it is possible to have rather high confidence in the values reported at most times.

Ambient data for all days on which field measurements were made, March 18, 19, 20, 21, 24, 25, and 26, 1975, are presented in detail in Appendix A. The values tabulated are: time-of-day; temperature measured by NCAR, PSC and MRI hydrothermographs; temperature measured by Assman psychrometer dry-bulb; temperatures measured on PSC stack at 76, 112 and 152 m; wind speed and wind direction from MRI at 2 m and from PSC at 10 m; relative humidity from NCAR and PSC hydrothermographs and mixing ratios from their average and from the Assman; and insolation.

The temperature values from the near-ground sensors do not always agree. In addition to differences in calibration, there are several possible reasons for this, including: the NCAR, PSC and MRI values were taken at the PSC weather station while the Assman readings were taken near the base of the cooling tower; the scale resolutions of the several sensors were not the same as discussed earlier; and the times on the recorder charts were not precisely synchronized. The NCAR readings on March 18 and 19 are definitely in error, the instrument was recalibrated against the Assman on March 20 and from then on it is probably the most accurate. Generally the readings from the three ground-temperature sensors agree within ±0.5°C of their average, but in a few cases the discrepancy is larger. It is believed that the average values are within ±1°C of the correct value. It is recommended that the average of the temperature values in Table A-1 be used.

Temperatures from the stack sensors generally are consistent with ground temperatures although it is noted that the sensor at 76 m may have been influenced by its proximity to the plant buildings. Crow (personal communication) has suggested that this sensor may tend to read high for this reason, especially when the ambient temperature is low. The absolute values should be well within ±1°C but differences, hence the lapse rate, could easily be off by a factor of 2.

The agreement between the two wind-speed sensors is quite good but not precise. It is recommended that they be averaged.

Wind direction values are hourly averages from PSC and MRI. The agreement is generally excellent within ±10° most of the time, within ±30° virtually all the time, and certainly always within the variability of the wind itself. The values are relative to magnetic north. It is recommended that they be averaged.

Relative-humidity values generally agreed quite well when the relative humidity was less than 50 percent (which was most of the time). At higher relative humidities the agreement is not so good. In most cases the agreement is fair and these values usually agree well with values at other locations from the Assman psychrometer and the balloon sonde. It is recommended that the average relative humidity value be used.

In Table 2 are summarized the ambient data for March 25, 1975, the day

TABLE 2. AMBIENT DATA, MARCH 25, 1975.

Time	Avg. Temp, °C	Pressure, mm Hg	Mixing Ratio, g/kg	Avg. wind speed m/s	Avg. wind direction	Sonde Wind speed, m/s	Sonde Dir.
0700	-6.2	670.3	1.37	1.5	325		
0730	-6.4		1.32			3.4	340
0800	-5.5	670.3	1.42	1.1	285	3.4	21
0830	-3.6		1.57				
0900	-2.7	670.3	1.64	1.2	30	0.7	9
0930	-1.0		1.78			3.0	13
1000	-0.8	670.3	1.77	1.9	15		
1030	0.0		1.83			2.3	43
						2.6	36
1100	+1.1	670.3	1.95	2.0	40	3.0	65
						3.9	61
1130	4.6		2.07			3.7	58
						4.0	82
1200	3.6	668.8	2.05	3.0	80		
						4.1	72
1230	4.4		2.11			4.0	82
1300	5.1	666.5	2.22	2.3	70		
						2.5	46
1330	6.1		2.32			2.0	43
						1.4	42
1400	6.7	665.0	2.35	1.2	15	1.7	1
1430	8.0		2.49			2.9	353
1500	8.3	663.5	2.47	2.0	330	3.0	329
1530	10.6		2.71				
1600	10.6	662.8	2.53	3.2	10		
1630	11.1		2.62			4.6	353
						5.0	332
1700	11.3	662.7	2.65	4.8	310	6.5	300
1730	10.8		2.56				
1800	10.2	--	2.46	5.5	285		

most of the balloon data were obtained. The data presented are pressure, average temperature, mixing ratio, average wind speed and wind direction. Wind speeds and directions from the balloon sonde are included for comparison.

WATER VAPOR SOURCE

The source of water vapor above background was the water evaporated in the cooling tower. Droplets condensed due to supersaturation in the tower and "drift" (entrained water drops) also represent potential sources of vapor downwind from the tower. It is important that this source term be known in any modeling effort.

Normal operating procedure, in effect at all times when our measurements were being made, was to operate the water-circulating pumps at full capacity. The design capacity was 9.026 m^3/s. The water flowrate was not measured, so the design value has been assumed to be correct and has been used in all subsequent analysis.

The design capacity of each of the ten fans on the cooling tower was 749.5 m^3/s. Normal operating procedure was for all fans to operate at design capacity. This was in effect at all times when measurements were being made.

The velocity traverse results are shown in Figure 5. A striking bi-modal velocity profile can be observed. Near the center of the fan cylinder, above the fan hub, the gas velocity was slightly negative (i.e., downward). The velocities were quite reproducible. On one occasion, the probe was left in one position for four hours and the average velocity remained constant within the readibility of the recorder chart throughout that period. Wind speed and direction may have had a slight effect on the velocity profiles as can be seen by comparing the points for March 21 and March 26. It does not appear that the total volumetric flow was changed by the wind within the accuracy of the measurements. There were no apparent effects of plant load or ambient conditions on the velocity profile.

Values taken from the curve of Figure 5 at six equal-area points on each radius were averaged to give an average exit velocity of 10.15 m/s and a volumetric flowrate of gas out of the cylinder of 711.7 m^3/s per cell. This value is an excellent agreement (5 percent lower) with the design value of 749.5 m^3/s. The measured value, 711.7 m^3/s per cell, 7117 m^3/s for the tower, has been used in the subsequent calculations.

Plant loads, water temperatures, ambient air temperature and mixing ratio, and a few measured efflux-air temperatures are given in Table 3 for the days of interest. It may be noted that the outlet water temperature at 1400 hours on March 24 is inconsistent with the other values that day. It is suspected that the value recorded as 65°F (18.3°C) should be 60.5°F (15.8°C).

Had good values for the efflux-air wet- and dry-bulb temperatures been obtained, the mixing ratios and enthalpies of the efflux air could have been calculated. The consistency of these values then could have been checked against an enthalpy balance around the cooling tower. However, this could not be done because good efflux-air-temperature values were not obtained. As a

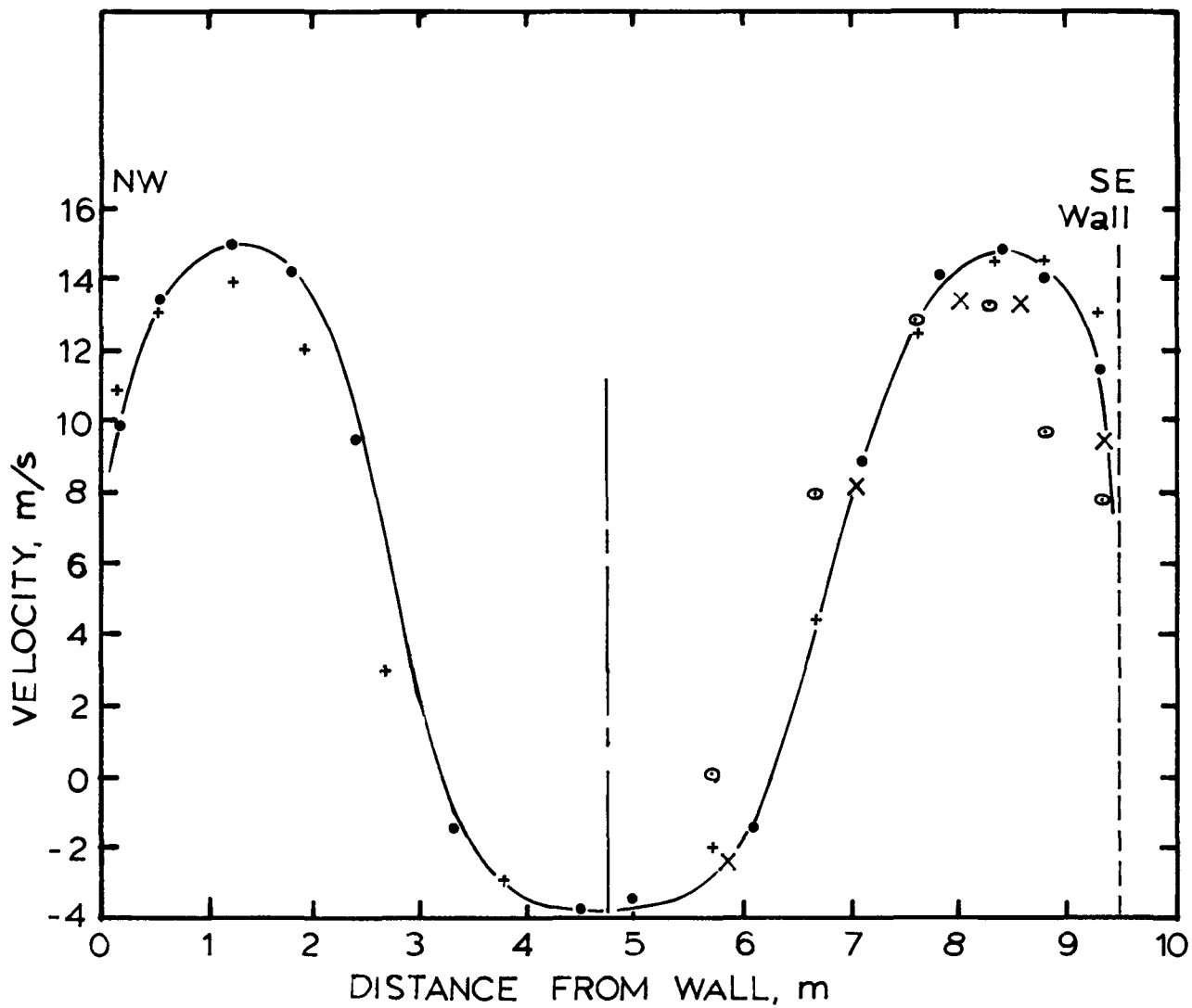

Figure 5. Cooling tower velocity profile.

TABLE 3. PLANT LOADS, WATER TEMPERATURES, AMBIENT AIR CONDITIONS & EFFLUX TEMPERATURES, COMANCHE COOLING TOWER

Date	Time	Plant Load, MW	Water Temperature °C Into Tower	Water Temperature °C Out of Tower	Ambient Air Temp °C	Ambient Air Mixing Ratio g/kg	Efflux Air Temp °C	Efflux Air Wet-Bulb Temp °C
3/18	0600	280	23.3	12.2	-2.5	1.0		
	1000	295	25.2	14.4	7.2	3.5		
	1400	272	27.5	16.1	17.5	2.4		
	1800	260	27.5	16.7	16.4	2.2		
3/19	0600	296	27.2	15.5	7.5	2.7		
	1000	300	28.6	17.2	15.3	2.7		
	1800	300	30.6	18.9	20.8	3.1		
3/20	0600	316	28.3	15.5	4.4	3.0		
	1000	300	29.1	17.2	15.1	3.2		
	1700	301	32.2	21.4	22.2	2.5	23.6	21.8
	1800	302	30.6	18.9	20.8	2.8		
3/21	0600	305	29.5	17.8	8.6	3.9		
	1000	335	31.7	18.9	14.8	3.7		
	1400	334	31.4	18.3	11.7	3.0		
	1600	307	30.6	18.9	15.9	2.8		
	1800	333	31.1	18.3	15.5	2.4		
3/24	0600	282	23.9	12.8	0.5	1.2		
	1000	346	28.0	15.0	2.8	1.4		
	1400	338	28.6	18.3	10.7	1.6		
	1800	360	30.8	17.5	10.7	1.8		
3/25	0600	171	18.9	10.0	-5.3	1.4		
	1800	330	28.9	16.7	10.2	2.5		
	2200	330	28.9	16.1	6.7	2.3		
3/26	0600	330	28.3	15.5	-1.0	2.6		
	1000	283	25.8	13.3	0.6	2.5		
	1200						28.0	23.2
	1300						22.5	22.5
	1400	285	27.8	15.6	12.1	3.2		

consequence, a different approach had to be taken to estimate the efflux-air conditions.

An energy balance around the cooling tower is as follows:

energy water in + energy air in + energy gains - energy losses

= energy water out + energy air out (3)

It was assumed that energy losses and gains were negligible compared to the changes in energy of the air and water streams. The energy input of the fans, for example, was calculated and was negligible. The energies associated with blowdown and make-up were assumed negligible, since their flowrates and temperatures were not available. Further, the fact that the measured temperature change through the cooling tower agreed with that across the condenser, confirms this assumption to within the accuracy of the temperature measurements.

Thus, from equation (3),

enthalpy change water (in - out) = enthalpy change air (out - in) (4)

which can be written as

$$m_{w,in}C_{pw}(T_{wa,in} - T_{ref}) - m_{w,out}C_{pw}(T_{wa,out} - T_{ref})$$

$$= m_{da}(h_{a,out} - h_{a,in}) \quad (5)$$

Rearranging equation (5) yields

$$h_{a,out} - h_{a,in} = \frac{m_{w,in}}{m_{da}} C_{pw}(T_{wa,in}) - \frac{m_{w,out}}{m_{da}} C_{pw}(T_{wa,out}) \quad (6)$$

With known flowrates, water temperatures and ambient-air conditions, equation (6) could be solved for the enthalpy of the air out. However, the water flowrate was not constant (due to evaporation) nor was the dry-air mass flowrate known (the wet-exit-air volumetric flowrate was known). The solution thus was iterative.

Equation (6) was solved first by assuming the water flowrate to be constant at the known outlet value and the exit air was assumed to be dry air, i.e., the dry-air flowrate was assumed to be that of the exit air. The enthalpy of the exit air was then calculated by equation (6). Then the assumption was made that the exit air was saturated with water vapor. For saturated air, the enthalpy and mixing ratio are unique functions of temperature, so with this assumption the temperature and the mixing ratio were determined from the calculated exit-air enthalpy. The values so obtained allowed estimation of the change in water flowrate due to evaporation and of the dry-air flowrate. With these new estimates, the procedure was repeated to give new values for the conditions of the exit air. Further iterations were not

justified, since the changes in the calculated values (less than one percent) were considerably less than the errors involved in the measurements and the assumptions in the procedure.

Values of the exit-air temperatures and mixing ratios calculated as described, and the total water-vapor efflux are given in Table 4.

The assumption that the efflux air was saturated was examined in several ways. It was observed that under most conditions in the field, water condensed in the efflux air just above the top of the fan cylinder. This indicated that the efflux air must have been close to saturation. The one set of measurements made with the Assman psychrometer, at 1300 hours on March 26, at the cylinder edge gave equal wet- and dry-bulb temperatures, establishing saturation at that time. However, the temperatures on the two sides of the fan cylinder differed by 2°C (21.5°C on one side and 23.5°C on the other) so the uniformity of the conditions of the efflux air, which has been assumed throughout, was not established. The average of the measured temperatures was 22.5°C. No value could be calculated at 1300 hours, but the calculated efflux temperature was 22.9°C at 1000 hours and 25.8°C at 1400 hours. So, the values obtained by the calculation procedure are consistent with the measured value.

The efflux-air temperatures, calculated by assuming saturation, were compared with the temperature of the inlet water measured at the same time. The calculated efflux temperatures were always less than those of the entering water, as they must be. Further, the entering-water temperature minus the calculated efflux-air temperature was usually about 4°C (range 2 to 6°C, average 4°C). The enthalpy of moist air is almost completely independent of dry-bulb temperature for a given wet-bulb temperature. Thus, if the calculated efflux-air enthalpies are correct, the temperature calculated by assuming saturation is the wet-bulb temperature of the efflux air, even if the air is not saturated. The efflux-air dry-bulb temperature may not exceed the inlet-water temperature, however, so the maximum error in the mixing ratio (if the efflux-air dry-bulb temperature equalled the inlet-water temperature) may be estimated. This was done and it was found that if the dry-bulb temperature was 4°C higher than that calculated, the mixing ratio calculated assuming saturation would be high by 6.5 percent.

The other major sources of error in this procedure are: water-temperature-measurement errors, and the liquid and gas flowrates used. Temperature-measurements errors presumably are random. The measured gas flowrate was 5 percent less than the design value, so it may be slightly low (which would cause the calculated efflux-air temperature to be high). The error in the water flowrate is unknown, but neglecting heat losses, makeup, and blowdown would tend to make calculated mixing ratios too high. Thus, the tendency is for the assumptions made to give efflux-air temperatures and mixing ratios higher than they should be. It is concluded that the calculated values should be within 10 percent of the true values and that they tend to be higher than the true values.

A procedure was needed so that the efflux-air conditions could be estimated for times when tower conditions were not being measured, but balloon

TABLE 4. WATER VAPOR EFFLUX CALCULATED FROM MEASURED WATER TEMPERATURE CHANGE

		Calculated Efflux Air Conditions			
Date	Time	Temp °C	Mixing Ratio g/kg	Total Water Vapor Rate, 10^5 g/s	Water Vapor Rate Above Ambient 10^5 g/s
3/18	0600	18.9	15.9	1.156	1.083
	1000	22.9	20.4	1.462	1.211
	1400	25.5	24.0	1.701	1.531
	1800	24.4	22.4	1.591	1.435
3/19	0600	23.7	21.4	1.526	1.333
	1000	25.2	23.5	1.663	1.472
	1800	26.9	26.1	1.854	1.634
3/20	0600	24.5	22.6	1.605	1.392
	1000	26.1	24.8	1.766	1.521
	1700	26.0	24.7	1.737	1.563
	1800	26.9	26.1	1.828	1.632
3/21	0600	24.7	22.8	1.616	1.340
	1000	27.3	26.8	1.878	1.619
	1400	26.7	25.8	1.809	1.599
	1600	25.9	24.5	1.726	1.529
	1800	26.8	26.0	1.821	1.653
3/24	0600	20.0	17.0	1.237	1.149
	1000	23.5	21.1	1.506	1.406
	1400	22.0	19.3	1.387	1.272
	1800	26.0	24.7	1.738	1.611
3/25	0600	14.5	12.0	0.896	0.791
	1800	24.8	23.0	1.630	1.467
	2200	24.7	22.8	1.617	1.454
3/26	0600	23.5	21.1	1.505	1.319
	1000	22.9	20.4	1.462	1.283
	1400	25.8	24.4	1.722	1.496

flights were being made. It was expected that the amount of energy dissipated at the cooling tower would be closely related to the plant power-load. The change in specific enthalpy of the air through the cooling tower is directly proportional to the energy dissipated (with constant dry-air flowrate). So, the calculated change in the air specific enthalpy was plotted versus the plant load as shown in Figure 6. The central line is a line fitted-by-eye to the points. The two lines bounding the central line are calculated lines based upon the water-temperature difference 0.5°C greater or less than that corresponding to the average line. This reflects the range of uncertainty in the air-enthalpy change due to the likely error in the measurement of water-temperature change. Only five of the twenty-six data points fall outside that band and only one, that at a load of 338 MW is excessively far off. That particular point was included even though it is suspected that the water-temperature reading may be in error (that is the point at 1400 hours on March 24 mentioned earlier). This result suggests that within the probable error of the water-temperature-difference values, the air-enthalpy change can be estimated from the plant load.

Given a value of air-enthalpy change, the temperature and mixing ratio of the efflux air (assuming saturation) may be determined as described above. This was done using the central line of Figure 6. Comparison of the water-vapor-efflux values by this method with those obtained by energy balance (Table 4) shows that, except for the questionable point at 338 mW, the agreement is excellent. Thus, it was concluded that this method could be used to estimate the total- and the above-ambient water-vapor-efflux rate at any time the plant load was known. This was done for all the time periods when field measurements were being made and these results are presented in Table 5.

Unfortunately, there is no absolute check on the values of the efflux-air temperatures, mixing ratios, the total water-vapor-efflux rates, and the rates-of-water-vapor-efflux above ambient. The procedure which was developed and used here gives results which are consistent with the available data, and it is recommended that the values in Table 5 be used. The values estimated from the plant load are certainly within the accuracy of the available data and it is recommended that, for consistency, these values be used even for those times when measured water-temperature changes are available.

BALLOON SONDE RESULTS

An adequate test of plume models requires data on the spatial distribution of water vapor in the atmosphere downwind from the source. Such data were obtained from the sensors on the balloon sonde. These results are presented and discussed in this section. Related data obtained by the EPA team are presented elsewhere (4).

Figure 7 shows the approximate location of each of the balloon flights on the Comanche plot plan.

The reduced data from the sonde sensors included: pressure, dry-bulb temperature, wet-bulb temperature, wind speed and wind direction. These data are tabulated in detailed in Appendix B. For convenience, the values were reduced to point values of the sonde height, the dry-bulb temperature and the

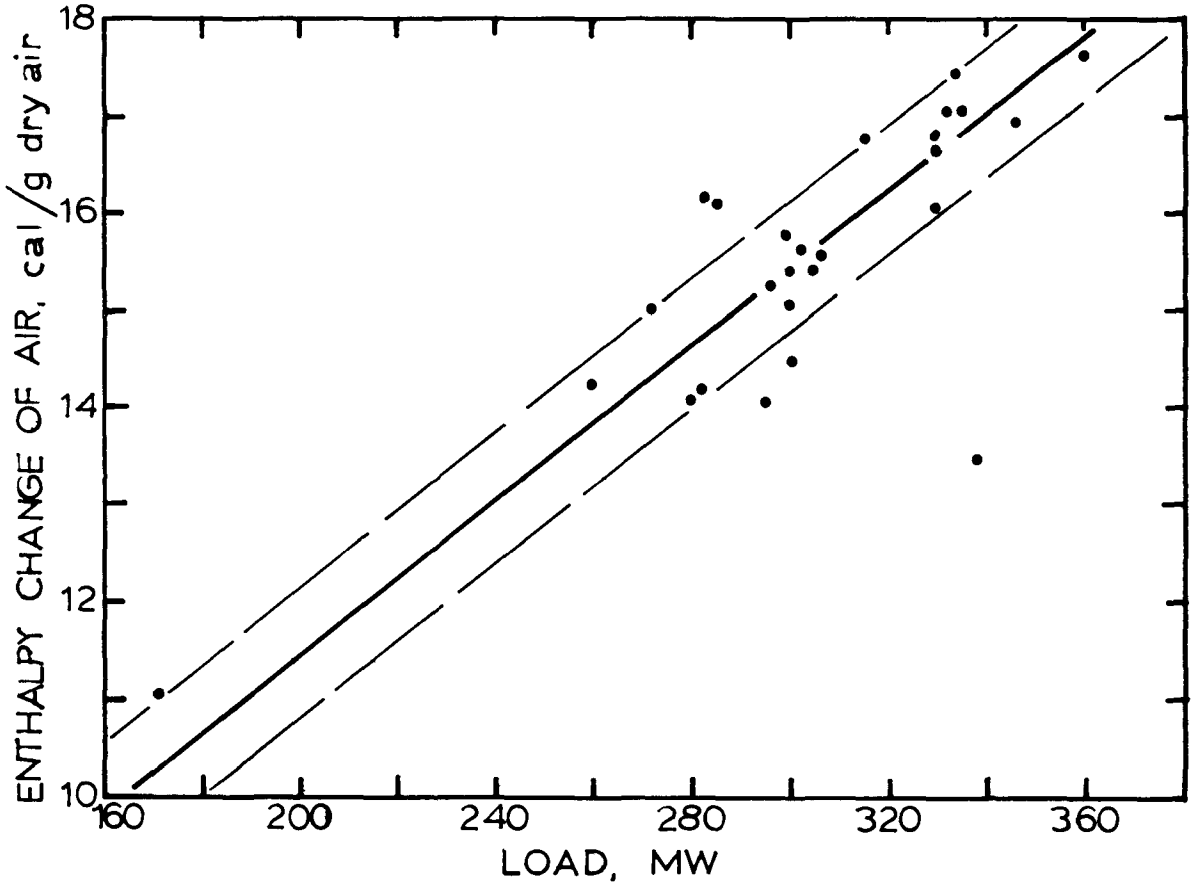

Figure 6. Calculated air-enthalpy change versus plant load.

TABLE 5. WATER VAPOR EFFLUX BASED ON PLANT LOAD

			Calculated Efflux Air Conditions			
Date	Time	Temp °C	Mixing Ratio g/kg	Total Water Vapor 10^5 g/s	Water Vapor Above Ambient 10^5 g/s	Plant Load, MW
3/19	0600	23.8	21.5	1.533	1.341	296
	1000	25.6	24.1	1.705	1.514	300
	1100	26.0	24.8	1.744	1.547	300
	1200	26.2	25.0	1.756	1.567	300
	1300	26.5	25.5	1.788	1.599	300
	1400	26.7	25.8	1.805	1.609	300
	1500	27.0	26.4	1.846	1.643	300
	1600	27.3	26.8	1.871	1.668	300
	1800	26.9	26.1	1.854	1.634	300
3/20	0600	23.9	21.7	1.541	1.328	316
	0900	25.4	23.8	1.680	1.454	315
	1000	25.8	24.4	1.718	1.493	300
	1200	26.8	26.0	1.820	1.596	302
	1400	26.9	26.1	1.826	1.651	298
	1500	26.9	26.1	1.826	1.665	302
	1600	26.8	26.0	1.827	1.665	300
	1700	26.8	26.0	1.829	1.653	301
	1800	26.8	26.0	1.821	1.625	302
3/21	0600	25.0	23.2	1.645	1.368	305
	0900	26.6	25.7	1.801	1.563	335
	1000	27.1	26.5	1.857	1.598	335
	1100	26.7	25.8	1.807	1.590	336
	1200	26.2	25.0	1.756	1.560	334
	1400	26.1	24.8	1.739	1.529	334
	1600	25.9	24.5	1.726	1.529	307
	1800	26.5	25.5	1.786	1.618	333
3/24	0600	20.5	17.5	1.273	1.186	282
	0800	21.3	18.5	1.335	1.263	308
	1000	23.7	21.4	1.528	1.428	346
	1100					318
	1200	24.2	22.1	1.570	1.492	335
	1400	25.3	23.7	1.704	1.589	338
	1500	25.7	24.2	1.705	1.606	352
	1600	26.0	24.7	1.737	1.632	358
	1700	26.1	24.8	1.743	1.638	359
	1800	26.1	24.8	1.745	1.619	360

(continued)

TABLE 5 (continued)

Date	Time	Temp °C	Calculated Efflux Air Conditions: Mixing Ratio g/kg	Total Water Vapor 10^5 g/s	Water Vapor Above Ambient 10^5 g/s	Plant Load, MW
3/25	0600	13.5	11.1	0.829	0.724	171
	0900	22.4	19.7	1.413	1.291	332
	1000	22.8	20.3	1.453	1.325	336
	1100	23.5	21.1	1.505	1.362	336
	1300	24.4	22.4	1.590	1.433	336
	1400	25.0	23.2	1.641	1.471	338
	1500	25.2	23.5	1.660	1.484	336
	1600	25.4	23.8	1.680	1.503	327
	1700	25.6	24.1	1.699	1.516	327
	1800	25.3	23.7	1.680	1.517	328*
	1900	25.1	23.4	1.654	1.491	330
	2200	24.5	22.6	1.603	1.440	330**
3/26	0600	23.4	21.0	1.498	1.305	330
	0900	21.3	18.5	1.335	1.111	282
	1000	21.4	18.6	1.333	1.154	283
	1200	23.3	20.9	1.492	1.278	285
	1300	24.0	21.8	1.550	1.323	283
	1400	24.6	22.7	1.602	1.376	285
	1500	27.0	26.4	1.846	1.615	340
	1700	26.6	25.6	1.794	1.542	338

* - interpolated

** - extrapolated

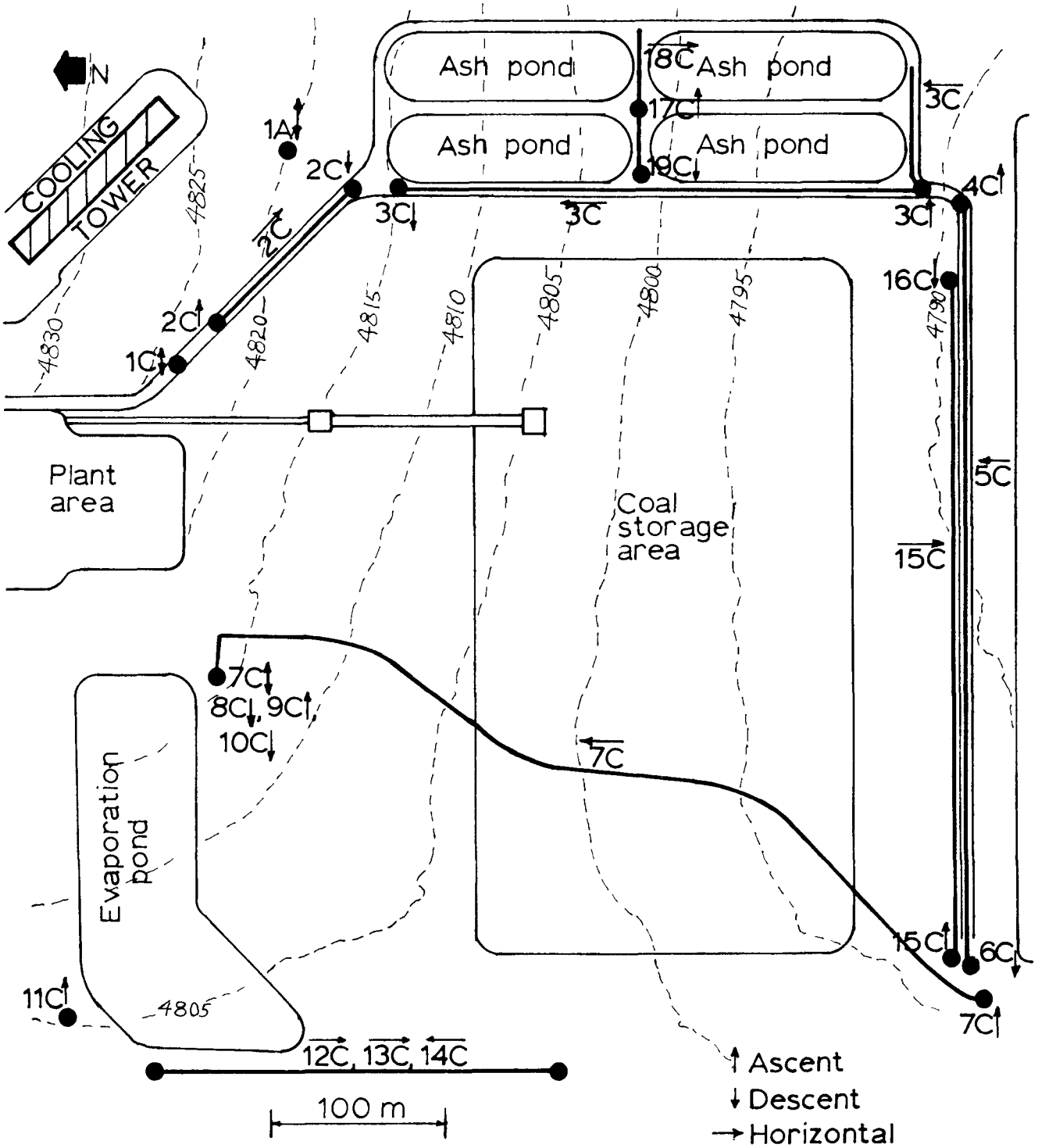

Figure 7. Balloon flight locations at Comanche.

mixing ratio, and these are presented in the form of plots of the temperature and the mixing ratio versus sonde height (or, in the case of horizontal traverses, versus time) in Figures 8 through 26. Some features of each of the profiles are discussed.

