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VERTICAL FLUXES AND EXCHANGE COEFFICIENTS IN THE AIR OVER ST. LOUIS
Field Program 1975

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VERTICAL FLUXES AND EXCHANGE COEFFICIENTS IN THE AIR OVER ST. LOUIS
Field Program 1975

by

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ABSTRACT

A field program was carried out in the greater metropolitan area of St. Louis, Missouri during February and July of 1975 as part of the Regional Air Pollution Study (RAPS). The purpose of the program was to collect atmospheric measurements needed for future studies of the planetary boundary layer (PBL) over urban and industrial areas and surrounding rural areas. The overall goals of the PBL study are to (1) describe the thermodynamic, wind and turbulence fields over the region; (2) determine the magnitude and vertical variation of the vertical fluxes of heat, moisture and momentum as a function of land use; (3) obtain estimates of the exchange coefficients of these variables; and (4) determine the dependence of turbulence intensity on land use.

Three measurement systems were used: 1) a network of double-theodolite pilot-balloon stations; 2) two tethered-balloon sounding stations; and 3) an aircraft instrumented for air motion measurements. The pilot-balloon stations provided simultaneous measurements of the wind profile with vertical resolution of about 50 m up to 2 km from five or six locations in the area. The tethered-balloon sounding systems yielded thermodynamic and wind profiles, with vertical resolution of 20 m from surface to about 500 meters. The instrumented airplane provided measurements of the three components of wind velocity and of high frequency fluctuations in velocity, temperature and humidity.

The observational periods were scheduled for 3 or 4 hour durations during field experiments, or missions, in which all available measurement systems were operated in modes to best attack particular experimental objectives. The mission objectives served the overall goals listed above. They were (a) mapping missions to delineate the thermodynamic, wind and turbulent fields over the region, (b) flux missions to provide estimates of the true vertical fluxes of momentum, heat and moisture simultaneously with vertical profiles of these variables, and (c) nocturnal missions to provide information on the strength of the nocturnal heat island circulation.

About 1000 wind profiles were obtained from the pibal wind measuring network, and the tethered-balloon systems yielded over 200 good thermodynamic and wind profiles. One hundred hours of scientific data were collected during 25 flights with the instrumented airplane. All of these data have been processed and are stored on magnetic tape for further processing and computer analysis.

This report was submitted in fulfillment of Grant Number EPA 803682 by the Illinois State Water Survey under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period February 1, 1975 to November 15, 1976 and work was completed under this grant as of December 20, 1976.

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ACKNOWLEDGMENTS

A field program the size of that carried out during 1975 can be successful only through the dedicated efforts of many people. The contributions of the many who assisted in this program and in the massive processing task are gratefully acknowledged.

Mr. J. William Mansell supervised the field operations of the pilot balloon component and, with the able assistance of Mrs. Yueh Liu, the data reduction. The field observations were made by the 5th Weather Squadron the Air Weather Service, U. S. Air Force under the supervision of M. Sgt. Lewis Jones in February and of M. Sgt. Joe Markham in July. There would, of course, be no data without the efforts of the 20 enlisted observers who spent so many hours driving through St. Louis traffic and peering through theodolite telescopes.

Mr. Gregory Fetter and Mr. Gregory Dzurisin operated the Boundary Layer Profilers during the July program and Dr. Peter H. Hildebrand supervised the development of the computer processor and of the data reduction of these measurements. Mr. R. B. McBeth and his colleagues at the Field Observing Facility of NCAR provided invaluable cooperation in providing immediate assistance in the frequent repair of the profiler sensor packages.

NCAR pilots, Mr. Tom McQuade and Mr. Clay Orum, masterfully guided the airplane through the tall towers, aircraft and deep-blue haze of the St. Louis boundary layer, while maintaining good relations and cooperation with the FAA controllers at the St. Louis control tower, who were most helpful in working the air operation into their heavy work schedule. Mr. Richard Friesen, NCAR technician, kept the complicated scientific package running with a minimum of down time.

The personnel of the Creve Coeur offices of RAPS were extremely helpful during both the pre-program installations and the data collection. It would be difficult to name all those who provided assistance at one time or another, but the cooperation of Frank Schiermeier was an important key to the success of this effort.

Credit for the success of this program must go to all of these people and to many others back at the various home facilities who pitched in to respond to emergency calls. Most of all the professionalism and the most willing and good-natured cooperation of all under the fatiguing and stressful conditions of a concentrated field program was greatly appreciated.

SECTION 1

INTRODUCTION

BACKGROUND

The dispersion of surface-generated materials and gases in the lower atmosphere is determined by transport with the mean wind and by spreading due to small-scale turbulence. The direction of the mean wind determines the general orientation of the pollutant transport, whereas the pollutant concentration is a function of the variability of the wind, the small scale turbulence, and the mechanically and convectively driven vertical currents.

Urban pollutant dispersion models have proliferated over the past few years. A few are relatively simple but many have very elaborate source distributions in space and time. Virtually all have a major weakness -- the simplicity of the atmospheric module, which frequently consists of a single wind measurement and simple diffusion parameters. Applications of these models usually use estimates of the air motion from the surface boundary layer and from a single urban or rural site. However both the mean and turbulent components of the wind vary with height and with the character of the underlying surface and pollutant concentration is strongly affected by the wind structure throughout the atmospheric boundary layer over-riding the area of interest.

The simplicity of the atmospheric modules in most models stems from lack of information, not from lack of importance. Both the mean and turbulent components of the regional wind field in the lower atmosphere must be considered in models predicting regional air quality or regional climate. This is particularly true in the case of metropolitan areas since the physical structure of cities and the concentration of human activities may cause systematic differences in the structure of the planetary boundary layer, and thus in the wind distributions over urban and surrounding rural terrains.

The mean winds are expected to change in the vicinity of a city, first, because differences in the surface roughnesses of urban and rural terrains modify the frictional force and, secondly, because distortion in pressure surfaces arising from differences in the thermal characteristics of urban and rural surfaces causes local modification of the pressure gradient force. The magnitude and characteristic of the turbulent component of the air motion is also expected to vary over a region including an urban complex. The mechanical turbulence should vary because of the differences in the nature, size and number of the roughness elements, and the convective turbulence because of urban-rural differences in the low-level static stability stemming from surface temperature differences.

There have been reports of observations which indicate that the mean winds do indeed change as the air approaches and passes over a metropolitan area, both at the surface (Chandler, 1960; Findlay and Hirt, 1969), and some distance into the planetary boundary layer (Angell et al., 1971, 1973; Ackerman, 1972, 1974a, b; Hass, et al., 1967). There have been very few observations of the turbulence in air passing from rural to urban sites, but the work by Bowne and Ball (1970) indicates that there are significant urban-rural differences in turbulence intensity. Beyond some "plume" studies, virtually nothing is known of the magnitudes of the vertical fluxes and flux divergences -- yet these are critically important in determining the depth of mixing, the dilution, and large-scale transport of pollutants.

All in all, knowledge is fragmentary and there continues to be a great need for detailed documentation and description of the three-dimensional airflow in the planetary boundary layer over a metropolitan area, if it is to be adequately treated in urban dispersion models. The following sections of this report describe a field program which was designed to collect the data needed to develop such a description. The program was carried out in the St. Louis metropolitan area in 1975 in conjunction with the Regional Air Pollution Study (RAPS) and the Metropolitan Meteorological Experiment (METROMEX).

OBJECTIVES OF THE STUDY

The research carried out under this grant is part of an urban boundary layer program which seeks to describe in detail the three-dimensional wind field in the planetary boundary layer over-riding a mesoscale region which includes an urbanized area. This program was initiated in 1971 as part of METROMEX and has continued since then, becoming part of the RAPS program also in 1975. It has been supported over the years by the National Science Foundation (NSF), the Atomic Energy Commission (AEC), the Energy Research and Development Administration (ERDA), the National Center for Atmospheric Research (NCAR), and the United States Air Force (USAF). Under this grant, the Environmental Protection Agency has provided support for the collection of boundary layer measurements during the 1975 RAPS winter and summer field expeditions and for the basic reduction of the data collected.

The overall urban boundary layer program at the Illinois State Water Survey has the following objectives:

1. Description of the wind, temperature, humidity, and turbulence fields over the city and surrounding country side and delineation of the perturbations induced by the city on the ambient fields.

2. Determination of the vertical fluxes of momentum, heat, moisture, and aerosols in the Ekman layer, and their variations with height and land use.

3. Estimation of the exchange coefficients of the four parameters given in (2) and their variations with height and land use.

4. Determination of the variations in turbulence intensity and in the input scales with land use.

The field efforts of this 1975 project addressed all of these objectives, with particular emphasis on the second and third. They were implemented during the periods of 15 through 28 February and 1 through 30 July so as to study conditions in both winter and summer.

SECTION 2

FACILITIES

Observations were made with three measurement systems: a network of double theodolite pilot balloon stations, an aircraft instrumented for measurements of air motion, and (during July only) two tethered balloon sounding stations. Supplementary routine measurements are available from the EPA/RAPS radiosonde and tower networks, from the Illinois State Water Survey METROMEX surface networks and from the St. Louis Air Pollution Control and Illinois EPA networks. During some experimental periods additional data are available from other RAPS and METROMEX field experiments.

AIRCRAFT

An instrumented aircraft, pilot, and technician were provided by the Research Aviation Facility of NCAR. In February the airplane was based at Lambert Field; in July it was based at Alton Civic Memorial Airport, Illinois.

The airplane was the Queenair 306 which was instrumented to provide measurements of three components of wind velocity and high frequency fluctuations in velocity, temperature and humidity, as well as standard state parameters and aircraft position. Equipment to measure concentration of total condensation nuclei, obtained on loan from EPA-Las Vegas, was added during the July program.

Measurements of the turbulent or fluctuating components of the atmospheric structure were obtained using rapidly responding instruments, most of which were mounted on a boom extending about 3 meters out in front of the aircraft. The remaining instruments were either wing- or fusilage-mounted.

The airplane instrumentation permitted measurement of the following atmospheric, surface, and aircraft parameters:

1. Air Temperature
   a. Slow response (a few seconds) -- NCAR reverse-flow thermometer.
   b. Medium response (a few tenths of a second) -- Rosemount platinum resistance thermometer.
   c. Fast response (a few hundredths of a second), fluctuations only -- NCAR "K-probe", platinum resistance thermometer.

2. Dew-point temperature (slow response -- about 2 seconds). Cambridge dew-point hygrometer.

3. Atmospheric refractive index (response, a few hundredths of a second). NCAR microwave refractometer.

4. Cloud liquid water content -- Johnson-Williams liquid water content meter.

5. Concentration of condensation nuclei (July only) -- Environment I nuclei counter.

6. Surface Characteristics
   a. Radiation-temperature (analog IR), Barnes PRT-5.
   b. Visual, aerial color photography -- downward-viewing time lapse movies, 4 sec/frame.

7. Altitude
   a. Static pressure probe (transducer).
   b. Geometric altitude above ground (for altitudes of less than one kilometer only) -- Radio altimeter.

8. Airspeed (dynamic pressure)
   a. Wing-mounted Rosemount pitot.
   b. Boom-mounted pitot and transducer.

9. Orientation to airstream (boom-mounted)
   a. Angle of attack, fixed vane.
   b. Angle of attack, rotating vane.
   c. Sideslip angle, fixed vane.

10. Boom accelerations -- vertical and lateral accelerometers, boom-mounted.

11. Orientation to fixed system, aircraft attidude angles, pitch, roll, and yaw.

12. Aircraft velocity relative to ground -- Inertial Navigational System (INS)
    a. Heading
    b. Ground speed
    c. Vertical velocity
    d. Vertical acceleration

13. Aircraft position
    a. INS-computed latitude and longitude.
    b. Distance to several DME stations (July only).

In Figure 1 are photographs of the airplane and externally-mounted sensors or sensor housings.

All measurements (except the aerial photography of course) were recorded on magnetic tape. All analog outputs were recorded at 16 times

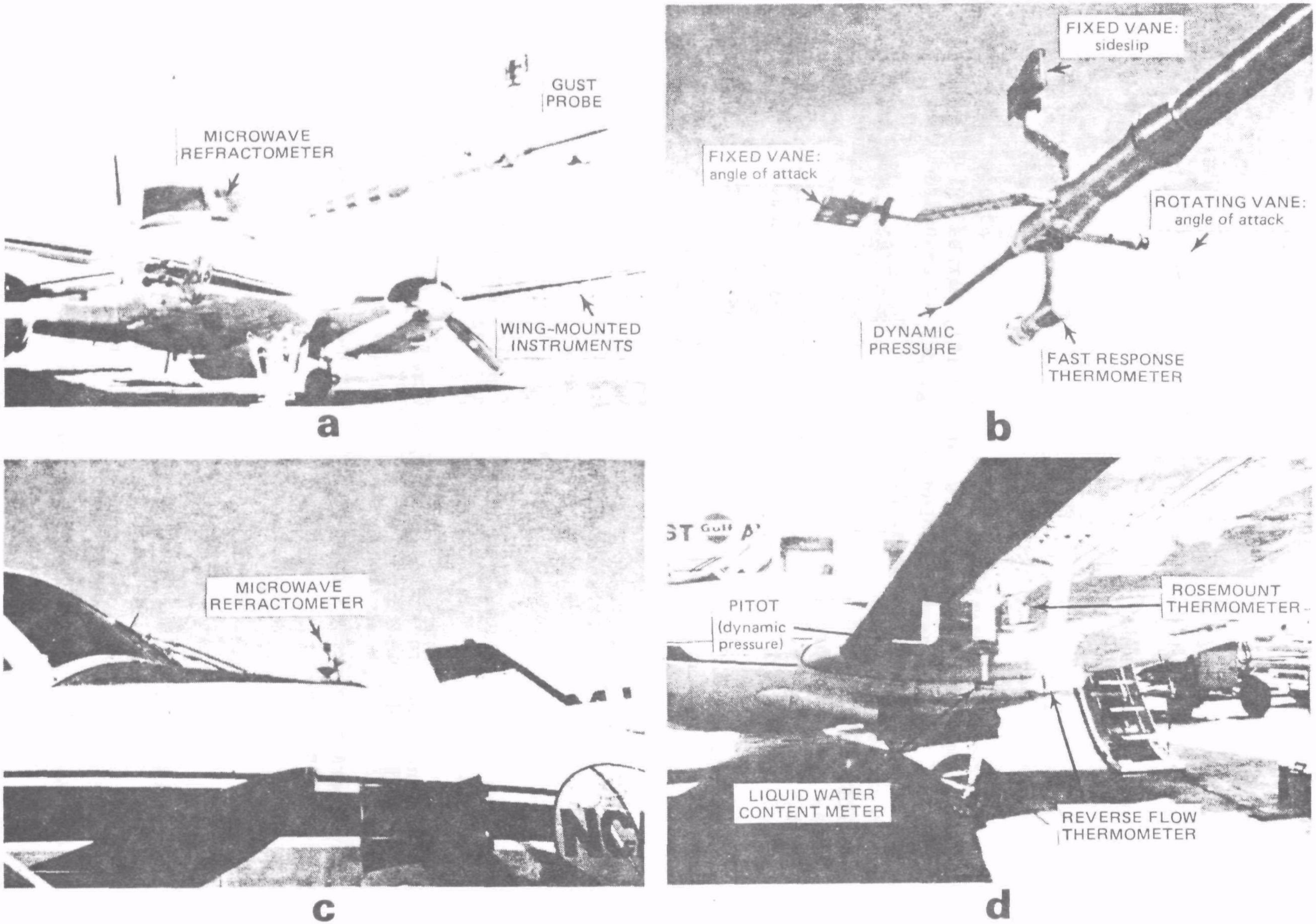

Figure 1. (a) The NCAR Queenair 306 instrumented to collect air motion measurements. (b) Closeup of the gust probe. (c) Closeup of the micro-wave refractometer. (d) Closeup of wing-mounted instruments.

per second; digital outputs (e.g. from the INS) were recorded at 8 or 10 times per sec. Some of the basic instruments were fitted with electronic filters having 4 Hz bandwidth. During the basic processing, which was provided by NCAR, all measurements were brought to a common rate and frequency response through a series of cubic interpolations and application of a "matching" digital filter. The "standard rate" processed data provided by NCAR on magnetic tape were recorded 8 times per second, and 1-second (8 point) averages at a one second rate. However, all data have been filtered so that the measurements contain information only for frequencies of 4 Hz or lower.

The fast response boom-mounted dynamic pressure and temperature, and refractometer measurements were also recorded, before electronic filtering at high rates of 256, 128, and 64 times per second, respectively. These data were scaled and recorded, without any digital filtering, at the original rates. This permits study of the fluctuations in total air motion, temperature and humidity in the high frequency domain.

Some of the parameters to be analyzed were measured directly; others were calculated from the measurements from several sensors. The parameters required for the study are listed below. The numbers in parentheses refer to the basic measurements listed above which enter into their calculation.

a. Aircraft position, in the horizontal, by integration of measurements from (12), with update from (6b) and (13b) when available; height from (7b) below 900 m and calculated pressure altitude from (7a) at all altitudes.
b. Surface characteristics and land use -- qualitative (6b).
c. Surface temperature -- computed from (6a) assuming black body radiation.
d. *Absolute air temperature (1b), with (1a) as backup.
e. *Absolute air humidity (2).
f. Pressure changes (spatial) below 900 m AGL: D-values computed from (7a) and (7b).
g. Turbulence intensity: (8b).
h. Temperature fluctuations: (1c) and (1b).
i. Humidity fluctuations -- computed from (3), (1c), (7a), (8b).
j. Wind components, u, v, w, computed from (11), (12), (8a), or (8b), (9a or b), (9c), with corrections based on (7a), (10).
k. Turbulent fluxes of momentum, heat, and moisture, based on auto-correlations of derived parameters (h), (i), and (j) above.
l. Spectra and co-spectra of fluctuations in total wind, temperature, humidity, and vertical wind component, based on derived parameters (h), (i), (j) listed above and from (8b).

* Absolute used here in sense of "mean" value, as opposed to fluctuating component.

PILOT-BALLOON MEASUREMENTS

Wind measurements were obtained up to about 2000 m using double-theodolite techniques. These involve tracking a pilot balloon (pibal) with theodolites from two well-separated locations.

The personnel required to make these observations were provided by the Air Weather Service (AWS) of the U. S. Air Force from the 6th Weather Squadron (Mobile). During February the AWS unit consisted of 6 two-man double theodolite teams plus two supervisors. During July, only 5 two-man teams and one supervisor were available for this assignment. Standard equipment required for the observations plus the vehicles necessary to transport personnel and equipment to observation sites were also provided by the AWS.

Personnel and the pibal operations center were based at Scott Air Force Base, Illinois, about 32 km ESE of downtown St. Louis. During each operational period (see Section 3) the observers were deployed to specified sites scattered in and around St. Louis. The sites varied from operation-to-operation depending on the mission for the day. These were selected from 12 previously surveyed locations (Figure 2).

The 12 pibal sites were established on the basis of a number of criteria, some scientific, some logistic.

a. Sites should be arrayed such that experiments pertinent to the objectives could be carried out.
b. The area around each site should have, as much as possible, homogeneous surface conditions.
c. The baseline (distance between the observers) should be 600 m or longer.
d. The two observers should be able to see each other through their theodolites, and it should be possible to string telephone line between them without crossing walks or heavily traveled roads.
e. There should be no obstructions to the view of the balloon in any direction.
f. Personal safety of the observers must not be endangered in any way, and phone and toilet facilities must be within reasonable walking distance.
g. Equipment could be set up in a reasonable length of time.
h. The site must be within 1-hour driving time from Scott AFB (an AWS regulation).
i. Permission to use the property from the owner or the responsible public official must be granted.

It was not always possible to meet all of these criteria. Those which were essential and had to be met were (a), (d), (f), (h), and (i). Criterion (c) was met in seven of the sites. The shortest baseline was about 378 m long, and the longest was nearly 800 m in length. The other criteria were met with varying degrees of success. The most difficult one to satisfy was (b), particularly at sites in the city. In fact, even for

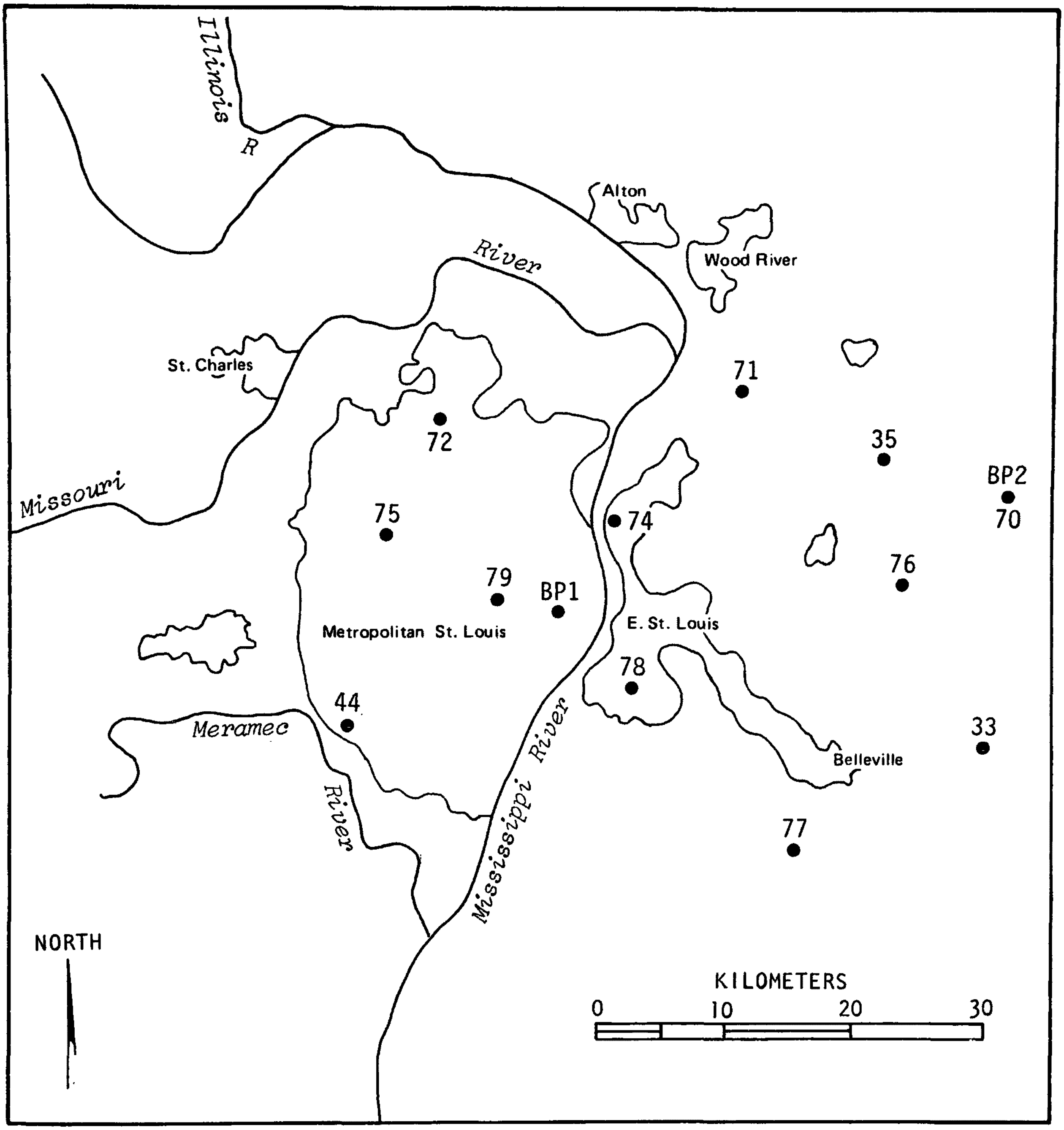

Figure 2. Map of St. Louis showing the location of the pilot balloon sites (numbered) and the boundary-layer profiler stations (BP1 and BP2).

criterion (a), the locations, although suitable, were not always optimal. The locations and baseline lengths of the 12 sites are given in Table 1.

TABLE 1. DOUBLE-THEODOLITE PILOT-BALLOON STATIONS USED DURING 1975.

Station Number	Location	Baseline length (m)
33	East side of main runway, Scott Air Force Base, IL.	657
35	Troy Road, just south of I-270, 4 km east of Glen Carbon, IL.	763
44	South side of parking lot, Korvette Shopping Center, Rott Road and Hwy. 61, Sunset Hills, MO.	611
70	Triad High School, Hwy 40, 3 km west of Hwy. 4, IL.	449
71	Poag Road, southwest of Poag, IL.	790
72	Brown Road, opposite northeast corner of Lambert Field, Berkeley, MO.	457
74	Granite City Army Depot, Granite City, IL.	795
75	Army Publication Center, Woodson Road and Page Ave., Overland, MO.	552
76	County Road, 6 km north of O'Fallon, IL.	640
77	Peabody Road, just west of Hwy. 159, about 8 km south of Belleville, IL.	663
78	Along taxiway north side of Bi-States Airport, Cahokia, IL.	541
79	Forest Park, along Hwy. 40, east of Hampton Avenue, St. Louis, MO.	378

When establishing the site, the survey team selected two suitable spots for the theodolite "pads", requiring that the two be line-of-sight. They then measured off the straight line distance between the two with transit and tape and the difference in elevation with a stadia rod. The orientation of the baseline relative to true north was determined later from sightings on Polaris on clear nights.

Almost all of the pibal sites were on unprotected public and private property, so that only small wooden ground stakes marking the theodolite locations were located permanently at the sites. The observers had to transport, set up, and then dismantle all equipment for each day's observations. This took roughly an hour at both the start and the end of the day, in addition to travel time.

Two observers, one at each theodolite, composed a pibal "team". They were linked by a land phone line for communication. Into this line were hooked a tape recorder and a tone generator that was activated by a timer. These, along with pertinent electrical connectors were packaged into a small attache case for convenience of transport and storage. The timing tone was set for a timing interval of 20 seconds and sounded for roughly 3 seconds. At the start of the tone the observers centered the balloon on the cross-hairs of the theodolite and kept it there until the tone ended. Then, before changing the dial settings, each observer, in turn, read the azimuth and elevation angles of the balloon (to hundredths of a degree) into their head phones for recording on a cassette tape. Azimuth angles, as given, were in the coordinate system with y-axis parallel to the baseline. Rotation of the coordinate system to true north is accomplished in the data reduction.

Pilot balloons were inflated (to within the accuracy of the gas-flow meters) for estimated rise rates of about 2.2 to 2.5 meters per second (mps). Flow meters, rather than weights were used in inflation because of the short time between the termination of one run and the start of the next and the difficulty of inflating balloons in the open. Although inflation rates were assigned, and were adhered to as closely as possible, this was not an essential factor since the computation of the wind velocity is independent of the ascent rate of the balloon when double theodolite measurements are available. In fact, the rise rates are calculated and provide valuable estimates of the vertical air motions in the boundary layer.

TETHERED BALLOONS: BOUNDARY LAYER PROFILERS

Two tethered-balloon systems for measuring detailed profiles up to a nominal operational altitude of 750 m were loaned to the State Water Survey for the July field effort by the Field Observing Facility of the National Center for Atmospheric Research. One profiler (BP1) was located at the RAPS radiosonde station 141 in downtown St. Louis and the second (BP2) at Triad High School on Highway 40 about 2.5 km west of Highway 4 (Figure 2).

Each balloon system required a senior operator and an assistant. The operators were State Water Survey staff who were quartered at Collinsville, Illinois, about midway between the two sites. The assistants were local area college students.

Details of the system may be found in a paper by Morris et al., 1975. Briefly, the system consisted of a relatively small plastic balloon (inflated volume about 3.25 m^3) with an aerodynamic shape from which was suspended the sensor package. The balloon was tethered to the surface and was raised and lowered using an electric winch in order to obtain measurements in the vertical.

TABLE 2. NCAR BOUNDARY LAYER PROFILER SENSORS AND THEIR CHARACTERISTICS

Variable	Sensor	Precision	Resolution
Pressure	Sealed aneroid capsule	±1 mb	0.5 mb
Temperature	Ventilated bead thermister in radiation shield	±0.5°C	0.1°C
Wet-bulb temperature	Wick-covered thermister, mounted 2-cm behind dry temperature sensor	±0.5°C	0.1°C
Wind speed	3-cup anemometer, small, light-weight cups (min. speed: 0.5 m/s)	±.25m/s	0.1 m/s
Wind direction	Magnetic compass, based on assumption that balloon is effective vane	±5°	2°

The sensor package provided measurements of pressure, dry and wet bulb temperature, wind speed and wind direction. The sensors and their precision and resolution are given in Table 2. However, this is a new system, and these estimates of precision may prove optimistic, particularly those for the wind measurements. The airborne package also carried a 403 MHz transmitter and circuitry to condition sensor output and modulate the transmitter. The ground station consisted of a receiver and Esterline-Angus chart recorder. Photographs of the balloon and sensor package are shown in Figure 3.

The recording was in a time-multiplex data format with cycling through 8 channels in 20 seconds. As operated during the July field program, dry and wet bulb temperatures and wind speed were each recorded on two channels. Thus, these variables were sampled twice every cycle whereas pressure and wind direction were sampled once. Each channel recorded for approximately 1.5 second.

The maximum height actually reached by the profiler depended on the stability and wind speed, decreasing with increasing stability and wind speed. The balloon was let out at 150-feet per minute and brought back to the surface at nearly twice that rate. This equipment cannot be operated under strongly turbulent conditions or in wind speeds of greater than 10 m/sec.

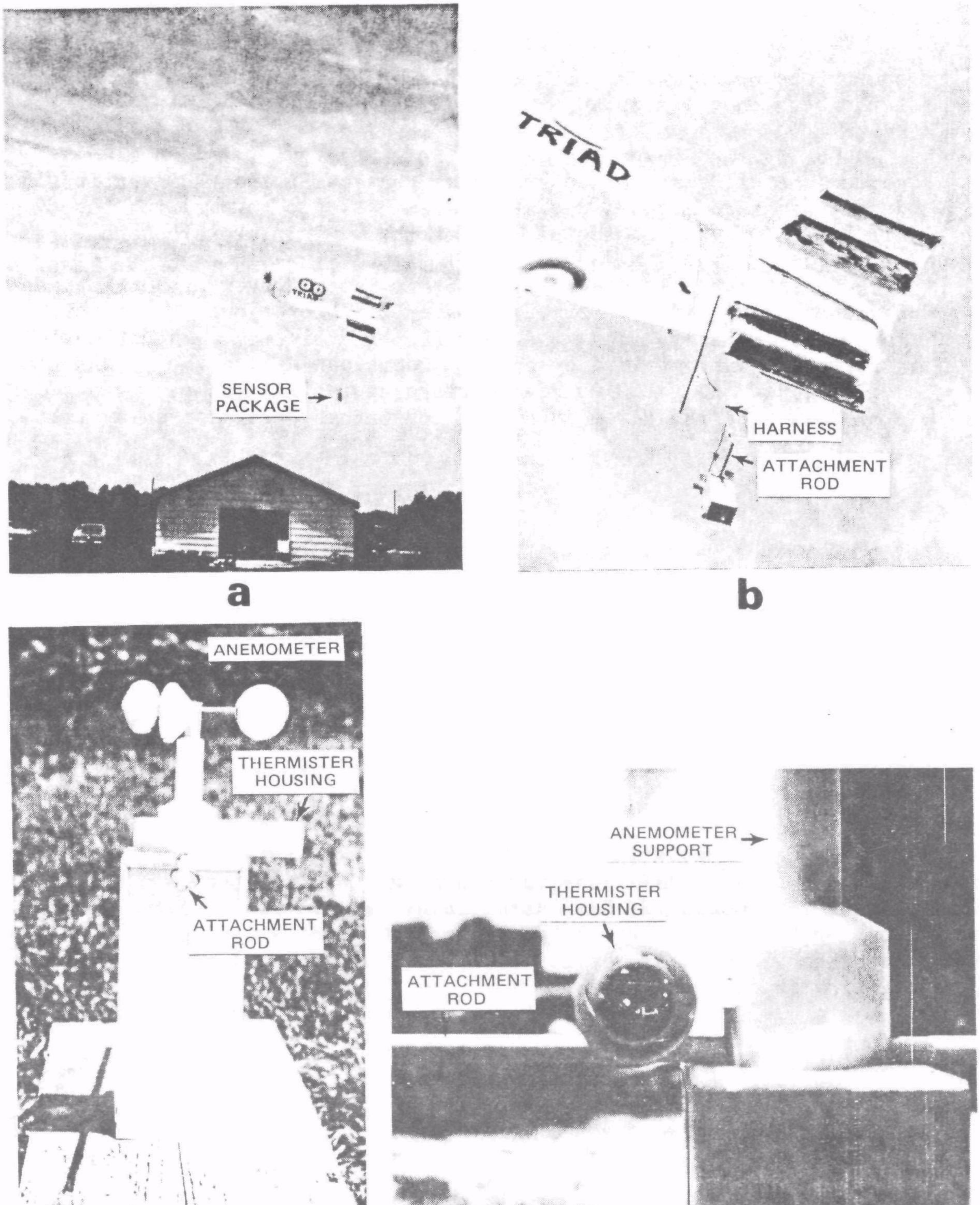

Figure 3. (a) Boundary layer profiler tethered in parked position. (b) Close-up of sensor package showing harness by which it was attached to balloon. (c) Sensor package. The rectangular base box contains electronics and radio transmitter. (d) End-on view of thermister housing.

OPERATIONS BASE

The Principal Investigator under this grant directed the day-by-day operations during both field efforts. She also served as observer and technician on the airplane.

During the February program, the RAPS offices in Creve Coeur, Missouri served as a base of operations. Following the RAPS weather briefing, decisions as to mission operations were relayed to the pibal unit at Scott Air Force Base and to the pilot at Lambert Field by telephone.

During the July program, the State Water Survey METROMEX base at Alton Civic Memorial Airport served as base of operations. Facilities included facsimile weather maps and Service A teletype. Additional weather information was obtained by phone. Decisions as to the planned operations were relayed to the RAPS headquarters and to FAA (necessary because of the profilers) and the three observing components were alerted by telephone.

SECTION 3

OPERATIONS SUMMARY

GENERAL FIELD PROCEDURES

The operations were usually scheduled as 3- to 4-hour field experiments, or missions, in which all available systems were operated in manners to best attack particular experimental objectives. The mission objectives served the overall goals listed in Section 1.

Missions fell into the following general categories:

1. Mapping Mission:

   Objective: To map the fields of temperature, moisture, wind, vertical velocity, turbulence intensity, and vertical fluxes over the region.

   Flight Pattern: "Checkerboard" pattern at one or two levels over and around the greater St. Louis area, with tracks oriented parallel and perpendicular to the wind (Figure 4a).

   Pilot Balloon Array: Five or six sites activated in as uniform an areal distribution as feasible. Balloons launched at 20-min intervals.

2. Flux Cross-Sections:

   Objective: To estimate vertical exchange coefficients for momentum, heat and moisture and their variation with height over urban and rural surfaces.

   Flight Pattern: Two "cross" patterns with arms about 15 to 20 km long, one parallel and the other perpendicular to the mean wind. One cross pattern was over a rural area and the other over metropolitan St. Louis (Figure 4b). During July, the two "crosses" were centered near the two boundary-layer profiler sites; in February they were near an urban and a rural pibal site. Traverses were made at three levels, and the entire pattern repeated at least once.

   Pilot Balloon Array: Three sites were activited, two located in "homogeneous" urban and rural locations (in July at or near the boundary-layer profiler sites), and the third at a downwind urban site. Balloons were launched every 10 minutes at the two key sites, and at 20-minute intervals at the third site.

3. General Cross Section:

   Objective: To map, in vertical planes across the city parallel and perpindicular to the mean wind, the vertical fields of temperature, moisture, wind, vertical velocity, turbulence intensity, and vertical fluxes.

   Flight Pattern: Long traverses extending across the city and well into surrounding areas, one parallel to the mean wind direction, and

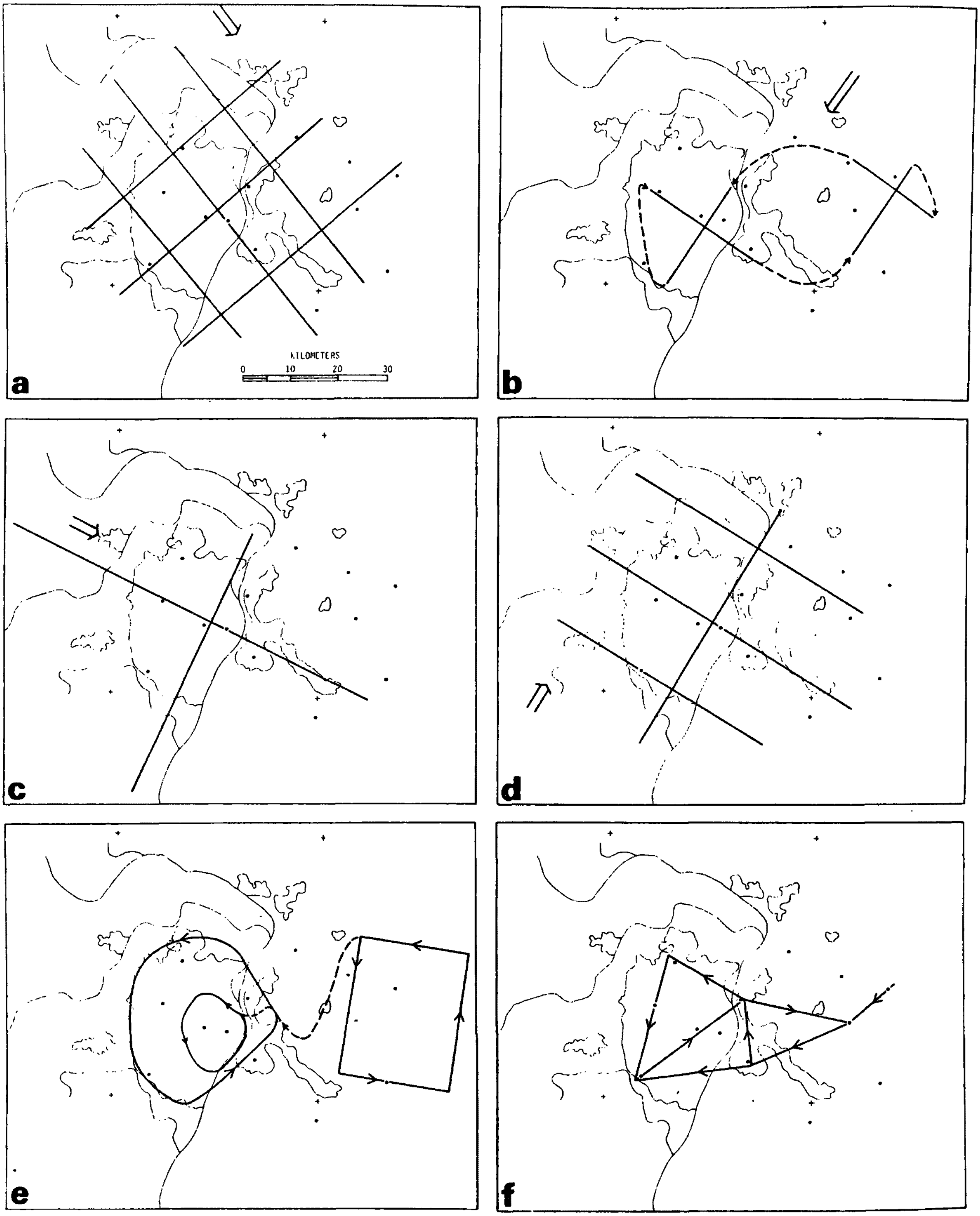

Figure 4. Typical flight tracks on (a) mapping missions, (b) flux cross sections, (c) and (d) general cross sections, and (e) and (f) nocturnal heat island circulation missions.

one or more perpendicular to the wind (Figures 4c and 4d). All tracks were repeated at three levels, and in some cases the whole pattern repeated.

Pilot Balloon Array: Five or six sites activated, in a "cross" array to the extent possible, with one arm parallel and the other perpendicular to the wind.

4. Nocturnal Circulation:

Objectives: (a) To check on the existence of the nocturnal urban heat island circulation and to measure its strength and (b) to check on the linearity of the wind field which is assumed when calculating divergence over an area from point measurements, and to evaluate the error in these divergence estimates.

Flight Patterns: Circuits around the inner city, greater metropolitan area, and an urban area equal in size to the metropolitan area, made at two levels and repeated at least once (Figure 4e) or straight tracks between activated pibal sites which formed triangular areas (Figure 4f).

Pilot Balloon Array: Five sites activated to form a box around the metropolitan area and a triangle over a predominately rural area. (Optimal array not possible because of limited personnel.)