Profiles

Figure 8 shows the temperatures and mixing ratios obtained on a vertical-ascent and -descent flight on March 20, 1975. Shown for comparison are ground-level and stack-sensor temperatures, the adiabatic-lapse rate and the background mixing ratio. The air-dry-bulb-temperature values as measured on the ascent and the descent are within ±0.5°C of each other at a given height and the lapse rate is near the adiabatic value, except perhaps for the lowest 30 m. All the mixing-ratio values from the sonde are greater than the ambient value by more than experimental error, indicating that the sonde was in the vapor plume. Mixing ratio values at a given height on ascent and descent differ from each other by more than experimental error. Close examination of the wind-speed and wind-direction data from the sonde showed that while the wind direction was essentially constant at 282 ± 27° (the ± values are ± one standard deviation), there was a significant change in wind speed from 5.55 ± 0.93 m/s to 3.48 ± 0.84 m/s while the balloon was sitting at the top of the profile (before and after 1110 hours). This presumably was the cause of the significant change in mixing ratio.

Figures 9 through 26 represent flights made on March 25, 1975, time time-of-day is given on the graph.

Figure 9 shows a flight, run 1C, made close to the tower at a time when the tower was emitting a visible plume. Indeed, at times the balloon was within the visible plume and the high turbulence therein caused roll of the balloon and finally resulted in puncture of the balloon by the sonde antenna. There is a large excess of the mixing ratio above ambient. Above 80 m height, the temperatures are quite reproducible on ascent and descent, but below 80 m they are rather different. The mixing ratios are less reproducible, but show trends similar to the temperature.

Figures 10, 11 and 12 show the ascent, horizontal traverse and descent made in a single run, run 2C. Between ground level and 110 m height on the ascent, Figure 10, the wet-bulb sensor was not functioning properly so there are no mixing-ratio data. The mixing ratio exceeded ambient for the entire duration of this flight.

Figures 13, 14 and 15 represent the ascent and two horizontal traverses in run 3C. Near the end of the north traverse, Figure 15, the balloon entered the visible plume and once again the extreme turbulence caused balloon roll and the puncture of the balloon by the sonde antenna. This and the earlier observation indicate the high degree of turbulence in the visible plume. Outside the visible plume the air was calm, the bouncing and rolling commenced immediately upon entering the visible plume. These observations suggest that a plume model must account for the high degree of turbulence within the visible plume.

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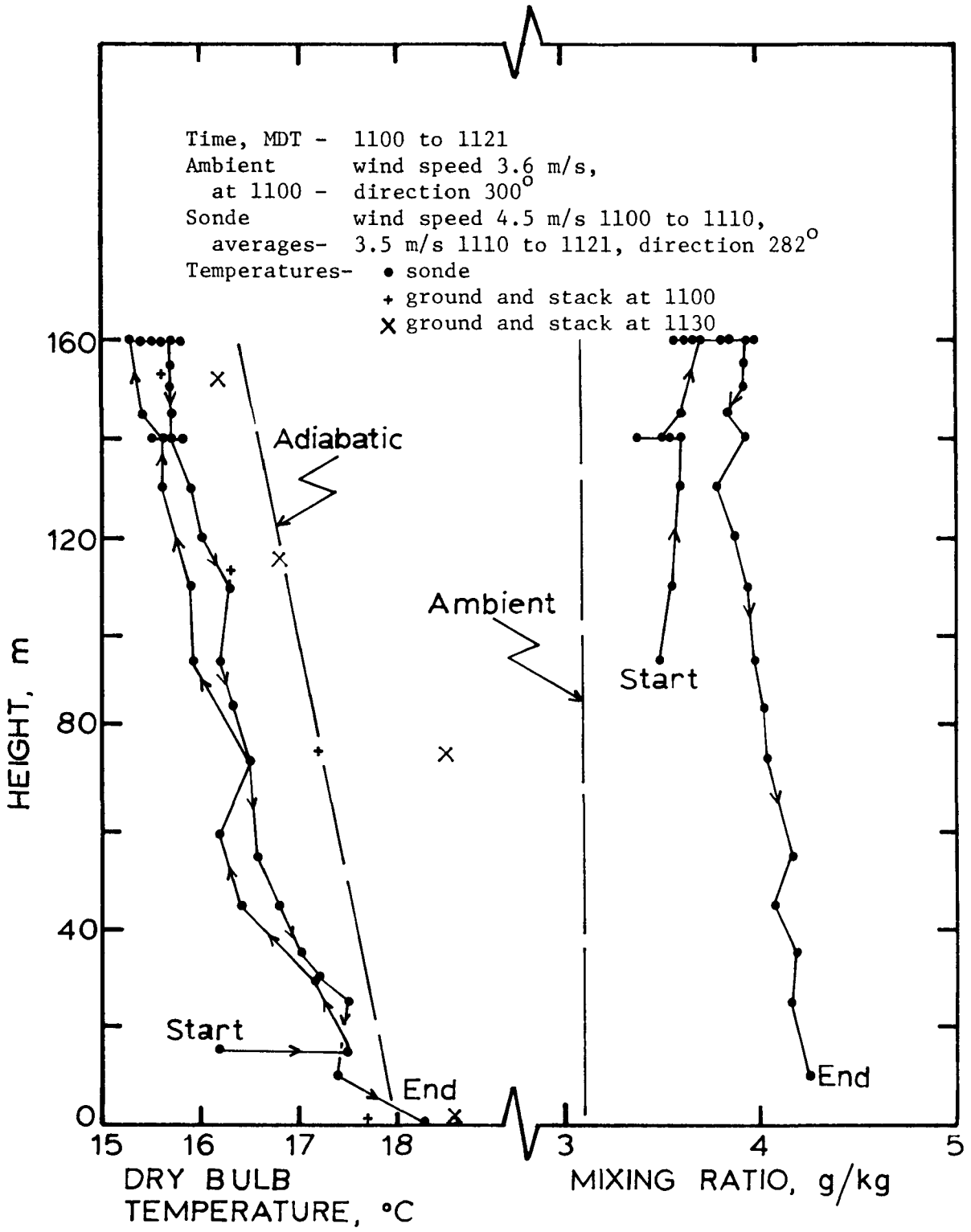

Figure 8. Run 1A, ascent and descent, March 20, 1975, at Comanche.

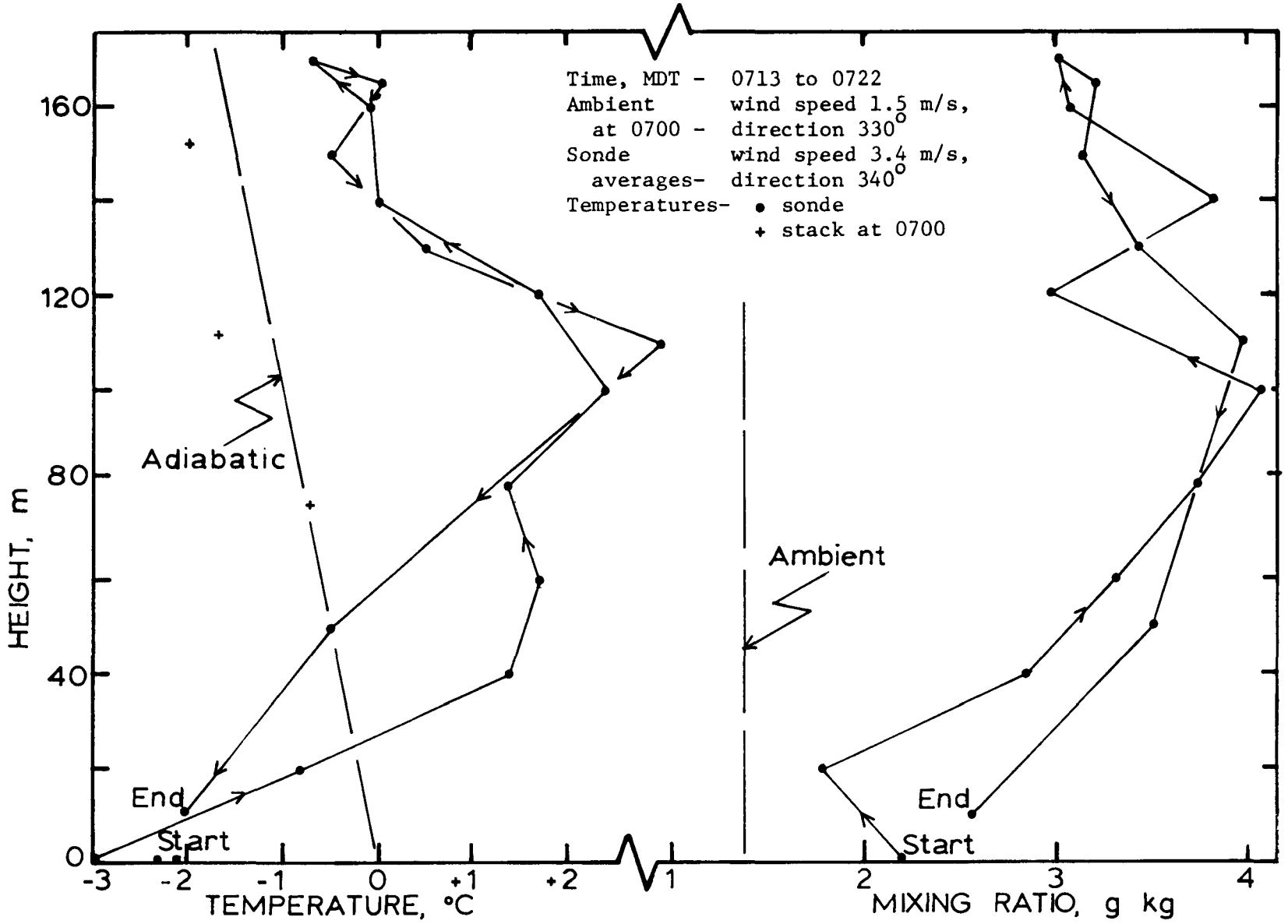

Figure 9. Run 1C, ascent and descent, March 25, 1975, at Comanche.

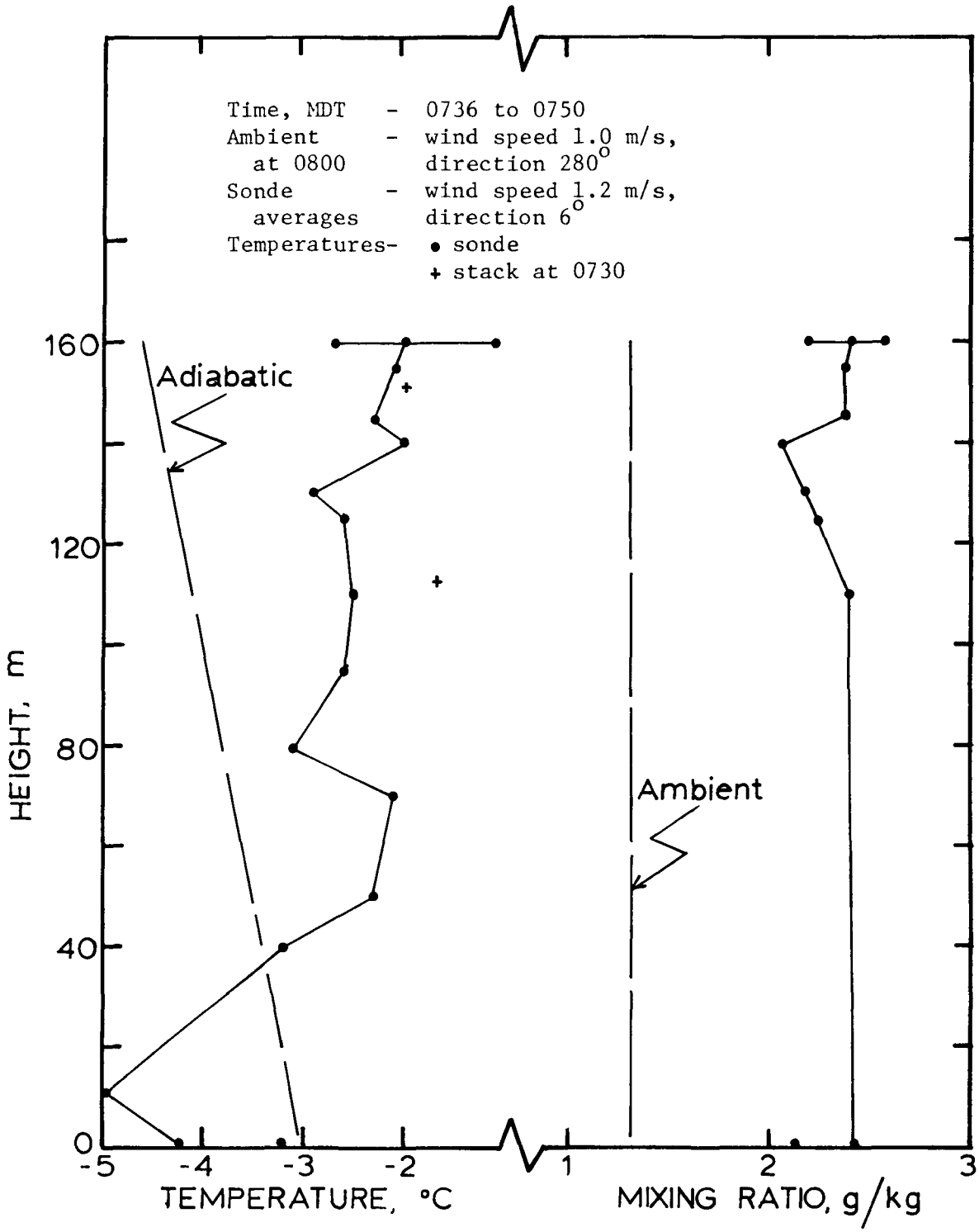

Figure 10. Run 2C, ascent, March 25, 1975, at Comanche.

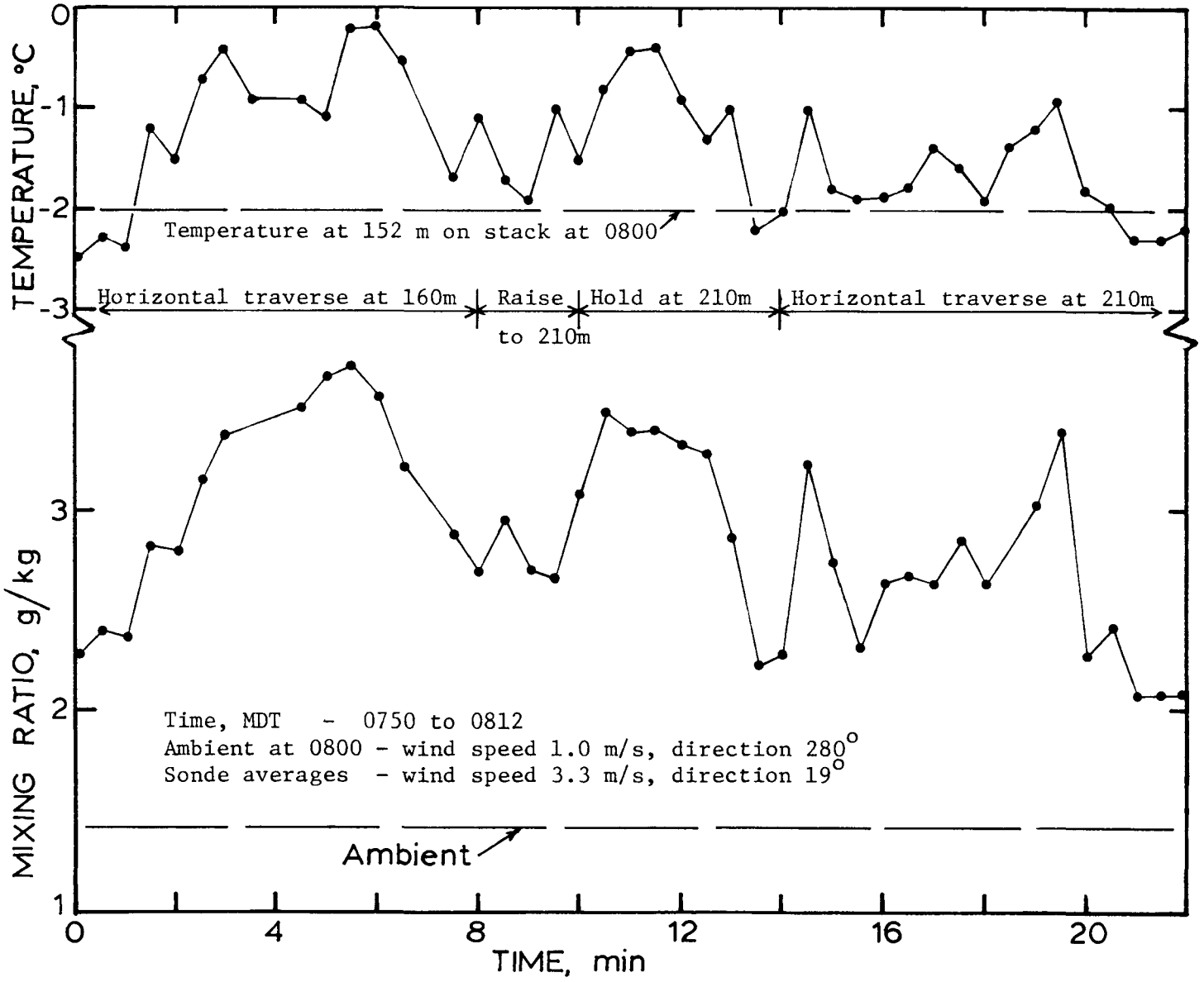

Figure 11. Run 2C, horizontal traverse, March 25, 1975, at Comanche.

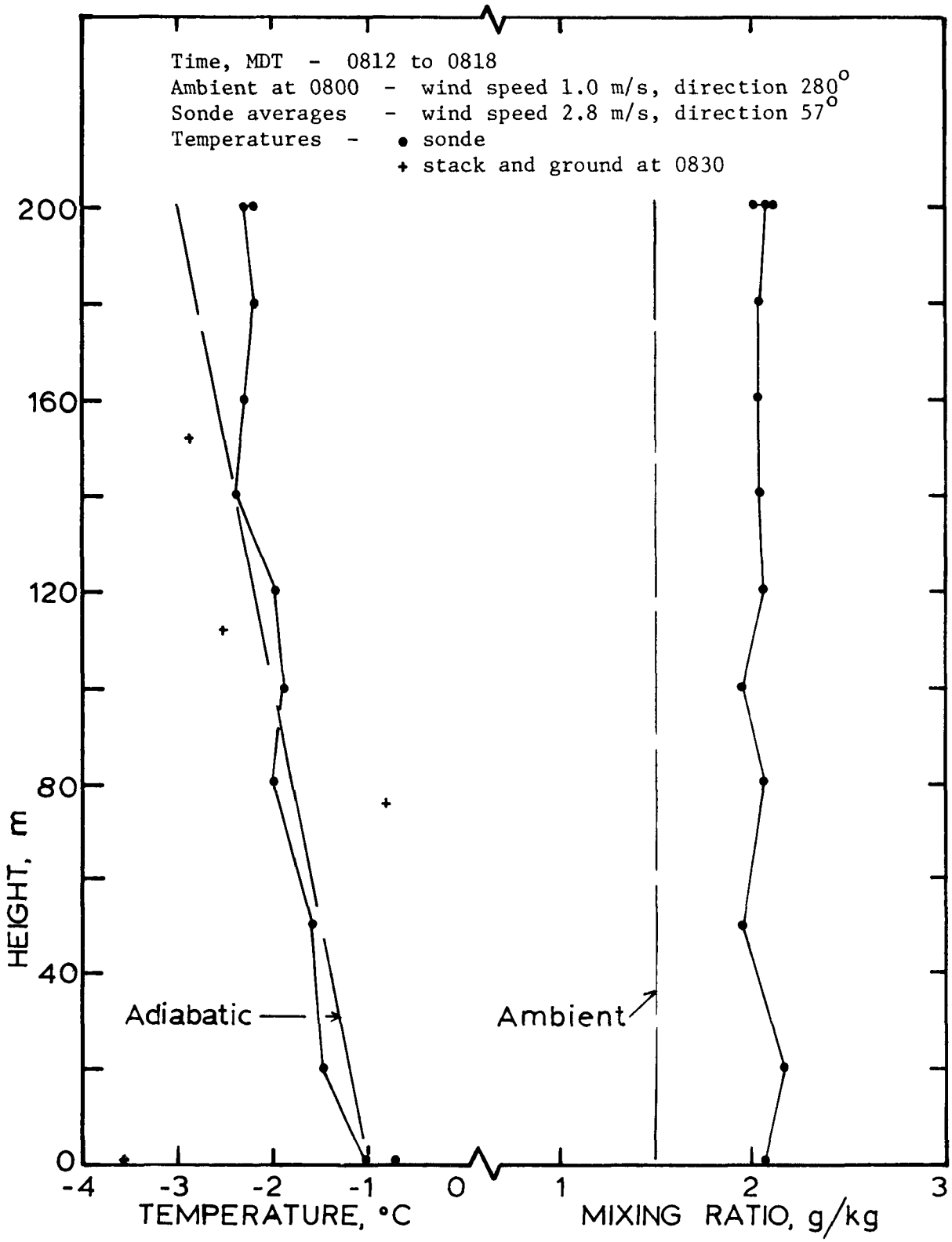

Figure 12. Run 2C, descent, March 25, 1975, at Comanche.

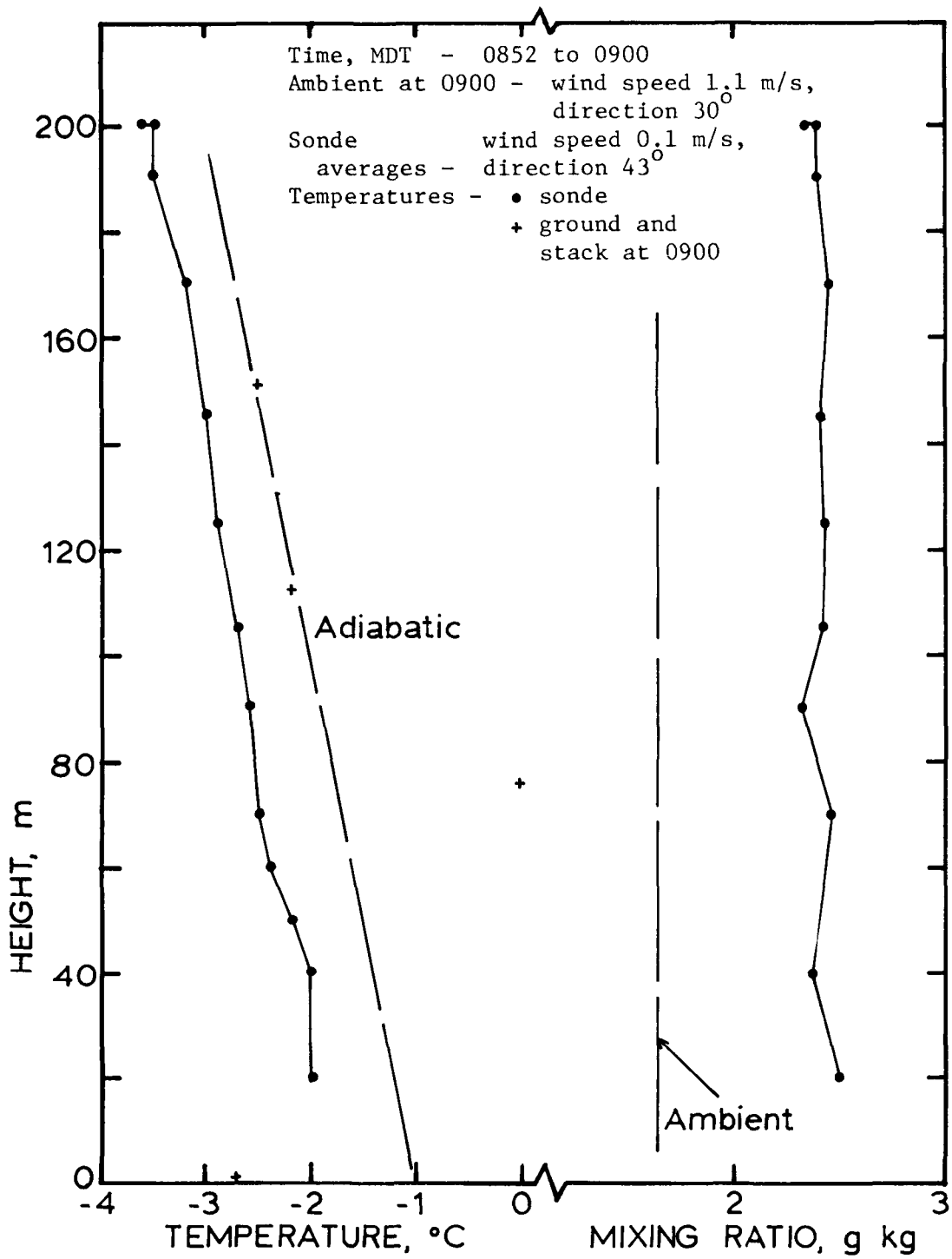

Figure 13. Run 3C, ascent, March 25, 1975, at Comanche.

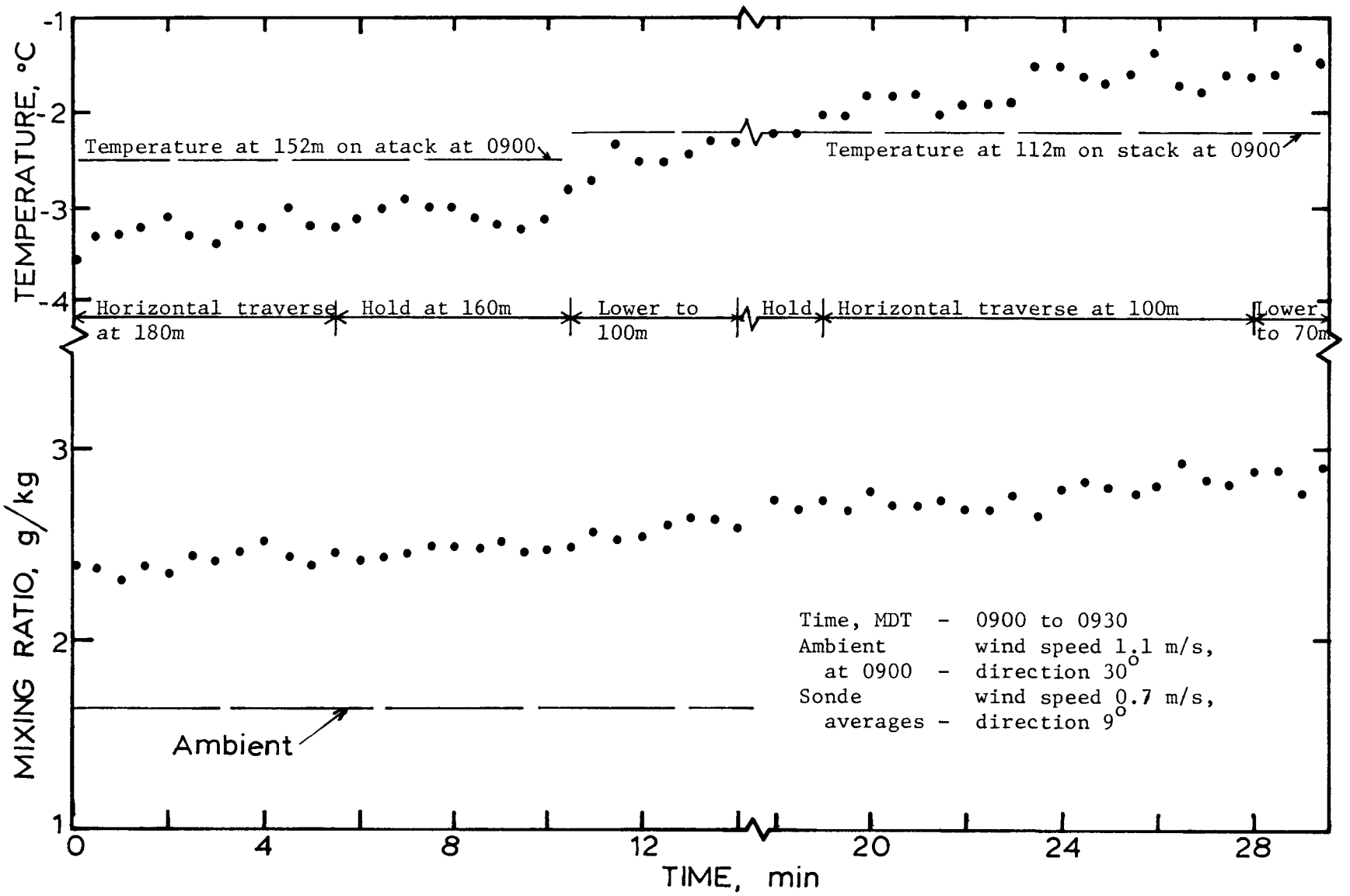

Figure 14. Run 3C, horizontal traverse west to east, March 25, 1975, at Comanche.

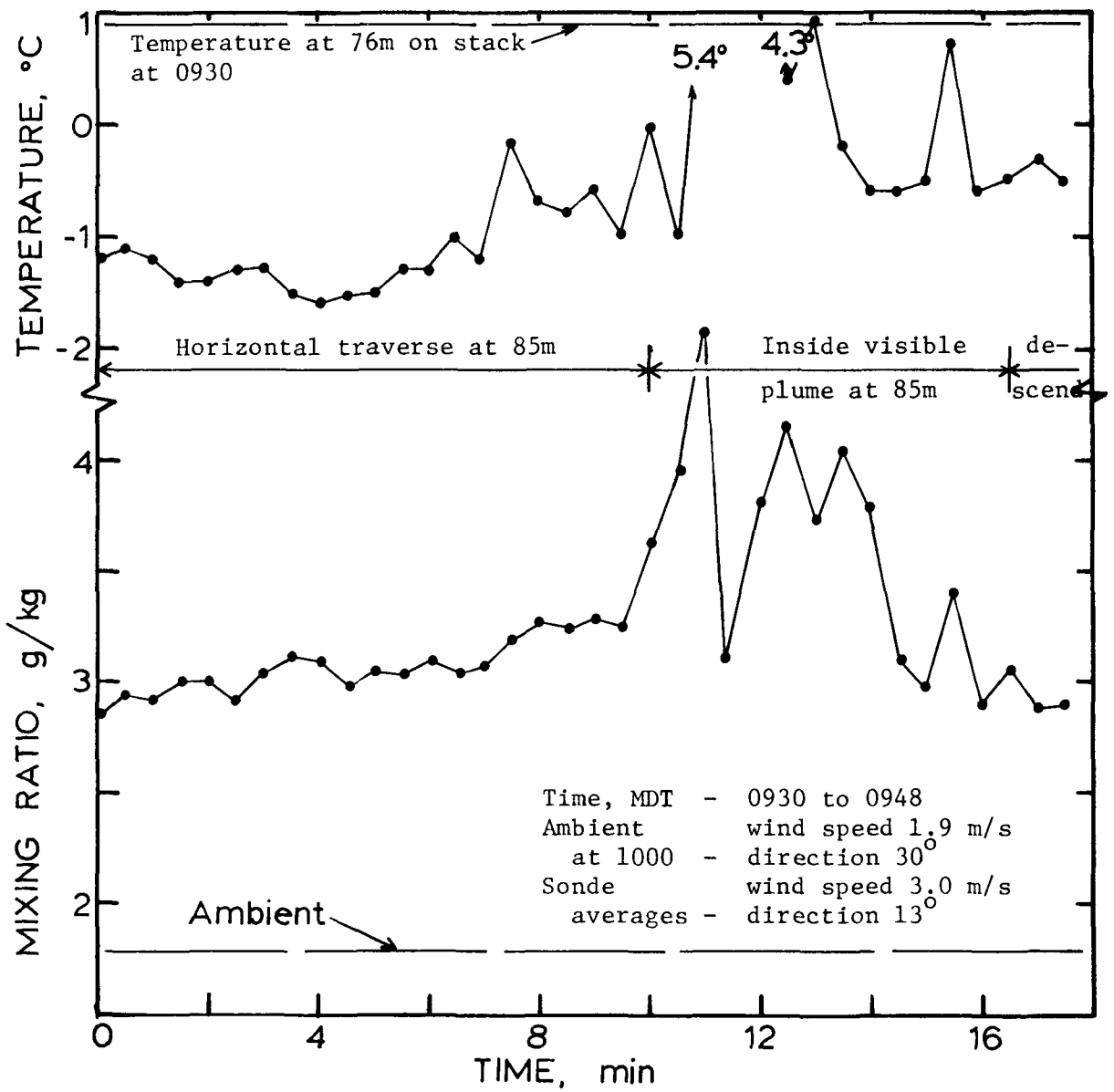

Figure 15. Run 3C, horizontal traverse south to north, March 25, 1975, at Comanche.