5. Miscellaneous:

A few special missions were carried out to address particular objectives which did not necessarily require corrdinated use of all facilities. These were usually carried out when one or more of the facility components was not available due to malfunction of equipment or to unavailability of personnel.

These missions were of two types:

a. Tests and/or checkout of systems.
b. Study of the diurnal evolution of the temperature, moisture, and humidity profiles or evolution during the morning and evening transition periods. These utilized only pibals at two sites and the boundary layer profilers.

On all missions in July the boundary layer profilers were operated in 40-minute sequences, from their permanent sites.

Decision as to mission was made by the Program Director (the Principal Investigator under this grant) by 9 a.m. each morning on the basis of the general weather conditions. Following decisions as to timing, flight pattern and balloon sites to be used in the mission, all units were notified by telephone as to their particular operations. This had to be done two to three hours prior to the start of the mission because of the travel and preparation time required by the various observational components. Because of this lead time and lack of field communication, missions could not be changed when late changes in weather forecast or some equipment failure indicate a modification might be desirable.

February Program

The winter program was carried out during the last half of February. The AWS personnel and equipment arrived in the St. Louis area on the 12th and the NCAR airplane and personnel on the evening of the 15th. Rain fell nearly continuously between the 12th and 15th, making it impossible to carry out any operation. However, this time was needed to modify some of the AWS equipment and to relocate some of the previously located pibal sites. The pibal sites had been located and surveyed in January and early February. However, much-above normal precipitation in January and February resulted in very soft muddy surfaces at some of these locations, rendering them unworkable.

The weather continued to be considerably less than optimal for the program during the last half of the month, with predominately low ceilings, frequent heavy rains and snow, and unusually strong winds on about one-fourth of the days. Nevertheless nine missions were carried out (Table 3). In one instance last minute failure of a key piece of the scientific package on the airplane caused cancellation of that part of the mission.

TABLE 3. FEBRUARY 1975 OPERATIONS

		Airplane	Pibal	
Date	Mission	Time* (Local)	Time* (Local)	No. of Stations
2/17	Mapping	1345--1745		
2/19	Mapping	1135--1440	1220--1520	6
2/20	General cross section	1120--1445	1150--1500	6
2/20	Mapping	1915--2130		
2/21	Mapping; general cross section	1140--1540	1140--1450	6
2/25	General cross section	1210--1600	1320--1520	6
2/26	Mapping	1230--1615	1220--1550**	3
2/27***	Mapping	2045--2358	1210--1510	6
2/28	Flux cross section	1325--1650	1230--1520**	3

* CST prior to 23 February, CDT 23-28 February
** Pibals on 10-min launch schedule
*** Flight delayed because of equipment malfunction

July Program

The NCAR equipment (airplane and profilers) and personnel arrived in St. Louis on 30 June. The AWS equipment and personnel arrived late on the evening of 2 July. The NCAR units departed on 31 July and the AWS on 1 August. The effective period for full-scale missions was 5 through 30 July. Although a slip of 10 days would have been preferable in order to fit the dates of the main RAPS expeditions, NCAR scheduling made the aircraft available to this program only during the month of July.

The approach to the operations was to work the weather, rather than any set schedule. However, in practice, AWS and NCAR guidelines for their personnel necessitated scheduling some days-off a day or so in advance. Although this resulted in the loss of a few good days, the weather was generally favorable and did not seriously affect the overall data collection.

There were few failures in the pibal systems and a relatively small fraction of the scheduled launches were lost because of equipment problems. Except for an early failure in the inertial navigation system, the scientific package on the airplane also presented few problems detectable in the field. However, failures of aircraft equipment did force cancellation of missions on at least three occasions.

Major equipment failures did occur however in the sensor packages of the boundary layer profiler systems and occassionally in the recorders. NCAR had not provided substitute parts, wiring diagrams, or repair instructions, largely because these were new systems and such things did not exist. Consequently the sensor packages had to be returned to NCAR in Boulder each time there was a malfunction. Although repairs were made immediately and the malfunctioning instrument was back within 36 to 48 hours, there was still nearly a 30% loss in desired profiles.

A total of 25 missions were carried out between the 1 July and 31 July (Table 4). Three of these were tests or calibration missions.

TABLE 4. JULY 1975 OPERATIONS

Date	Mission	Airplane Time (Local)	Pibal Time (Local)	Pibal No. of Stns.	Profilers Time (Local)	Profilers No. of Stns.
7/01	Test	1510-1627				
7/02	Test				1210-1405	1
7/03	Mapping	1420-1806			1100-1600	2
7/05	Mapping		1100-1400	5	1100-1400	2
7/07	Mapping	1255-1700	1320-1640	5	1300-1730	2
7/08	Flux cross section	1218-1550	1230-1530	3	1200-1700	2
7/09-10	Nocturnal	2133-0010	2140-0020	5	2120-0040	2
7/10-11	Nocturnal	2132-0025	2140-0020	5		
7/12	Mapping	1300-1700	1340-1620	5		
7/14	Flux cross section	1250-1627	1310-1610	3	1300-1700	2
7/15	Flux cross section	1319-1705	1310-1610	3	1220-1700	2
7/16	Mapping	1142-1435	1200-1500	5	1240-1440	2
7/18	Pre-rain mapping	1106-1457	1120-1420	5	1040-1320	2
7/21	Flux cross section	1230-1620	1320-1620	3	1200-1700	2
7/22	Mapping	1247-1702	1320-1620	5	1200-1720	1
7/24-25	Nocturnal	2133-0020	2130-0010	5	1940-0100	2
7/25-26	Nocturnal	2100-2230 0010-0130 0300-0425	2120-2400	5	2040-0420	2
7/26-27	Nocturnal	2116-2342	2140-0020	5	2020-0020	2
7/27	Mapping	1300-1450			1350-1500	1
7/28	Profile				1700-2150	1
7/29	evolution		0600-1500	2	0030-1500	1
7/29	Mapping	1350-1525*				
7/30	Flux cross section & Profile evolution	1155-1430	0600-1500	2	0600-1500	2
7/31	Test		0920-1145	1		

* Note airplane flight period included in period of pibal and profiler observations for profile evolution mission on 7/28 and 29.

SECTION 4

DATA SUMMARY

AIRCRAFT DATA

Basic processing of the digitally-recorded measurements was done by the Research Aviation Facility at NCAR. Because of a huge backlog of flight programs to be processed at NCAR, reduced aircraft data did not become available to ISWS until late Spring and Summer of 1976.

The reduced data was recorded on magnetic tape as described in Section 2, in a convenient form for further computer processing and analysis. These tapes contain scaled values (in appropriate units) of parameters 1 through 13 listed in the aircraft section of Section 2. In some instances, the measurements have been corrected for known performance characteristics of the instruments (e.g., temperature has been corrected for compressional heating of the air). In addition position, based on integration of track information from the navigation equipment, and the three components of the air velocity were also provided at a rate of once per second.

The voice recordings of observer comments have all been transcribed. Flight track information has been extracted from the time-lapsed aerial photographs for three flights of particular interest for use in correcting the computed tracks. Programs to read the NCAR tapes (generated on the CDC 6600-7600) on the University of Illinois IBM 360 have been written and others for initial "massaging" of the data are under development. A program for calculating divergence around closed tracks has been written and debugged.

Because of the delay in receiving the data and the mass of numbers involved, it is not possible to estimate the overall quality or the quantity of useable data at the time of this writing. Review by NCAR personnel of the processed data and a spot check at ISWS after it was received, have not indicated any unexpected problems with the basic data. However during initial exploratory analyses of two flights, timing problems have been discovered. These arose during generation of computer-compatible tapes from the air tapes. The problem is easily corrected but does require reprocessing of parts of the flights by NCAR. This discovery has precipitated review of all 25 processed tapes, now underway, to detect errors of this type on other flights.

PILOT BALLOON WIND MEASUREMENTS

The pilot balloon measurements consisted of two sets of azimuth and elevation angles to the balloon, one from each end of the "baseline".

These angles, read from the theodolite scales and orally recorded on cassette recorders, plus the site baseline statistics (length, orientation relative to true north, and elevation difference in elevation at the two ends) permit calculation of the average wind for the layer through which the balloon passes between successive sightings.

The theodolite readings have been computer-processed to obtain winds. The computations were based on the methods described by Thyer (1962). This technique solves for location of the shortest distance between the rays from the two theodolites and estimates the most probable position of the balloon along the line joining the rays at this location. The minimum distance between the two rays provides an estimate of the error in the calculated position of the balloon due to errors in the angles to the balloon. Thus, the technique provides a means for detecting errors in the theodolite readings and for correcting them.

The average wind velocity for the layer between two successive reading times is provided by the difference between the two balloon positions divided by the difference in the two times. The rate of ascent of the balloon is determined by the height difference divided by the time interval.

During the 1975 operations sightings to the balloons were recorded at 20-second intervals, which nominally permits calculation of average wind velocity for layers of about 50 meter depths. In actuality there was considerable variation in the depth of the layer covered in the 20 seconds both because of inaccuracies in the flow meters used to gauge the amount of gas entering the balloon and because of the frequent existence of atmospheric vertical currents which provided increments to the ascent rate of the balloon due to the free lift.

Because of the 20-minute launch interval the balloons were scheduled for abandonment after 13 minutes of tracking, providing, in still air, wind data up to about 2 km. Although a fair number of the soundings did go the full distance, many did not, either because the balloon entered a cloud or because it passed behind a cloud or surface obstruction.

In Tables A-1 and A-2 of Appendix A are tabulated the profiles obtained during the winter and summer programs. Of the 1068 wind soundings scheduled, 1000 (94%) were actually made. About half of the missed soundings were cancelled because of rain. Of the 1000 balloons launched, 739 (74%) were tracked to heights in excess of 1 km by both theodolites.

Computer processing of the 1000 soundings has been completed. They have been stored on magnetic disk for editing, and further processing. After editing, the data are archived on magnetic tape, in unformatted binary code. The tapes contain the following: (a) site information; (b) at each reading time, the azimuth and elevation angles, height and position of the balloon relative to the release point, and the "shortest" distance between the two theodolite rays; (c) calculated wind velocity (u, v, components and speed, direction), position mid-point in layer (height and position relative to the Arch), and the rate of rise of the balloon, all for the interval between two successive readings. To date 30% of the soundings have been edited and archived.

The personnel making the pilot balloon observations were trained Air Force upper-air observers. In addition they were given several days of special training and practice in the methods used in this program prior to start of the field expedition. Therefore there is considerable confidence in the general quality of the data.

Nevertheless the overall accuracy of winds determined from pilot balloons, even using double theodolite techniques is generally unknown. The Thyer method permits an estimate of the possible uncertainty in the angular reading and therefore in balloon position. An analysis of these estimated uncertainties for a similar wind program in 1971 (Ackerman et al, 1975) indicates that at times they can be sizeable. However, they represent position errors and are usually systematic so that the errors largely cancel out when time differentials are taken in the wind calculations.

In order to try to obtain estimates of the accuracy of the wind calculations, special experiments were carried out in July 1975, and during an earlier similar program in 1972. In these experiments several double theodolite teams set up with parallel baselines, tracked the same balloon for 6 or 8 launches. Lacking a standard, the average of the individual measurements may be considered as the best estimate of the true value. The square root of the pooled variances, which is referred to hereafter as the root mean square (RMS) deviation, gives an estimate of the error in the wind measurements. A summary of the results of these experiments are given below. A detailed description of the experiments and description of the results are given in Appendix B.

In Figure 5 are shown the profiles of the RMS deviations for wind speed, wind direction, wind vector, and ascent rate of the balloon, and in Figure 6 the wind profiles for the three experiments. The RMS deviation in wind direction was very small -- of the order of 2° to 3° up to 1500 m, and very similar in magnitude in all 3 tests. The RMS deviation in wind speed was more significant, and unfortunately also varied significantly between the three experiments, ranging from about 0.2 mps in the most stable case in 1972 to 0.5 to 2 mps for the 1975 test. The RMS deviations in ascent rate were far smaller, from 0.1 to 0.2 mps on the most stable day to 0.2 to about 0.8 mps on July 31, 1975.

A number of factors can contribute to these differences in indicated errors. Perhaps the over-riding one is the velocity structure itself -- the ease and accuracy with which the balloon can be tracked is directly related to the turbulence, the wind speed and the variability in direction. Other factors include the individual measurement "system," in this instance the personnel and equipment, the angle of the wind to the baseline, and the distance (range) to the balloon.

All factors were present in this set of tests. The personnel and equipment were different in 1975 than in 1972 and were not identical even

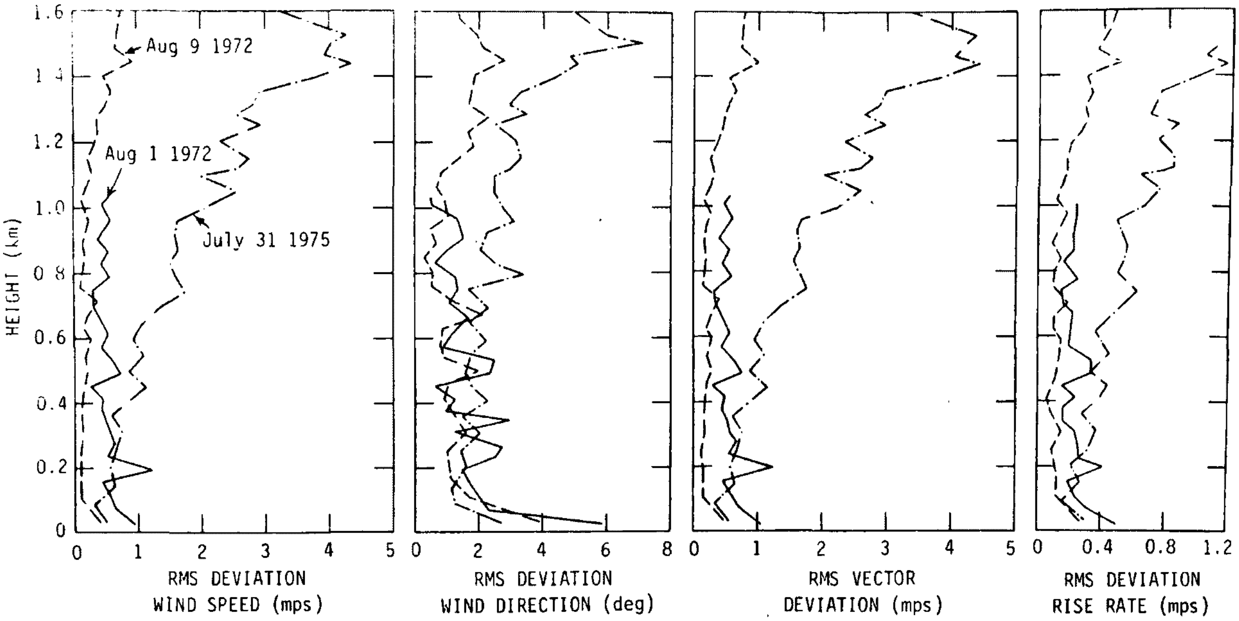

Figure 5. Root mean square (RMS) errors for wind speed and direction, balloon ascent rate and RMS vector error for three field tests.

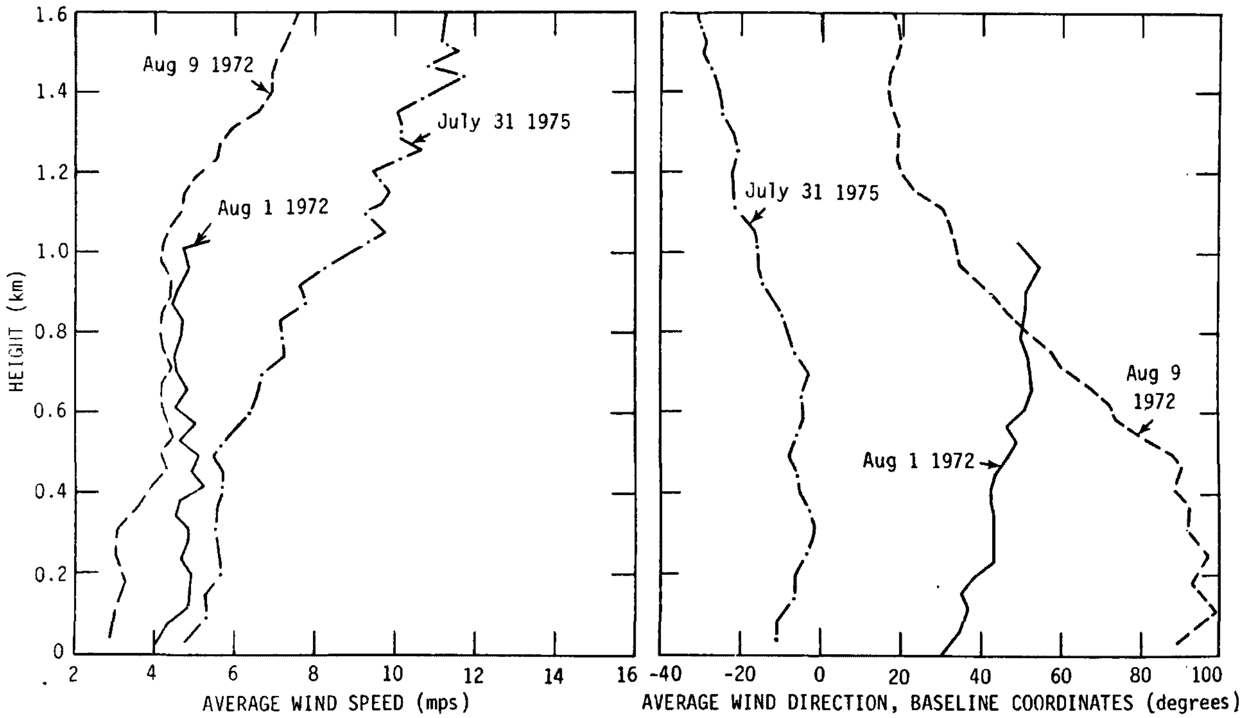

Figure 6. Mean profiles of wind speed and wind direction (in baseline coordinates) for the durations of the three tests of the double theodolite system.

in the two 1972 experiments. The angle of the wind to the baseline averaged 50° on August 1972, 42° on August 1, 1972, and 18° on 31 July 1975. The computational technique developed by Thyer is not as sensitive to "small angle" problems as other methods. However, the fact that the largest RMS deviation occurred where the crossing angle to the baseline was largest suggests that even with this method the double theodolite technique loses some of its advantage when the triangle becomes very obtuse.

For this group of experiments, the crossing angle and the wind speed appear to be the important elements in determining accuracy. The RMS error was largest on the day that the crossing angle was smallest. The RMS deviation was also larger the stronger the wind, increasing from 0.2 or 0.3 mps (less than 5% of the speed) in the lower kilometer on 9 August 1972 when the wind speed was 3 or 4 mps to 0.5 to 2 mps (10 to 20%) on July 31, 1975 when the wind speed was 5 to 9 mps. In addition to increased difficulty in tracking, strong winds also result in greater range to the balloon at a given level so that small angular errors, either because of reading error or because the balloon was not exactly on the crosshairs at reading time, represent larger (non-systematic) position errors.

BOUNDARY LAYER PROFILER (BLP) MEASUREMENTS

The sensors on the BLP package were interrogated and recorded in sequence over a 20-second interval. The system used a pen recorder that provided a chart similar to the standard radiosonde chart. Ten values were recorded sequentially in each record covering 20 seconds, in the following order: high reference, low reference, temperature, wet bulb, pressure, wind speed, temperature, wet bulb, wind speed, wind direction.

The BLP records have been digitized using a digitizer (the Autotrol) which produces punched IBM cards. All of the useable profiler data have been processed through a program which scales the input parameters according to the calibration provided by NCAR and generates, in addition, the height (using the hypsometric equation), vapor pressure, mixing ratio, dewpoint, relative humidity, saturation vapor pressures at both dry and wet bulb temperatures, virtual temperature, potential temperature, and potential wet bulb temperatures. The vertical "gradient" of potential temperature, vertical shears in speed and direction, and Richardson number are calculated for successive readings also but are not very meaningful because small variations in basic values introduce large variations in these terms due to the shallowness of the layer over which the differentials are taken.

Although the design limit of the balloon and package is 750 m, the maximum height attained varied as a function of wind speed, turbulence, and stability. All but 11 exceeded 300 m and nearly half exceeded 500 m.

Both the ascending and descending sections of the soundings have been processed. The rate of ascent was approximately 45 m/min, the rate of descent was at least twice that rate. Comparison of the profiles of temperature and humidity for the two parts of the run indicated that the descending sections were useable despite the faster rate except for the wind speed and direction, and particularly the former. The rapid rate of descent introduced large error in wind speed and a smaller less significant error in wind direction.