There are other features of run 3C worthy of note. Throughout this run, whether within the visible plume or not, the ambient mixing ratio was exceeded at the sonde location. Upon entering the visible plume, the mixing ratio values are at or near saturation corresponding to the local dry-bulb temperature. Saturated values in the visible plume lend support to the validity of the sonde measurements. Values less than saturation and the rapid changes in mixing ratio suggest, as was visually observed, that near the edge of the visible plume there exist unsaturated as well as saturated regions in rapid fluctuation and mixing. The picture given by the sonde measurements corresponds to that which was observed visually. Further, a rapid descent was made upon puncture of the balloon and when the visible plume was left the mixing ratio dropped to lower and more stable values.

A shift in wind direction around 0900 hours led to a search for the plume. At the low wind speeds prevalent, it was difficult to determine the plume location far downwind from the tower, even though there was still a visible plume near the tower. Runs 4C, 5C, 6C and 7C, Figures 16, 17, 18, 19 and 20, were made while searching for the plume.

In Figures 16, 17 and 18 the mixing ratio remained remarkably constant and agreed, within experimental error, with the background value, another source of confirmation of the sonde values. The mixing ratio was always about 5 percent in excess of the background value. This could be due to differences in calibration, but it might also be due to residual excess water vapor, since the plume had passed through the areas of measurement somewhat before the balloon. However, the differences cannot be considered significant.

The early part of run 7C, Figure 19, showed background, but the latter part of the horizontal traverse and the descent and ascent, Figure 20, began to show excess water vapor above ambient. The edge of the plume had been found.

Figure 21, run 8C, shows a mixing ratio exceeding ambient by an amount essentially equal to the experimental uncertainty up to 140 m and equal to ambient above that.

Figures 22 and 23, runs 9C and 10C, show substantial excesses of mixing ratio above ambient between about 50 and 250 m height. These two flights show excellent vertical profiles of the plume at a time when the balloon was downwind of the cooling tower. Conditions at the top of these flights are essentially background, so the profiles include the entire vertical section of the plume. These two profiles are mildly suggestive of a bimodal mixing ratio, i.e., two maxima in mixing ratio in the vertical direction. It was frequently visually observed that, at some point downwind of the tower, the visible plume tended to split into two sections, one of which continued to rise and to be visible and a second which tended to move horizontally and soon to become invisible.

Figure 24, run 11C, shows an excess mixing ratio somewhat greater than the experimental uncertainty. By the time of this flight the wind had shifted away from the measurement location again.

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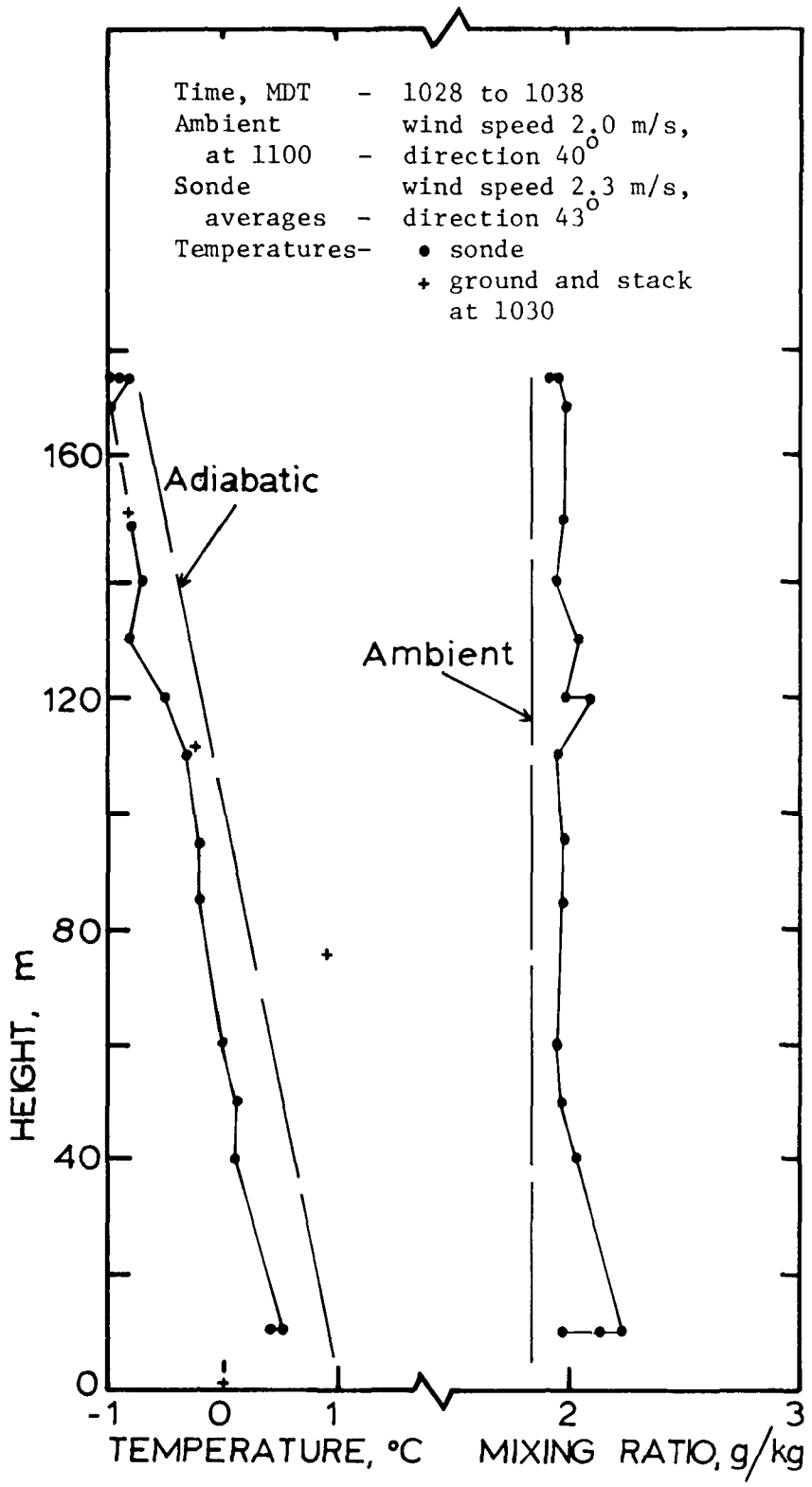

Figure 16. Run 4C, March 25, 1975, at Comanche.

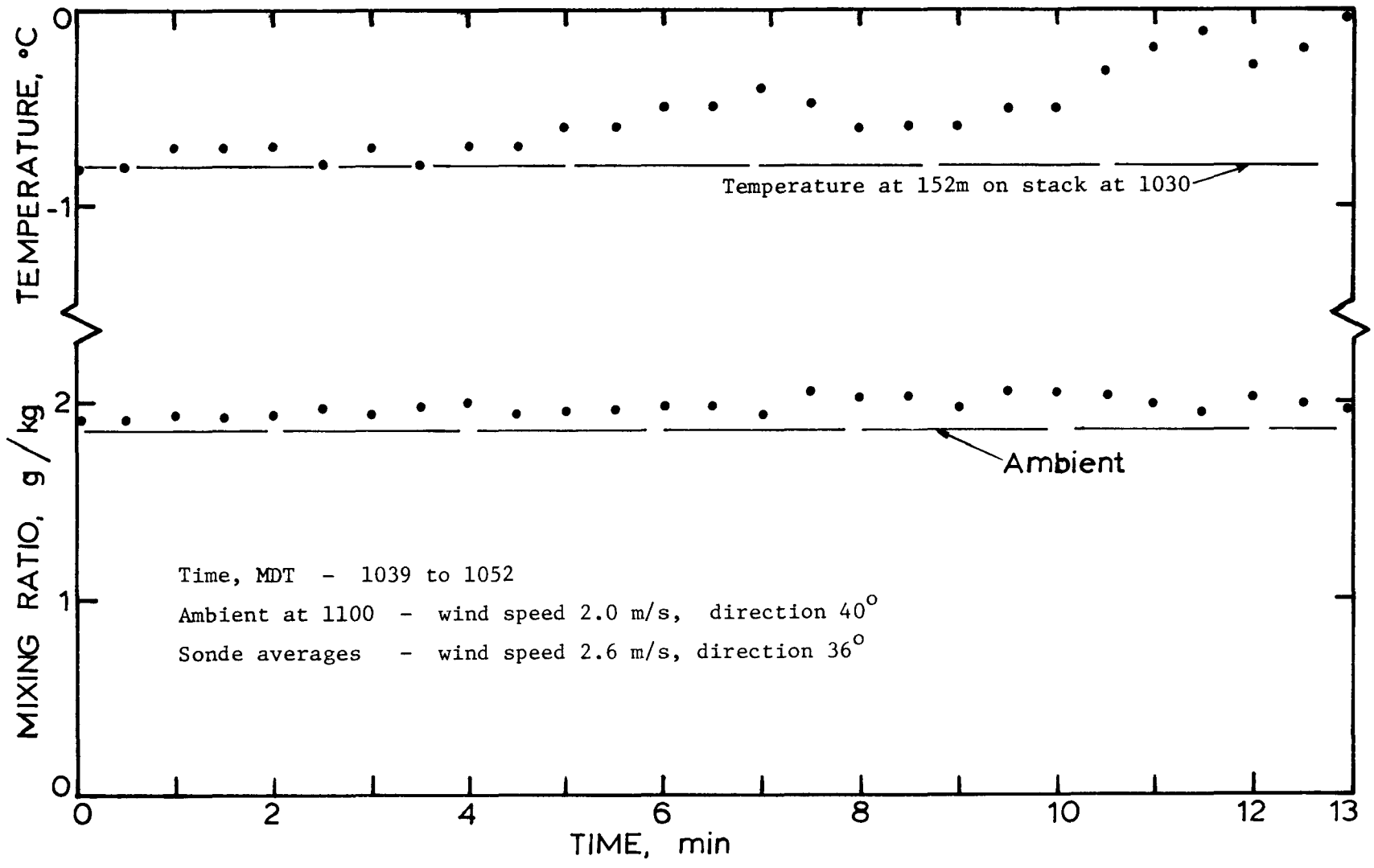

Figure 17. Run 5C, March 25, 1975, horizontal traverse at Comanche.

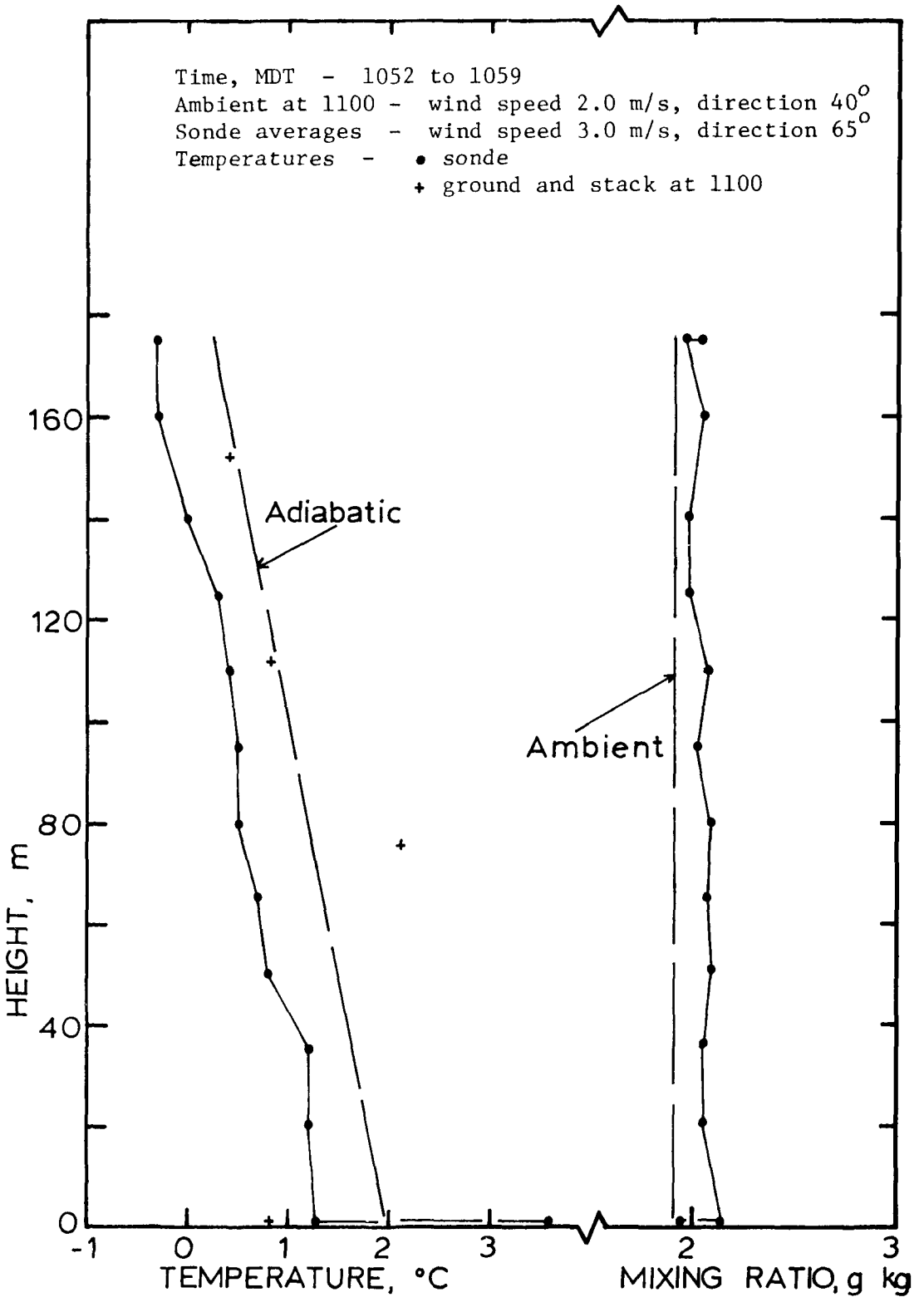

Figure 18. Run 6C, March 25, 1975, at Comanche.

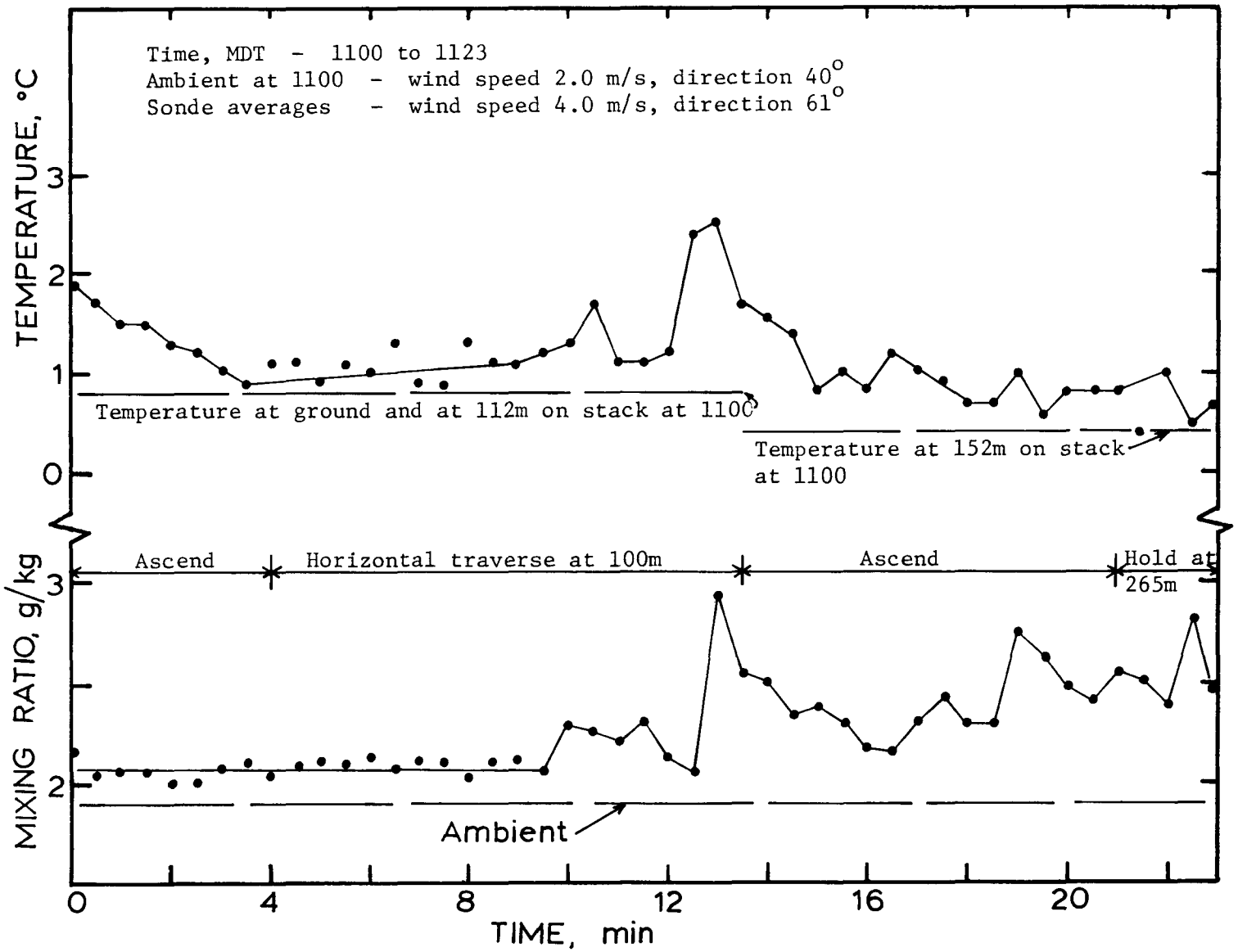

Figure 19. Run 7C, ascent and horizontal traverse, March 25, 1975, at Comanche.

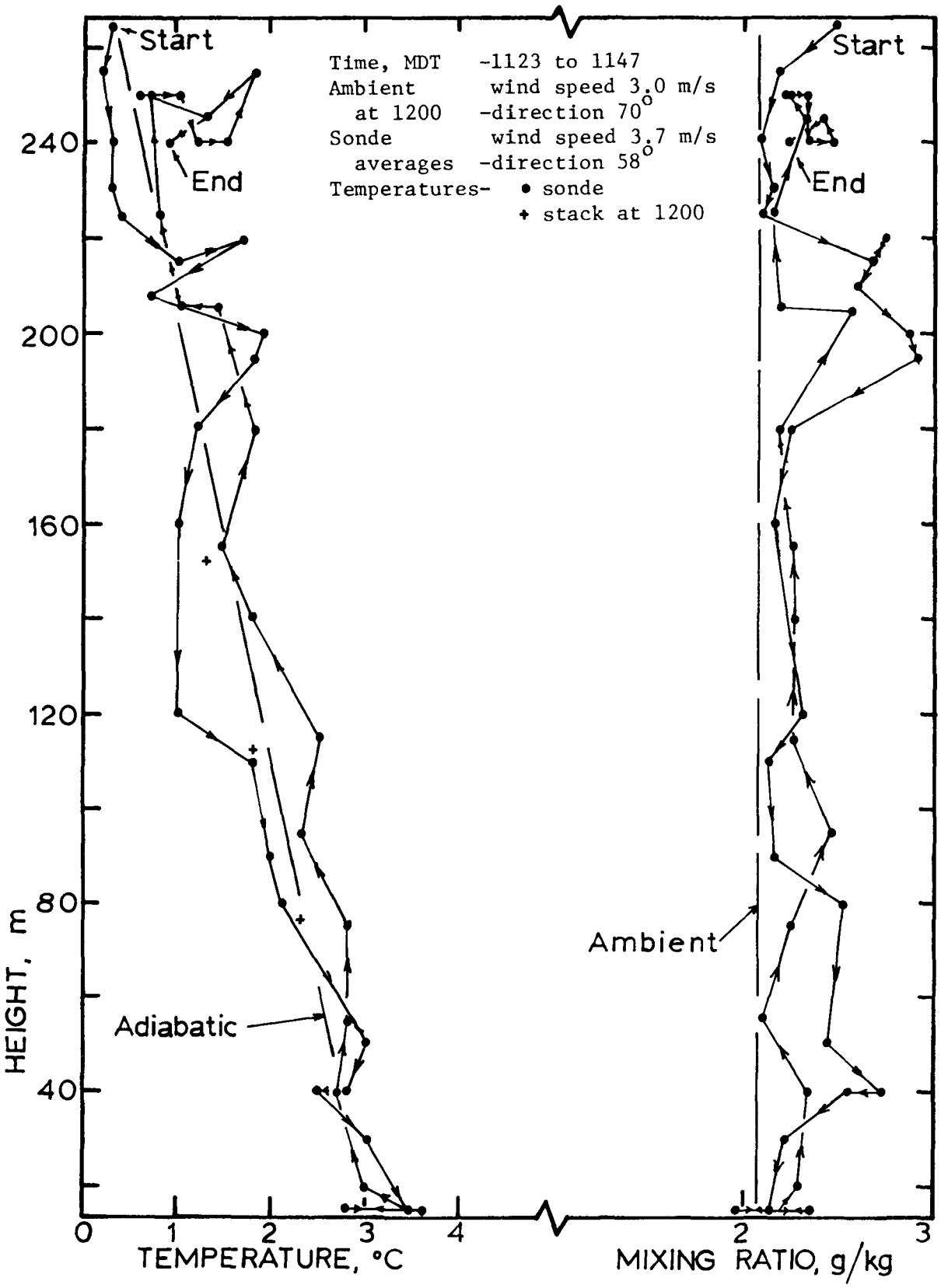

Figure 20. Run 7C, descent and ascent, March 25, 1975, at Comanche.

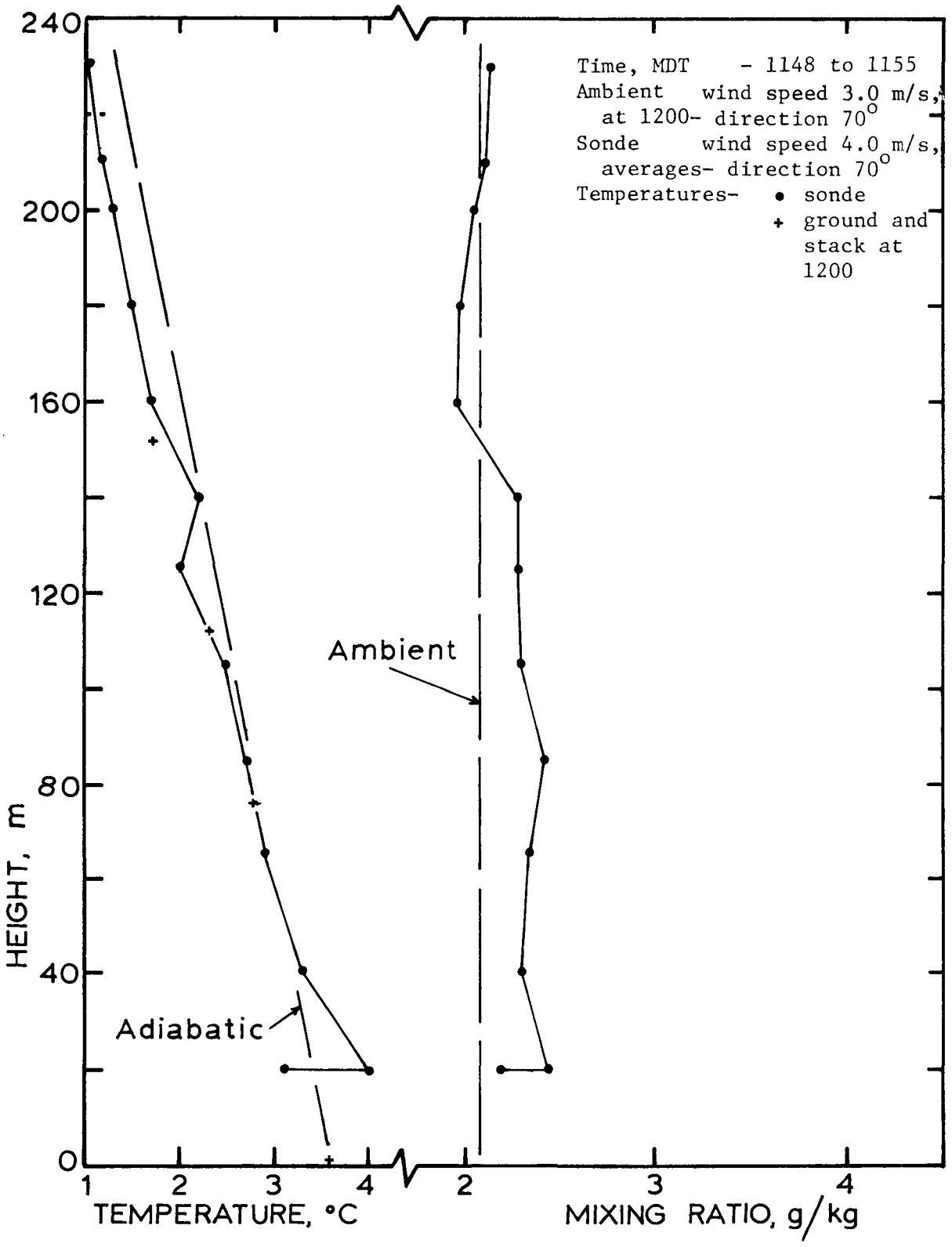

Figure 21. Run 8C, descent, March 25, 1975, at Comanche.

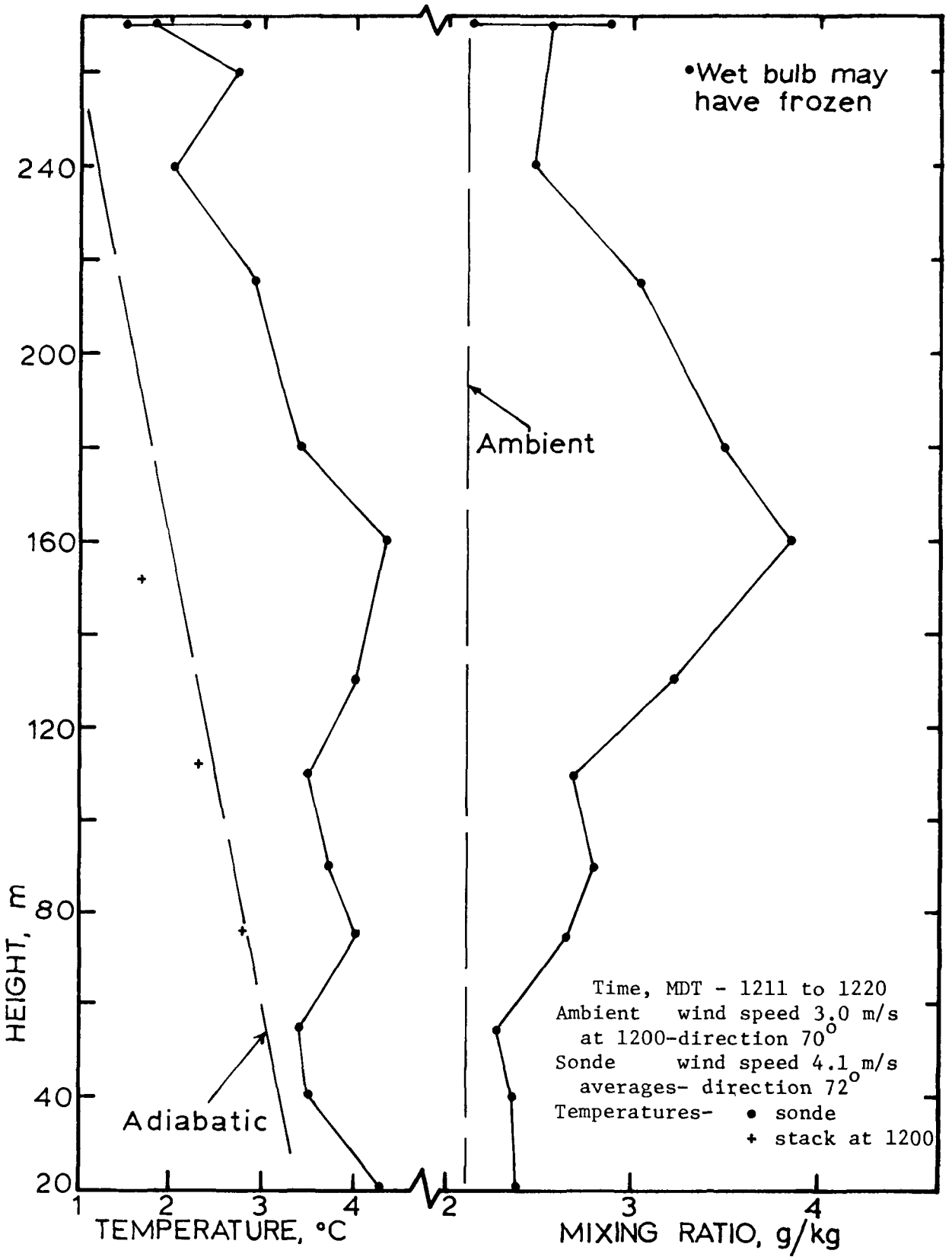

Figure 22. Run 9C, ascent, March 25, 1975, at Comanche.

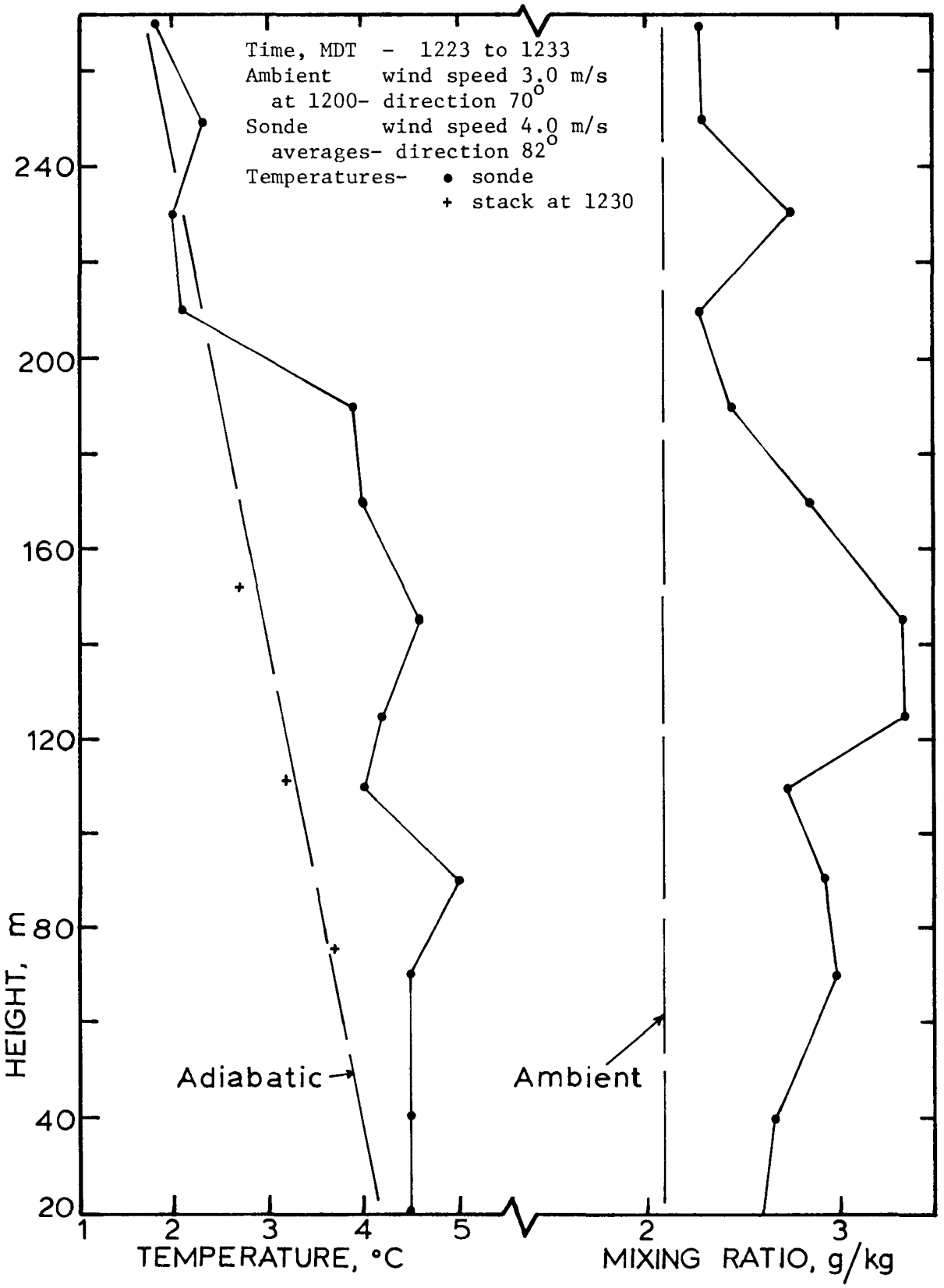

Figure 23. Run 10C, descent, March 25, 1975, at Comanche.

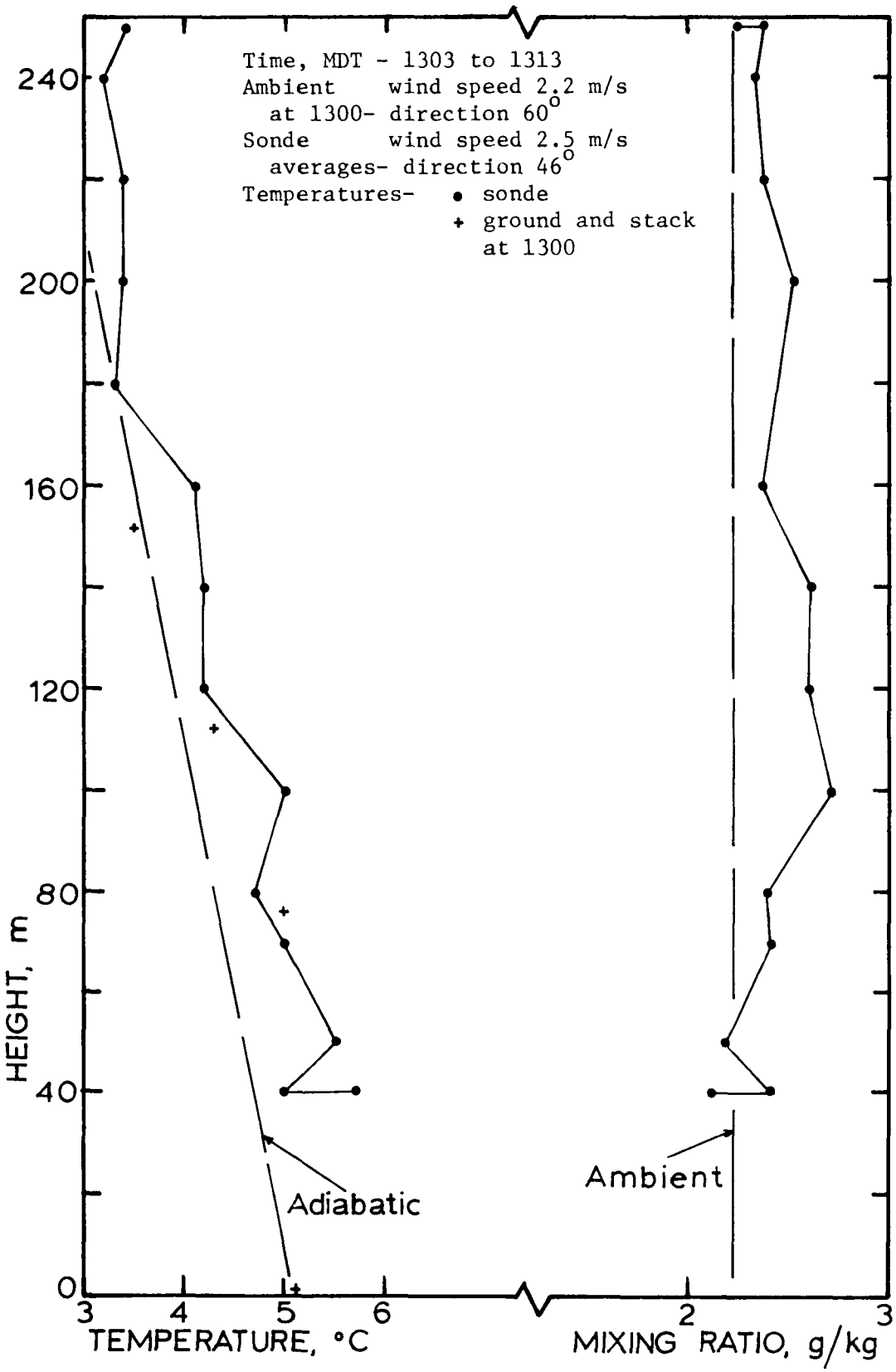

Figure 24. Run 11C, ascent, March 25, 1975, at Comanche.

Figure 25 includes runs 12C, 13C and 14C, continued portions of a horizontal traverse, which show essentially background. The sonde readings consistently exceeded background by an amount about equal to the experimental uncertainty.

Figure 26, run 15C, again shows the mixing ratio exceeding background by an amount about equal to the experimental uncertainty. The constancy of the mixing ratio with height suggests that this probably is background. The wet-bulb thermistor on the sonde failed at the top of the ascent during this run and did not work thereafter. Apparently a short developed in the electronics, as only a full-scale signal was obtained. Runs 16C through 19C have not been plotted, since no wet-bulb temperatures, hence no mixing ratios were obtained. The dry-bulb-temperature values suggested that flight 16C may have caught the plume but the other three probably did not. The wind was shifting in direction and increasing in speed during this period. Following run 19C, the balloon was moved and, while being held at about 40 m height, the tether line snapped and the flight gear was lost.

Discussion

Wind speed and direction data from the balloon sonde were compared with the average background results in Table 2. The wind direction shows excellent agreement between the ground stations and the sonde, always well within the uncertainty of the values. The wind speed from the sonde always exceeded the average from the ground stations, usually by about 1 m/s. The higher wind speeds from the sonde may be due to differences in calibration, or due to the fact that the ground values are averaged over a longer (one hour) period (although this seems unlikely as the sonde values consistently exceeded the ground station values, rather than differing randomly). These differences may well be a result of the normal wind-velocity profile near the ground, since most of the sonde values are from aloft. Changes in wind speed with height are not noticable in a single flight, but when speeds aloft are averaged, they would be expected to exceed those near the ground. This question cannot be resolved with the present data.

The wind speed data from the two channels of a data frame were averaged separately and found to agree. It is suggested that the average wind speed and wind direction values from the sonde be used, since they are representative of the conditions at the measurement location.

Flights which found essentially background conditions are of some value in model evaluation. Since they show locations outside the plume, they indicate where the plume was not. A model must agree with the absence of the plume as well as with its presence.

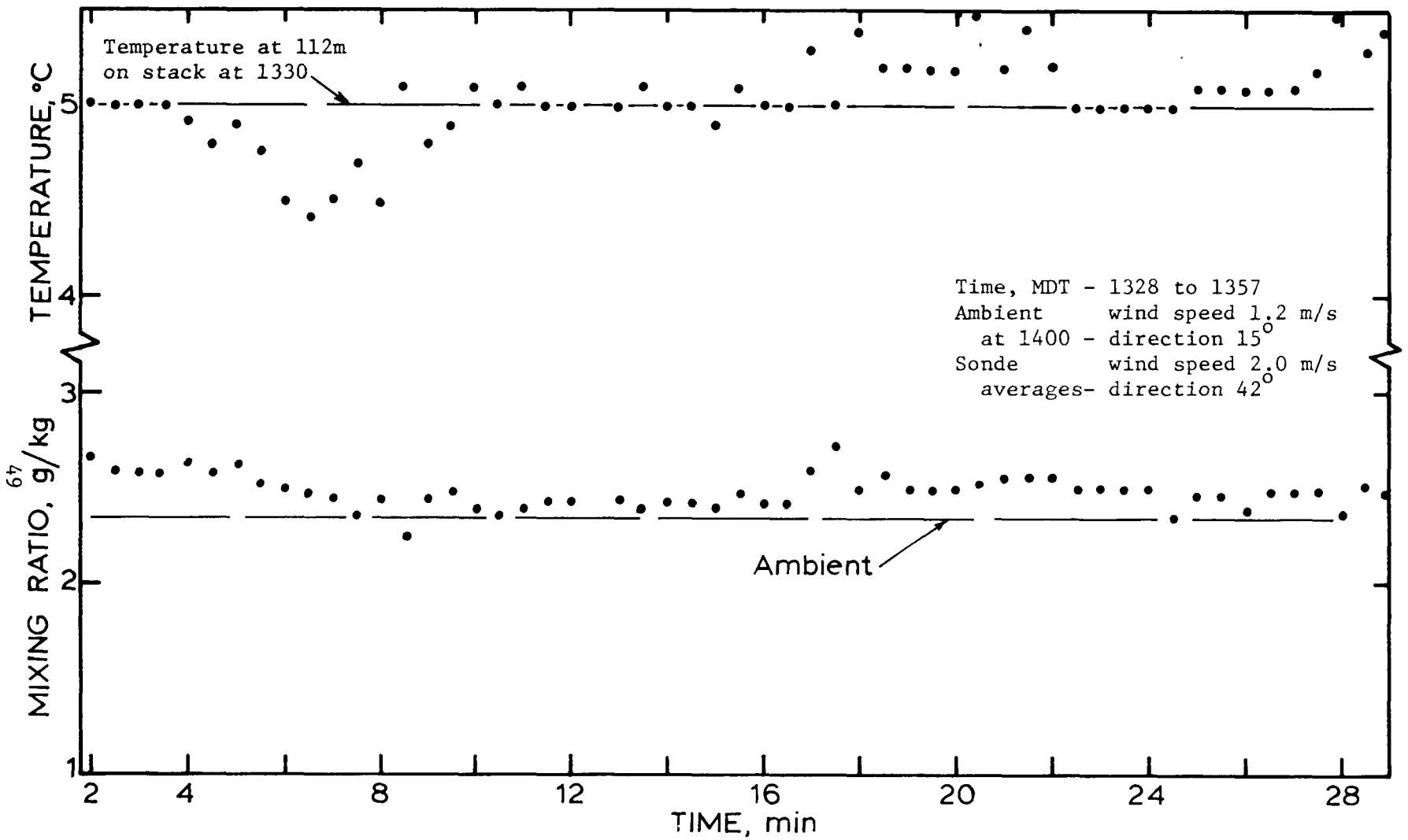

Figure 25. Runs 12C, 13C and 14C, horizontal traverses at 120m, March 25, 1975, at Comanche.

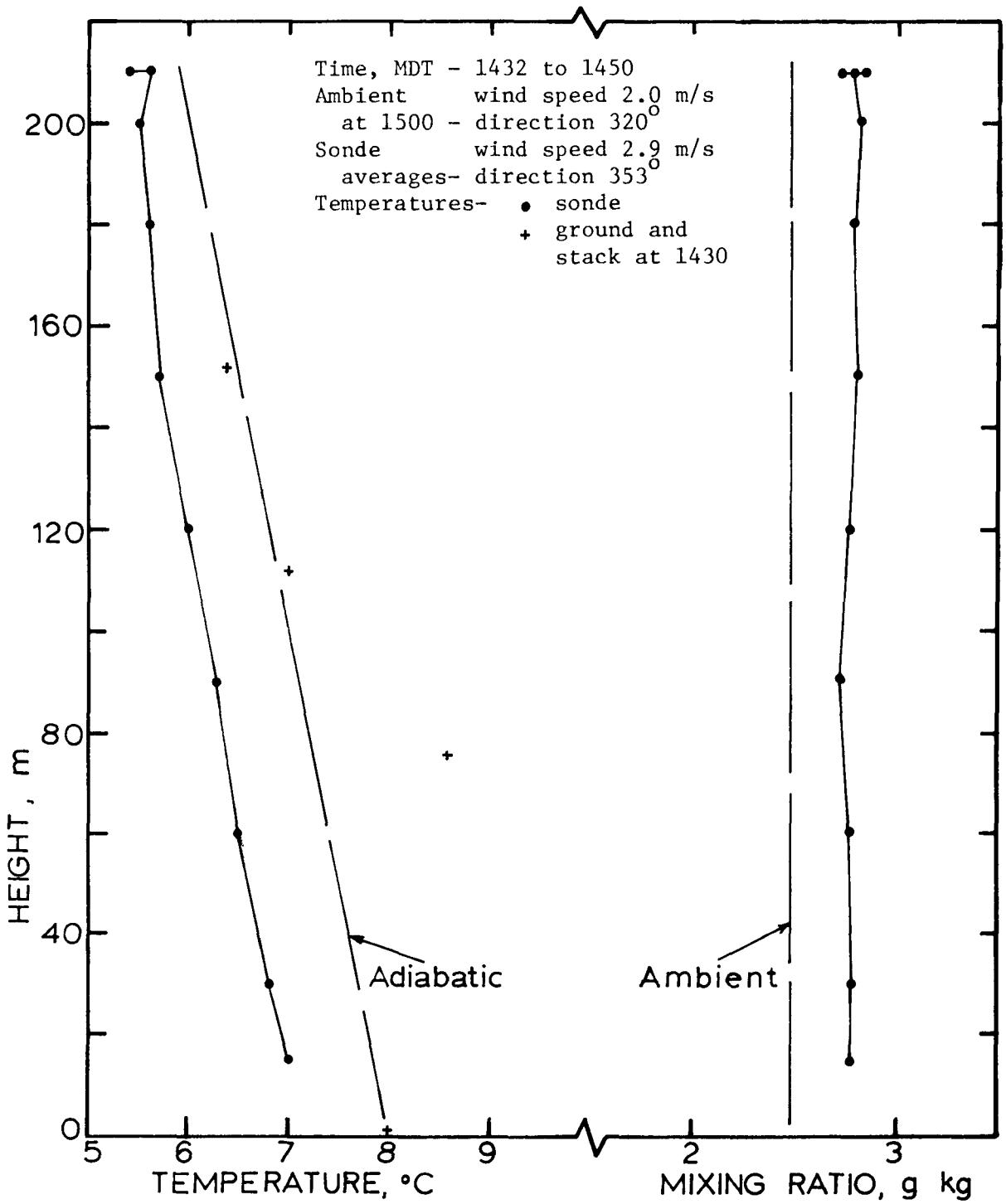

Figure 26. Run 15C, ascent, March 25, 1975, at Comanche.

SECTION 6

COOLING POND RESULTS

AMBIENT DATA

Ambient conditions were measured only with the MRI and the Assman at Valmont. There were no backup measurements, so the ambient data are somewhat less certain than the values for Comanche. This is especially true of the ambient temperature because of the resolution on the MRI temperature scale (10°F, 5.6°C). Thus the uncertainty in the ambient temperature is of-the-order-of ±2°C. Ambient data for the measurement periods at Valmont are presented in Table A-2, Appendix A.

SOURCE DATA

It is impossible to measure directly the evaporation from large, operating cooling ponds. Rather, methods developed in earlier EPA projects and other studies must be used along with weather and load data to estimate the evaporation rate. There had been an earlier study of evaporation losses from the Valmont lakes which was of considerable help in the present project (5).

The state-of-the-art in cooling pond evaporation work is well summarized in a recent EPA report (6). The basic approach described therein has been followed with modifications appropriate to the particular situation. Since no measurements were made of the pond temperatures, only the PSC condenser-inlet and outlet temperatures and the water flowrate were available as basic data. The cooling water flowrate was taken as constant at 4.23 m^3/s (670,000 gal/min), the design rate.

The pond areas were: Owen Reservoir, 367,000 m^2 (90 acres); Hillcrest Lake, 489,000 m^2 (120 acres); and Valmont Lake, 1,300,000 m^2 (320 acres).

The total-surface-heat exchange, H_t, of a pond is represented by (6):

$$H_t = H_s + H_a + H_b + H_e + H_c \tag{7}$$

At steady-state,

$$H_t + H_p = 0 \tag{8}$$

and

$$H_p = \frac{m_w C_{pw}}{A} (T_{wa,out} - T_{wa,in}) \tag{9}$$

At steady-state it is assumed that the quantity and temperature of the water in the pond remain constant. For a natural, unheated pond, H_t is zero at steady-state.

The solar and sky radiation terms were estimated from solar data (6), the ambient temperature and the cloud cover at the time of the measurements. The terms for back radiation, evaporation and convection are given by:

$$H_b = .97\ \sigma\ (T_s + 273)^4 \tag{10}$$

$$H_e = f(w)(p - p^*_{sw}) \tag{11}$$

$$H_c = C\ f(w)\ (T - T_s) \tag{12}$$

When the surface-water temperature, T_s, is unknown, equation (7) must be solved iteratively. In the Valmont situation, there were two ponds, Owen and Hillcrest, in the cooling loop, and they were not at the same temperature. It was assumed that the surface temperature of each pond was uniform. Further it was assumed, following Throne (5), that the surface temperature of Hillcrest Lake was equal to the measured condenser-inlet temperature plus 1.1°C (2°F). This left only the temperature of Owen Reservoir as an unknown. However, a wind function must be chosen.

Several wind functions, including that recommended by Throne (5) for Valmont, were used. Equation (7) with the terms given in equations (9), (10), (11) and (12) substituted, was solved iteratively for the surface temperature of Owen Reservoir. Bounds were established for realistic values of the temperature of Owen Reservoir. It could not be less than the temperature of Hillcrest Lake and further, it was highly unlikely (although not impossible) that it would exceed the condenser-discharge temperature. Most wind functions were found to give temperatures clearly either too high or too low. The wind function recommended by Brady (7),

$$f(w) = 2.21 + .111\ u^2 \tag{13}$$

was found to give the most realistic results and it has been used in the calculation in this work.

Once the surface temperature had been established, the evaporation rate was given by equation (11). This same procedure and the same wind function was used to estimate the surface temperature and evaporation rate of Valmont Lake, the unheated pond. The results of these calculations are summarized in Table 6. Even with the Brady wind function, on two days the calculated temperature of Owen Reservoir exceeded the condenser-discharge temperature. It seems probable that either the wind function gave too low a value or that the estimated net solar input was too high (or both) on these days.

TABLE 6. ESTIMATED POND EVAPORATION RATES

Date	Condenser Temp., °C In	Condenser Temp., °C Out	Avg. Wind Speed* m/s	Ambient Air Temp. °C	Ambient Water Vapor Partial Pressure, mm Hg	Calculated Values: Temp., °C Owen Res.	Evaporation Rate, 10^4 g/s: Owen Res.	Hill-crest Lake	Val-mont Lake	Total
3/8/74	12.2	22.8	1.8	2.8	5.30	20.9	2.10	1.29	0.44	3.84
3/13	13.3	23.9	1.2	4.7	2.77	22.2	2.54	1.87	2.20	6.61
3/15	13.9	24.4	1.8	-1.0	3.22	22.2	2.67	2.10	0.75	5.43
4/8	16.7	26.7	1.2	3.7	2.92	29.8	4.21	2.41	1.83	8.45
4/12	17.8	27.2	2.1	11.8	2.51	29.7	4.82	3.06	5.38	13.26
4/14	15.6	23.3	2.7	0.9	2.45	19.5	2.73	2.94	1.89	7.56

* from MRI ground station

Pond-heat balances are usually done with monthly or daily-average data. Data for the measurement period (about two hours on most days) were used herein. This may introduce some error in the calculations tending to overestimate the pond temperature, since the pond temperature probably changes less rapidly than was indicated by using short-term data.

Since the values of pond-evaporation loss must be estimated, and since the radiation terms in the overall pond heat balance are relatively quite large, the reliability of the estimated evaporation values must be questioned. Differences of as much as 30 percent in evaporation rates occurred with different wind functions. The assumption of steady-state, the use of short-term weather data and the use of the Brady wind function all probably tend to make too high the estimated pond temperatures.

BALLOON SONDE DATA

Figure 27 shows the location of the balloon flights on the Valmont Site (the run number each day corresponds to the location number on the map). The MRI weather station was at location G1 through March 13, 1974 and at G2 thereafter.

Computer-generated plots of measured-wet- and dry-bulb temperatures and calculated-dew-point temperatures vs. height and plots of humidity, g/m^3, are shown for both the ascent and the descent of several flights in Figures 28 through 31 and 33 through 37. These figures show results from four flights on March 13, three on March 15, one on April 12 and one on April 14, 1974.

Eight other flights made on March 8 and 15 and April 8, 12 and 14 all showed essentially background conditions, so graphs of these profiles are not included. Fogging did not occur on any of the measurement days. Wind speed profiles are not shown, but the average and the range of wind speed indicated by the sonde anemometer are given on the profile plots. Wind direction was not measured with the sonde used at Valmont.

The conversion from humidity, in g/m^3, to mixing ratio, in g/kg, is given by

$$mr = \frac{RT}{M(P - p)} H$$

The conversion is $mr = 0.946\ H$ for a pressure of 625 mm Hg, a temperature of 0°C, and an H of 4.84 g/m^3 (saturated at 0°C). The conversion is always near 1, but varies slightly with T, P and H.

The results on March 13, 1974 are interesting because of the existence of a temperature inversion that day as is clearly shown by the temperature profiles in Figures 28, 29, 30 and 31. The height of the inversion was around 60 m, but changed rapidly, varying from about 30 to about 100 m. The humidity values shows significant excesses above ambient up to the inversion height and then rapid decreases to essentially ambient above that height. Thus, the

(Text continues on page 60)

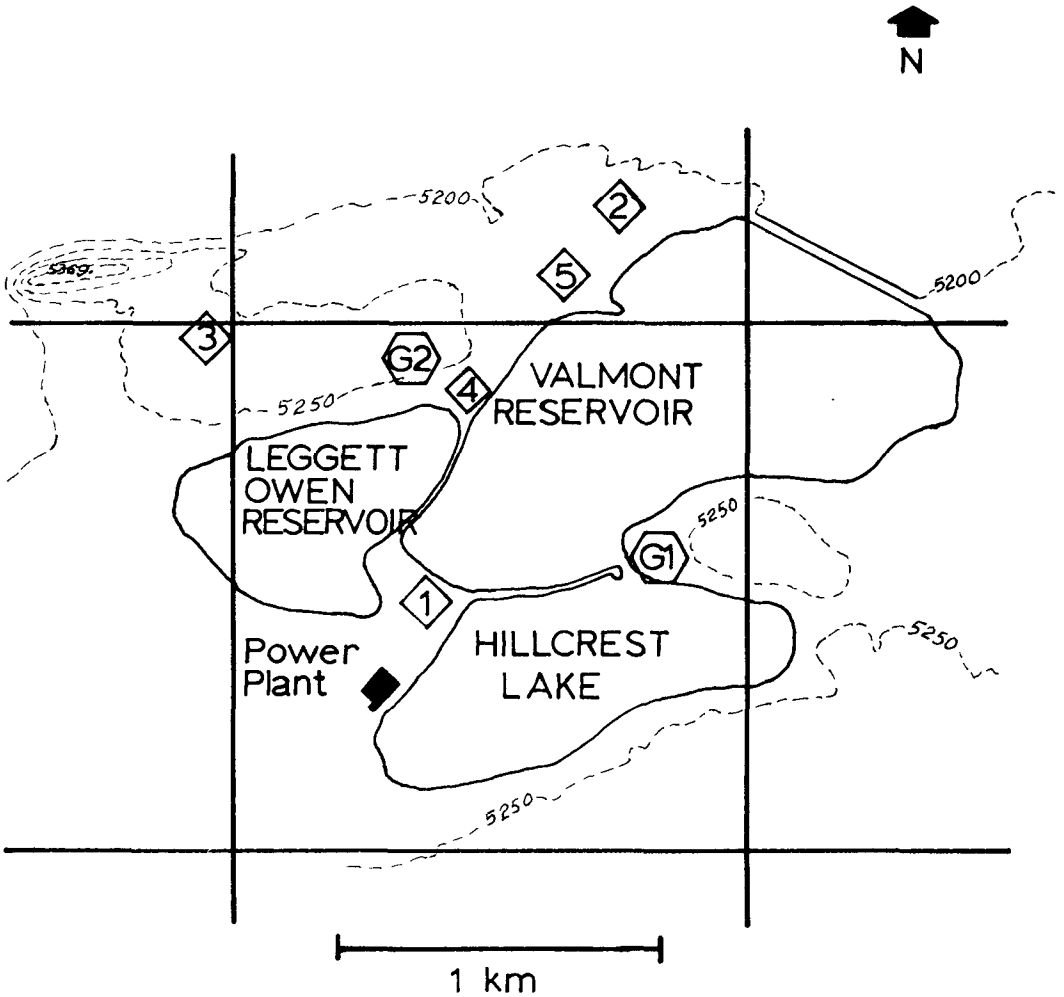

Figure 27. Balloon flight locations at Valmont.

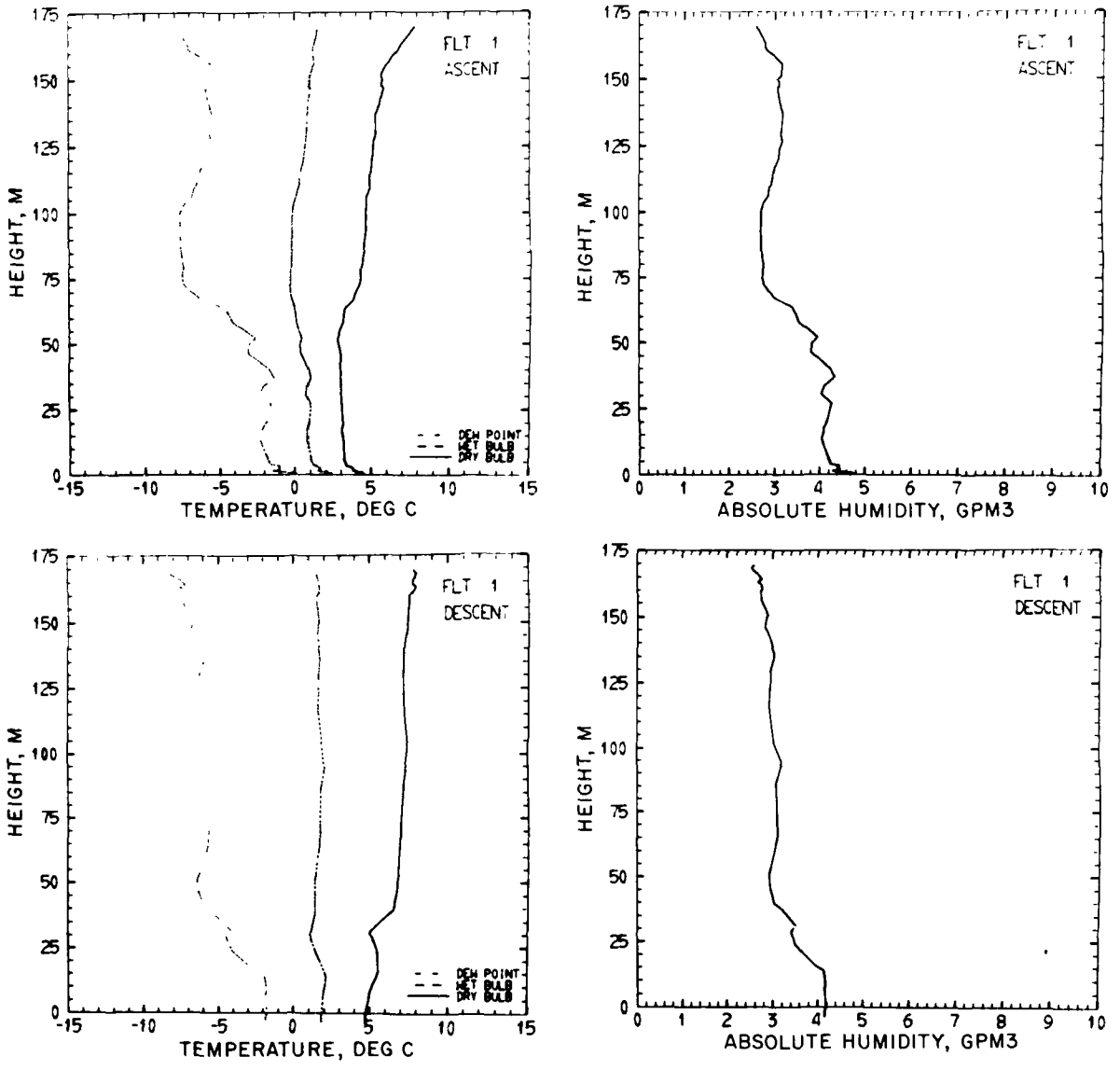

Figure 28. Run 1, March 13, 1974, at Valmont.