The performance of the BLP systems was very disappointing. Twenty-six percent of the scheduled soundings could not be made because of instrument malfunction or unavailability of sensor backage. Of the 228 soundings that were made, nearly 20% are unuseable because of instrument malfunction. The remaining 208 soundings appear to be good, although they have not been subjected to an in-depth review.

As of this date, all of the profiler data have been processed. In Table A-3 of Appendix A are tabulated the dates and times for which useable profiler data are available. These data have been edited for large errors but require some additional examination for less obvious errors before incorporation into analyses. Scaled and derived values, and the basic chart readings are archived on magnetic tape.

Status of Data Reduction

As has been indicated, the basic reduction of the data collected by each of the facility components has been completed, but only a small fraction of the data has been edited. The pilot balloon data, when completely edited, will be available through the RAPS data bank. The airplane and profiler data will reside at the Illinois State Water Survey. Data are available to RAPS researchers, subject to the Illinois State Water Survey data policy (Appendix C).

SECTION 5

DATA SAMPLE AND RESEARCH PROJECTIONS

The analysis of the data collected under this grant is being funded by the National Science Foundation*. Because of unfortunate delays and lapses in funding analysis of the data is barely underway. A study of the nocturnal heat island circulation, based in part on data collected in the field program described above, is nearing completion and a report of the results will be available by midsummer 1977. Currently funded research covers a study of the turbulent fluxes of heat, moisture and momentum over urban and rural surfaces. Initial results of this research should become available by the end of 1977.

One of the case studies carried out in the research on heat island circulation was based on data obtained on July 26-27, 1975. In the course of this study, the profiler data were analyzed to determine the temporal evolution of the nocturnal boundary layer at both the downtown and country locations (BP1 and BP2, resp, Figure 2). This analysis and a similar one for the night of July 25-26 are presented below, to illustrate the type of information contained in this portion of the data bank.

NOCTURNAL OBSERVATIONS, July 26-27, 1975

The weather conditions during the day and evening of July 26 were very favorable for the development of a significant nocturnal heat island. With only thin high cloudiness and light winds, the midafternoon temperatures reached around 30C. The heat island started to increase rapidly around 1400 CDT**, reached its maximum around 2200 and started to decrease very slowly shortly after midnight.

On the night of July 26-27 observations were made between 2020 and 2320 at the rural station (BP2) and 2100 to 0030 in downtown St. Louis (BP1). (Instrument problems forced cancellation of some of the scheduled soundings.) The boundary layer winds were light and from the SSE so that the two stations were located crosswind with respect to each other. Moreover the upwind fetches were homogeneous at both locations, urban for the downtown station and rural for the country station. Thus, the measurements should be representative of the general locale of the observing station.

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* Grants DES 74-13931 and ATM 76-15870.
**In the following discussion all times are given in Central Daylight Time (CDT).

Time-height analyses of temperature at both the urban and rural profiler stations are shown in Figure 7. At the country station most of the low-level cooling had already occurred by the time the observations started, and a strong surface-based inversion existed (Figure 7b). The top of the inversion was quite low, only 100 m above the surface, and increased only slightly in height (25 m) during the three hours of observation. The temperature at the top of the inversion also was nearly constant during the three hours, varying between 24.3 and 24.7C, but with no evidence of a trend with time. Most of the vertical temperature change (80-90%) occurred within the first 25 to 50 m above the surface. The region of maximum temperature at the top of the inversion extended through 50 m at least, and above that the temperature lapse was roughly neutral.

The situation in the city was quite different, as one would expect (Figure 7a). The temperature was still high at 2200 and although the rate of cooling at the surface was not very different than over the rural surface during the common period of observation, the cooling extended through a much deeper layer. A surface based isothermal, or very weak inversion, layer was very shallow (less than 50 m). The main nocturnal inversion was elevated, and delayed, barely forming by 2130. The base of the inversion lowered during the observation period from about 175 m to 125 m, while the top remained almost constant in height at 200 to 220 m.

In the city the whole layer from surface to 200 m was stable and apparently shared in the nocturnal cooling. In the country, on the other hand, the cooling was concentrated below 100 m. From 2200 on the base of the elevated inversion in the city lay just about at the height of the top of the stable layer in the country. The temperature at the top of the inversion was nearly the same as that at the top of the country inversion, varying from 23.6 to 24C, but with an indication of an increasing trend with time.

The urban heat island was very shallow (Figure 7c). The urban temperature excess dissappeared above 60 m during the part of the night covered by the observations. A 'negative' heat island (i.e. city cooler than country) occurred between 75 and 175 m from 2220 on. A comparison of the temperature profiles (Figure 8) indicates that the reversal in the sign of the urban-rural temperature difference was related to the fact that the low-level cooling in the city extended well beyond the top of the country inversion. Urban-rural equivalency in temperature occurred only above the urban stable layer.

The nocturnal moisture distributions over country and city sites are shown in Figure 9. Well mixed conditions existed downtown, but there was a significant vertical gradient in the moisture in the lower 50 m of the rural PBL. Initially this gradient was a lapse, but shortly after 2100 a moisture inversion developed in the lowest 25 m. A pocket of dry air about 200 m deep appeared late in the evening at both locations, slightly later and about 100 m higher downtown than in the country. At both locations the minimum mixing ratio observed was about 9.5 g/kg; however, since it occurred at the last observing time at both locations, this may not have been the minimum reached at either one. At both locations this dry pocket occurred at the top of the nocturnal inversion.

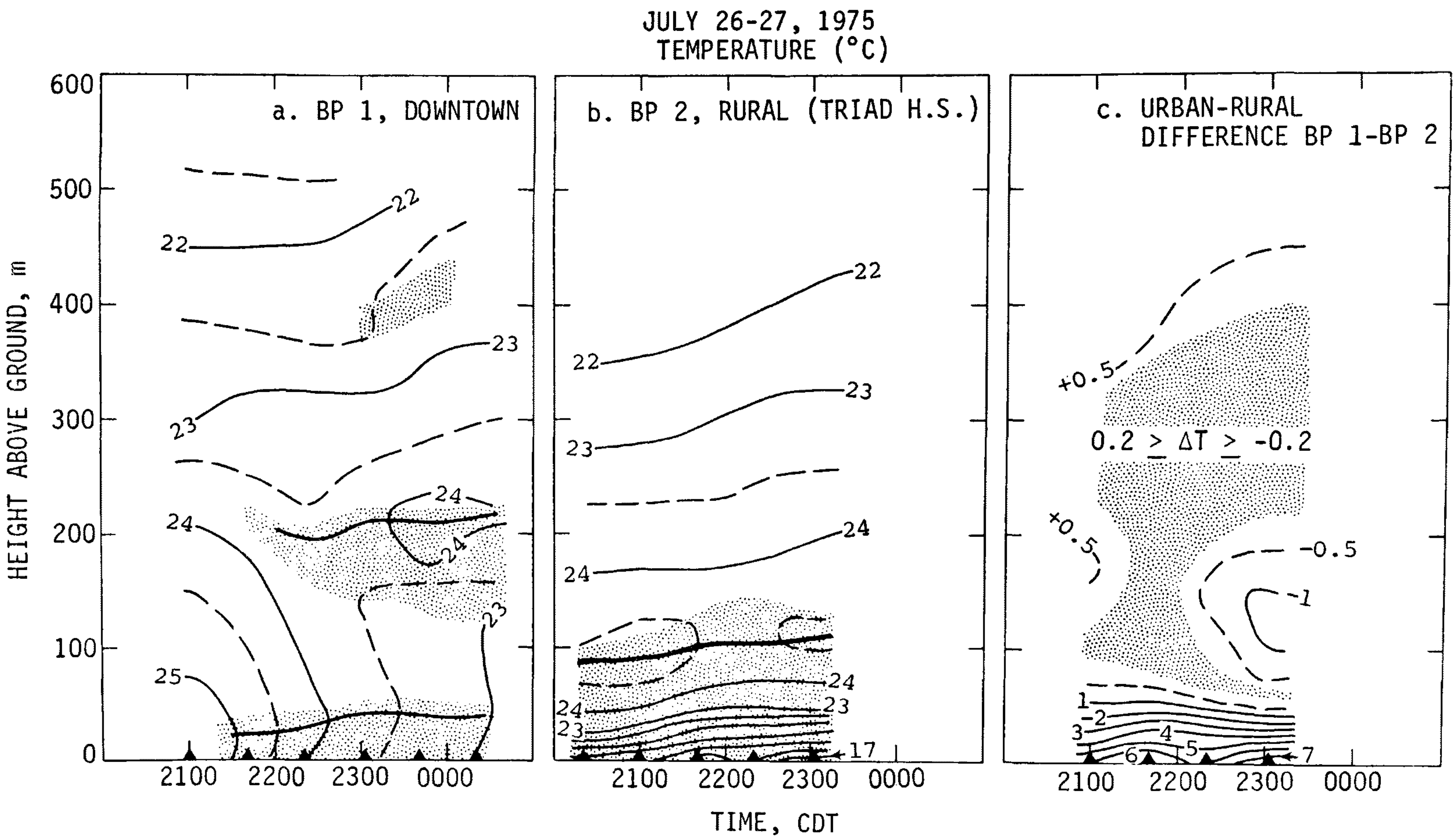


Figure 7. Time-height distributions of a) temperature in downtown St. Louis, b) temperature at Triad High School which is located in a rural setting surrounded by farmland, and c) temperature difference between the two stations, on the night July 26-27, 1975. In a) and b) shading indicates inversion or isothermal layers, and heavy lines the tops of inversions.

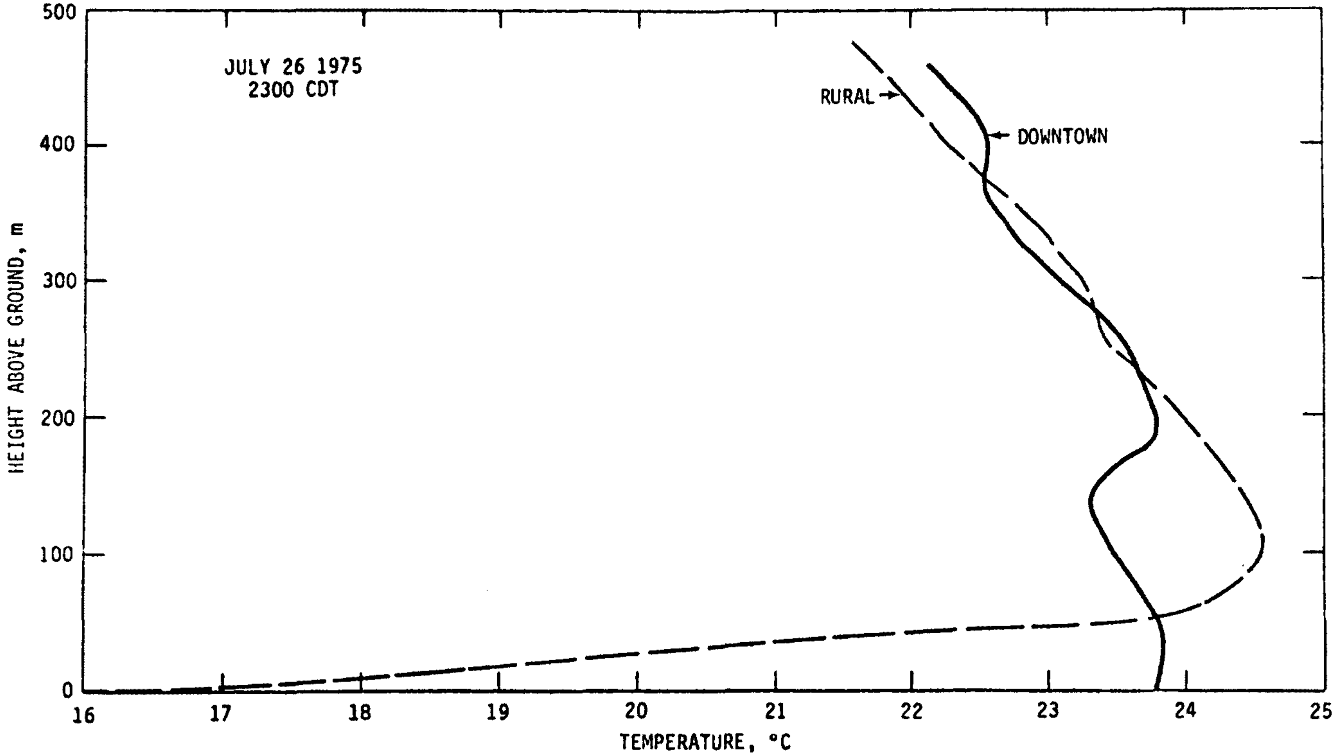


Figure 8. Temperature profiles at a station in downtown St. Louis (solid line) and at a rural station 20 miles to the ENE at 2300 CDT on July 26, 1975.

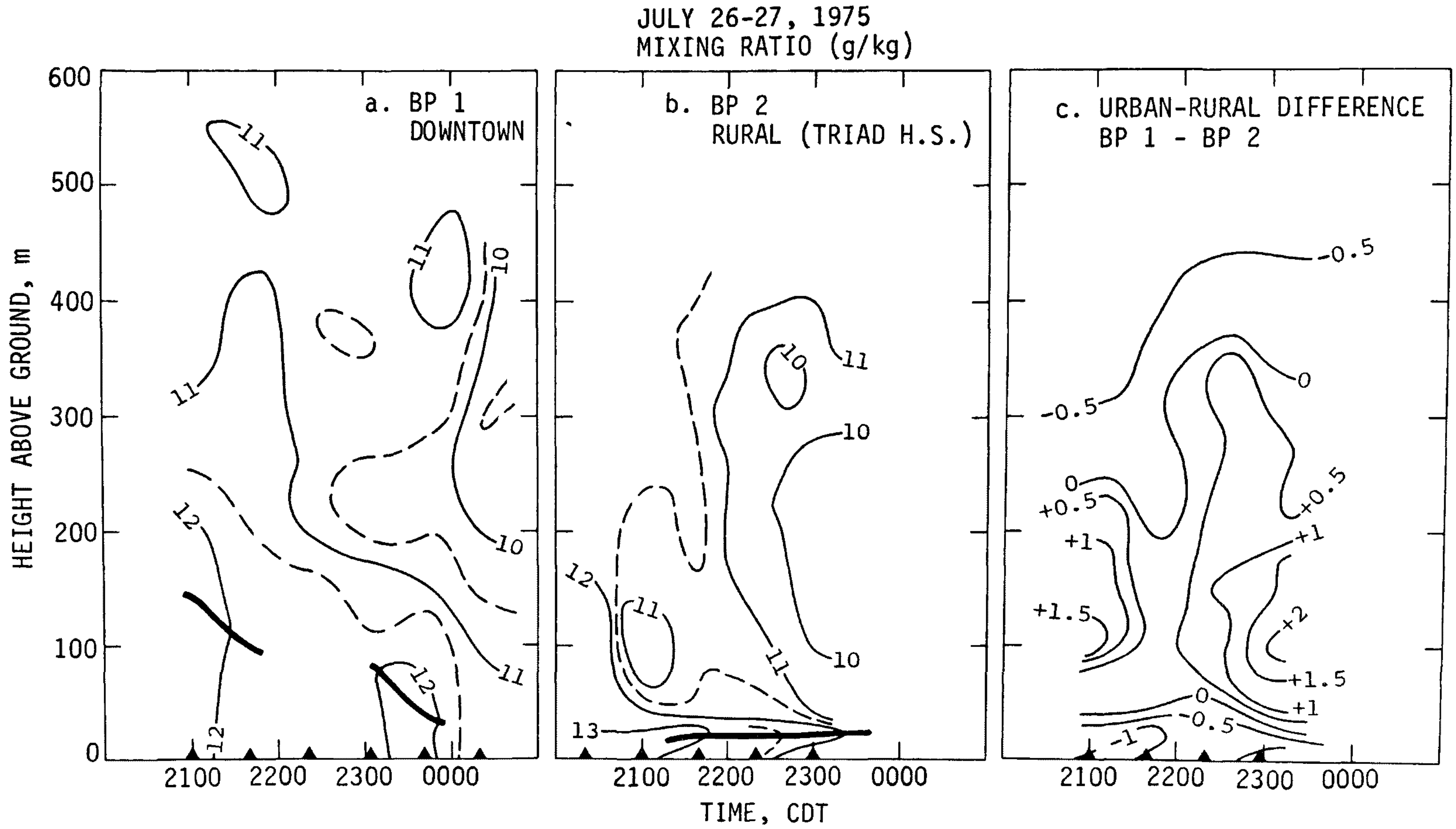
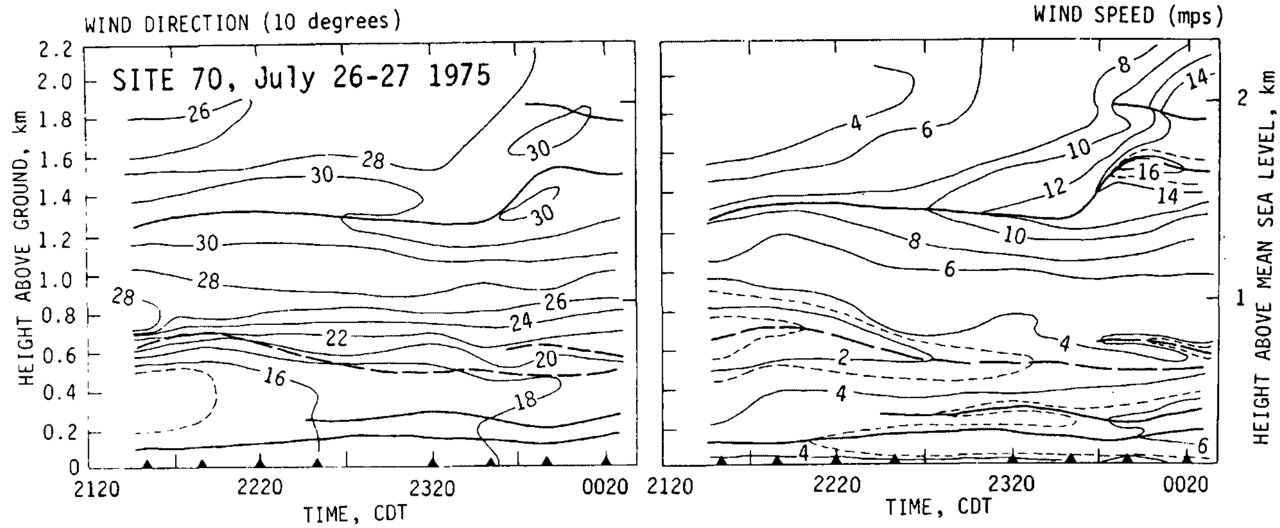
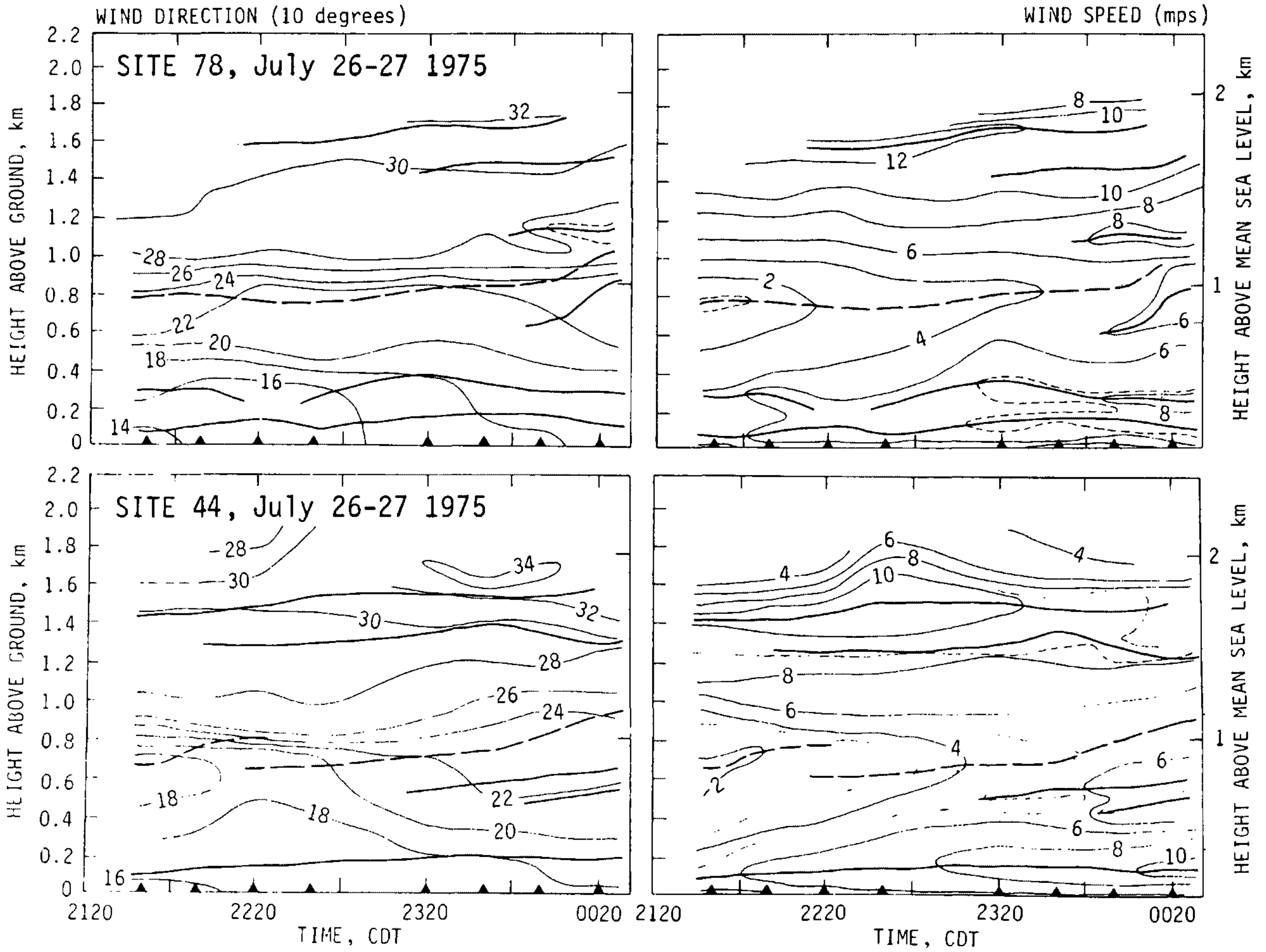