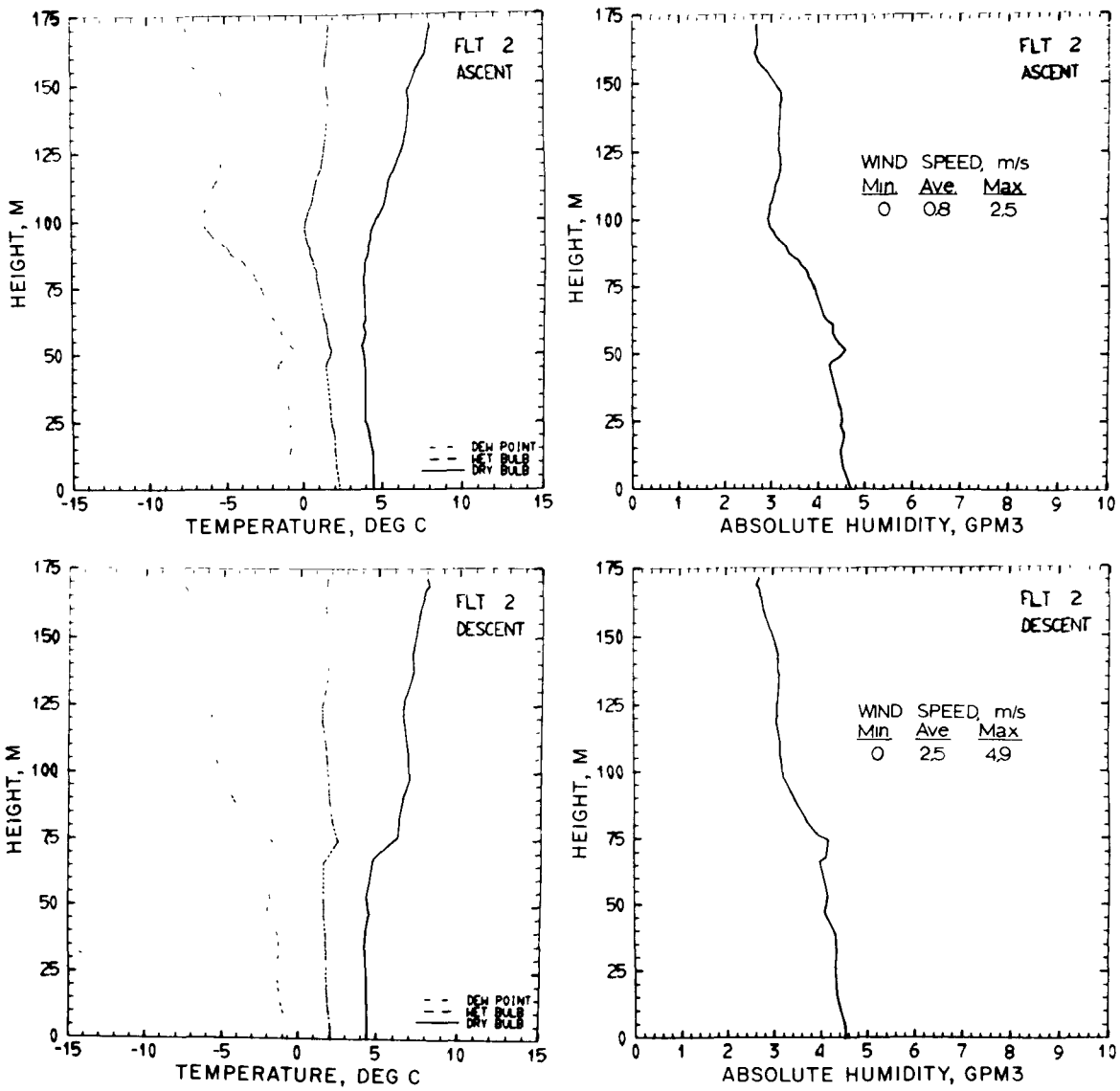

Figure 29. Run 2, March 13, 1974, at Valmont.

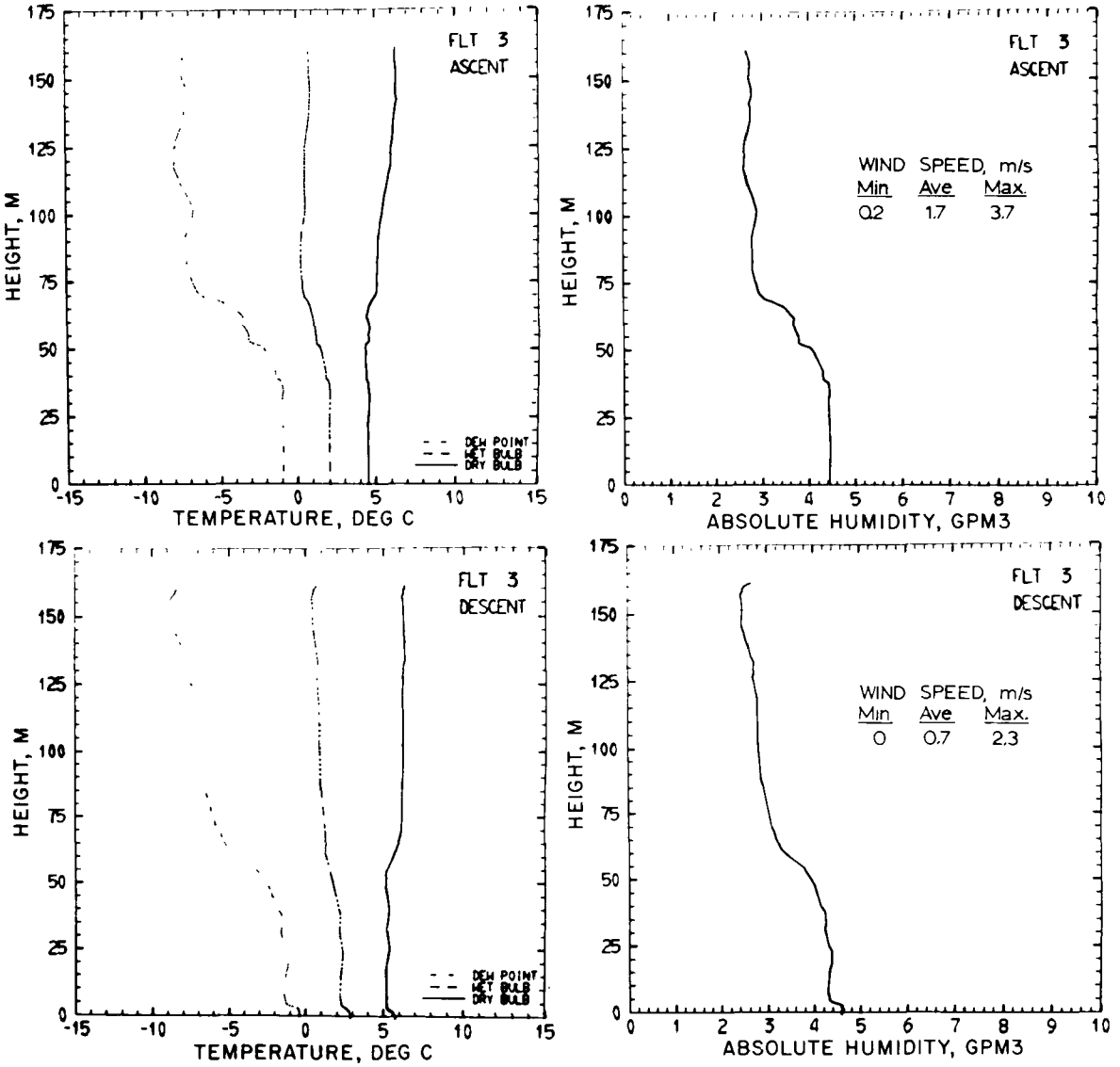

Figure 30. Run 3, March 13, 1974, at Valmont.

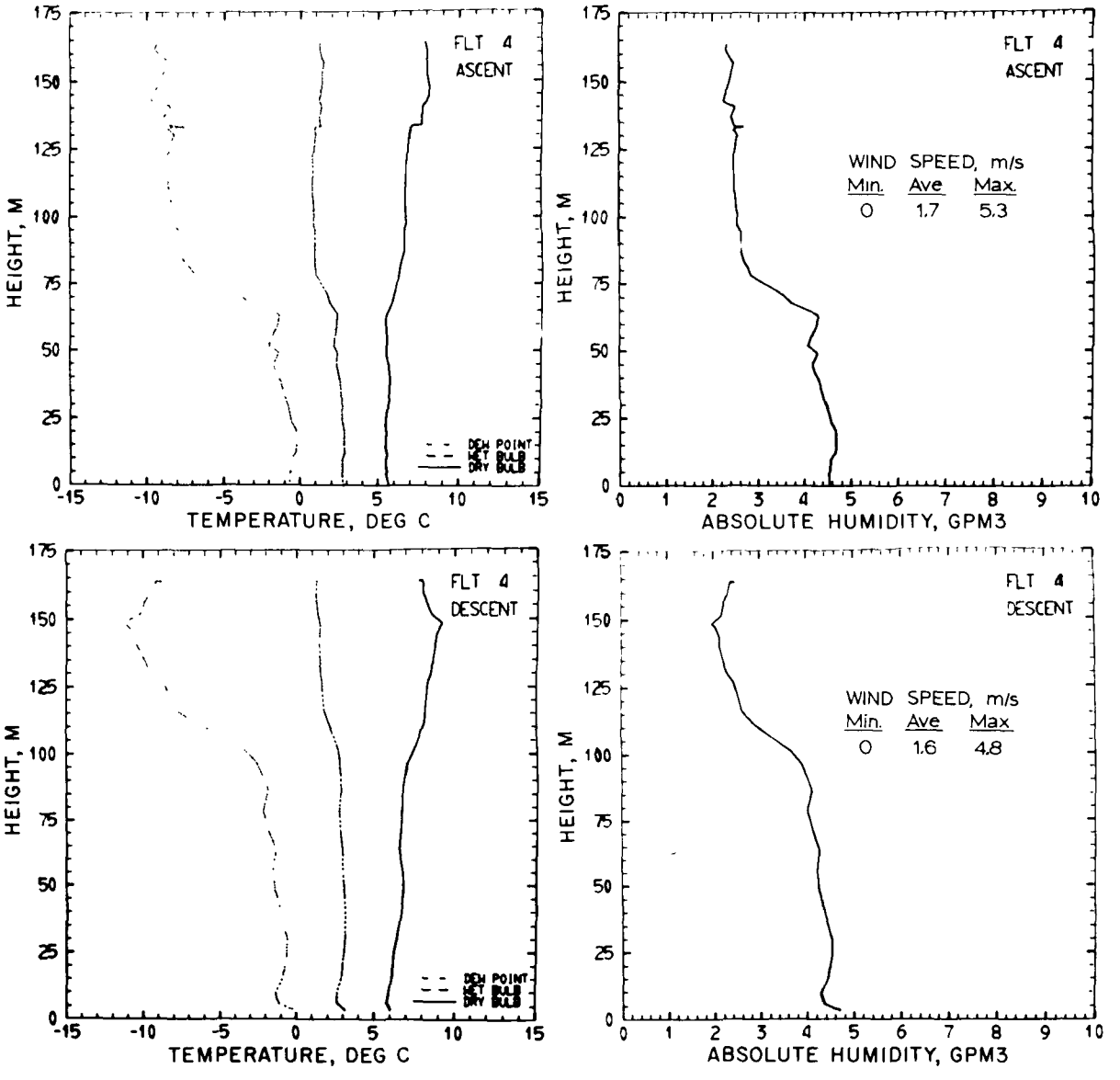

Figure 31. Run 4, March 13, 1974, at Valmont.

water-vapor plume was trapped by the inversion.

The wind direction was undergoing rapid shifts and the wind speed was rather low (1 to 1.4 m/s) during the measurement period. The wind was in every quadrant except between south and west, but the predominant direction was northerly, as shown in Figure 32, the MRI trace for that day. Measurement location 1 was between Owen Reservoir and Hillcrest Lake, while the other three flights were made at locations to the north and northwest of the ponds. The average wind direction during the time of flights 2 and 3 suggest that no excess water vapor should be found, yet in these runs the measured concentration significantly exceeded background. The wind-direction history must be examined to attempt to interpret this. From 0600 hours on, the wind speed was very low and the wind direction shows major changes. Hence, it would be expected that the water evaporated from the ponds tended to accumulate within a few km of the ponds and to be not strongly dispersed. The inversion tended to trap the vapor near ground level and vertical movement of the inversion may have mixed the air below and spread the water vapor in the immediate vicinity of the pond.

By assuming that the vapor cloud maintained an integrity of shape (because of entrapment by the inversion) and simply was moved around by the wind, a vectorial diagram representing the shape and location of the vapor cloud was constructed. This was done from 0600 hours up to the time the flights started, and it was found that the cloud was stretched to the south and southeast of the ponds, away from the locations of flights 2, 3 and 4. This suggests that little or no water vapor accumulated at those locations prior to flight time. Some periods of wind from the east during flight 1 and early in flight 2 probably account for the vapor found in flight 2. Indeed, the concentrations are somewhat lower in the descent than in the earlier ascent of flight 2, as would be expected, since the wind had shifted to westerly by the time of the descent. This procedure did not account, however, for the water vapor observed in flight 3.

It would be expected that the location of flight 3 would be devoid of excess water vapor. Nonetheless, flight 3 showed greater excesses than did 1 or 2. This might be a topographical phenomenon, as the location of flight 3 was somewhat protected by the Valmont Butte, a sharp ridge some 50 m higher than the ponds, and the excess water vapor was confined to approximately that height. Nonetheless, the results of flight 3 remain unexplained. Enough easterly and southerly wind preceeded flight 4 to account for the water vapor observed therein.

These results indicate that under inversion conditions, evaporated water is trapped by the inversion and at low wind speeds, it tends to be relatively uniformly distributed horizontally in the near vicinity of the source.

The water-vapor profiles on the measurement days generally conform qualitatively with expectations based upon wind direction and flight location.

Flights 2 and 3 on March 15, depicted in Figures 33 and 34, show detectable water vapor above background. Flight 4, Figure 35, shows essentially background. Flight 1, April 12, Figure 36, shows a slight water vapor excess

(Text continues on page 66)

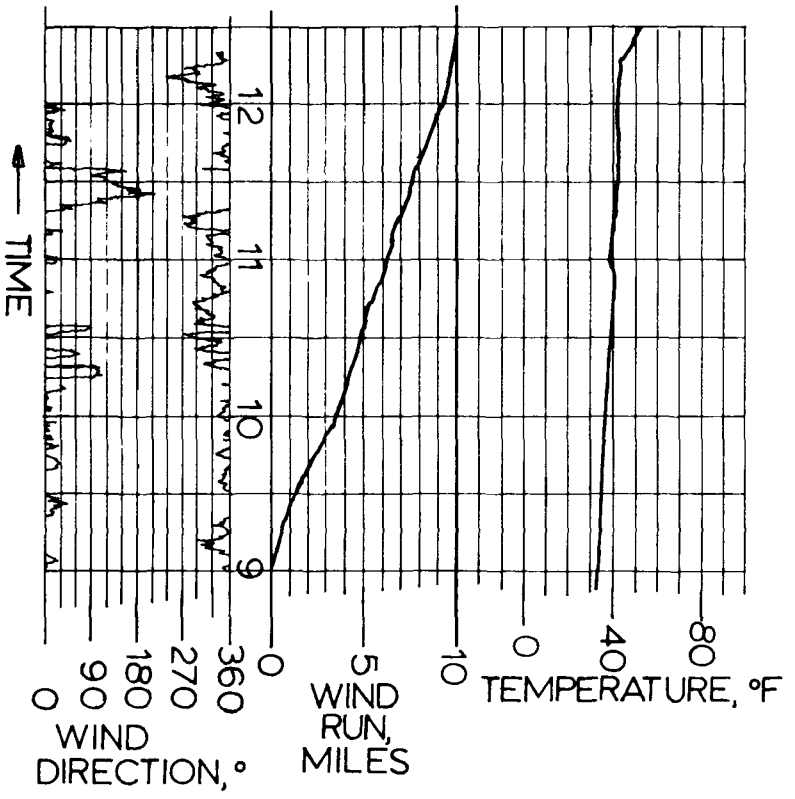

Figure 32. MRI recorder trace, March 13, 1974, at Valmont.

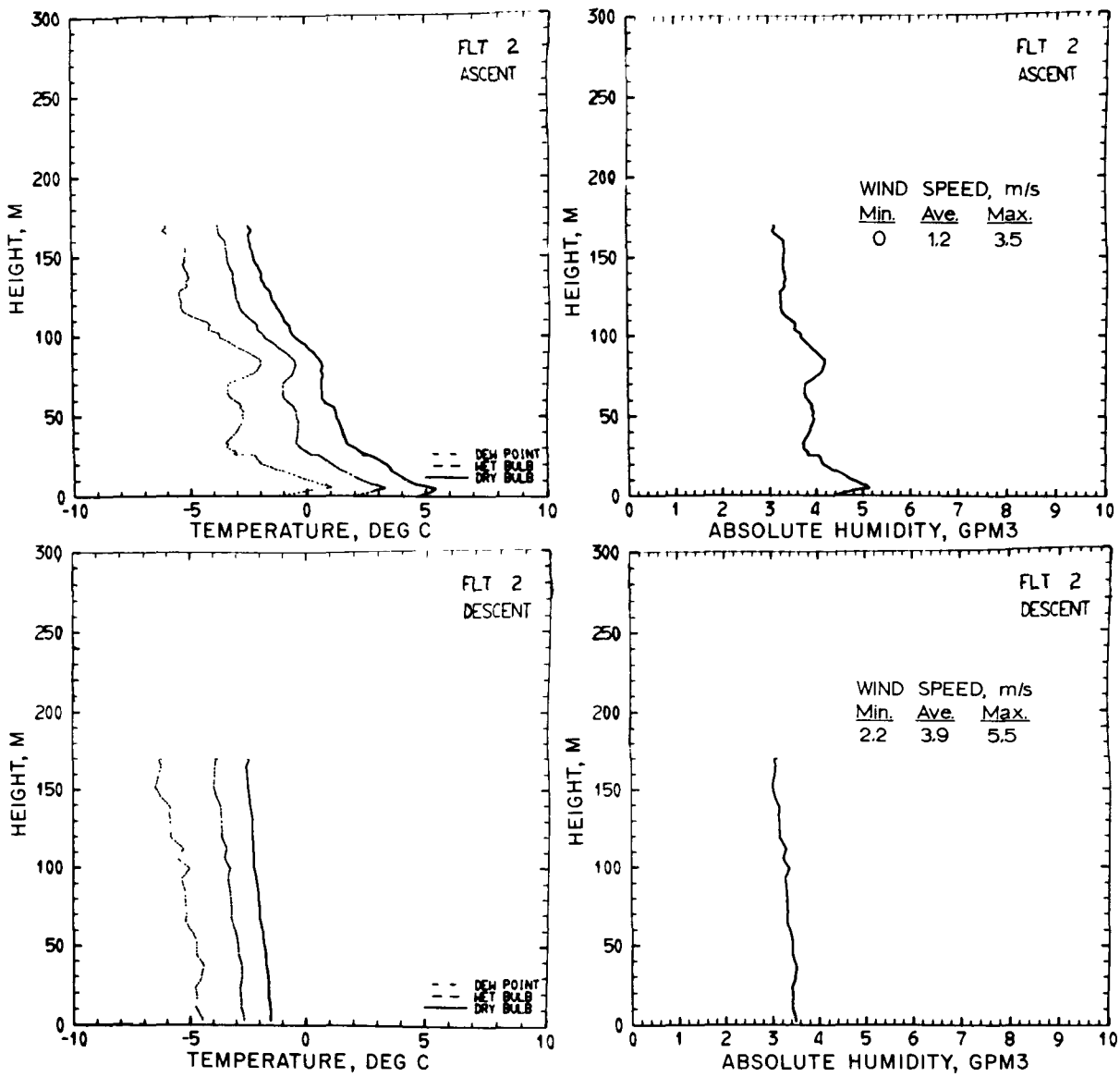

Figure 33. Run 2, March 15, 1974, at Valmont.

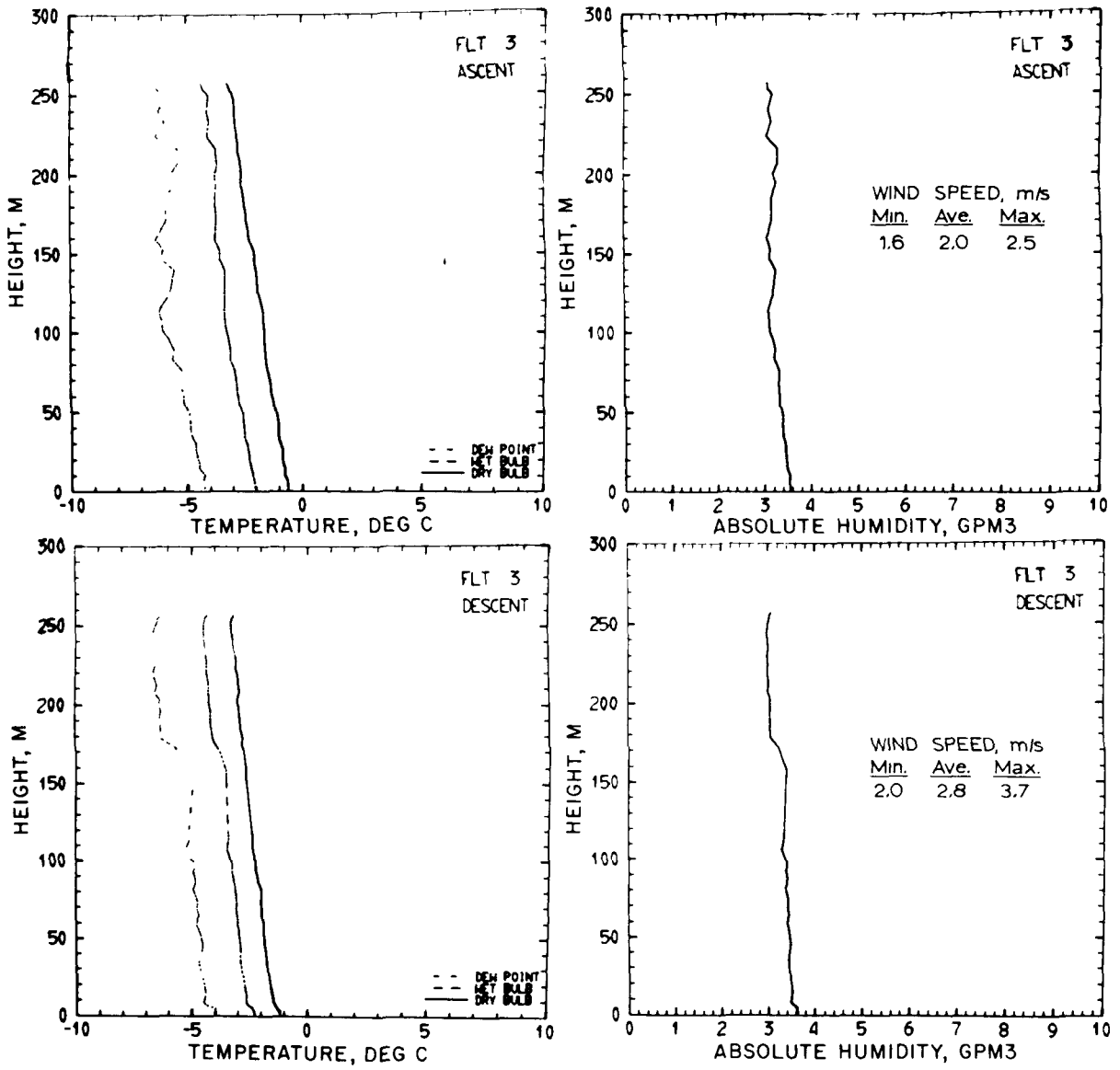

Figure 34. Run 3, March 15, 1974, at Valmont.

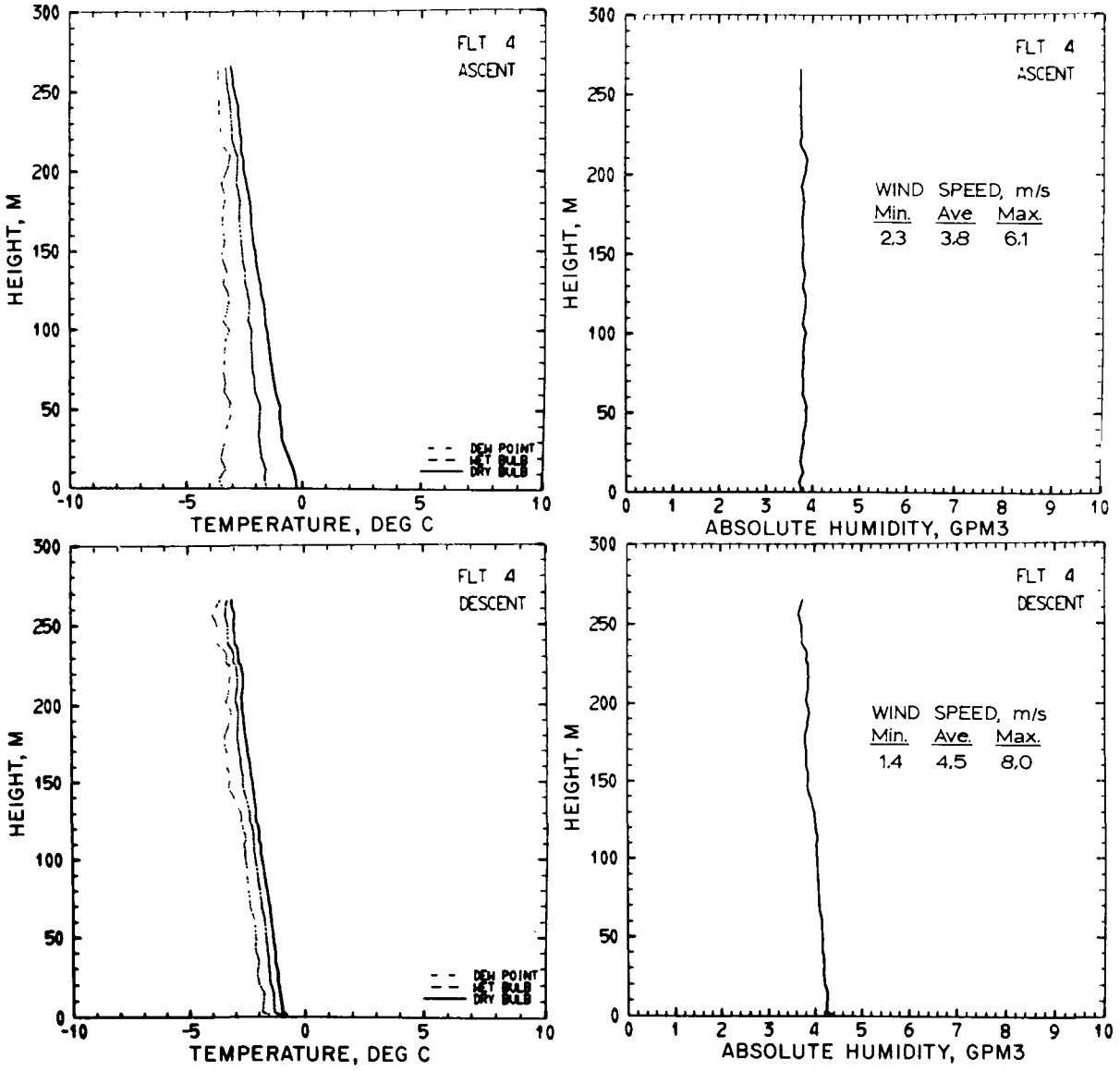

Figure 35. Run 4, March 15, 1974, at Valmont.

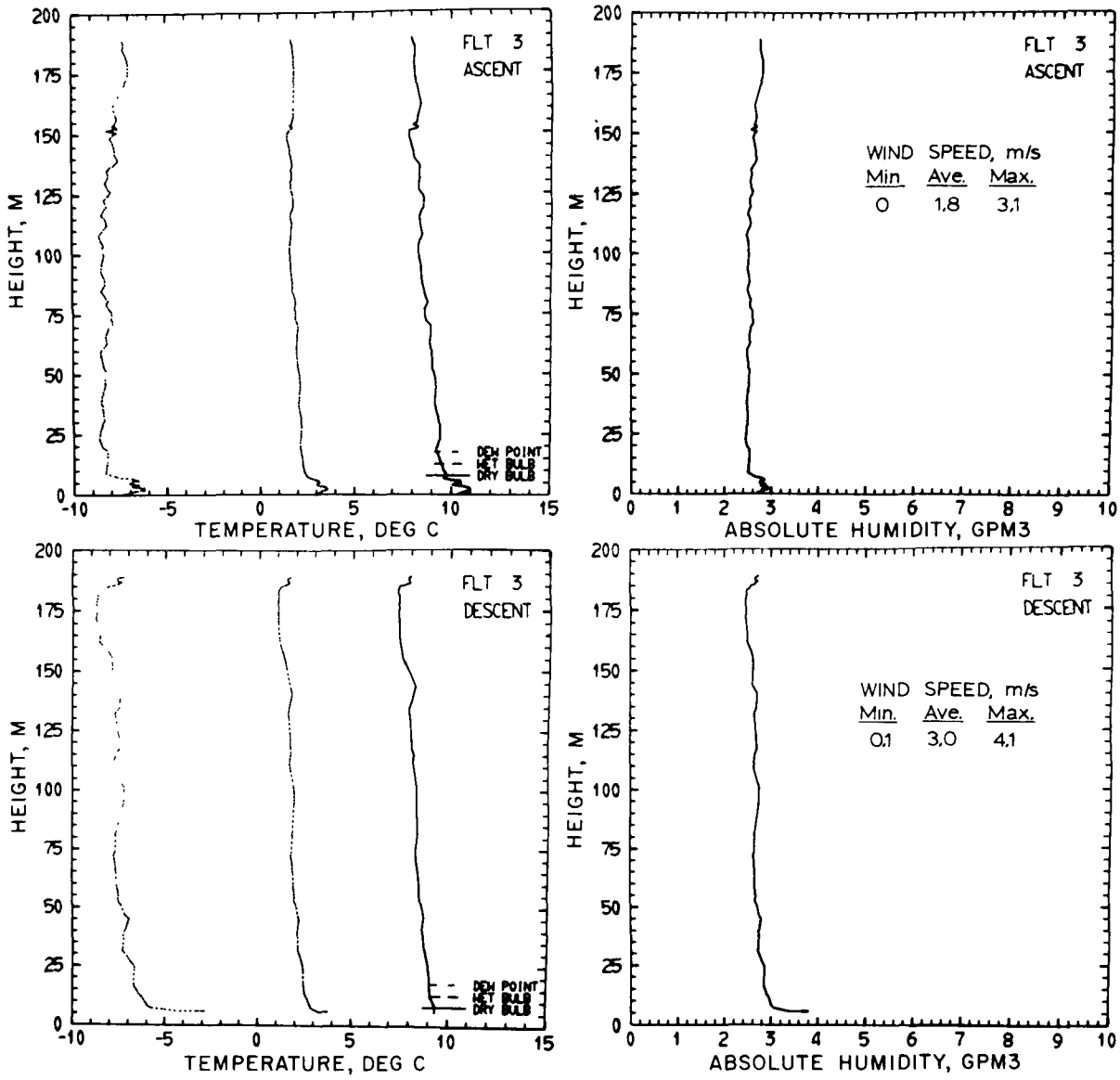

Figure 36. Run 3, April 12, 1974, at Valmont.

near the ground during ascent and essentially background during descent. Flight 1 on April 14, Figure 37, shows background.

Discussion

Important characteristics of cooling ponds are that they are large-area, ground-level water-vapor sources where the interest is in plume behavior near the source.

The ground-level-water-vapor data obtained earlier by Henderson (personal communication) indicated these features of cooling pond plumes: (1) within ±20° of the mean wind direction from the edges of the source, the downwind water-vapor concentration is essentially uniform in the cross-wind direction; (2) up to 2 km downwind of the trailing edge of the source, the concentration is not a strong function of downwind distance; and (3) the water-vapor concentration in the plume is strongly dependent upon the atmospheric stability conditions.

The present data are too few to support or challenge the first two observations above, but they are supportive of the third. These data do add another dimension, the vertical. They indicate that the vertical profile may be roughly represented by a half-Gaussian distribution. This is shown in Figure 38, wherein the measured excess water vapor divided by that at ground level is plotted against the height divided by an assumed normalizing height (this assumed value is equivalent to one standard deviation in the Gaussian distribution). For the inversion conditions of March 13, the assumed height is approximately equal to that of the inversion. The normalized Gaussian curve shows that, except for some of the March 15 data, the data do fit a Gaussian distribution reasonably well. Thus, it is concluded that a Gaussian distribution is a reasonable representation of the vertical-profile data for cooling ponds.

The profile data of this work have been compared with predictions based upon the method of Turner (8), and with a modification of that method which was identical except that the stability class was determined from the measured temperature-lapse rate rather than from meteorological parameters as in the Turner method. The measured-lapse rate indicated greater stability (with two exceptions) than did the meteorological conditions. The results of these comparisons are shown in Table 7. Neither model is quantitatively accurate but the version using the temperature-lapse-based stability generally did better. Both methods usually predict lower than the measured values, sometimes predicting zero concentrations when considerable was measured. The factor mostly responsible for these low values is the wind direction. When the wind direction is changing rapidly, the mean wind direction is an inadequate parameter to represent the plume travel.

The model described by Tsai and DeHarpporte (9) incorporates the essential features of cooling-pond plumes observed in this work and that of Henderson (personal communication). That is, it takes into account the area source, wind convection and vertical diffusion. It also accounts for vertical-wind-velocity gradient, plume bouyancy and cross-wind diffusion at the edges of the plume. It does not account directly for wind meander. The

(Text continues on page 71)

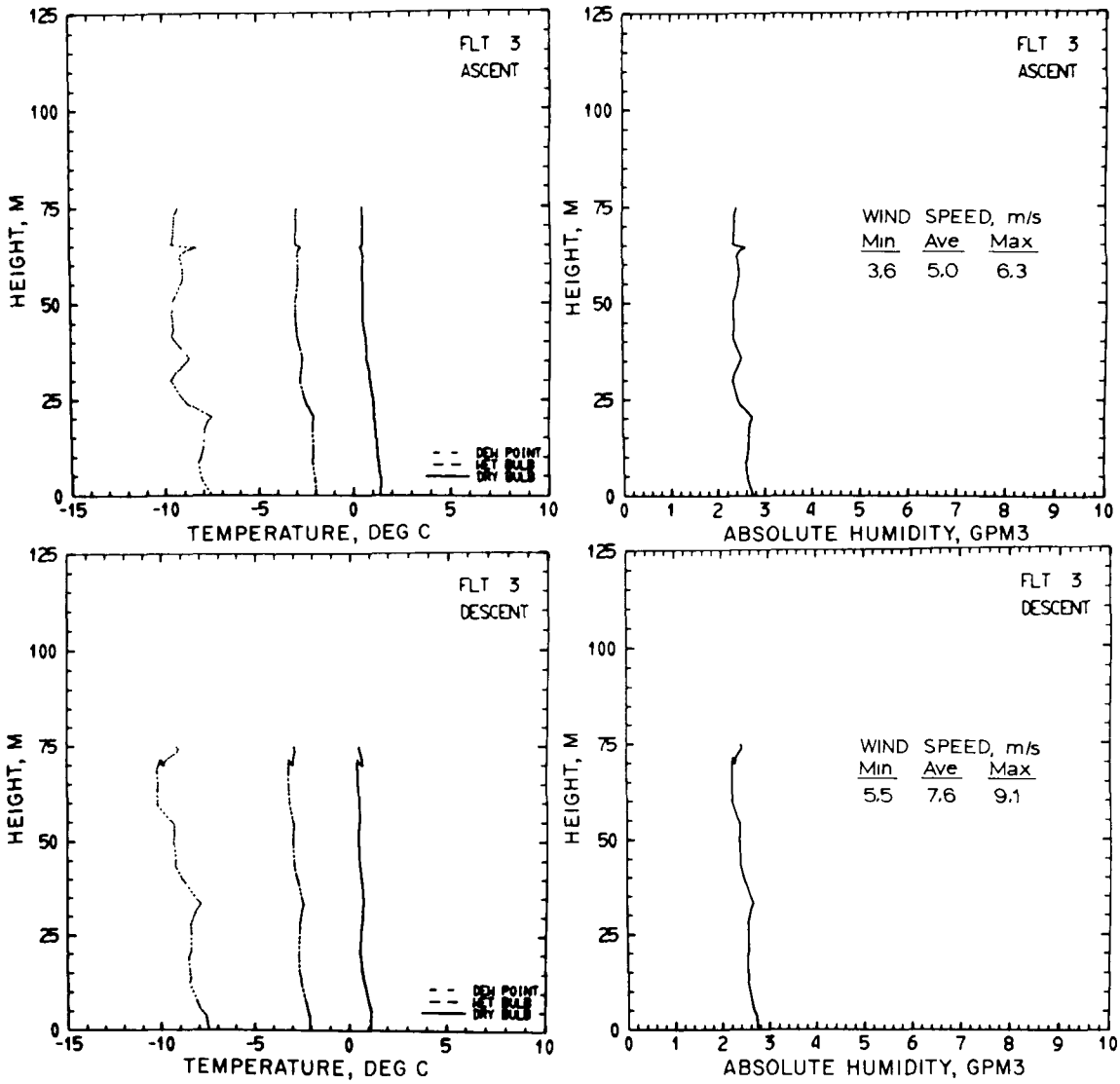

Figure 37. Run 3, April 14, 1974, at Valmont.

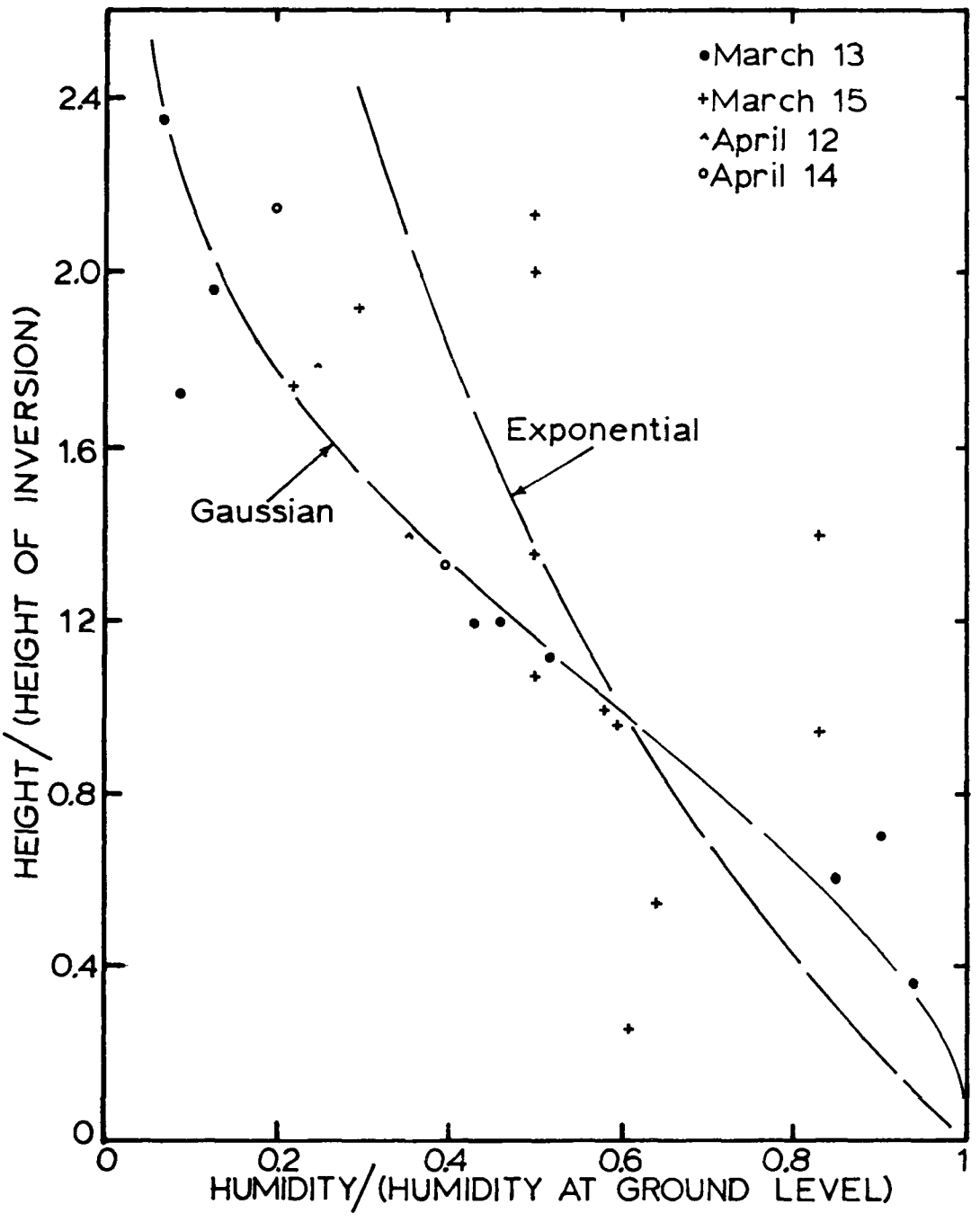

Figure 38. Normalized humidity profiles at Valmont.

TABLE 7. PREDICTED AND MEASURED WATER VAPOR CONCENTRATIONS ABOVE BACKGROUND, COOLING PONDS

Date	Flight Number	Stability Class EPA Work-Book	Stability Class Temp. Gradient	Height Above Ground m	Water Vapor above Ambient, g/m^3 Predicted EPA Work-Book	Predicted Temp. Grad.	Measured
3/13	1	B	D-G	0	0.27	1.11	1.50
				42	0.23	.31	.63
				85	.18	.01	-.05
				127	.11	0.0	.08
	2	B	D-E	0	0.0	0.0	1.50
				42			1.15
				85			0.50
				127			.05
	3	B	E	0	0.0	0.0	1.80
				40			1.55
				80			0.20
				120			0.0
	4	B	E	0	0.01	0.13	2.10
				41	0.0	0.0	1.80
				82			0.88
				123			0.0
3/15	1	E	D	0	0.25	0.18	1.05
				45	.02	.05	.80
				89	0.0	0.0	.90
				134			.20
				178			0.0
	2	E	D	0	0.10	0.07	0.70
				42	0.0	.01	.50
				85		0.0	.55
				127			0.0
	3	C	D	0	0.08	0.14	0.50
				64	.01	0.0	.30
				128	0.0		.20
				192			.05
	4	C	D	0	0.20	0.38	0.30
				66	.06	.02	.15
				133	.01	0.0	.10
				199	0.0		0.0

(continued)

TABLE 7 (continued)

Date	Flight Number	Stability Class EPA Work-Book	Stability Class Temp. Gradient	Height Above Ground m	Water Vapor above Ambient, g/m^3 Predicted EPA Work-Book	Predicted Temp. Grad.	Measured
4/12	1	C	E	0	0.12	0.33	0.75
				42	.05	.01	.30
				84	.01	0.0	.08
				126	0.0		-.05
	2	B	E	0	0.19	0.73	0.50
				44	.13	0.0	.15
				88	.04		.10
				132	.01		.10
	3	B	D	0	0.0	0.0	0.50
				47			-.05
				95			-.05
	4	B	D	0	0.20	0.45	0.45
				48	.13	.05	.03
				99	.05	0.0	0.0
4/14	1	B	E	0	0.71	2.58	0.25
				26	.60	.25	.03
				53	.36	0.0	.10
				79	.15		0.0
	2	B	E	0	0.13	0.70	0.20
				20	.13	.39	.20
				40	.11	.13	.20
				60	.09	.03	.05
				79	.07	.01	.10
	5	C	D	0	0.16	0.30	0.40
				19	.14	.21	.25
				38	.10	.09	.10
				57	.07	.04	.03
				75	.04	.01	.05

results of Tsai and DeHarpporte indicate good agreement with cooling-pond-fog-plume behavior. The inclusion of plume bouyancy causes a maximum concentration to occur somewhat above ground level downwind of the source, as indicated by some of the present profiles.

The Tsai and DeHarpporte model is described in some detail (9), but the computer code is proprietary so the model was not compared with the data of the present work.

REFERENCES

1. ASHRAE Handbook of Fundamentals. American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc., New York. 1972. p. 99.

2. Bindon, H. H. A Critical Review of Tables and Charts used in Psycrometry, in Humidity and Moisture, Measurement and Control in Science and Industry, A. Wexler, ed., vol. 1. Reinhold Corp., New York. 1965. pp. 3-15.

3. Weast, R. C., editor. Handbook of Chemistry and Physics, 49th ed., The Chemical Rubber Co. 1968, p. D109.

4. Winiarski, L. D., and Frick, W. F. Field Investigations of Mechanical Draft Cooling Tower Plumes: EPA-600/7-77-025. Corvallis Environmental Research Laboratory, U.S. Environmental Protection Agency, Corvallis, OR. 1977.

5. Throne, R. F. How to Predict Lake Cooling Action, Power, 95, #9, 1951. pp. 86-90, 210.

6. Thackston, E. L. Effect of Geographical Variation on Performance of Recirculating Cooling Ponds: EPA-660/2-74-085, U.S. Environmental Protection Agency, Washington, D.C. 1974.

7. Brady, D. K. Heat Dissipation at Power Plant Cooling Lakes, Proceedings of the American Power Conference, 32, 1970. pp. 528-536.

8. Turner, D. B. Workbook of Atmospheric Dispersion Estimates, U.S. Public Health Service Publication #999-AP-26. 1970.

9. Tsai, Y. J. and DeHarpporte, D. R. Cooling Pond Fog Prediction Model, in, Man-Made Lakes: Their Problems and Environmental Effects. American Geophysical Union, Geophysical Monograph 17, W. C. Ackerman, et al., ed., Washington, D.C. 1973. pp. 421-427.

APPENDIX A

EXPLANATION OF TABLES

AMBIENT DATA AT COMANCHE

Table A-1 includes ambient data for the Comanche Station at Pueblo, CO, for March 18, 19, 20, 21, 24, 25, and 26, 1975. The sixteen columns of Table A-1 are described as follows:

First -- Time, Mountain Daylight Time (MDT)
Second through fifth -- Temperature at ground, °C, as measured by:
- a. NCAR Hydrothermograph,
- b. PSC Hydrothermograph,
- c. MRI ground station, and
- d. Assman Psychrometer or metal thermometer near base of cooling tower.

Sixth through eighth -- Temperatures aloft, °C, from sensors on PSC stack at 76, 112 and 152 m heights.
Ninth -- Wind speed from PSC wind tower at 10 m height. Values are hourly average. A designation such as 3.1G10.7 means 3.1 m/s hourly average with gusts to 10.7 m/s.
Tenth -- Wind speed from MRI ground station at 3 m height. Values are hourly average.
Eleventh -- Wind direction from PSC tower at 10 m, hourly average. 0° North, 90° East, 180° South, 270° West.
Twelfth -- Wind direction from MRI ground station at 3 m. Values are hourly average with ± range of variability. HV means highly variable, direction varied up to 360° in one hour. V means variable, direction varied up to 180° in one hour.
Thirteenth through fifteenth -- Percent relative humidity as measured by:
- a. NCAR Hydrothermograph,
- b. PSC Hydrothermograph, and
- d. Assman Psychrometer near cooling tower base.

Sixteenth -- Insolation, Langleys per hour.

A blank means no data for that time.

TABLE A-1. AMBIENT DATA AT COMANCHE

Time, MDT	Temperature at Ground, °C a	b	c	d	Temperature Aloft, °C 76m	112m	152m	Wind Speed, m/s b	c	Wind Direction b	c	Relative Humidity,% a	b	d	Insolation, langley/hr
MARCH 18, 1975															
0800		-1.1	-4.1		+4.3	4.4	4.2	0.5	1.1	280	210 HV	29	37		
0830			-2.2		6.7	6.8	6.4								
0900		6.1	+3.3		7.2	7.1	6.6	3.1G10.7	3.6	320	300±30	30	29		
0930			6.1		7.5	7.2	6.8								
1000	7.9	7.2	6.1		8.9	8.3	8.6	4.9G9.9	5.1	290	280±15		25		
1030	8.8		7.2		9.2	8.5	8.5								
1100	13.1	10.0	8.3	12.0	11.7	10.7	10.6	8.0G12.1	7.6	280	280±15	22	22	16	
1130	15.1		12.2		12.4	11.2	10.9								
1200	16.5	13.3	12.8					9.0G12.1	7.6	290	300±20	20	19		
1230	17.3		14.4		13.1	12.4	12.2								
1300	19.0	15.6	15.6		13.9	13.3	12.8	8.0G12.1	6.7	280	280±20	19	17		
1330	20.0		16.1		14.4	13.6	13.4								
1400	27.8	16.1	16.1		15.0	14.5	13.9	5.8	5.4	290	290±30	17	17		
1430			16.7		15.5	15.0	14.4								
1500	30.5	17.2	17.2		16.4	15.6	15.0	5.4	5.4	300	300±40	14	17		
1530			17.2		16.3	15.6	15.1								
1600	24.9	17.8	17.2		16.8	15.9	15.6	5.4	5.1	290	290±40	14	17		
1630			17.8		17.7	16.2	16.0								
1700	21.8	17.2	17.2		17.7	16.3	16.0	4.9	4.6	270	270±30	16	17		
MARCH 19, 1975															
0800	19.7	8.3	6.7		11.1	10.0	10.6	3.1	3.6	260	260±30	19.5	31		
0830					12.1	10.8	11.7								
0900	16.0	12.8	10.5		12.4	11.5	11.5	4.0	4.9	280	270±15	16	26		
0930			12.8	13.5	13.3	12.8	12.3							23	
1000		15.6	15.0		14.5	13.6	13.2	6.2	5.6	280	280±20		22		
1030			16.1		15.4	14.9	14.1								
1100		17.2	17.2		15.7	15.2	14.8	5.8	5.4	290	290±20		20		64

continued

TABLE A-1. AMBIENT DATA AT COMANCHE (continued)

Time, MDT	Temperature at Ground, °C a	b	c	d	Temperature Aloft, °C 76m	112m	152m	Wind Speed, m/s b	c	Wind Direction b	c	Relative Humidity,% a	b	d	Insolation, langley/hr
MARCH 19, 1975 (Con't.)															
1130			18.3		16.7	16.1	15.5								
1200		17.8	18.9		18.2	16.7	16.3	4.9	4.3	280	270±40		18		66
1230			20.0		19.4	17.8	17.1								
1300		18.9	20.0		19.9	18.4	17.7	2.2	2.7	260	300 HV		17		72
1330			22.2		20.2	18.7	18.2								
1400		20.0	22.2		20.6	19.3	18.6	2.2	2.5	220	210 HV		16		72
1430			23.9		20.1	19.3	18.8								
1500		21.1	23.3	25.0	20.6	19.8	19.4	2.2	2.2	100	90 HV		16	11	62
1530			23.9		21.7	20.6	20.4								
1600		22.2	23.3		22.3	21.4	20.6	4.0	3.9	130	150 V		15		50
1630			23.3		22.3	21.3	20.7								
1700		21.7	22.8		22.3	21.3	20.6	6.3	6.0	170	160±30		18		36
MARCH 20, 1975															
0800		5.0	3.3		14.7	12.7	12.8	1.3	2.0	280	280 HV		40		
0830				7.6	13.0	12.1	12.4							36(SONDE)	
0900	10.9	11.7	10.0		15.2	13.5	12.9	0.9	1.4	280	270 V	35	31		
0930	13.6			15.0	15.1	13.8	13.2					29		17(SONDE)	
1000	15.2	14.5	15.5		16.7	15.2	14.1	1.3	2.1	310	290 HV	26	26		50
1030	16.9				17.2	15.9	15.3					24			
1100	18.0	17.2	17.8	18.0	17.2	16.3	15.6	3.6	3.5	300	300±30	22	23	17.5	64
1130	18.6				18.5	16.8	16.2					20			
1200	19.3	18.9	21.1		19.2	18.1	17.5	1.8	2.1	290	300±60	20	19		70
1230	20.1				20.5	18.4	17.9					18			
1300	20.9	20.0	22.2		21.1	18.9	18.3	1.3	2.0	270	270 HV	17	14		76
1330	22.1				21.1	19.9	19.9					15			
1400	22.4	21.7	22.2	22.6	20.8	20.1	19.6	7.6G11.2	6.9	290	300±30	13	12	8	72

continued

TABLE A-1. AMBIENT DATA AT COMANCHE (continued)

Time, MDT	Temperature at Ground, °C a	b	c	d	Temperature Aloft, °C 76m	112m	152m	Wind Speed, m/s b	c	Wind Direction b	c	Relative Humidity,% a	b	d	Insolation, langley/hr
MARCH 20, 1975 (Con't.)															
1430	22.3				20.6	19.9	19.4					12			
1500	22.2	21.7	22.2		21.1	20.2	19.7	7.6G10.7	6.5	300	310±30	12	12		66
1530	22.3				21.0	20.7	20.4					12			
1600	22.2	22.2	22.2		21.0	20.6	20.2	8.0G10.3	6.9	290	290±30	12	12		52
1630	22.2				22.4	21.4	21.3					12			
1700	22.0	22.2	22.2	23.9	22.2	21.5	21.5	4.9G11.6	4.6	260	250 HV	12	13		32
MARCH 21, 1975															
0800			9.5		12.5	12.2	12.2	2.2	2.2	250	240 HV				
0830	13.1		11.7		13.3	12.7	12.7					33			
0900	13.2	12.8	13.0	15.4	14.3	12.8	13.3	4.5G10.7	3.5	210	220 HV	32	35	44	36
0930	13.9		13.9		14.4	13.0	13.0					31			
1000	15.0	13.9	15.5	15.8	15.6	13.5	13.2	4.0	3.6	220	300 HV	30	32		44
1030	14.5		15.0		13.9	13.2	12.7					29		26	
1100	14.2	14.4	15.0		14.7	13.4	13.6	6.7G15.2	6.7	290	280±40	27	34		36
1130	14.0		13.9		14.4	13.0	12.9					26			
1200	12.5	14.4	12.2		12.7	11.4	11.5	13.9G21.5	11.6	280	290±20	27	32		46
1230	10.7		13.3		11.1	9.9	11.3					33			
1300	12.3	11.7	10.9		11.9	11.0	11.3	9.5G21.9	11.2	270	280±40	31	32		
1330	12.6		11.7		12.3	11.1	11.1					31			
1400	16.0	11.7	11.7		13.9	12.8	12.2	5.4G10.7	5.8	270	280 HV	28	29		
1430	16.2		15.0		14.4	14.4	13.9					25			
1500	16.7	15.6	15.6		14.4	13.3	13.7	10.7G16.5	10.0	280	290±30	24	24		
1530	16.5		15.6		14.6	13.7	13.7					23			
1600	16.3	15.6	15.9		14.5	14.2	13.5	10.3G20.1	10.7	280	290±20	22	21		
1630	16.3		15.9		15.6	14.6	14.3					20			
1700	16.2	16.1	15.9		15.3	14.6	14.3	10.3G15.2	8.5	290	290±20	19	18		

continued

TABLE A-1. AMBIENT DATA AT COMANCHE (continued)

Time, MDT	Temperature at Ground, °C a	b	c	d	Temperature Aloft, °C 76m	112m	152m	Wind Speed, m/s b	c	Wind Direction b	c	Relative Humidity,% a	b	d	Insolation, langley/hr
MARCH 24, 1975															
0730			-1.1		0.5	0.3	-0.1								
0800	1.4	-1.1	-0.5			0.5	0.0	7.6G11.2	6.3	300	290±20	26	25		
0830			-0.5		1.4	0.8	0.2								
0900		+0.5	+0.5			1.2	0.8	8.0G12.5	6.7	290	290±30				
0930			1.7			1.6	1.9								
1000		2.2	3.4		3.6	2.8	2.3	9.8G14.8	7.8	280	280±30				56
1030			4.5		4.7	4.1	3.6								
1100		4.4	5.6		5.8	4.7	4.3	9.4G13.0	8.0	290	280±30				66
1130			6.7		6.2	5.7	5.0								
1200			7.3		7.3	6.9	5.8	9.8G16.6	8.2	290	280±30		15		76
1230			7.5			7.2	6.5								
1300			9.5			7.3	7.1	9.8G13.4	8.5	300	290±40		15		78
1330			10.0		8.5	8.3	7.2								
1400			10.7			8.5	8.1	11.2G17.0	9.0	300	280±30		15		78
1430			10.8			9.1	8.9								
1500			10.6		9.5	8.8	8.3	10.7G17.9	8.7	300	290±40		16		52
1530			9.8		9.9	9.1	8.4								
1600		11.1	11.1		9.9	9.2	9.0	10.7G15.7	8.1	300	280±30		16		58
1630			11.1		10.5	9.2	9.1								
1700		11.1	11.1		10.5	9.5	9.1	10.7G15.2	8.0	290	280±30		16		
1730			10.7		10.0	9.3	8.8								
1800		11.1	10.3		9.5	8.9	8.6	10.3G13.9	8.0	290	280±30		17		
MARCH 25, 1975															
0700		-6.1	-6.4	-3.0	-0.7	-1.2	-2.0	1.8	1.3	320	330±30		51	54	
0730			-6.4			-1.7	-2.0								
0800		-5.8	-5.3			-1.7	-2.0	0.9	1.2	290	280±30		50		
0830			-3.6		-0.8	-2.5	-2.9								
0900		-3.3	-2.2		0.0	-2.2	-2.5	0.9	1.3	30	30±40		47		34

continued

TABLE A-1. AMBIENT DATA AT COMANCHE (continued)

Time, MDT	Temperature at Ground, °C a	b	c	d	Temperature Aloft, °C 76m	112m	152m	Wind Speed, m/s b	c	Wind Direction b	c	Relative Humidity,% a	b	d	Insolation, langley/hr
MARCH 25, 1975 (Con't.)															
0930			-1.0		+0.9	-0.5	-1.3								
1000		-0.8	-0.8		1.3	-1.1	-1.7	1.8	2.0	0	30±40		44		28
1030			0.0		0.9	-0.4	-0.8								
1100		+0.6	+1.6		2.1	+0.8	+0.4	1.8	2.2	40	40±40		42		50
1130	5.9		3.3		2.3	1.8	1.3					35			
1200	4.0	2.6	3.3		2.8	2.3	1.7	3.1	2.9	90	70±30	36	39		22
1230	4.4		4.4		3.7	3.2	2.7					36			
1300	5.4	4.4	5.6		5.0	4.3	3.5	2.2	2.3	80	60±40	36	37		30
1330	6.2		6.1		5.5	5.0	4.4					35			
1400	7.1	6.4	6.7		8.0	6.7	6.1	0.9	1.4	30	0 V	34	34		34
1430	8.2		7.8	8.0	8.6	7.0	6.4					33		28	
1500	8.9	8.1	7.8		8.9	7.8	7.8	1.8	2.2	340	320±40	32	31		36
1530	10.7		10.5		10.5	9.7	8.9					30			
1600	11.0	10.3	10.5		11.7	9.7	8.9	3.1	3.3	20	0±30	28	28		12
1630	11.8		10.5		11.1	10.0	9.4					28			
1700	11.8	11.0	11.1		10.5	10.0	9.4	4.9	4.7	320	300±30	28	27		14
1730	11.1		10.5		10.0	9.5	9.0					28			
1800	10.6	10.0	10.0		9.8	9.3	8.9	6.2	4.8	290	280±10	28	27		4
1830	10.0		9.0		9.5	9.1	8.5					28			
1900	9.7	8.8	8.5		9.6	8.8	8.3	7.1	5.4	280	280±10	28	27		
MARCH 26, 1975															
0800	-2.0	-3.1	-3.2			-2.3	-2.8	4.0	3.8	10	10±10		82		
0830	-1.5		-2.2			-2.1	-2.7				10±20				
0900	-0.8	-2.2	-1.1			-1.6	-2.3	4.0	3.2	30	40±30		78		
0930	0.0		0.0	+2.0		-1.6	-2.1				50±30	52		55	
1000	+1.1	+0.1	+0.6			-0.4	-0.7	3.1	2.5	40	60±30	56	74		54
1030	2.0		1.7		3.7	+0.7	0.0				20±30	54			
1100	3.7	2.2	4.5	5.5	4.4	2.2	+1.5	1.8	1.8	40	0±90	50	61		

continued

TABLE A-1. AMBIENT DATA AT COMANCHE (continued)

Time, MDT	Temperature at Ground, °C a	b	c	d	Temperature Aloft, °C 76m	112m	152m	Wind Speed, m/s b	c	Wind Direction b	c	Relative Humidity,% a	b	d	Insolation, langley/hr
MARCH 26, 1975 (Con't.)															
1130	5.1		6.1		5.9	4.2	2.7				0 HV	47			
1200	6.9	5.6	7.2		6.8	5.3	4.5	1.3	1.7	0	0 HV	43	56		
1230	7.8		11.1	11.5	8.6	6.9	6.1				30±40	39			
1300	9.6	8.6	10.0	7.5	8.6	7.8	7.6	1.8	2.0	0	30±60	37	50	63	
1330	10.9		11.7		10.0	8.9	8.3				70±90	34			
1400	12.2	10.2	13.9		12.0	11.3	10.7	2.2	2.6	90	90 HV	32	35		
1430	12.0		12.8		13.0	12.8	12.4				120±90	31			
1500	14.0	13.3	15.3		13.5	13.0	12.4	2.7	2.8	110	70±60	28	29		
1530	14.1		14.4		14.6	13.9	13.3				190±40	28			
1600	14.8	14.2	15.0		14.5	13.5	12.8	4.9	3.7	210	190±40	28	30		
1630	13.8		13.3		13.5	12.5	11.9				270±60	28			
1700	11.3	12.8			11.2	10.0	10.7	7.6		270		36	39		

AMBIENT DATA AT VALMONT

Table A-2 includes ambient data for run dates at the Valmont Station at Boulder, Colorado. The data are:

Date
Flight number
Temperature, °C, measured with the Assman psychrometer.
Humidity, g/m^3, calculated from Assman psychrometer readings.
Wind speed, m/s. Value is average from wind run recorder on MRI.
Wind direction, average and range from MRI.
Cloud cover, tenths, estimated.