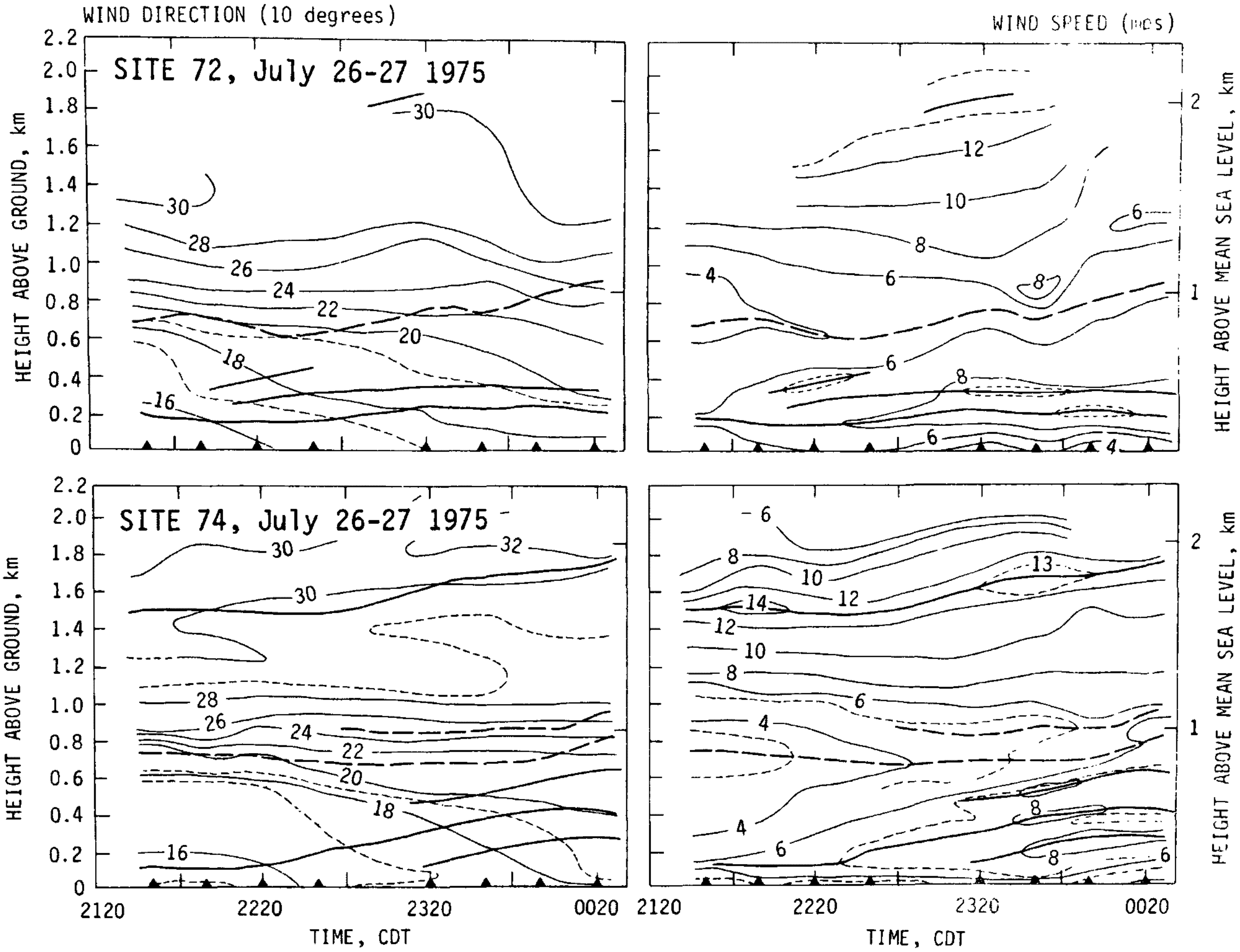
Figure 9. Time-height distributions of a) mixing ratio in downtown St. Louis, b) mixing ratio at Triad High School which is located in a rural setting surrounded by farmland, and c) difference in mixing ratio at the two stations, on the night of July 26-27, 1975. In a) and b) heavy lines indicate the tops of moisture inversions.



a. Rural location



b. Upwind metropolitan stations



c. Downwind metropolitan stations

Figure 10. Time-height distributions of wind direction and wind speed on the night of July 26-27, 1975 as obtained from double theodolite pibal observations a) at a rural location 25 miles east of St. Louis, b) at two stations on the south (upwind) side of the metropolitan area, and c) at two stations on the north (downwind) side of the metropolitan area. Solid heavy lines indicate maxima in the wind speed profiles and dashed heavy lines indicate minima.

The urban-rural differences in mixing ratio (Figure 9c) were negative (city dry) only in the lowest 50 m. The magnitude of the urban deficit decreased with time and by 2300 the near-surface moisture was slightly greater downtown (by 0.6 g/kg) than in the country. This change was no doubt due to the loss of moisture from the lowest air layers to the ground in the country as the surface cooled down and the air became saturated. In the city, on the other hand, the temperature remained so high that even at midnight the surface relative humidity was above 60%.

Above the lowest 50 m, the air downtown was more moist than the country air up to about 200 m (slightly higher later in the evening). This more moist layer coincided with the layer of relatively cool city air (Figure 7c), and was probably due to the same cause, namely the deeper mixed layer over the city.

On clear summer nights with low wind speeds, the wind profiles in the St. Louis area typically show speed maxima forming in the lowest 200 to 400 m around sunset or shortly thereafter, increasing in magnitude and height as the evening progresses and frequently splitting into two or three peaks late in the evening. The evolution of the wind structure, as indicated by the pibal observations (Figure 10) followed this sequence at all stations. At the rural location (Figure 10a) the 'jetlet' reached 6 mps while at the stations on the periphery of the metropolitan area (Figures 10b and c) the low level speed maxima reached 8 to 10 mps, 2 to 4 mps greater than the speed minima just above. The levels of these low level jetlets were generally higher, by several tens of meters, at the two downwind metropolitan stations (72 and 74) than at the country stations.

The wind was southerly through the lowest several hundred meters on this night, but at about 800 m it veered sharply from south to west. The depth of the shear layer was 200 or 300 m early in the night but increased (and consequently the magnitude of the shear decreased) as the night progressed. This shear could represent concentration of the shift to gradient flow to a shallow layer during the afternoon when the mixing distributed the frictional dissipation of gradient momentum vertically and the flow to the left of the gradient wind was found through the deeper layer. This is indicated also by the veering of the wind with time below the shear layer. This veering occured nearly simultaneously through depth at the rural and near rural sites (Stations 70 and 78) so that a layer of near constant wind direction was maintained. At the downwind urban sites, the isogonal analysis indicates a gradual turning of the wind with height.

The profiler data provides a more detailed look at the structure of the low-level maximum in wind speed. In Figure 11 are shown the height-time distributions of wind speed at the two profiler sites, with greater height exaggeration than in Figure 10 since the profilers provide much greater height resolution. There was a very strong gradient in wind speed off the surface in the country (Figure 11b), with most of the change occurring in the lowest 50 to 75m. The low level jetlet was at 200 m at 2030 but dropped rapidly to 125 m and remained between 125 and 175 m. Shortly after 2200 a secondary maximum formed around 300 m. Both the level

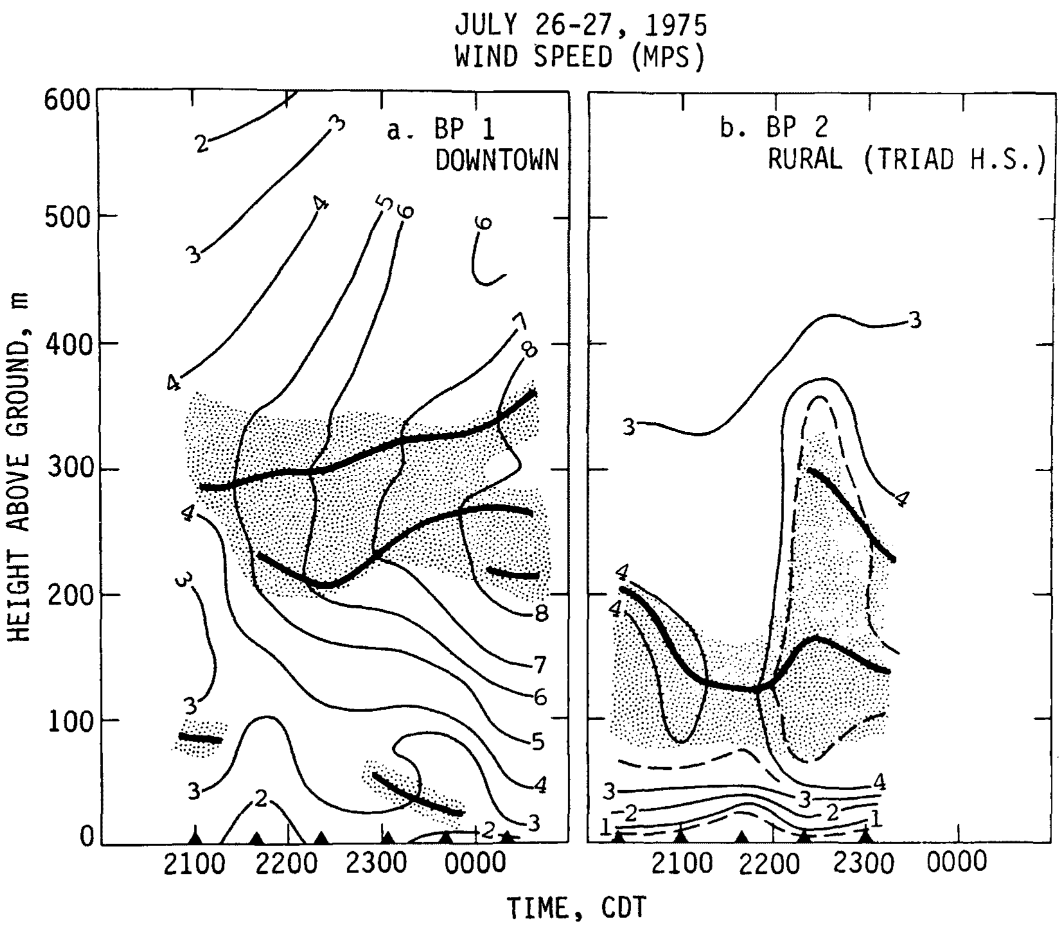


Figure 11. Time-height distributions of wind speed on the night of July 26-27, as measured by boundary layer profilers a) in downtown St. Louis and b) at Triad High School located in a rural setting surrounded by farmland. The shaded areas indicate regions of maxima and the heavy lines the peak values in the vertical profiles.

and the magnitude of the maximum in the speed profile are in good agreement with those in the profiles calculated from pibal measurements at the same location (Figure 10a).

The low level vertical gradient in wind speed was much smaller in the city than in the country. The surface wind (which was calm in the country) was about 2 mps downtown. Although there appears to have been some intermittent formation of maxima below 100 m, the primary maxima occurred between 200 and 350 m. There was definitely a double structure to the jetlet from 2130 on, with the lower maximum around 200 m, and the second about 75 m higher. Both increased in height and speed with time and a third maximum formed around 225 m again at about midnight. The maximum speed increased from under 5 mps to a little over 8 mps.

Blakadar (1957) has shown that nocturnal low level jets and nocturnal inversions are related. This relationship existed on this evening even though the speed maxima were relatively small. In both the urban and rural boundary layers, the layers of speed maxima (shaded in Figure 11) occurred just at the top of the nocturnal inversion (highlighted in Figure 7).

NOCTURNAL EXPERIMENT, July 25-26, 1975

The profiler data have also been examined for the night of July 25-26, 1975. On this night the period of overlapping observations at the two profiler stations was considerably longer, extending from 2100 on the 25th to 0400 on the 26th. The low level winds were from the east so that the upwind fetch at BP2 was rural and air arriving at the downtown site (BP1) had passed over several miles of urban- industrial surface. Therefore the measurements were again representative of the locale of the observations.

As will be seen in the following discussion, the boundary layer structures of all three variables, temperature, moisture and wind, were very similar to that found on the night of July 26.

Again, a strong surface-based inversion had developed in the country by 2100 and continued throughout the night (Figure 12b). The stable layer deepened from about 125 m early in the evening to about 250 m at 0400. Downtown, the main low-level stable layer was a rather shallow inversion at around 200 m, lifting about 50 m after midnight (Figure 12a). The base of the elevated inversion was just above the top of the rural inversion. The temperatures at the tops of the urban and rural inversion were about the same.

The urban heat island reached a maximum intensity of about 8C at the surface by 2300 and remained within a degree of that for the rest of the night. The heat island was less than 100 m in depth (Figure 12c). A reversal in the sign of the urban-rural temperature difference occurred above the low level heat island, but not until midnight and the negative heat island did not reach any significant magnitude until nearly 0300. The layer of the 'negative heat island' was based at about 100 m, or a little higher, and increased in depth and magnitude during the early morning hours. The magnitude of the urban temperature deficit reached a little

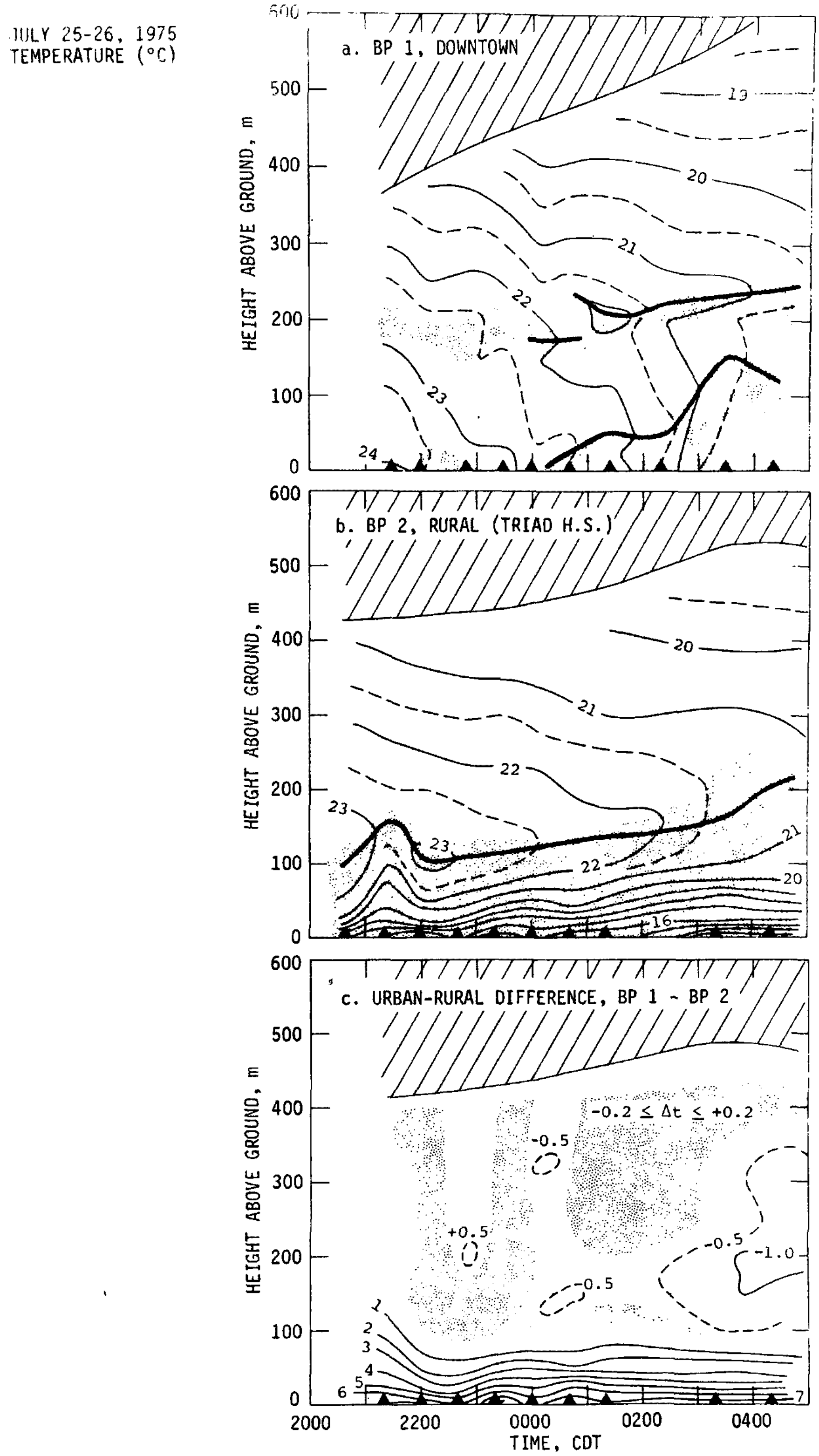


Figure 12. Time-height distributions of a) temperature in downtown St. Louis, b) temperature at Triad High School which is located in a rural setting surrounded by farmland, and c) temperature difference between the two stations, on the night of July 25-26, 1975. In a) and b) shading indicates inversion or isothermal layers, and heavy lines the tops of inversions.

over 1C by the time the observations ended at 0400. As on July 26-27 this reversal of temperature difference was a consequence of the mixing in the city and thus a sharing of the surface heat loss through a deeper layer in the city than in the country.

The urban and rural moisture distributions on the night of July 25-26 (Figure 13) were also similar to those observed on the night of July 26-27. The lowest 500 m were very well mixed downtown and little change occurred during the night except for the development of a weak moisture inversion at around 25 m above ground after 0100. In the country, there was a strong moisture gradient near the surface and a low level moisture inversion at about 25 m from 2120 on, which increased in strength as the night wore on. Whereas the surface mixing ratio remained between 10 and 10.7 gm/kg in the city it decreased from 11.9 to 9.1 in the country. Thus in the early morning hours the surface air was more moist downtown than in the country. Above 50 m, the boundary layer was fairly well mixed at both locations.

A dry pocket appeared about 200 m at both locations on this evening (slightly later in the city). The minimum mixing ratio was 0.5 g/kg lower in the city than in the country. This dry pocket could have been due to advection at both locations although it is unlikely that the air over the rural site (BP1) could have been the same that appeared downtown in St. Louis within the hour. Moreover the occurrence of these dry pockets around midnight on both nights would suggest that they are due to local effects rather than due to advection.

Between 100 and 200 m the urban moisture deficit decreased with time, and the urban-rural difference in moisture became positive in the early morning (Figure 13c). However on this evening the city remained drier than the country until well after midnight, both at the surface and in this elevated layer, and the urban moisture excess aloft was quite small.