TABLE A-2. AMBIENT DATA AT VALMONT

Date	Flight Number	Temp., °C	Humidity, g/m^3	Average Wind Speed, m/s	Wind Direction	Cloud Cover
3/8/74	1	2.8	2.76	1.8	280±30	10
3/13	1	4.7	4.52	1.0	45±90	9
	2			1.2	350±120	
	3			1.2	350±200	
	4			1.4	160±60	
3/15	1	-1.0	3.53	1.0	70±40	5
	2			1.1	120±90	
	3			2.3	190±90	
	4			2.7	170±40	
4/8	1	3.7	3.0	1.2	47±70	2
4/12	1	11.8	3.11	3.1	90±60	4
	2			1.8	130±70	
	3			1.8	30±80	
	4			1.6	190± 5	
4/14	1	0.9	2.60	0.7	290±90	0
	2			3.2	180±40	
	5			4.3	170±10	

APPENDIX B

COMANCHE BALLOON SONDE DATA

Tables B-1 through B-20 show the sonde data for flights at the Comanche Station. Columns 1 and 2 for the wind speed correspond to the two pulses of wind speed per data frame. In no case was there found a significant difference between the mean values for the two pulses. Means and standard deviations are reported for wind speed and wind direction. Background values are given for times closest to the flight times.

TABLE B-1. SONDE DATA RUN 1A, 3/20/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments	
1100	Background	663.5	17.7	--	3.6		300	3.15	17.2°C@76m 16.3°C@112m 15.6°C@152m	on stack
1130	Background	663.5	18.6	--	--		--	3.03	18.5°C@76m 16.8°C@112m 16.2°C@152m	on stack
1200	Background	663.5	19.8	--	1.9		300	3.26	19.2°C@76m 18.1°C@112m 17.5°C@152m	on stack
1100	15	662.4	16.2	19.4	4.5	2.7	276	--		
	15	662.4	17.5	19.5	2.0	3.8	190	--		
01	30	661.2	17.2	--	3.6	5.1	255	--	Wet-Bulb	
	45	660.1	16.4	16.2	4.5	4.6	286	13.25	Questionable	
02	60	658.6	16.2	13.5	3.8	5.5	290	10.02		
	75	657.8	16.5	14.8	4.1	4.2	286	11.45		
03	95	656.3	15.9	7.1	4.1	3.7	290	3.55		
	110	654.8	15.9	7.1	4.2	3.9	280	3.56		
04	130	653.2	15.6	7.0	3.3	3.7	275	3.60		
	140	652.5	15.6	7.0	4.3	5.0	248	3.61		
05	140	653.2	15.5	6.9	5.0	4.3	277	3.55		
	140	652.8	15.7	6.8	5.8	5.8	285	3.38		
06	140	652.8	15.8	7.0	5.4	4.0	320	3.52		
	145	652.5	15.4	6.9	4.2	3.9	288	3.60		
07	160	651	15.3	7.0	3.9	4.8	274	3.74	Stop Ascent	
	160	651.3	15.5	7.0	5.0	4.2	290	3.65	Hold	
08	160	651	15.4	7.0	4.7	5.4	285	3.70		
	160	651.3	15.5	7.0	4.9	5.3	273	3.65		
09	160	651.7	15.6	7.0	5.9	5.5	309	3.61		
	160	651	15.5	7.0	6.4	4.5	266	3.66		(continued)

TABLE B-1. (continued)

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed 1 m/s	Wind Speed 2 m/s	Wind Direction	Mixing Ratio g/kg	Comments
10	160	651.7	15.7	7.1	6.4	5.5	266	3.66	
	160	651.3	15.5	7.2	4.6	4.6	264	3.84	
11	160	651.3	15.5	7.2	5.0	3.6	287	3.84	
	160	651.3	15.7	7.3	4.1	4.4	233	3.85	
12	160	651.3	15.8	7.5	4.8	3.1	340	3.99	
	160	651.3	15.6	7.4	1.9	2.4	263	3.98	
13	160	651.3	15.7	7.4	2.3	2.3	320	3.94	Descent
	155	651.7	15.7	7.4	2.6	2.7	278	3.94	
14	150	652.1	15.7	7.4	4.0	4.0	309	3.94	
	145	652.8	15.7	7.3	3.1	2.5	300	3.84	
15	140	652.8	15.7	7.4	3.3	3.7	287	3.93	
	130	653.6	15.9	7.4	3.6	3.8	305	3.79	
16	120	654.4	16.0	7.5	3.4	3.5	292	3.89	
	110	655.1	16.3	7.7	3.5	3.3	264	3.95	
17	95	656.6	16.2	7.7	3.4	3.8	290	3.98	
	85	657	16.3	7.8	3.1	2.9	269	4.03	
18	75	657.8	16.5	7.9	2.9	-	285	4.04	
	55	659.7	16.6	8.1	2.2	2.4	-	4.17	
19	45	660.1	16.8	8.1	2.8	3.6	-	4.08	
	35	660.8	17.0	8.3	3.4	3.7	262	4.19	
20	25	661.2	17.5	8.5	3.1	2.7	343	4.16	
	10	662.7	17.4	8.5	3.7	5.1	308	4.20	
21	0	663.5	-	8.5	4.8	5.0	265	-	
	0	663.9	18.3	-	4.7	3.2	-	-	
	1100 - 1110								
			Mean		4.55		283		
			Standard Deviation		.86		27		
	1110 - 1121								
			Mean		3.48				
			Standard Deviation		.70				

TABLE B-2. SONDE DATA RUN 1C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
0700	Background	670.3	-6.2	-	1.5		330	1.38 1.37	Assman @ 7:15 -0.7°C@75m -1.7°C@112m on stack -2.0°C@152m
0713.5	0	670.0	-2.1	-4.8	1.2	0.6	40	1.89	
14	0	670.0	-2.3	-4.7	1.8	0.9	220	2.06	
	0	670.0	-3.0	-4.9	2.5	3.0	270	2.20	
15	20	668.8	-0.8	-4.4	3.1	4.4	287	1.68	
	40	667.3	+1.4	-1.1	4.0	5.8	8	2.84	
16	60	665.8	+1.7	-0.4	5.6	6.0	357	3.31	
	80	663.9	+1.4	0.0	3.0	1.8	342	3.74	
17	100	663.5	+2.4	+1.0	3.5	0.8	7	4.07	
	120	661.6	1.7	0.9	1.9	4.1	340	2.97	
18	140	660.4	0.0	-0.8	3.5	2.8	84	3.82	
	160	659.3	-0.1	-1.8	5.9	3.3	40	3.07	
19	170	657.4	-0.7	-2.3	6.9	3.8	334	3.01	Descend
	165	657.8	0.0	-1.6	0.8	4.0	24	3.21	
20	150	658.9	-0.5	-2.0	4.0	4.7	24	3.13	
	130	660.4	+0.5	-1.0	6.3	6.4	320	3.41	
21	110	662.0	+3.0	+1.2	3.7	6.3	6	3.98	
	50	665.4	-0.5	-1.4	6.6	4.2	340	3.52	
22	10	669.2	-2.0	-3.7	3.6	0	202	2.56	
	0	669.6	-	-	-	-	-	-	
			Mean		3.45		340		
			Standard Deviation		1.94		32		
0730	Background	670.3	-6.4	-	-		-	1.32	-1.7°C@112m on stack -2.0°C@152m

TABLE B-3. SONDE DATA RUN 2C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
0730	Background	670.3	-6.4	-	-		-	1.32	-1.7°C@112m -2.0°C@152m Stack
0736	0	670.3	-3.2	-5.0	0.7	0	0	2.21	
	0	670.3	-3.2	-5.0	0	0	345	2.21	
37	0	670.3	-3.3	-5.2	0	2.0	316	2.13	
	0	670.3	-3.5	-5.0	1.7	0.9	0	2.34	
38	0	670.3	-3.1	-5.0	0	0.2	310	2.17	
	0	670.3	-3.5	-5.0	0.3	1.5	122	2.34	
39	0	670.3	-4.2	-5.3	2.2	2.3	173	2.43	Ascent
	10	670.	-5.0	0.0	1.9	2.2	209	-	Wet-Bulb Froze
40	25	668.4	-	-	2.0	2.3	-	-	
	40	666.9	-3.2	-1.2	1.5	1.7	-	-	
41	50	666.5	-2.3	-2.0	1.3	1.9	155	-	Wet-Bulb
	70	666.	-2.1	-2.9	0.6	2.3	22	3.15	Questionable
42	80	664.2	-3.1	-3.6	1.5	2.0	205	3.10	
	95	662.7	-2.6	-3.8	0.9	1.7	215	2.77	
43	110	662.	-2.5	-4.3	1.3	1.7	175	2.40	
	125	660.8	-2.6	-4.6	0	0	287	2.25	
44	130	660.8	-2.9	-4.9	0	0	5	2.18	
	140	659.7	-2.0	-4.5	0.3	2.0	95	2.07	
45	145	659.3	-2.3	-4.2	1.8	1.6	0	2.39	
	155	658.3	-2.1	-4.1	2.4	-	353	2.38	
46	160	658.2	-2.0	-4.0	0.6	0	15	2.41	End Ascent
	160	658.2	-2.7	-4.4	0	1.5	195	2.43	Hold
47	160	658.2	-2.2	-	0.7	1.0	57	-	
	160	658.2	-2.6	-4.7	0.7	0	324	2.20	
48	160	658.2	-2.5	-4.1	1.5	5.5	110	2.59	
	160	658.2	-	-	1.7	3.3	70	-	
49	160	658.2	-1.1	-2.6	3.9	3.3	60	2.97	
	-	-	-1.2	-	4.2	3.3	325	-	

(continued)

TABLE B-3. (continued)

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
50	160	658.2	-1.2	-	2.9	-	-	-	
	160	658.2	-2.5	-4.5	4.6	1.5	294	2.29	
51	160	658.2	-2.3	-4.2	2.1	1.9	296	2.40	Start Horizontal
	160	658.2	-2.4	-4.3	-	2.1	-	2.37	Traverse
52	160	658.2	-1.2	-2.9	2.3	0.9	74	2.81	
	160	658.2	-1.5	-3.1	1.5	1.3	346	2.80	
53	160	658.2	-0.7	-2.1	2.4	-	0	3.15	
	160	658.2	-0.4	-1.6	4.0	4.0	255	3.37	
54	160	658.2	-0.9	-	2.5	3.6	280	-	
	160	658.2	-	-1.2	5.3	5.4	56	-	
55	160	658.2	-0.9	-1.7	7.0	5.0	-	3.51	
	160	658.2	-1.1	-1.6	3.6	5.0	6	3.67	
56	160	658.2	-0.2	-1.0	3.0	-	22	3.72	
	160	658.2	-0.2	-1.2	3.2	4.7	23	3.57	
57	-	-	-0.5	-1.9	-	3.0	10	3.21	
	-	-	-	-	-	2.7	58	-	
58	160	658.2	-1.7	-3.1	1.4	2.9	43	2.88	
	160	658.2	-1.1	-3.0	3.2	1.2	45	2.70	
59	170	657.4	-1.7	-3.0	0.5	1.6	187	2.95	Raise
	185	656.6	-1.9	-3.5	-	1.3	170	2.70	
0800	195	655.9	-1.0	-3.0	1.7	1.5	105	2.66	
	210	654.8	-1.5	-2.7	2.0	2.7	105	3.09	
01	210	654.8	-0.8	-1.7	4.0	3.4	45	3.49	
	210	654.8	-0.4	-1.6	6.0	3.0	-	3.38	
02	210	654.8	-0.4	-1.6	3.9	3.0	53	3.39	
	210	654.8	-0.9	-2.0	7.0	3.4	302	3.32	
03	210	654.8	-1.3	-2.3	4.6	4.1	75	3.28	
	210	654.8	-1.0	-2.7	2.1	3.1	12	2.88	
04	210	654.8	-2.2	-4.4	2.0	3.0	350	2.24	
	210	654.8	-2.0	-4.2	2.4	2.6	20	2.29	Start Horizontal
05	210	654.8	-1.0	-2.2	4.0	5.8	-	3.22	Traverse

(continued)

TABLE B-3. (continued)

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
	210	654.8	-1.8	-3.4	5.6	2.8	58	2.74	
06	210	654.8	-1.9	-4.1	3.1	3.2	25	2.31	
	210	654.8	-1.9	-3.6	3.3	2.0	25	2.64	
07	210	654.8	-1.8	-3.5	4.6	2.9	82	2.67	
	210	654.8	-1.4	-3.3	5.8	3.1	78	2.64	
08	210	654.8	-1.6	-3.1	3.1	2.2	353	2.85	
	210	654.8	-1.9	-3.6	2.1	1.5	0	2.64	
09	170	657.4	-1.4	-	2.0	2.7	272	-	
	170	657.4	-1.2	-2.6	-	7.6	335	3.03	
10	180	656.6	-0.9	-1.9	4.1	5.3	185	3.39	
	220	653.6	-1.8	-4.1	3.5	2.7	73	2.27	
11	220	653.6	-2.0	-4.0	2.4	2.1	44	2.42	End Horizontal
	210	654.4	-2.3	-4.7	2.3	2.4	45	2.08	Traverse
12	200	655.1	-2.3	-4.7	2.4	2.5	45	2.08	
	200	655.1	-2.2	-4.6	2.4	2.5	43	2.10	Descend
13	200	655.1	-2.3	-4.8	3.0	2.9	43	2.02	
	180	656.6	-2.2	-4.7	2.9	3.0	46	2.04	
14	160	658.2	-2.3	-4.8	2.4	3.3	52	2.04	
	140	660.0	-2.4	-4.8	3.2	3.3	58	2.04	
15	120	662.0	-2.0	-4.5	3.3	3.3	58	2.06	
	100	662.7	-1.9	-4.6	3.5	3.5	59	1.95	
16	80	664.2	-2.0	-4.5	2.4	2.5	37	2.06	
	50	666.5	-1.6	-4.4	2.9	3.5	67	1.95	
17	20	668.8	-1.5	-4.0	3.7	3.5	58	2.16	Visible Plume
	0	670.3	-1.0	-3.9	1.7	3.1	78	2.06	Touching Ground
0818	0	670.3	-0.7	-3.5	1.9	1.9	110	2.16	

Ascent	Mean	1.15	6
	Standard Deviation	.87	102
First Horizontal	Mean	2.73	18
	Standard Deviation	1.62	81

(continued)

TABLE B-3. (continued)

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments	
Second Horizontal			Mean		3.40		21			
			Standard Deviation		1.45		68			
Descent			Mean		2.83		57			
			Standard Deviation		.55		19			
0800	Background	670.3	-5.5	-	1.0		280	1.42	-1.7°C@112m -2.0°C@152m	Stack
0830	Background	670.3	-3.6	-	-		-	1.57	-0.8°C@76m -2.5°C@112m -2.9°C@152m	Stack

TABLE B-4. SONDE DATA RUN 3C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed 1 m/s	Wind Speed 2 m/s	Wind Direction	Mixing Ratio g/kg	Comments
0830	Background	670.3	-3.6	-	-		-	1.57	-0.8°C@76m -2.5°C@112m Stack -2.9°C@152m
0900	Background	670.3	-2.7	-	1.1		30	1.64	0°C @76m -2.2°C@112m Stack -2.5°C@152m
0852	20	668.8	-2.0	-3.8	0	0	120	2.50	Ascent
	40	667.3	-2.0	-4.0	0	0	130	2.37	
53	50	668.5	-2.2	-	0	0	110	-	
	60	665.8	-2.4	-	0	0	125	-	
54	70	665.0	-2.5	-4.2	0.3	0.1	97	2.46	
	90	663.5	-2.6	-4.5	0.2	0.1	107	2.31	
55	105	662.4	-2.7	-4.4	0	0	300	2.42	
	125	660.8	-2.9	-4.5	0	0.2	44	2.44	
56	145	659.3	-3.0	-4.6	0	0	88	2.42	
	170	657.4	-3.2	-4.7	0	0	340	2.45	
57	190	655.9	-3.5	-5.0	0	0.4	355	2.39	
	200	655.1	-3.5	-5.0	0	0	345	2.39	
58	200	655.1	-3.5	-5.0	0	0	0	2.39	
	200	655.1	-3.4	-5.0	0	0	345	2.35	
59	195	655.5	-3.4	-5.0	0	0	0	2.35	
	190	655.9	-3.5	-5.0	0	0	350	2.39	
0900	190	655.9	-3.5	-5.0	0	0	0	2.39	
	185	656.3	-3.3	-4.9	0	0	355	2.37	
01	185	656.3	-3.3	-5.0	0	0	10	2.30	Start Traverse
	180	656.6	-3.2	-4.8	0	0	0	2.39	
02	175	656.3	-3.1	-4.8	0	0	10	2.35	
	170	657.4	-3.3	-4.8	0	0	12	2.43	
03	170	657.4	-3.4	-4.9	0	0	0	2.40	
	180	656.6	-3.2	-4.7	0	0	10	2.45	

(continued)

TABLE B-4. (continued)

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
04	180	656.3	-3.2	-4.6	0	0	0	2.51	
	170	657.4	-3.0	-4.6	0	0	20	2.43	
05	165	657.8	-3.2	-4.8	0	0.3	10	2.38	
	160	658.2	-3.2	-4.7	0.4	0.1	355	2.45	
06	160	658.2	-3.1	-4.7	0.5	0.5	7	2.41	
	160	658.6	-3.0	-4.6	0.4	0.4	12	2.43	
07	160	658.6	-2.9	-4.5	0.2	0.9	52	2.45	Mark
	160	658.2	-3.0	-4.5	0.8	0.9	51	2.49	
08	160	658.2	-3.0	-4.5	0.6	0.6	25	2.49	
	160	658.2	-3.1	-4.6	0.3	0.2	25	2.47	
09	160	658.2	-3.2	-4.6	0	0.3	0	2.51	
	160	658.2	-3.2	-4.7	0.3	0.5	352	2.45	
10	160	658.2	-3.1	-4.6	0.4	1.2	0	2.47	
	160	658.2	-2.8	-4.4	0.8	1.1	352	2.48	Lower
11	145	659.3	-2.7	-4.2	0.7	1.5	0	2.56	
	135	660.1	-2.3	-4.0	1.7	1.6	0	2.52	
12	130	660.4	-2.5	-4.1	1.9	2.2	28	2.54	
	125	660.8	-2.5	-4.0	2.7	3.1	16	2.60	
13	120	661.2	-2.4	-3.9	1.8	1.7	346	2.63	
	110	662.0	-2.3	-3.8	0.7	1.8	14	2.63	
0930	Background	670.3	-1.0	-	-		-	1.78	+0.9°C@76m -0.5°C@112m -1.3°C@152m Stack
0914	100	663.1	-2.3	-3.9	0	0.8	0	2.58	
	100	663.5	-2.1	-3.7	1.0	0.3	0	2.62	
15	100	662.7	-2.2	-3.7	0.2	0.6	29	2.67	
	100	662.7	-2.1	-3.7	0.2	0	0	2.63	
16	100	662.5	-2.1	-3.7	0.2	0	0	2.63	
	100	663.1	-2.2	-3.7	0	0	355	2.67	
17	100	663.5	-2.1	-3.7	0	0	285	2.63	
	100	662.0	-2.1	-3.7	0	0	290	2.63	
18	100	661.6	-2.2	-3.6	0	1.4	296	2.74	

(continued)

TABLE B-4. (continued)

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed 1 m/s	Wind Speed 2 m/s	Wind Direction	Mixing Ratio g/kg	Comments
	100	661.2	-2.2	-3.7	2.0	0.5	302	2.68	
19	100	660.4	-2.0	-3.5	0	0	294	2.73	Start Traverse,
	100	661.2	-2.0	-3.6	0	0	292	2.66	East
20	100	661.6	-1.8	-3.3	0	0	22	2.77	
	100	662.7	-1.8	-3.4	0	0	45	2.70	
21	100	662.7	-1.8	-3.4	0	0.1	15	2.70	
	100	662.7	-2.0	-3.5	0.6	0.5	36	2.72	
22	100	662.7	-1.9	-3.5	0.4	0.2	49	2.68	
	100	662.7	-1.9	-3.5	0.3	1.0	40	2.68	
23	100	662.7	-1.9	-3.4	1.0	1.4	56	2.75	
	100	662.7	-1.5	-3.3	2.4	0	79	2.65	
24	100	662.7	-1.5	-3.1	2.0	0.8	40	2.78	
	100	662.0	-1.6	-3.1	1.9	2.1	66	2.82	
25	100	662.0	-1.7	-3.2	1.3	0.6	12	2.80	
	100	662.0	-1.6	-3.2	1.5	1.6	23	2.75	
26	100	662.0	-1.4	-3.0	1.0	1.8	64	2.81	
	100	662.0	-1.7	-3.0	1.0	1.8	15	2.93	
27	100	662.7	-1.8	-3.2	1.7	1.5	4	2.84	
	100	662.4	-1.6	-3.1	1.3	1.4	8	2.82	
28	100	662.4	-1.6	-3.0	3.1	3.3	355	2.89	Lower
	100	662.4	-1.6	-3.0	1.9	1.9	35	2.89	
29	95	663.1	-1.3	-3.0	0.5	2.3	0	2.76	
	90	663.1	-1.5	-2.9	2.1	2.2	43	2.91	
30	75	664.6	-1.2	-2.8	2.0	1.0	0	2.85	Start Traverse,
	70	665.0	-1.1	-2.6	2.2	1.7	36	2.94	North
31	70	665.0	-1.2	-2.7	1.4	2.1	52	2.91	
	75	664.6	-1.4	-2.7	1.4	1.6	23	3.00	
32	75	664.6	-1.4	-2.7	1.0	0.9	22	3.00	
	80	663.5	-1.3	-2.8	0.5	1.1	8	2.90	
33	85	663.9	-1.3	-2.6	1.0	0.6	23	3.03	
	85	663.9	-1.5	-2.6	1.0	0.2	352	3.11	
34	90	663.5	-1.6	-2.7	0.3	1.3	358	3.09	

(continued)

TABLE B-4. (continued)

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed 1 m/s	Wind Speed 2	Wind Direction	Mixing Ratio g/kg	Comments
	85	663.1	-1.5	-2.8	1.3	1.8	6	2.98	
35	85	663.5	-1.5	-2.7	1.2	2.0	353	3.05	
	85	663.5	-1.3	-2.6	1.9	2.9	29	3.03	
36	85	663.9	-1.3	-2.5	3.4	2.8	17	3.10	
	85	663.9	-1.0	-2.4	3.3	3.6	339	3.04	
37	85	663.9	-1.2	-2.5	3.2	3.5	353	3.06	
	85	663.5	-0.2	-1.7	3.7	5.3	78	3.20	
0938	85	663.9	-0.7	-1.9	5.1	3.1	24	3.26	
	85	664.6	-0.8	-2.0	4.2	5.4	0	3.23	
39	85	663.9	-0.6	-1.8	5.8	3.5	285	3.29	
	85	663.1	-1.0	-2.1	2.5	4.7	324	3.25	
40	85	663.1	0.0	-1.0	4.1	5.9	347	3.61	Into Visible
	100	662.7	-1.0	-1.1	4.4	-	338	3.95	Plume
41	110	662.0	+1.2	+1.0	4.0	7.5	166	4.58	
	105	662.4	+5.4	1.3	4.5	8.5	150	3.06	
42	75	664.8	4.3	1.7	10.0	7.0	350	3.80	
	80	664.2	0.4	0.0	4.4	3.8	353	4.15	
43	80	664.2	0.9	-0.3	3.6	2.7	354	3.73	
	90	663.5	-0.2	-0.5	3.5	2.5	354	4.04	
44	85	663.9	-0.6	-1.1	2.6	2.8	0	3.78	
	85	663.9	-0.6	-2.1	2.8	2.1	10	3.08	
45	80	664.2	-0.5	-2.2	2.1	2.1	0	2.97	
	80	664.2	+0.7	-0.9	3.5	2.2	350	3.38	
46	75	664.6	-0.6	-2.4	1.9	4.0	350	2.87	Descend
	75	664.6	-0.5	-2.1	2.7	1.7	7	3.04	
47	65	665.4	-0.3	-2.2	2.7	2.9	0	2.88	
	40	667.3	-0.5	-2.3	2.8	-	-	2.89	
0948	30	668.0	-						
Ascent			Mean		.04		44		
		Standard Deviation			.01		65		

(continued)

TABLE B-4. (continued)

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments	
E-W Traverse			Mean		.74		9			
		Standard	Deviation		.84		33			
N Traverse			Mean		3.05		13			
		Standard	Deviation		1.98		46			
1000	Background	670.3	-0.8	-	1.9		30	1.77	+1.3°C@76m -1.1°C@112m -1.7°C@152m	Stack

TABLE B-5. SONDE DATA RUN 4C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
1030	Background	670.3	0.0	-	-		-	1.83	0.9°C@76m -0.4°C@112m -0.8°C@152m Stack
1028.5	10	669.6	+0.4	-3.1	1.6	1.9	30	1.97	
29	10	669.6	0.5	-2.8	2.5	2.7	25	2.13	
	10	669.6	0.4	-2.7	2.6	2.5	36	2.24	Ascend
30	40	667.3	0.1	-3.2	2.3	2.4	30	2.04	
	50	666.2	0.1	-3.3	2.3	2.5	48	1.97	
31	60	665.8	0.0	-3.4	2.5	2.4	22	1.95	
	85	663.9	-0.2	-3.5	2.6	2.5	48	1.97	
32	95	663.1	-0.2	-3.5	2.6	2.7	25	1.97	
	110	662.0	-0.3	-3.6	2.4	3.3	36	1.95	
33	120	661.2	-0.5	-3.5	3.9	2.4	44	2.10	
	120	661.2	-0.5	-3.7	2.5	2.4	33	1.97	
34	130	660.4	-0.8	-3.8	2.3	1.9	50	2.03	
	140	659.7	-0.7	-3.9	1.9	2.0	52	1.93	
35	150	658.9	-0.8	-3.9	2.2	2.3	52	1.97	
	170	657.4	-1.0	-4.0	2.6	2.6	48	1.99	
36	175	657.0	-1.0	-4.1	1.7	2.3	52	1.93	
	175	657.0	-1.0	-4.1	2.0	2.0	54	1.93	Stop Ascent
37	175	657.0	-1.0	-4.1	1.9	2.6	62	1.93	Hold
	175	657.0	-0.8	-4.0	1.9	1.8	36	1.91	
1038	175	657.0	-0.9	-4.0	1.4	1.3	38	1.95	
	175	657.0	-0.9	-4.0	1.8	2.2	75	1.95	
			Mean		2.29		43		
			Standard Deviation		.47		13		
1100	Background	670.3	+0.8	-	2.0		40	1.90	+2.1°C@76m +0.8°C@112m +0.4°C@152m on stack

TABLE B-6. SONDE DATA RUN 5C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
1030	Background	670.3	0.0	-				1.83	0.9°C@76m -0.4°C@112m Stack -0.8°C@152m
1039	175	657.4	-0.8	-4.0	1.7	2.4	37	1.91	Horizontal
	175	657.4	-0.8	-4.0	3.1	3.6	58	1.91	Traverse
40	175	657.0	-0.7	-3.9	1.7	2.3	35	1.93	
	175	657.4	-0.7	-3.9	1.7	2.5	33	1.93	
41	175	657.4	-0.7	-3.9	1.8	2.1	45	1.93	
	175	657.4	-0.8	-3.9	2.2	2.2	55	1.97	
42	175	657.0	-0.7	-3.9	2.2	2.5	28	1.93	
	175	656.6	-0.8	-3.9	2.4	2.7	8	1.97	
43	175	657.0	-0.7	-3.8	2.1	2.3	12	2.00	
	175	657.0	-0.7	-3.9	2.7	2.9	12	1.93	
44	175	657.0	-0.6	-3.8	3.5	3.0	51	1.96	
	175	657.0	-0.6	-3.8	2.7	3.6	25	1.96	
45	175	657.0	-0.5	-3.7	2.5	3.0	73	1.98	
	175	656.6	-0.5	-3.7	2.2	1.4	46	1.98	
46	175	656.6	-0.4	-3.7	1.5	2.2	40	1.94	
	175	656.6	-0.5	-3.6	2.4	2.0	350	2.05	
47	175	657.0	-0.6	-3.7	2.3	2.2	45	2.02	
	175	656.6	-0.6	-3.7	2.4	3.1	56	2.02	
48	175	657.0	-0.6	-3.8	2.8	2.3	51	1.96	
	175	657.0	-0.5	-3.6	2.6	2.7	31	2.05	
49	175	657.4	-0.5	-3.6	3.4	3.6	14	2.05	
	175	657.4	-0.3	-3.5	0.8	2.0	5	2.03	
50	175	658.2	-0.2	-3.5	1.8	3.3	38	1.99	
	175	658.2	-0.1	-3.5	4.5	3.7	57	1.95	
51	175	658.2	-0.3	-3.5	3.4	3.9	42	2.03	
	175	657.4	-0.2	-3.5	4.6	3.6	51	1.99	
1052	175	657.8	0.0	-3.4	3.7	2.3	32	1.97	

(continued)

TABLE B-6. (continued)

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments	
				Mean	2.63		36			
			Standard Deviation		.77		19			
1100	Background	670.3	+0.8	-	2.0		40	1.90	+2.1°C@76m +0.8°C@112m +0.4°C@152m	Stack

TABLE B-7. SONDE DATA RUN 6C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
1100	Background	670.3	+0.8	-	2.0		40	1.90	+2.1°C@76m +0.8°C@112m Stack +0.4°C@152m
1052.5	175	657.4	-0.3	-3.5	2.5	3.7	65	2.03	Descent
53	175	657.4	-0.3	-3.6	3.6	2.8	36	1.96	
	160	658.6	-0.3	-3.5	3.0	2.8	40	2.03	
54	140	659.7	0.0	-3.4	2.7	3.0	51	1.97	
	125	660.8	+0.3	-3.2	2.9	3.1	67	1.97	
55	110	662.4	0.4	-3.0	3.3	3.4	73	2.06	
	95	663.5	0.5	-3.0	4.1	3.6	47	2.01	
56	80	664.2	0.5	-2.9	3.9	3.5	51	2.08	
	65	665.4	0.7	-2.8	2.8	3.6	54	2.06	
57	50	665.8	0.8	-2.7	3.8	3.0	85	2.09	
	35	667.3	1.2	-2.5	4.4	2.8	74	2.05	
58	20	668.3	1.2	-2.5	2.5	2.8	80	2.05	
	0	670.3	1.3	-2.3	2.5	1.9	90	2.14	
59	0	671.0	3.6	-1.2	1.0	1.5	93	1.95	
			Mean		3.02		65		
			Standard Deviation		.75		19		

TABLE B-8. SONDE DATA RUN 7C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
1100	Background	670.3	+0.8	-	2.0		40	1.90	+2.1°C@76m +0.8°C@112m Stack +0.4°C@152m
1059.5	0	670.3	+2.1	-1.2	2.8	3.5	36	2.57	
1100	0	670.3	+1.9	-1.9	3.8	3.3	62	2.16	
	0	670.3	1.7	-2.2	2.7	2.5	87	2.04	Ascend
01	15	669.2	1.5	-2.3	2.5	2.5	51	2.06	
	35	667.3	1.5	-2.3	2.8	2.4	67	2.06	
02	50	666.5	1.3	-2.5	3.3	2.8	94	2.01	
	65	665.4	1.2	-2.5	2.7	2.5	48	2.01	
03	80	664.2	1.0	-2.6	3.5	2.9	110	2.08	
	90	662.7	0.9	-2.6	2.9	3.2	89	2.12	
04	90	663.5	1.1	-2.6	2.5	2.2	66	2.04	Start Horizontal
	90	663.9	1.1	-2.5	2.8	3.1	38	2.10	Traverse
05	90	664.2	0.9	-2.6	3.3	3.0	38	2.12	
	90	664.2	1.1	-2.5	3.9	3.1	85	2.10	
06	90	664.2	1.0	-2.5	4.7	4.9	50	2.14	
	90	663.5	1.3	-2.4	6.1	4.2	103	2.09	
07	90	663.5	0.9	-2.6	4.1	5.6	35	2.12	
	95	663.1	0.9	-2.6	3.5	3.9	42	2.12	
08	100	662.7	1.3	-2.5	5.9	3.9	53	2.03	
	100	662.4	1.1	-2.5	3.3	3.6	35	2.11	
09	100	662.7	1.1	-2.5	4.7	6.2	35	2.11	
	100	662.4	1.2	-2.5	4.9	3.3	106	2.07	
10	100	662.7	1.3	-2.1	3.1	5.0	60	2.30	
	100	662.7	1.7	-1.9	4.5	4.1	80	2.27	
11	100	662.7	1.1	-2.3	5.0	4.7	57	2.25	
	100	662.7	1.1	-2.2	5.2	4.5	66	2.31	
12	100	662.4	1.2	-2.4	5.5	5.0	83	2.14	
	100	662.4	2.4	-1.8	4.6	5.5	37	2.05	
13	100	662.7	2.5	-0.5	3.8	5.0	34	2.93	End Traverse
	100	663.1	1.7	-1.5	3.1	4.7	60	2.55	Ascend