Low level wind speed maxima also occurred on this evening, extending into the early morning hours (Figure 14). In the country a single jetlet was well established by shortly after sunset and continued at a height of about 125 to 150 m throughout the night. The maximum wind speed however occurred in the middle of the night and had started to decrease by the morning hours. Multiple low level maxima in wind speed occurred in downtown St. Louis. The main layer of maximum speed was based between 200 and 250 m with considerable variation in height with time. The maximum speed was observed early in the night rather than in the middle, and was slightly higher than the maximum value in the country. However, it then decreased so that by the morning hours the maximum speeds in the country and city were about the same.

The base of the layer of high winds occurred just above the top of the inversion during most of the night in the city. However, this was the case only until shortly after 0200 in the country, at which time the inversion started to deepen significantly but the height of the main maximum in wind speed remained fairly constant.

SUMMARY

The material above has been presented to illustrate some of the kinds of information contained in the data collected with the boundary layer

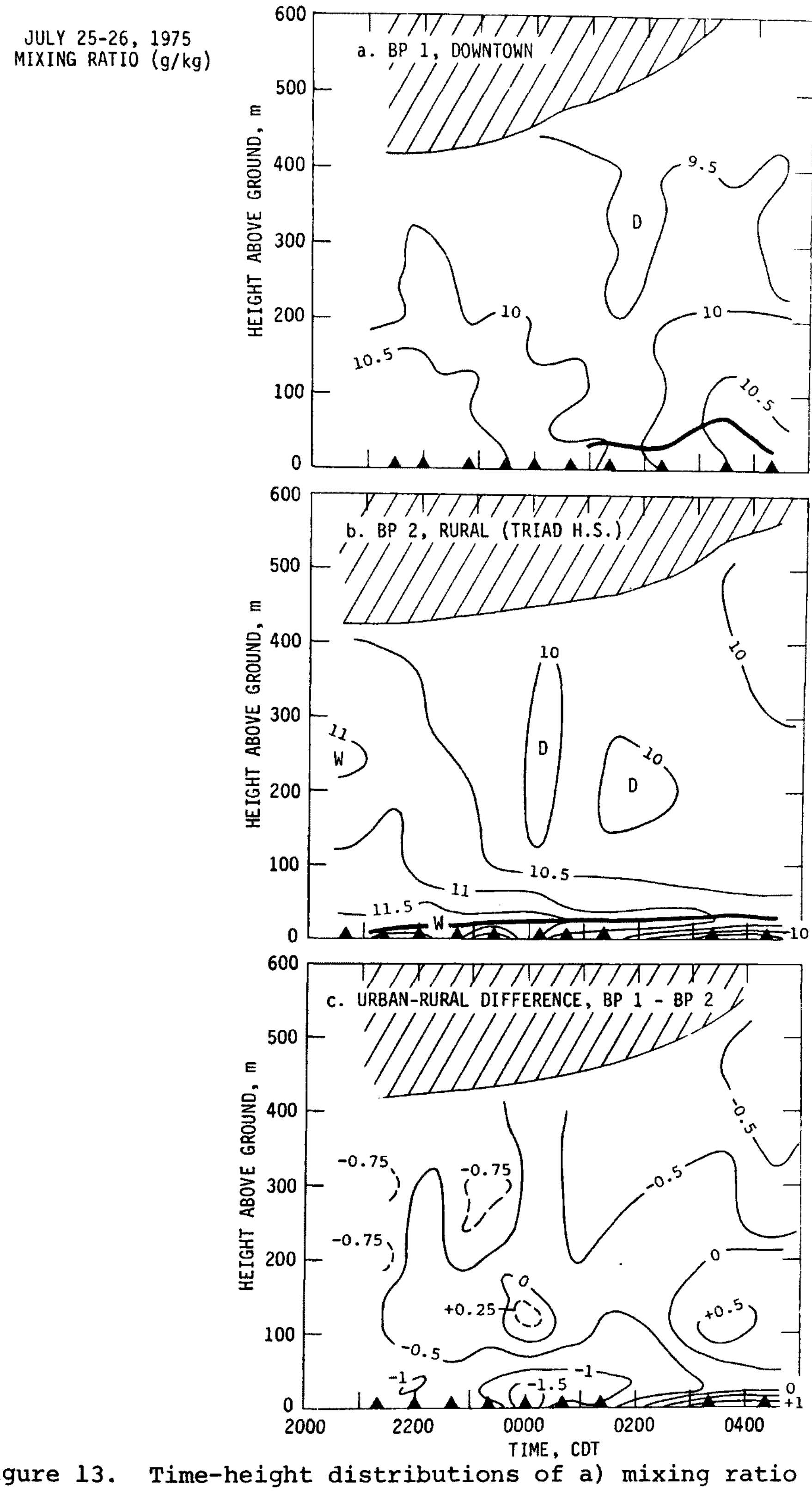


Figure 13. Time-height distributions of a) mixing ratio in downtown St. Louis, b) mixing ratio at Triad High School which is located in a rural setting surrounded by farmland, and c) difference in mixing ratio at the two stations, on the night of July 25-26, 1975. In a) and b) heavy lines indicate the tops of moisture inversions.

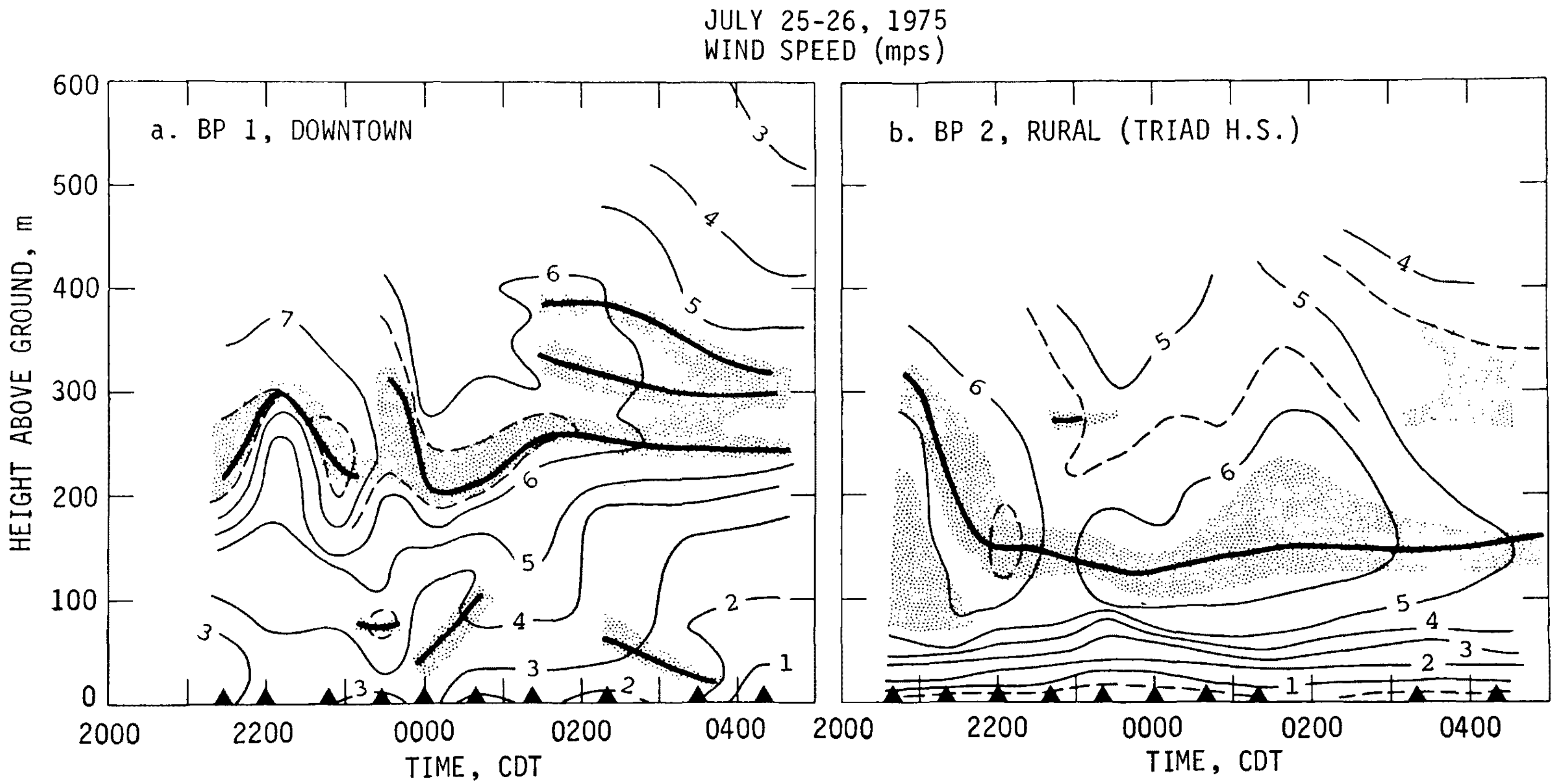


Figure 14. Time-height distributions of wind speed on the night of July 25-26, 1975, as measured by boundary layer profilers a) in downtown St. Louis and b) at Triad High School located in a rural setting surrrounded by farmland. The shaded areas indicate regions of maxima and the heavy lines the peak values in the vertical profiles.

profiler. These examples indicate that a great deal can be learned about the evolution of the structure in the lower PBL from these data. In the currently funded studies of the turbulent fluxes the profiler data will be used in quite a different manner. However it is the intention to seek funding at a later date to do intensive studies of the evolution of PBL structure over the inner city and country surfaces.

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APPENDIX A

AVAILABILITY OF DATA: BOUNDARY LAYER PROFILES

The availability of useable profile data collected in the ISWS Boundary Layer Program during the field efforts in 1975 are shown in the following three tables.

Tables A-1 and A-2 show the times and stations for which wind profiles obtained using pilot balloons are available. Table A-3 shows the times and stations for which temperature, humidity and wind profiles obtained with the boundary layer profiler (tethered balloon) system are available. The locations of all stations are shown in Figure A1.

The equipment and techniques used in both systems are described in the main body of this report. All the data are archived on 9-track-1600 BPI magnetic tapes in IBM unformatted binary code.

Table Al. Pilot balloon measurements available for February 1975.

Symbols: 0 = *no data*, ✓ = *data to 200 m or higher*, – = *data for less than 200 m.*

SITE	DATE	RELEASE TIMES (local)**								
	19 Feb.	1220	1240	1300	1320	1400	1420	1440	1500	
33		✓	✓	✓	✓	✓	✓	✓	✓	
44		✓	✓	✓	✓	✓	✓	✓	✓	
71		0	✓	✓	✓	0	✓	✓	✓	
75		✓	0	✓	✓	✓	✓	✓	✓	
78		✓	0	✓	✓	0	0	✓	0	
79		✓	✓	✓	✓	✓	✓	✓	✓	
	20 Feb.	1150	1210	1230	1250	1340	1400	1420	1440	
33		0	✓	✓	✓	✓	✓	✓	✓	
44		✓	✓	✓	✓	✓	✓	✓	✓	
71		✓	✓	✓	✓	0	✓	✓	✓	
74		✓	✓	✓	✓	✓	✓	✓	✓	
75		✓	✓	✓	✓	✓	✓	✓	✓	
79		✓	✓	✓	✓	✓	✓	✓	✓	
	21 Feb.	1140	1200	1220	1240	1330	1350	1410	1430	
33		✓	✓	✓	✓	✓	✓	✓	✓	
44		✓	✓	✓	✓	✓	✓	✓	✓	
71		✓	✓	✓	0	✓	✓	✓	✓	
74		✓	✓	✓	✓	✓	✓	✓	✓	
75		✓	✓	✓	✓	✓	✓	✓	0	
79		✓	✓	✓	✓	✓	✓	✓	✓	
	25 Feb.	1320	1340	1400	1420	1440	1500			
33		0	0	0	0	✓	✓			
44		✓	✓	✓	✓	✓	✓			
71		0	✓	✓	✓	✓	✓			
75		0	0	✓		✓	✓			
78		✓	✓	✓	✓	✓	✓			
79		0	✓	✓	✓	✓	✓			
	*26 Feb.	1220	1240	1300	1320	1400	1420	1440	1500	1520
74		✓	✓	✓	✓	✓	✓	✓	✓	✓
75		✓	✓	✓	✓	✓	✓	✓	✓	✓
79		✓	✓	✓	✓	✓	✓	✓	✓	✓
		1230	1250	1310	1330	1410	1430	1450	1510	1530
74		✓	✓	✓	✓	✓	✓	✓	✓	✓
75		✓	✓	✓	✓	✓	✓	✓	✓	✓
79		✓	✓	✓	✓	✓	✓	✓	✓	✓
	27 Feb.	1210	1230	1250	1310	1350	1410	1430	1450	
33		✓	✓	✓	✓	✓	✓	✓	✓	
44		✓	✓	✓	✓	✓	✓	✓	✓	
71		0	0	✓	0	0	0	0	0	
74		✓	✓	✓	✓	✓	✓	✓	✓	
75		0	0	0	0	✓	✓	✓	✓	
79		0	✓	✓	✓	✓	✓	✓	✓	
	*28 Feb.	1230	1250	1310	1330	1350	1410	1430	1450	
33		✓	✓	✓	✓	✓	✓	✓	✓	
78		–	✓	0	0	✓	✓	✓	✓	
79		✓	✓	✓	✓	✓	✓	✓	✓	
		1240	1300	1320	1340	1400	1420	1440	1500	
33		✓	✓	✓	✓	✓	✓	0	✓	
78		✓	✓	✓	✓	✓	✓	✓	✓	

* = *10 min staggered releases at sites 33 and 78, 2 teams at each site.*
** = *Local times are CST through 22 February, and CDT 23 February et seq.*

Table A2. Pilot balloon measurements available for July 1975

Symbols: 0 = no data, ✓ = data to 200 m or higher, - = data for less than 200 m.

SITE	DATE	RELEASE TIMES (CDT)									
	[illegible] July	1[illegible]0	1120	1140	1200	1240	1300	1320	1340		
44		✓	✓	✓	✓	✓	✓	✓	✓		
72		0	0	✓	✓	✓	✓	✓	✓		
74		✓	✓	✓	✓	✓	✓	✓	✓		
78		0	0	0	0	✓	✓	✓	✓		
7[illegible]		0	0	0	0	✓	✓	✓	✓		
	7 July	1320	1340	1400	1420	1440	1500	1520	1540	1600	1620
3[illegible]		✓	✓	✓	✓	✓	0	✓	✓	✓	✓
44		✓	✓	✓	✓	✓	0	✓	✓	✓	✓
72		✓	✓	✓	✓	0	✓	✓	✓	✓	✓
77		✓	✓	✓	✓	✓	0	✓	✓	✓	✓
7[illegible]		✓	✓	✓	✓	✓	0	✓	✓	✓	✓
	[illegible]8 July	1[illegible]	1250	1310	1330	1350	1430	1450	1510	1530	
7[illegible]		✓	✓	✓	✓	✓	✓	✓	✓	✓	
7[illegible]		✓	✓	✓	✓	✓	✓	✓	✓	✓	
79		✓	✓	✓	✓	✓	✓	✓	✓	✓	
		12[illegible]	1300	1320	1340	1400	1440	1500	1520	1540	
70		✓	✓	✓	✓	✓	0	✓	✓	✓	
7[illegible]		✓	✓	✓	✓	✓	✓	✓	✓	✓	
	9-10 July	2140	2200	2220	2240	2320	2340	2400	0020		
33		✓	✓	✓	✓	✓	✓	✓	✓		
44		0	0	0	✓	✓	✓	✓	✓		
70		✓	✓	✓	✓	✓	✓	✓	✓		
72		0	0	0	✓	✓	✓	0	✓		
78		✓	0	✓	✓	✓	✓	✓	✓		
	10-11 July	2140	2200	2220	2240	2320	2340	2400	0020		
33		✓	✓	✓	✓	✓	✓	✓	✓		
44		✓	0	✓	0	0	0	0	0		
7[illegible]		✓	✓	✓	✓	✓	✓	✓	✓		
72			✓	✓	✓	✓	✓	✓	✓		
78		✓	✓	✓	✓	✓	✓	✓	✓		
	12 July	1340	1400	1420	1440	1520	1540	1600	1620		
71		✓	✓	✓	✓	✓	0	0	0		
7[illegible]		✓	✓	✓	✓	✓	✓	✓	✓		
7[illegible]		✓	✓	✓	✓	✓	✓	✓	✓		
7[illegible]			✓	✓	✓	✓	✓	✓	✓		
7[illegible]		✓	✓	✓	✓	✓	✓	0	✓		
	*14 July	1310	1330	1350	1410	1450	1510	1530	1550	1610	
70		✓	✓	✓	✓	✓	✓	✓	✓	✓	
7[illegible]		✓	✓	✓	✓	✓	✓	✓	✓	✓c	
	*14 July	1320	1340	1400	1420	1440	1520	1540	1600	1620	
7[illegible]		✓	✓	✓	✓	✓	✓	✓	✓	✓	
7[illegible]		✓	✓	✓	✓	✓	✓	✓	✓	✓	
7[illegible]		✓	✓	✓	✓	✓	✓	✓	✓	✓	
	[illegible] July	1310	1330	1350	1410	1450	1510	1530	1550	1610	
[illegible]		✓	✓	✓	✓	✓	✓	✓	✓	✓	
		✓	✓	✓	✓	✓	✓	✓	✓	✓	
		1320	1340	1400	1420	1440	1520	1540	1600	1620	
7[illegible]		✓	✓	✓	✓	✓	✓	✓	✓	✓	
7[illegible]		0	✓	✓	✓	✓	✓	✓	✓	✓	
[illegible]		✓	✓	✓	✓	✓	✓	✓	✓	✓	
	1[illegible] July	1[illegible]	1220	1240	1300	1340	1400	1420	1440	1500	
3[illegible]		✓	✓	✓	✓	✓	✓	✓	✓	✓	
[illegible]4		✓	✓	✓	✓	✓	✓	✓	✓	✓	
[illegible]		✓	✓	✓	0	✓	✓	✓	✓	✓	
[illegible]			✓	✓	✓	✓	✓	✓	✓	✓	
[illegible]		✓	✓	✓	✓	✓	✓	✓	✓	✓	

SITE	DATE	RELEASE TIMES (CDT)								
	18 July	1120	1140	1200	1220	1240	1320	1340	1400	1420
44		✓	✓	✓	✓	✓	0	0	0	0
72		✓	✓	✓	✓	✓	✓	✓	✓	✓
74		✓	✓	✓	✓	✓	✓	0	0	0
76		✓	✓	✓	✓	✓	✓	✓	✓	✓
78		0	✓	✓	✓	✓	0	0	0	0
	* 21 July	1320	1340	1400	1420	1500	1520	1540	1600	1620
70		✓	✓	✓	✓	✓	✓	✓	0	✓
79		✓	✓	✓	✓	✓	✓	✓	✓	✓
		1330	1350	1410	1430	1450	1530	1550	1610	1630
70		✓	✓	✓	✓	✓	✓	✓	✓	✓
72		✓	✓	✓	✓	✓	✓	✓	✓	✓
79		✓	✓	✓	✓	✓	✓	✓	✓	✓
	22 July	1320	1340	1400	1420	1440	1520	1540	1600	1620
44		✓	✓	✓	✓	✓	✓	✓	✓	✓
72		✓	✓	✓	✓	✓	✓	✓	✓	✓
74		✓	✓	✓	✓	✓	✓	✓	✓	✓
76		✓	✓	✓	✓	✓	✓	✓	✓	✓
78		✓	✓	✓	✓	✓	✓	✓	✓	✓
	24-25 July	2130	2150	2210	2230	2310	2330	2350	0010	
44		✓	✓	✓	✓	✓	✓	✓	✓	
72		✓	✓	✓	✓	✓	✓	✓	✓	
74		✓	✓	✓	✓	✓	✓	0	0	
76		✓	✓	✓	✓	✓	✓	✓	✓	
78		✓	✓	✓	✓	✓	✓	✓	✓	
	25-26 July	2120	2140	2200	2220	2300	2320	2340	0000	
44		✓	✓	✓	✓	✓	✓	✓	✓	
72		✓	✓	✓	✓	✓	✓	✓	✓	
74		✓	✓	✓	✓	✓	✓	✓	✓	
76		✓	✓	✓	✓	✓	✓	✓	✓	
78		✓	✓	✓	✓	✓	✓	✓	✓	
	26-27 July	2140	2200	2220	2240	2320	2340	0000	0020	
44		✓	✓	✓	✓	✓	✓	✓	✓	
70		✓	✓	0	✓	✓	✓	✓	✓	
72		✓	✓	✓	✓	✓	✓	✓	✓	
74		✓	✓	✓	✓	✓	✓	✓	✓	
78		✓	✓	✓	✓	✓	✓	✓	✓	
	2[illegible] July	0600	0620	0640	0700	0740	0800	0820	08[illegible]	0[illegible]00
76		✓	✓	✓	✓	✓	✓	✓	✓	✓
79		✓		0	0	0	✓	✓	✓	✓
	29 July	0920	0940	1000	1020	1040	1120	1140	1200	1220
76		✓	✓	✓	✓	✓	✓	✓	✓	✓
79		✓	✓	✓	✓	✓	✓	✓	✓	✓
	29 July	1240	1300	1320	1340	1400	1440	1500	1520	1540
79		0	✓	✓	✓	✓	✓	✓	✓	✓
	30 July	0600	0620	0640	0700	0740	0800	0820	0840	0900
70		✓	✓	✓	✓	✓	✓	✓	✓	✓
79		✓	✓	✓	✓	✓	✓	✓	✓	✓
	30 July	0920	0940	1000	1020	1040	1120	1140	1200	1220
70		0	0	0	0	0	0	0	[illegible]	✓
79		✓	✓	✓	✓	✓	✓	✓	✓	✓
	30 July	1240	1300	1320	1340	1400	1420	1440	1500	
70		✓	✓	✓	0	✓	✓	✓	✓	
79		✓	✓	✓	✓	✓	0	0	0	
	31 July	0922	0943	1000	1020	1045	1100	1120	1154	
33	Team 2	✓	✓	✓	✓	✓	✓	✓	✓	
	4	✓	✓	✓	✓	✓	✓	✓	✓	
	1	✓	✓	✓	✓	✓	✓	✓	✓	
	3	✓	✓	✓	✓	✓	✓	✓	✓	
	5	✓	✓	✓	✓	✓	✓	✓	✓	

** 10 min staggered releases at sites 70 and 7[illegible], two teams at each site.*

Table A3. Availability of data from tethered balloon, boundary layer profilers. Times, sites when useable data are available are shown by ✓ symbol.

STN.	DATE	SOUNDING TIMES (GMT)										
	2 July	1210	1405									
BP1		✓	✓									
	3 July	1115	1300	1400	1500	1600						
BP1			✓	✓	✓							
BP2		✓	✓									
	5 July	1100	1140	1220	1300	1340	1420					
BP1		✓				✓						
BP2		✓	✓	✓	✓	✓	✓					
	7 July	1300	1330	1400	1430	1500	1530	1600	1630	1700	1730	
BP1		✓	✓	✓	✓	✓	✓	✓	✓			
BP2		✓		✓		✓	✓	✓	✓	✓	✓	
	8 July	1200	1240	1320	1400	1440	1520	1600	1640			
BP1								✓	✓			
BP2		✓	✓	✓	✓	✓	✓					
	9-10 July	2120	2200	2240	2320	0000	0040					
BP1		✓	✓	✓	✓	✓	✓					
	14 July	1300	1340	1420	1500	1540	1620	1700				
BP1		✓	✓	✓	✓	✓						
BP2						✓	✓	✓				
	15 July	1220	1300	1340	1420	1500	1540	1620	1700			
BP1					✓	✓	✓	✓	✓			
BP2		✓	✓	✓	✓	✓	✓	✓	✓			
	16 July	1240	1320	1400	1440							
BP1		✓	✓	✓	✓							
*BP2		✓	✓	✓	✓							
	18 July	1040	1120	1200	1240	1320						
BP1		✓	✓	✓	✓	✓						
*BP2				✓	✓	✓						
	21 July	1200	1240	1320	1400	1440	1520	1600	1640	1720		
BP1		✓	✓	✓	✓	✓	✓	✓	✓	✓		
BP2		✓	✓	✓	✓	✓	✓	✓	✓			
	22 July	1200	1240	1320	1400	1440	1520	1600	1640	1720		
BP1		✓	✓	✓	✓	✓	✓	✓	✓	✓		
	24-25 July	1940	2020	2100	2140	2220	2300	2340	0020	0100		
BP1		✓	✓	✓	✓	✓	✓	✓	✓	✓		
BP2		✓	✓	✓	✓	✓	✓	✓	✓	✓		
	25-26 July	2040	2120	2200	2240	2320	0000	0040	0120	0220	0320	0420
BP1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
BP2		✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
	26-27 July	2020	2100	2140	2220	2300	2340	0020				
BP1			✓	✓	✓	✓	✓	✓				
BP2		✓	✓	✓	✓	✓						
	27 July	1220	1300	1340	1420	1500	1540					
BP1			✓	✓	✓	✓						
	28 July	1700	1740	1820	1900	1940	2020	2100	2140			
BP1		✓	✓	✓	✓	✓	✓	✓	✓			
	29 July	0020	0100	0140	0220	0300	0340	0420	0500	0540	0620	0700
BP1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	29 July	0740	0820	0900	0940	1020	1100	1140	1220	1300	1400	1500
BP1		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	30 July		0820	0840	0900	0920	1000	1100	1200	1300	1400	1500
BP1			✓	✓		✓	✓	✓	✓	✓	✓	
BP2					✓	✓	✓	✓	✓	✓	✓	✓

* *Wet bulb thermometer malfunctioning*

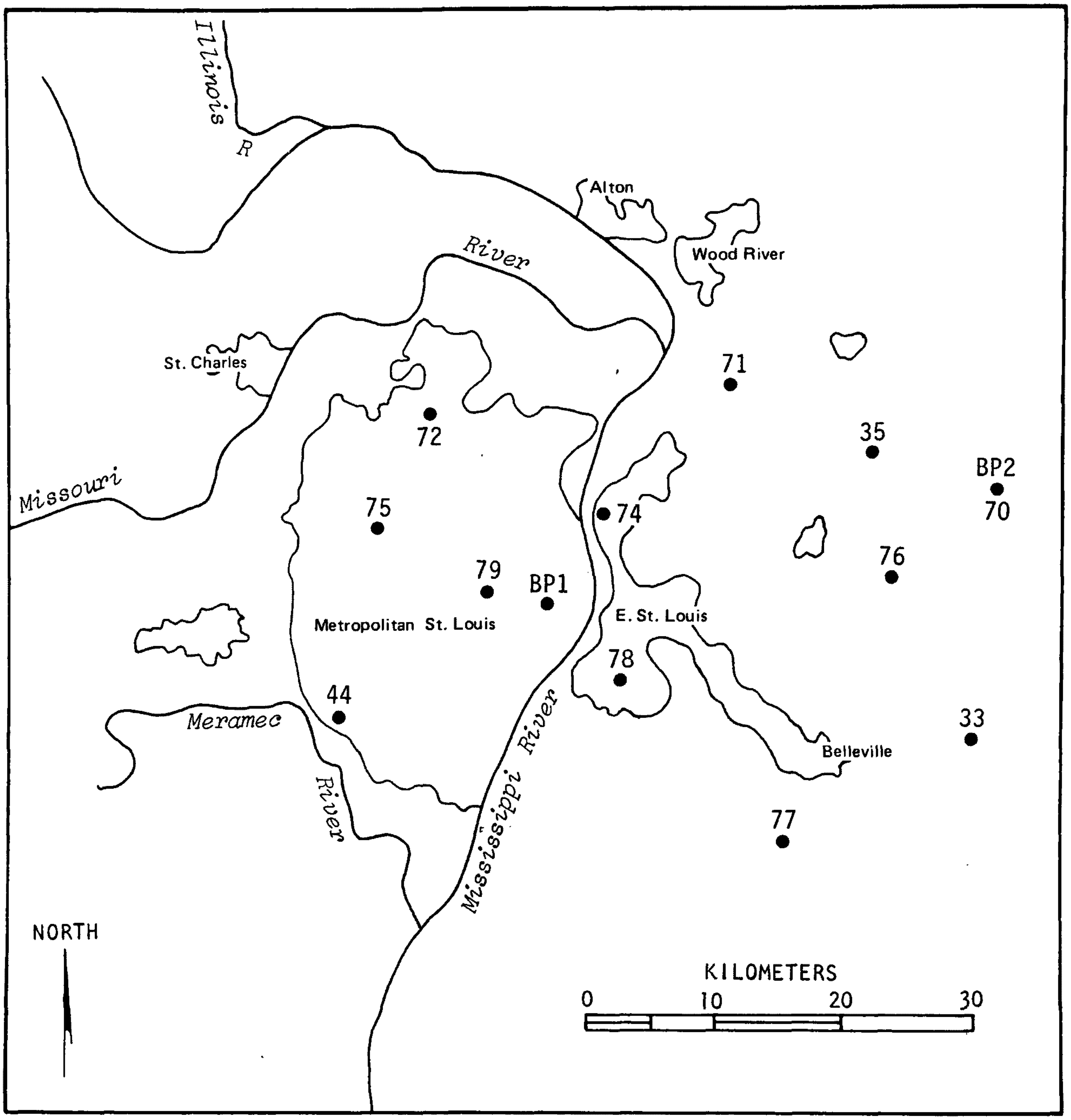

Figure A-1. Locations of the double-theodolite pilot-balloon observing sites (numbered) and the two boundary-layer profiler stations, BP1 and BP2.

APPENDIX B

AN INVESTIGATION OF THE ERRORS IN ESTIMATING WIND VELOCITY BY DOUBLE-THEODOLITE PILOT-BALLOON OBSERVATIONS

INTRODUCTION

In studying the planetary boundary layer (PBL) wind field over a small meso-scale region such as the METROMEX area (4000 or 5000 km) it is important to establish that the observed variations are larger than the "noise" arising from errors in the basic measurements. Thus an investigation of the probable error in the estimates of wind velocity obtained in the ISWS boundary layer program has been an integral part of the overall effort.

Measurement of wind in the PBL over the complex meso-region around St. Louis has been by visual tracking of pilot balloons in the ISWS field programs. Field efforts designed to provide detailed study of the velocity structure has utilized two theodolites, spaced a few hundred meters apart, to track the balloons (double theodolite system). The double theodolite system is an improvement over single theodolite tracking since it does not require the assumption of a constant rate of balloon ascent, an assumption which is poorly justified for the PBL, particularly during summer days. Nevertheless, there are still several potential sources of error in the wind estimate, arising from both human and equipment factors.

Three potential sources of error were recognized before the field efforts began in 1971 and procedures were incorporated to minimize their effects on the measurements. These expected sources of uncertainty were (1) observer stress and fatigue, (2) faulty equipment, and (3) faulty orientation of the theodolite in the horizontal plane (level) and/or in the horizontal coordinate system (azimuthal orientation).

Human stress and mental and physical fatigue are factors in any type of prolonged use of a precision instrument. Bellucci (1960) has discussed the importance of experience when accurate measurements for frequently launched balloons are needed. High observational frequency (frequent dial readings) is needed for good vertical resolution in the profiles but increases fatigue and decreases reading accuracy. Barnett and Clarkson (1955) have reported that measurement error decreased rapidly with

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The analysis of the test data was carried out by W. J. Mansell.
This analysis was supported by funds from the National Science Foundation under grant number DES 74-13931.

decreasing observing frequency, reaching an acceptable level at 20-sec observation interval with no significant improvement for longer intervals. Rachele and Duncan (1967) also report that a better estimate of the average wind in a layer is obtained by several readings within a layer but concluded that for a layer depth comparable to 20-sec reading interval single readings at this rate does just as well as more frequent readings.

In order to minimize the human stress and fatigue while maximizing the vertical and temporal resolution of the wind profiles the following procedures were followed: (1) special additional training and practice were given to already experienced observers; (2) a 20-sec measurement interval was used; (3) the balloon was tracked for only 13 minutes out of each 20-min; and (4) a 30-min break was provided midway during the 3-hr experimental period.

Theodolites are precision mechanical instruments and, although hardy, are not immune to problems. The theodolites were thoroughly checked and adjusted by skilled technicians prior to the field programs. In addition the observers checked their equipment daily and any problems detected were rectified before the next operation. However transport in military trucks is hard on precision equipment and it was not uncommon for misalignment between short- and long-range optics or loosening of the gears to occur. The observers recorded when they shifted from short to long scope and if there was misalignment (evident as a single spike in the processed data) the resultant error was corrected. Errors resulting from slippage of the gear train are frequently detectable and correctable using the Thyer computational method.

A theodolite can lose orientation in the horizontal plane (level) in several ways. For instance, the observer may accidentally jar the tripod or the tripod may settle unevenly, particularly in soft soil. The observers carefully leveled the theodolite at the beginning of the experiment and checked the level periodically during the observational period. Azimuthal orientation in the fixed cartesian coordinate system was accomplished by lining up on the marker at the opposite end of the baseline and on two other marked landmarks off the baseline which had been established when the site was surveyed. The theodolite was azimuthally-oriented at the beginning of the period and checked for azimuth to at least one of the markers once or twice during the experiment.

Although it is believed that the procedures described above helped to reduce errors in the measurements, it is unlikely that they erased them. Consequently special field tests were conducted in the summers of 1972 and 1975 in order to establish the probable errors in the measurements of wind speed, wind direction, height of the balloon, and balloon ascent rate obtained with the double theodolite systems used in the boundary layer program. These tests were made during the forenoon of August 1, 1972 (Test I), late afternoon of August 9, 1972 (Test II) and forenoon of July 31, 1975 (Test III) using the same observers and equipment as were used during the field experiments of those years. The tests were all carried out at Scott Air Force Base, Illinois, about 30 km southeast of St. Louis, Missouri. The local terrain is mostly level farmland with sparse population. The upwind fetch for the test days was fairly flat with some slight roll.

TEST PROCEDURES

The design of the test was very simple. Several teams set up along parallel baselines tracked a common balloon, making synchronized readings to the balloon at 20-sec intervals. In the 1972 tests the mini-network consisted of 8 observers utilized as 4 double theodolite teams (Figure B-1a). All baselines were the same length (about 610 m) and were separated from their nearest neighbors by 7.6 m. The mini-network used during the 1975 test was similar (Figure B-1b). Ten observers were involved, providing 5 double theodolite teams. Baseline separations were 3.1 m and baseline lengths were 656.8 m. In all tests the balloons were released from the center of the perpendicular to the baselines at the downwind end of network. The baselines were aligned approximately NW-SE.

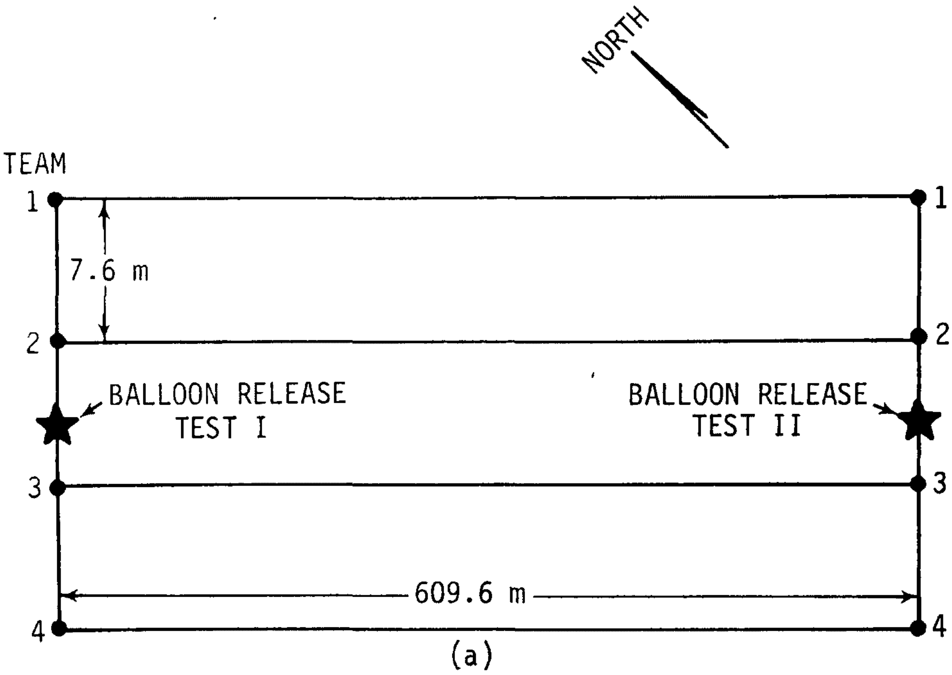
On each test day, 30-gm balloons were released every 20-min during the testing period. On Tests I and II (August 1 and August 9, 1972), 6 releases were made during the testing period, while on Test III (July 31, 1975), 8 releases were made. All teams tracked each balloon. Angular measurements to the balloon were made by each team every 20 seconds using synchronized timers. Angles were read from the theodolite dials to the nearest tenth of a degree with an estimate of the nearest hundreth of a degree and were orally recorded on cassette tape recorders. The timer and recorder systems, the measurement interval and the angular resolutions were all identical with procedures used during the field experiments.

In order to determine the magnitudes of errors introduced when theodolites were improperly leveled or azimuthally-oriented, one theodolite was purposely misoriented by 1° or tilted by 1 bubble during a couple of test runs on each test day. Azimuth orientation errors of one degree are small and may easily occur due to slackness in the theodolite gears. Error in vertical orientation (level) of this magnitude is extreme and is unlikely to occur except in cases of settling on very soft ground or accidental jostling of the tripod.

A total of 88 independent double-theodolite estimates of mean wind profiles were collected, 24 on each of the two test days in 1972, and 40 on the test day in 1975. The basic data were computer processed using the Thyer (1962) technique and carefully edited for errors due to obviously misread angles.

ERROR ANALYSIS

Since there are no standards available against which to check the observations, the "true" wind was assumed to be the average of the independent estimates made by the double theodolite teams. In carrying out the analysis, the square root of the pooled variance taken over all teams and all balloon releases during a given test period was considered the best estimate of the probable error in the estimate of the parameter of interest. Only measurements taken by teams with properly oriented theodolites were used in the calculation of these estimates, i.e., measurements involving deliberately misoriented or tilted theodolites as mentioned in the preceding section were excluded from the analysis.



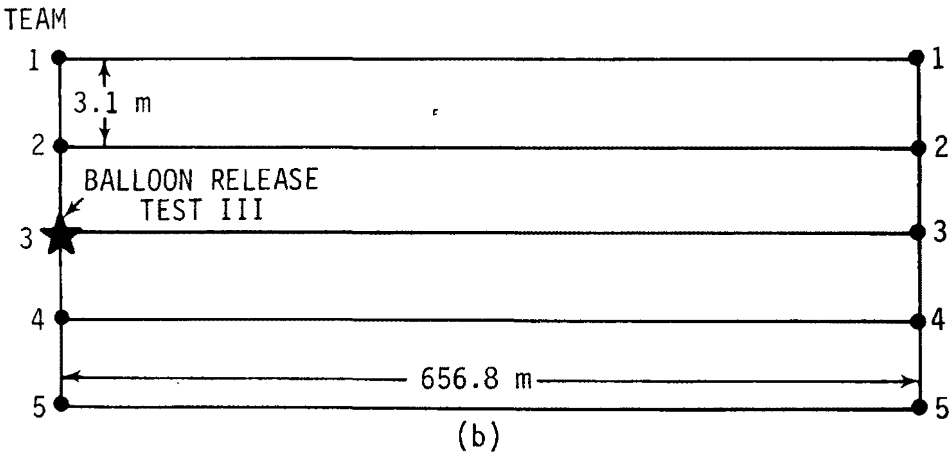


Figure B-1. The "mini-networks" used in tests of the accuracy of the double-theodolite pilot-balloon wind-measuring system in (a) 1972 and (b) 1975. The two men on each team were placed at opposite ends of a baseline as indicated by the heavy dots and matched team numbers.

All three tests were carried out on days of undisturbed weather. The profiles of mean wind direction (relative to baseline coordinates, with 0° looking along baseline from the release end) during the test periods are shown in Figure B-2 for all three tests. Also shown are bars of $\pm$ one standard deviation (1σ) calculated from the averages of the several estimates on each run to indicate the temporal variability.

The profiles of the mean wind speed for the test periods and the 1σ values of temporal variability are shown in Figures B-3. The winds during test period I were southerly 4 to 4.5 mps and fairly constant with height. During the third test, the winds were southeasterly or ESE throughout the lower 1.5 km, but the wind speeds, which were 5 to 6 mps below 500 m, gradually increased with height to about 12 mps at 1.5 km. The winds were lightest during Test II, ranging from 3 to 4 mps in the lowest kilometer. There was a zone of rapidly shifting winds during Test II, with backing from a northeasterly direction below 500 m to NNW at about 1.2 kilometers.