(continued)

TABLE B-8. (continued)

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed 1 m/s	Wind Speed 2 m/s	Wind Direction	Mixing Ratio g/kg	Comments
14	110	661.6	1.5	-1.7	4.4	2.9	68	2.50	
	120	659.7	1.4	-2.0	4.8	6.5	85	2.34	
15	130	658.2	0.8	-2.3	5.3	5.5	18	2.39	
	145	657.8	1.0	-2.3	2.8	3.5	73	2.30	
16	155	657.8	0.8	-2.6	3.4	3.7	84	2.18	
	165	657.8	1.2	-2.4	2.8	4.1	55	2.15	
17	180	655.5	1.0	-2.3	4.1	4.3	17	2.31	
	190	654.0	0.9	-2.2	2.8	6.1	260	2.43	
18	200	655.5	0.7	-2.5	3.6	3.7	56	2.30	
	210	654.0	0.7	-2.5	3.7	3.5	22	2.30	
19	225	652.1	1.0	-1.7	4.1	3.3	99	2.75	
	235	652.1	0.6	-2.1	7.0	-	133	2.63	
20	245	651.3	0.8	-2.2	3.2	3.0	90	2.48	
	255	651.7	0.8	-2.3	3.2	3.9	75	2.41	
21	265	650.2	0.8	-2.1	4.9	2.6	90	2.55	Hold
	265	650.2	0.4	-2.4	3.7	3.3	75	2.51	
22	265	650.2	1.0	-2.2	3.9	7.7	37	2.40	
	265	650.2	0.5	-1.9	6.6	4.0	38	2.82	
23	265	650.6	0.3	-2.5	4.1	2.6	92	2.49	Descend
	255	651.3	0.2	-3.0	3.1	3.2	56	2.18	
24	240	651.3	0.3	-3.1	3.8	3.3	70	2.07	
1130	Background	670.3	+4.6	-	-		-	2.07	2.3°C@76m 1.8°C@112m Stack 1.3°C@152m
1124.5	230	651.3	0.3	-3.0	3.0	3.9	60	2.14	
25	225	651.7	0.4	-3.0	4.0	5.0	58	2.09	
	215	652.5	1.0	-1.8	5.3	4.7	87	2.67	
26	220	652.1	1.7	-1.3	4.3	4.5	25	2.73	
	210	652.8	0.7	-2.1	4.9	4.5	48	2.59	
27	200	653.6	1.9	-1.0	4.8	6.7	35	2.86	
	195	654.0	1.8	-1.0	5.7	5.3	0	2.90	

(continued)

TABLE B-8. (continued)

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed 1 m/s	Wind Speed 2 m/s	Wind Direction	Mixing Ratio g/kg	Comments
28	180	655.1	1.2	-2.3	5.6	2.9	73	2.23	
	160	656.6	1.0	-2.5	3.2	2.4	85	2.17	
29	120	659.7	1.0	-2.3	3.1	4.8	73	2.30	
	110	660.1	1.8	-2.1	5.8	6.5	100	2.11	
30	90	662.0	2.0	-1.9	6.4	4.3	122	2.15	
	80	662.7	2.1	-1.3	5.1	3.9	6	2.52	
31	50	665.0	3.0	-0.9	4.2	4.7	352	2.43	
	40	665.8	2.8	-0.6	4.7	4.0	66	2.72	
32	40	665.8	2.7	-0.9	5.1	3.3	24	2.55	
	40	665.8	2.5	-1.0	2.5	2.7	53	2.56	
33	30	666.5	3.0	-1.2	2.9	2.7	73	2.21	
	15	667.7	3.5	-1.0	1.9	2.9	55	2.14	Hold
34	15	667.7	3.4	-1.3	2.6	2.2	23	1.97	
	15	667.7	2.8	-1.3	2.4	3.1	50	2.22	
35	15	667.7	3.0	-1.4	1.6	2.8	68	2.07	
	15	667.7	3.2	-1.1	2.8	2.5	85	2.19	
36	15	667.7	3.6	-1.0	1.6	2.4	50	2.10	
	15	667.7	3.0	-1.0	2.9	2.5	74	2.35	
37	15	667.7	3.4	-1.0	1.6	2.4	103	2.18	Ascend
	20	667.3	3.0	-1.1	2.5	2.5	103	2.28	
38	40	665.8	2.7	-1.2	2.4	4.3	94	2.34	
	55	664.6	2.8	-1.5	4.4	4.1	107	2.09	
39	75	663.1	2.8	-1.3	3.4	4.5	105	2.23	
	95	661.6	2.3	-1.3	3.6	4.0	16	2.45	
40	115	660.1	2.5	-1.5	2.2	2.3	40	2.23	
	140	658.2	1.8	-1.9	2.0	1.7	87	2.25	
41	155	657.0	1.5	-2.1	3.5	3.1	0	2.24	
	180	655.1	1.8	-2.0	3.6	4.3	66	2.19	
42	205	653.2	1.4	-1.7	4.3	3.3	32	2.57	
	205	653.2	1.0	-2.5	4.0	4.4	44	2.18	
43	225	651.7	0.8	-2.7	4.3	3.2	43	2.13	
	245	650.2	1.3	-2.1	5.5	4.7	146	2.34	

(continued)

TABLE B-8. (continued)

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed 1 m/s	Wind Speed 2 m/s	Wind Direction	Mixing Ratio g/kg	Comments
44	250	649.8	0.7	-2.6	4.1	3.5	51	2.25	
	250	649.8	0.6	-2.7	3.4	4.0	60	2.22	
45	250	649.8	1.0	-2.3	3.4	3.8	36	2.33	
	240	650.6	1.2	-2.2	3.1	3.5	44	2.31	
46	240	650.6	1.5	-1.8	3.5	4.6	0	2.47	
	255	649.4	1.8	-1.5	5.3	5.8	16	2.56	
47	245	650.2	1.3	-2.0	3.8	3.3	88	2.41	
	240	650.6	0.9	-2.5	3.6	4.3	52	2.23	
1100 - 1123			Mean		3.95		58		
		Standard	Deviation		1.16		34		
1123 - 1147			Mean		3.72		61		
		Standard	Deviation		1.15		36		
1200	Background	668.8	+3.6	-	3.0		70	2.05	2.8°C@76m 2.3°C@112m Stack 1.7°C@152m

TABLE B-9. SONDE DATA RUN 8C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments	
1130	Background	670.3	+4.6	-		-	-	2.07	2.3°C@76m 1.8°C@112m 1.3°C@152m	Stack
1148	230	651.3	1.0	-2.6	4.6	5.0	52	2.12	Descend	
	210	652.8	1.2	-2.5	5.6	5.6	55	2.10		
49	200	653.6	1.3	-2.5	5.8	5.0	53	2.05		
	180	655.1	1.5	-2.5	4.7	5.0	81	1.96		
50	160	656.6	1.7	-2.4	4.5	5.3	80	1.95		
	140	658.2	2.2	-1.6	5.3	4.6	83	2.29		
51	125	659.3	2.0	-1.6	4.7	3.6	70	2.29		
	105	660.8	2.5	-1.4	4.3	4.3	98	2.30		
52	85	662.4	2.7	-1.1	4.3	4.4	106	2.42		
	65	663.9	2.9	-1.1	4.3	4.5	81	2.33		
53	40	665.8	3.3	-0.9	3.9	2.6	69	2.30		
	20	667.3	4.0	-0.3	3.1	2.8	83	2.43	Hold	
54	20	667.3	3.5	-0.7	2.6	3.2	90	2.35		
	20	667.3	3.1	-1.1	3.3	3.2	92	2.24		
55	20	667.3	3.3	-1.1	2.5	3.0	95	2.19		
	20	667.3	3.2	-1.0	3.0	3.3	95	2.27		
56	20	667.3	3.4	-1.0	3.3	3.1	102	2.18		
	20	667.3	3.3	-0.9	3.1	3.0	88	2.29		
			Mean			4.01	82			
			Standard Deviation			.98	16			
1200	Background	668.8	+3.6	-		3.0	70	2.05	2.8°C@76m 2.3°C@112m 1.7°C@152m	Stack

TABLE B-10. SONDE DATA RUN 9C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
1200	Background	668.8	+3.6	-	3.0		70	2.05	2.8°C@76m 2.3°C@112m Stack 1.7°C@152m
1210	20	667.3	4.3	-0.2	5.2	4.7	102	2.38	Ascend
	40	666.5	3.5	-0.7	4.1	3.5	104	2.36	
11	55	664.6	3.4	-0.9	3.7	3.9	110	2.26	
	75	663.1	4.0	+0.3	4.3	4.6	93	2.64	
12	90	662.0	3.7	0.1	4.0	4.6	96	2.79	
	110	660.4	3.5	-0.3	5.2	3.7	114	2.67	
13	130	658.6	4.0	+0.7	2.6	4.3	50	3.21	
	160	657.4	4.3	+1.7	2.8	5.2	54	3.85	
14	180	653.6	3.4	0.7	5.1	5.4	60	3.48	
	215	652.5	2.9	-0.2	4.5	3.9	160	3.03	
15	240	652.5	2.0	-1.5	4.2	5.3	73	2.46	
	260	649.0	2.7	0.0	7.6	2.9	44	3.28	Possible Wet-bulb Freeze
16	270	648.7	1.8	-1.5	3.3	2.0	90	2.56	Hold
	270	648.7	1.6	-2.0	2.2	2.4	75	2.29	
17	270	649.0	1.5	-2.3	3.2	3.7	70	2.12	
	270	649.4	2.3	-1.6	3.4	5.1	90	2.28	
18	270	647.5	2.0	-1.4	5.3	5.4	22	2.55	
	270	647.2	2.4	-0.7	3.5	3.5	297	2.89	
19	270	648.3	1.5	-2.0	3.3	3.9	62	2.34	
	270	648.3	2.7	-1.0	5.5	3.3	36	2.54	
20	270	648.3	2.0	-1.2	3.1	1.9	83	2.70	
	270	648.3	2.5	-1.0	4.5	5.6	0	2.63	
21	270	647.5	2.3	-1.3	6.7	3.5	120	2.50	
	270	647.9	1.6	-2.0	3.3	4.0	50	2.30	
22	270	648.3	2.8	-0.8	6.0	2.9	88	2.65	
	270	648.3	2.1	-1.2	2.1	2.7	86	2.65	
23	270	648.7	2.3	-1.0	6.4	2.6	75	2.71	

(continued)

TABLE B-10. (continued)

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
			Mean		4.07		72		
			Standard Deviation		1.25		43		
1230	Background	668.8	+4.4	-	-		-	2.11	3.7°C@76m 3.2°C@112m Stack 2.7°C@152m

TABLE B-11. SONDE DATA RUN 10C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
1200	Background	668.8	+3.6	-	3.0		80	2.05	2.8°C@76m 2.3°C@112m Stack 1.7°C@152m
1223.5	270	648.7	1.8	-1.9	2.4	3.2	70	2.28	Descent
24	250	649.8	2.3	-1.6	3.9	6.6	40	2.28	
	230	649.4	2.0	-1.1	6.5	5.3	48	2.76	
25	210	652.1	2.1	-1.7	3.0	4.4	83	2.28	
	190	654.8	3.9	-0.4	4.4	6.8	92	2.45	
26	170	655.1	4.0	+0.2	4.7	3.7	55	2.85	
	145	657.8	4.6	1.2	4.8	5.8	28	3.34	
27	125	659.7	4.2	1.0	4.6	5.1	58	3.35	
	110	660.4	4.0	0.6	3.4	5.3	103	2.74	
28	90	662.0	5.0	0.9	6.4	5.5	65	2.93	
	70	663.5	4.5	0.7	1.7	3.9	67	2.98	
29	40	665.8	4.5	0.3	4.3	4.0	136	2.67	
	20	667.3	4.5	-	4.5	3.8	90	-	
30	10	668.0	-	-	2.0	1.9	-	-	
	-	-	-	0.2	-	-	-	-	
31	0	668.8	-	-	2.8	2.5	113	-	Hold
	0	668.8	5.5	0.7	-	1.7	92	2.54	
32	0	669.2	-	0.8	3.0	3.3	116	-	
	0	668.8	5.0	0.3	2.5	2.8	135	2.45	
33	0	668.0	5.0	-	2.6	-	-	-	
			Mean		3.98		82		
			Standard Deviation		1.45		32		
1230	Background	668.8	+4.4	-	-	-	-	2.11	3.7°C@76m 3.2°C@112m Stack 2.7°C@152m

TABLE B-12. SONDE DATA RUN 11C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
1300	Background		5.1	-	2.2		60	2.22	5.0°C@76m 4.3°C@112m 3.5°C@152m
1303	40	663.5	5.5	0.1	3.2	2.3	122	2.12	
	40	663.5	5.7	0.3	2.3	3.8	73	2.18	
04	40	663.5	5.2	0.2	3.3	3.0	324	2.32	
	40	663.9	5.4	0.3	1.2	2.5	29	2.30	
05	40	663.9	5.4	0.3	2.4	1.5	80	2.30	
	40	663.9	5.0	0.2	2.7	2.7	44	2.40	Ascend
06	-	-	-	-	-	-	-	-	
	50	662.7	5.5	0.2	2.9	2.1	44	2.19	
07	-	-	4.7	-	2.7	3.2	58	-	
	70	660.4	5.0	0.2	3.5	3.2	80	2.41	
08	80	659.7	4.7	0.0	2.9	2.3	51	2.39	
	100	658.9	5.0	0.6	2.6	3.1	58	2.71	
09	120	658.2	4.2	0.0	2.6	2.1	80	2.60	
	140	656.6	4.2	0.0	1.8	2.5	51	2.61	
10	160	654.4	4.1	-0.4	3.9	2.8	73	2.37	
	180	652.8	3.3	-	2.1	2.8	29	-	
11	200	651.3	3.4	-0.6	3.2	3.5	66	2.53	
	220	650.6	3.4	-0.8	3.4	3.5	36	2.38	
12	240	648.3	3.2	-1.0	1.9	3.4	73	2.33	
	250	647.5	3.4	-0.8	2.4	2.8	90	2.39	Hold
13	250	647.5	-	-0.9	1.2	1.2	44	-	
	250	647.5	3.4	-1.0	2.5	1.8	90	2.25	
			Mean		2.52		46		
		Standard	Deviation		.76		40		
1330	Background		6.1	-	-	-	-	2.32	5.5°C@76m 5.0°C@112m 4.4°C@152m Stack

TABLE B-13. SONDE DATA RUN 12C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
1330	Background	665.8	6.1	-	-		-	2.32	5.5 C@76m 5.0 C@112m Stack 4.4 C@152m
1328	125	656.3	5.0	0.2	3.5	2.8	158	2.42	Horizontal
	125	656.3	5.0	0.2	3.0	3.6	231	2.42	Traverse
29	125	656.6	5.0	0.3	4.0	1.4	58	2.50	
	125	656.6	4.9	0.2	2.0	3.3	51	2.47	
30	125	656.6	5.0	0.5	2.5	3.3	66	2.65	
	125	655.9	5.0	0.4	2.2	3.0	18	2.58	
31	125	656.3	5.0	0.4	2.0	3.0	130	2.57	
	125	656.6	5.0	0.4	4.2	3.4	332	2.57	
32	125	655.9	4.9	0.4	0.9	1.2	73	2.62	Stop
	125	656.6	4.8	0.3	2.7	3.3	55	2.58	Hold
33	125	656.3	4.9	0.4	4.0	4.0	353	2.62	Hold
	125	655.9	4.8	0.2	2.3	2.3	110	2.51	Hold
34	120	655.5	4.5	0.0	1.2	2.0	73	2.49	Hold
	120	655.1	4.4	-0.1	1.0	0.6	50	2.48	Hold
35	120	655.1	4.5	-0.1	1.6	2.0	92	2.44	Hold
	120	655.1	4.7	-0.1	2.9	1.7	112	2.35	Hold
36	120	655.1	4.5	-0.1	1.9	2.4	29	2.44	Hold
	120	655.1	5.1	0.0	0	0	10	2.24	Hold
37	120	656.6	4.8	+0.1	1.0	0.2	60	2.43	Hold
	120	656.6	4.9	0.2	0	0	38	2.47	Hold
38	120	657.0	5.1	0.2	0	0	355	2.38	Hold
	120	656.6	5.0	0.1	1.0	0.5	340	2.35	Hold
39	120	656.6	5.1	0.2	1.3	2.2	68	2.38	Hold
	120	656.6	5.0	0.2	1.0	1.7	0	2.42	Hold
40	120	656.6	5.0	0.2	2.7	0.7	357	2.42	Hold
			Mean		1.95		42		
			Standard Deviation		1.24		60		

TABLE B-14. SONDE DATA RUN 13C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
1330		665.8	6.1	-	-		-	2.32	5.5°C@76m 5.0°C@112m Stack 4.4°C@152m
1341	120	656.3	5.0	+0.2	1.2	3.0	10	2.43	Hold
	120	656.6	5.1	0.2	1.1	2.5	47	2.38	Hold
42	120	656.6	5.0	0.2	1.5	0.9	73	2.42	Horizontal Traverse
	120	656.6	5.0	0.2	1.5	1.5	130	2.42	
43	120	656.6	4.9	0.1	0.5	0.3	93	2.39	
	120	656.6	5.1	0.3	1.5	1.3	53	2.46	
44	120	656.6	5.0	0.2	1.7	0.6	14	2.42	
	120	656.6	5.0	0.2	0	1.0	56	2.42	
45	120	656.6	5.3	0.6	1.6	2.3	44	2.60	
	120	656.6	5.0	0.6	0.3	2.3	66	2.72	
46	120	656.6	5.4	0.5	0.5	0	202	2.48	
	120	657.0	5.2	0.5	1.0	1.6	353	2.56	
47	120	-	5.2	0.4	2.5	0	180	2.49	
	120	656.6	5.2	0.4	1.7	3.5	100	2.49	
48	120	656.3	5.2	0.4	2.5	0.7	93	2.49	
	120	656.6	5.5	0.6	1.1	1.3	22	2.51	
49	120	656.6	5.2	0.5	2.1	0.9	316	2.56	
	120	656.6	5.4	0.6	3.5	2.5	50	2.56	
50	120	656.6	5.2	0.5	1.3	0.5	80	2.56	
	120	656.6	5.0	0.3	1.3	1.7	15	2.50	
51	120	656.6	5.0	0.3	1.3	1.6	14	2.50	Mark
	120	656.6	5.0	0.3	1.7	1.4	0	2.50	
			Mean		1.43		42		
			Standard Deviation		.86		67		
1400	Background	665.0	6.7	-	1.2		15	2.35	8.0°C@76m 6.7°C@112m Stack 6.1°C@152m

TABLE B-15. SONDE DATA RUN 14C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
1330	Background	665.8	6.1	-	-		-	2.32	5.5°C@76m 5.0°C@112m Stack 4.4°C@152m
1352	120	656.6	5.0	0.3	1.1	1.9	0	2.50	Horizontal
	120	656.6	5.0	0.1	1.6	2.0	0	2.35	Traverse
53	120	656.3	5.1	0.3	1.9	2.2	346	2.46	
	120	655.9	5.1	0.3	2.2	2.0	0	2.46	
54	120	655.5	5.1	0.2	2.6	2.4	353	2.39	
	120	656.3	5.1	0.3	0.7	2.0	0	2.48	
55	120	656.3	5.1	0.3	2.1	2.1	0	2.48	
	120	655.9	5.2	0.4	2.7	2.0	0	2.49	
56	120	655.9	5.5	0.4	1.9	1.0	0	2.37	Hold
	120	655.9	5.3	0.5	0.7	0.8	36	2.52	
57	120	655.9	5.4	0.5	1.6	0	-	2.48	
			Mean		1.70		1		
		Standard	Deviation		.69		13		
1400	Background	665.0	6.7	-	1.2		15	2.35	8.0°C@76m 6.7°C@112m Stack 6.1°C@152m

TABLE B-16. SONDE DATA RUN 15C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed 1 m/s	Wind Speed 2 m/s	Wind Direction	Mixing Ratio g/kg	Comments
1430	Background	664.2	8.0	-	-		-	2.49	8.6°C@76m 7.0°C@112m Stack 6.4°C@152m
			8.0	1.5				2.13	Assman
1432	15	663.1	7.0	1.8	3.0	2.9	350	2.78	
	30	662.0	6.8	1.7	3.4	3.7	324	2.79	
33	60	659.7	6.5	1.5	3.2	2.7	310	2.77	
	90	657.4	6.3	1.3	2.7	2.4	310	2.71	
34	120	655.1	6.0	1.2	2.1	3.5	320	2.77	
	150	652.8	5.7	1.1	2.6	2.6	290	2.83	
35	180	650.2	5.6	1.0	2.7	2.3	353	2.80	
	200	648.7	5.5	1.0	2.1	2.0	330	2.85	
36	210	648.7	5.6	1.0	2.4	2.5	0	2.81	Hold
	210	648.3	5.6	1.0	2.6	2.8	6	2.82	
37	210	648.3	5.5	1.0	2.7	2.9	0	2.85	
	210	648.3	5.4	0.9	3.1	4.6	15	2.82	
38	210	648.3	5.4	0.8	4.5	4.3	0	2.74	
	210	648.3	5.4	0.8	3.8	3.2	7	2.74	
39	210	647.9	5.6	-	3.4	3.8	7	-	Wet-Bulb Failed
	210	647.9	5.6	-	3.7	3.0	0	-	
40	210	648.3	5.5	-	2.9	3.3	36	-	
	210	648.3	5.6	-	3.4	2.8	0	-	
41	220	647.5	5.7	-	2.7	2.1	7	-	Horizontal
	220	647.2	5.5	-	2.8	1.9	14	-	Traverse
42	220	646.8	5.5	-	2.4	1.8	22	-	
	220	646.8	5.5	-	2.2	1.9	0	-	
43	220	647.2	5.3	-	2.5	2.4	0	-	
	220	647.5	5.5	-	2.3	2.8	0	-	
44	220	647.9	5.5	-	2.7	3.0	7	-	
	220	647.9	5.5	-	4.1	3.3	0	-	
45	220	647.2	5.3	-	2.0	3.3	0	-	

(continued)

TABLE B-16. (continued)

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
	220	647.2	5.4	-	3.3	3.0	0	-	
46	220	646.4	5.7	-	2.5	0	346	-	
	220	646.8	5.6	-	0.6	1.9	355	-	
47	220	647.5	5.5	-	3.3	3.7	330	-	
	220	647.5	5.4	-	3.3	3.6	350	-	
48	220	647.5	5.5	-	2.7	3.2	25	-	
	220	647.5	5.5	-	2.9	2.0	25	-	
49	220	647.2	5.4	-	2.9	3.0	0	-	Stop
	220	647.2	5.5	-	2.9	4.6	320	-	
50	220	647.2	6.4	-	4.7	5.2	315	-	
			Mean		2.91		353		
		Standard	Deviation		.85		24		
1500	Background	663.5	8.3	-	2.0		320	2.47	8.9°C@76m 7.8°C@112m Stack 7.8°C@152m

TABLE B-17. SONDE DATA RUN 16C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
1500	Background	663.5	8.3	-	2.0		320	2.47	8.9°C@76m 7.8°C@112m Stack 7.8°C@152m
	220	647.2	6.1	-	0.2	0	36	-	Descent
1455	220	647.5	6.1	-	0	1.7	44	-	
	220	647.5	6.4	-	1.2	3.2	335	-	
56	205	648.7	6.0	-	3.8	4.0	339	-	
	190	649.4	6.7	-	4.0	4.1	262	-	
57	170	651.3	7.4	-	4.8	6.5	355	-	
	145	652.2	7.4	-	4.0	4.8	0	-	
58	120	655.1	7.1	-	3.3	2.7	250	-	
	95	657.0	7.3	-	3.3	3.3	325	-	
59	75	658.6	7.5	-	2.9	3.1	302	-	
	50	660.4	8.2	-	3.1	1.8	315	-	
1500	30	661.6	8.7	-	2.7	3.1	350	-	
	25	662.0	8.3	-	2.6	3.0	310	-	
01	25	661.2	8.5	-	4.3	-	302	-	
				Mean	3.02		329		
				Standard Deviation	1.50		44		

TABLE B-18. SONDE DATA RUN 17C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
1600	Background	663.2	10.6	-	3.2		10	2.53	11.7 @ 76m 9.7 @ 112m Stack 8.9 @ 152m
1624	20	661.2	12.9	-	3.6	-	-	-	Ascent
	20	-	-	-	-	-	-	-	
25	30	660.4	12.0	-	5.3	4.2	0	-	
	45	659.3	11.7	-	4.6	5.1	22	-	
26	60	657.8	11.5	-	2.8	2.8	7	-	
	75	657.0	11.5	-	3.9	5.9	308	-	
27	90	655.1	10.7	-	5.6	6.3	0	-	
	105	654.8	10.0	-	4.8	5.3	353	-	
28	120	654.0	10.4	-	6.4	5.4	55	-	
	140	651.7	11.0	-	5.3	4.2	320	-	
29	150	651.3	10.3	-	6.0	6.3	0	-	
	150	651.3	9.9	-	5.1	4.5	0	-	
30	150	651.3	10.6	-	4.6	4.8	338	-	
	170	649.8	10.2	-	3.8	2.7	338	-	
31	170	649.8	10.1	-	5.0	3.3	320	-	
	170	649.0	9.6	-	3.9	3.7	0	-	
32	170	649.8	9.5	-	4.0	2.6	350	-	
			Mean		4.57		352		
			Standard Deviation		1.10		26		
1630	Background	662.0	11.1	-	-		-	2.62	11.1 @ 76m 10.0 @ 112m Stack 9.4 @ 152m

TABLE B-19. SONDE DATA RUN 18C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
1630	Background	662.0	11.1	-	-		-	2.62	11.1°C@76m 10.0°C@112m Stack 9.4°C@152m
1635	170	649.4	10.0	-	3.1	4.6	325	-	
	170	649.0	10.8	-	3.2	3.2	350	-	
36	170	649.4	10.5	-	3.3	3.5	7	-	
	170	650.2	10.1	-	4.4	5.3	315	-	Lower
37	150	651.3	11.0	-	5.5	6.9	25	-	
	140	651.7	10.6	-	5.0	5.4	300	-	
38	140	651.3	11.3	-	6.8	4.8	260	-	
	140	651.7	11.5	-	4.1	4.3	302	-	
39	140	651.3	12.0	-	5.1	5.1	350	-	
	140	652.1	10.9	-	4.9	4.8	300	-	
40	140	652.5	10.7	-	3.9	6.3	35	-	
	140	650.6	10.3	-	2.3	5.5	350	-	
41	140	650.6	10.5	-	5.2	5.2	346	-	Horizontal
	140	651.3	10.5	-	6.4	-	320	-	Traverse
42	140	651.3	-	-	-	-	-	-	
	140	652.1	10.9	-	6.0	5.3	325	-	
43	140	652.8	9.9	-	6.3	6.0	320	-	
	140	652.8	10.2	-	6.4	6.5	302	-	
44	140	652.5	10.0	-	6.5	6.3	0	-	
	140	652.1	10.1	-	5.8	6.2	340	-	
			Mean		5.04		332		
			Standard Deviation		1.21		33		
1700	Background	661.7	11.3	-	4.8		300	2.65	10.5°C@76m 10.0°C@112m Stack 9.4°C@152m

TABLE B-20. SONDE DATA RUN 19C, 3/25/75

Time	Height m	Pressure mm Hg	Temp °C	Wet-Bulb Temp °C	Wind Speed m/s 1	Wind Speed m/s 2	Wind Direction	Mixing Ratio g/kg	Comments
1630	Background	662.0	11.1	-	-		-	2.62	11.1°C@76m 10.0°C@112m Stack 9.4°C@152m
1650	50	658.9	12.1	-	7.8	7.0	270	-	Ascent
	40	659.7	11.1	-	5.8	5.7	305	-	
51	20	661.2	11.3	-	6.4	7.2	300	-	
	20	661.2	11.5	-	7.2	5.7	294	-	
52	20	661.2	11.7	-	4.3	7.5	270	-	
	25	660.8	11.1	-	6.7	7.3	310	-	
53	40	659.7	11.1	-	6.9	6.0	294	-	
	55	658.6	11.0	-	7.2	6.6	293	-	
54	75	657.0	10.7	-	6.6	6.5	305	-	
	95	655.5	10.5	-	6.3	6.1	290	-	
55	110	654.4	10.4	-	6.1	5.8	290	-	
	130	652.8	10.1	-	6.4	6.2	324	-	
56	135	652.5	10.1	-	6.2	5.7	0	-	
	140	652.1	10.0	-	6.5	6.9	294	-	
57	140	653.2	10.2	-	7.5	-	-	-	
			Mean		6.49		300		
			Standard Deviation		.73		22		
1700	Background	661.7	11.3	-	4.8		310	2.65	10.5°C@76m 10.0°C@112m Stack 9.4°C@152m

TECHNICAL REPORT DATA
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1. REPORT NO. EPA-600/7-78-059	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE "Field Investigation of Cooling Tower and Cooling Pond Plumes"		5. REPORT DATE April 1978 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Ronald E. West		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Chemical Engineering Dept University of Colorado Boulder, Colorado 80309		10. PROGRAM ELEMENT NO. IHE625 11. CONTRACT/GRANT NO. R802893
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency - Corvallis, OR Corvallis Environmental Research Center 200 S.W. 35th Street Corvallis, OR 97330		13. TYPE OF REPORT AND PERIOD COVERED Final 14. SPONSORING AGENCY CODE EPA/600/02
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

Measurements were made relating to the behavior of water-vapor plumes from forced-draft cooling towers and from cooling ponds. There were three categories of measurements. (1) Ambient weather data including temperature, humidity, wind speed and wind direction. These measurements were made with standard meteorological equipment. (2) Source data, including the temperature, mixing ratio and flowrate of the air leaving the cooling tower or cooling pond. Cooling-tower measurements were made with a traverse rig. Cooling-pond source data were estimated using correlations. (3) Water-vapor distribution in the atmosphere in the vicinity of the source, including temperature and mixing ratio of air above the ground at various locations with respect to source. These measurements were made with tethered-balloon-borne radio sondes.

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 131+

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* UNCLASSIFIED 20 SECURITY CLASS *(This page)* UNCLASSIFIED	21. NO. OF PAGES 130 22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

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