In order to establish estimates of probable errors in wind speed, direction, rise rate and balloon height, the pooled variances (over all releases) for each of these parameters were calculated for every 20-sec layer on each of the three test periods. The square root of the pooled variance for any one variable is taken as the best estimate of the probable error in that variable, and is the quantity discussed below. The discussion is confined to the layer below the level where, due to missing data, less than 50% of the maximum number of available degrees of freedom were used in calculating the statistic.

Error in Wind Direction

The estimated error in wind direction was only 1 or 2 degrees for Tests I and II and 2 or 3 degrees for Test III (Fig. B-4). The error in wind direction tends to be largest in the first 100 m because the short range to the balloon and its rapidly changing position as it responds to the unsteady low level winds make it extremely difficult to keep the balloon on the cross-hairs of the theodolite. The error tends to become larger again above a kilometer or so, a consequence of the fact that position errors for small angular errors are amplified as the range to the balloon increases. Comparison of the error to the temporal variability in the mean wind direction (Fig. B-2) clearly shows that the error is considerably less than the temporal variability, particularly below 1 km.

Error in Wind Speed

The estimated error in the wind speed is shown as a function of height for all three tests in Fig. B-5a. It was smallest during Test II on August 9, 1972, ranging from 0.2 to 0.3 mps in the first 1200 m, increasing with height to 0.8 mps at 1600 m. The average wind speed for this test increased from 3 mps at the surface to about 7.5 mps at 1600 m (Fig. B-3b). Thus the percentage error increased from 3% at 200 m, to 5% at 1 km to 10% at 1600 m.

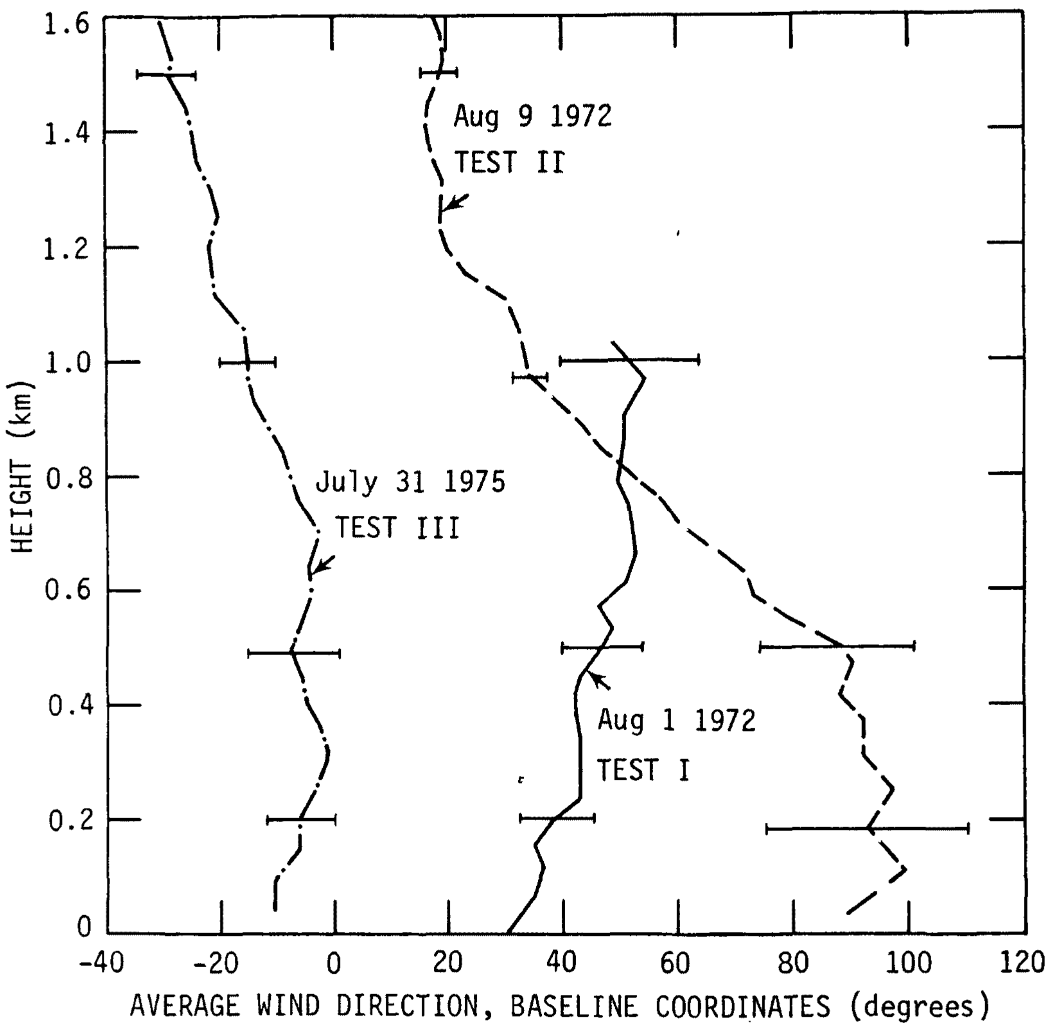


Figure B-2. Mean profiles of wind direction, in baseline coordinates, taken over the test duration for the three tests of the accuracy of the double-theodolite pibal wind-measuring system. The horizontal bars are a measure of the temporal variability (± 1 root-mean square deviation calculated from the average for each balloon launch).

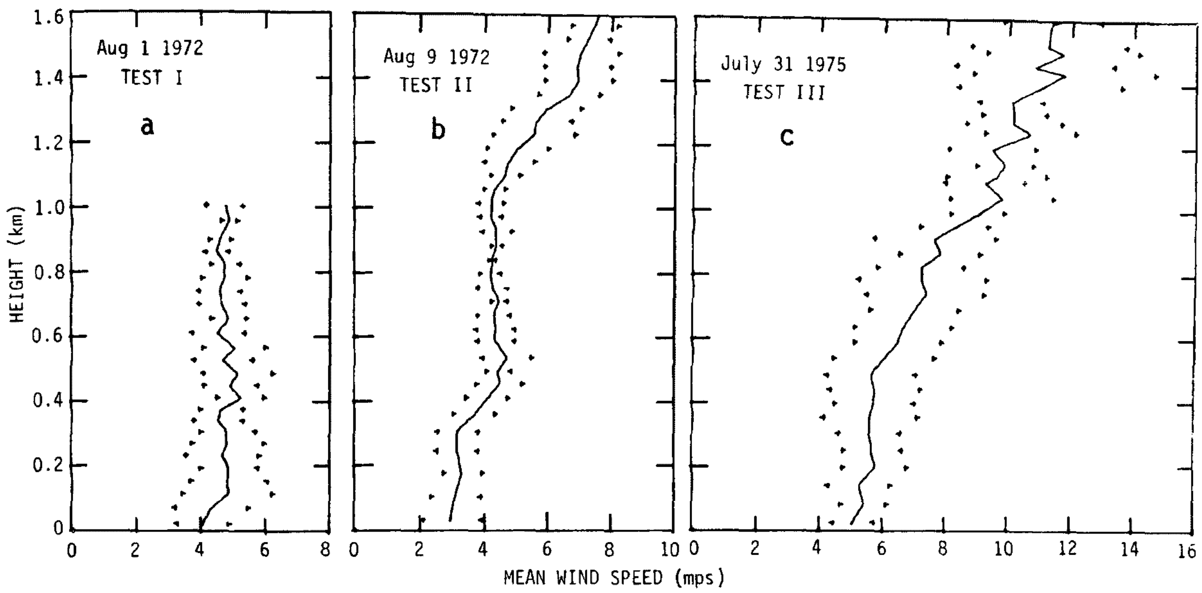


Figure B-3. Mean profiles of wind speed (solid line) for the duration of each of the three double-theodolite accuracy tests. The small +'s give a measure of the temporal variability as indicated by ± 1 RMS deviation calculated from the average profiles for each balloon launch.

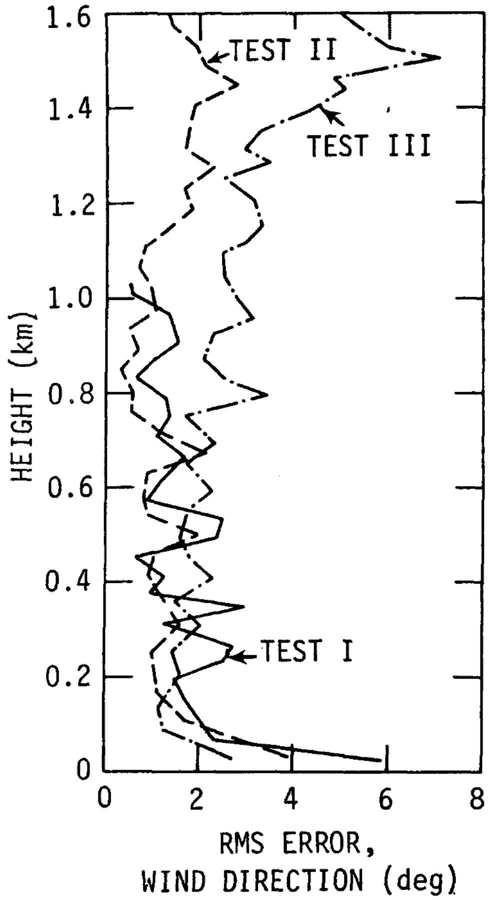


Figure B-4. Profiles of the estimated error in wind direction, for three tests of the accuracy of the double-theodolite wind measurement.

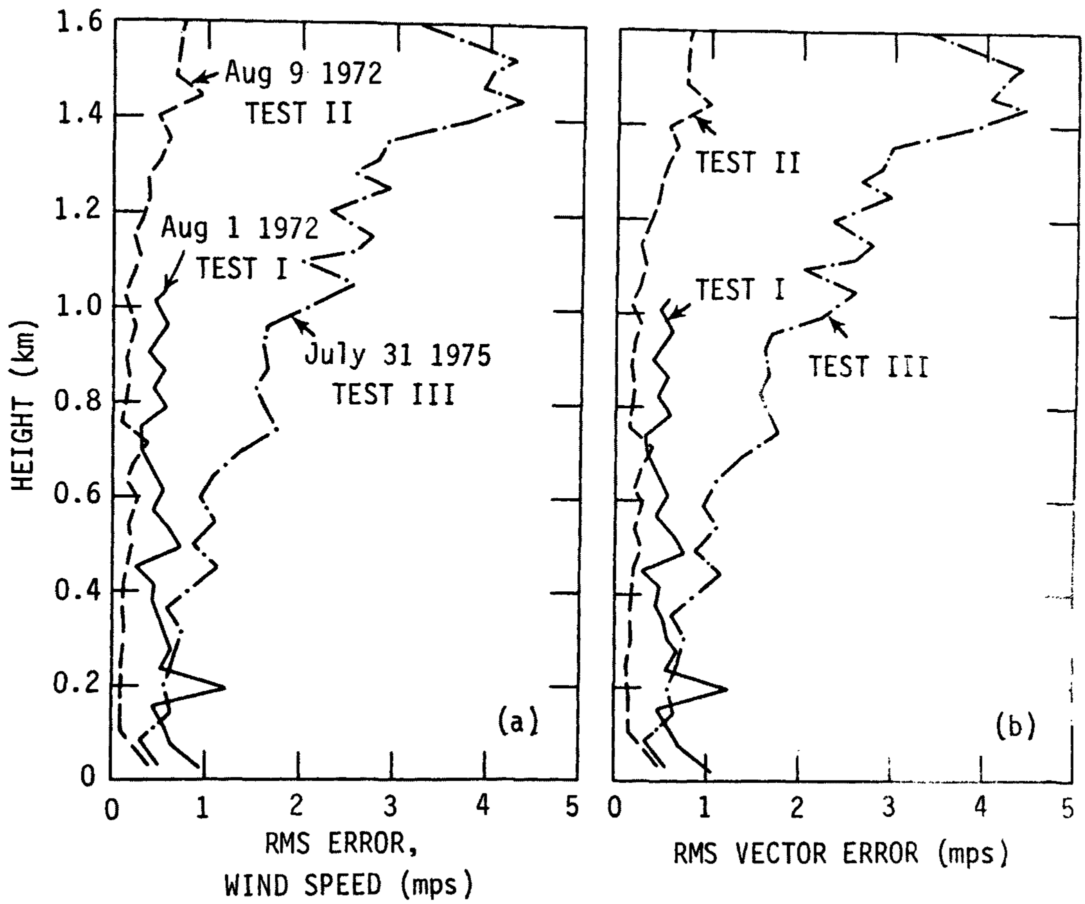


Figure B-5. Profiles of the estimated error in wind speed and of the estimated vector error for three tests of the accuracy of the double-theodolite wind measurement.

During Test I, the estimated error below 1 km was between 0.4 and 0.6 mps, roughly 10% of the average speed during the test. (The spike at 200 m was due to the switch from short to long scope by one team. As mentioned above this is a correctable error but has been left in in this instance to demonstrate the magnitude of the error when the two scopes are badly out of alignment.) The estimated error from Test III is quite a bit larger than that for either of the other two tests ranging from 0.6 mps (12% of the mean wind) at 200 m to 2 mps (20% of the average wind) at 1 km.

It can be seen from Fig. B-3 that the estimated error was much smaller than the temporal variability in the mean wind speed during Test II and was less than half the temporal variability of the mean wind during Test I. During Test III, the estimated error was roughly half the temporal variability below 600 or 700 m but above that level approached the temporal variability.

Vector Error

The root-mean-square vector error is shown in Fig. B-5. Considering the small error indicated for the wind direction, it is not surprising that the profile for the RMS vector error is similar to the error profile for the wind speed. The conclusions to be drawn are the same as that drawn for wind speed, i.e., significantly smaller values for the first two tests than for the third, and increasing vector error above a kilometer, particularly during the third test period.

Error in Calculated Balloon Ascent Rate

The double theodolite computations yield the values of the three components of the balloon velocity, so that no assumptions are made as to constancy of balloon ascent rate. Nevertheless during the field experiments the amount of helium used to inflate the balloon was kept constant, to within the accuracy of the meters used to measure the gas flow. Thus in still air the ascent of the balloon would have always been the same, and errors could have been determined from the difference between calculated and design ascent rates. However, the atmosphere is seldom still and the rate at which the balloon rises is strongly affected by the vertical motions of the air. In Figure B-6 a to c are shown the profiles of computed ascent rate and the temporal variability, as indicated by the RMS deviations of the average profiles for each release. The ascent rate tends to "settle down" at about 800 m (in the mean) to about 2.1 or 2.2 mps, which was the design value, but varied considerably from this in the lower levels.

The profiles of estimated error in the balloon ascent rate is shown in Fig. B-6d. Again the error was smallest for Test II, nearly uniform at 0.1 to 0.2 mps up to 1200 m (representing 5 to 10% of the average rate of rise), and then increasing slightly about 1200 m. The estimated error in the first test period was about twice that of the second, at least up to the 1 km level. The profile of estimated error for ascent rate during Test III exhibited characteristics similar to that for the wind speed. The errors on Test III were comparable to those on the other two tests in the

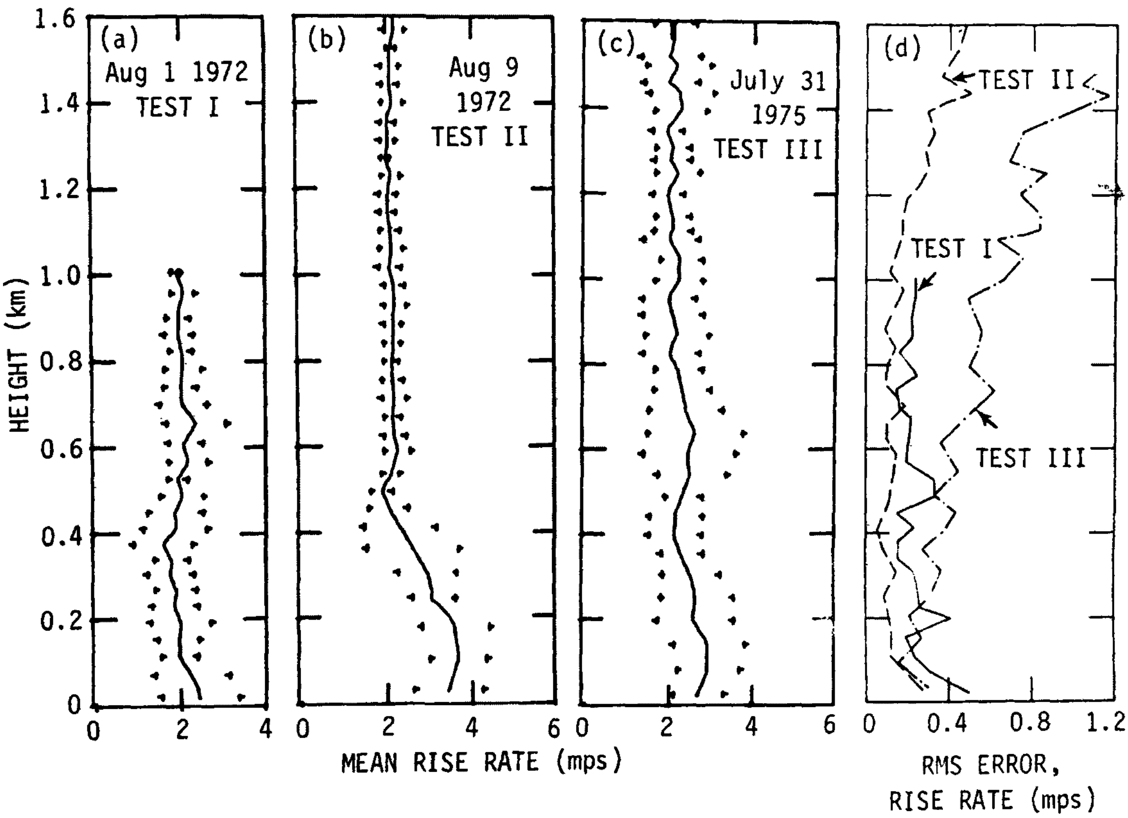


Figure B-6 (a), (b), (c). Mean profiles of balloon ascent rate for the duration of each of the three double-theodolite accuracy tests. Small +'s indicate ± 1 RMS deviation calculated from average profiles of each balloon launch.
(d). Profile of estimated error in balloon ascent rate for the three tests.

lower layers, but increased with height so that by a kilometer they were larger by a factor of three.

Error in Balloon Height

The profiles of the estimated error in the height of the balloon at each 20-second reading are shown in Fig. B-7. It should be pointed out that each height estimate is independent since the calculation uses independent angular measurements and time. The height error increases with height, partly a consequence of increasing position error for a given angular error as the range to the balloon increases.

By and large the errors in height are not significant below 500 m (less than 20 m), only a few per cent of the height. In fact the errors remain insignificant for the first two tests to at least a kilometer. Although the height error estimated on Test III was nearly the same as the estimates on the other days up to 600 m, it increased rapidly above that, reaching 10% of the height at 1200 m.

DISCUSSION

Field tests of the double theodolite systems used in the ISWS boundary layer program have provided estimates of errors that must be taken into account in interpreting the results of the field experiments. These tests indicate that for the lowest 500 or 600 m the probable errors are not excessive and, at least for wind direction, are not significant. Moreover it has been shown that up to 500 or 600 m the error is considerably less than the temporal (non-systematic) variability expected over two or three hours. Although the errors may remain small to a kilometer or more under certain wind conditions, the non-uniformity of the results from the three tests indicate that they can become significant under other conditions.

The differences in the results for the three test periods point up a number of factors that need to be considered in estimating possible error in wind measurements by the double theodolite tracking of balloons. Although the basic systems were the same on the three tests, the components were not identical, i.e., both men and equipment were different on the three days. During Test I there were more than the usual number of problems with one of the theodolites, which, despite realignment at the beginning of each run, would not maintain orientation through the 10 or 12 minute tracking period. This may help to explain why the error was larger on this test than on Test II. However, no unusually-faulty equipment was noted for Test III, which provided larger estimates of error than the other two tests.

A more reasonable explanation of the differences of the results of the three tests appear to lie in the differences in wind speed and in the crossing angle between the balloon track and the baseline. In computational techniques which use only three of the four angles available, the advantage of the double theodolite tracking over single theodolite sighting decreases as the wind direction (and therefore the balloon track angle) approaches the angle of the baseline, and in fact the computations fail when they are parallel.

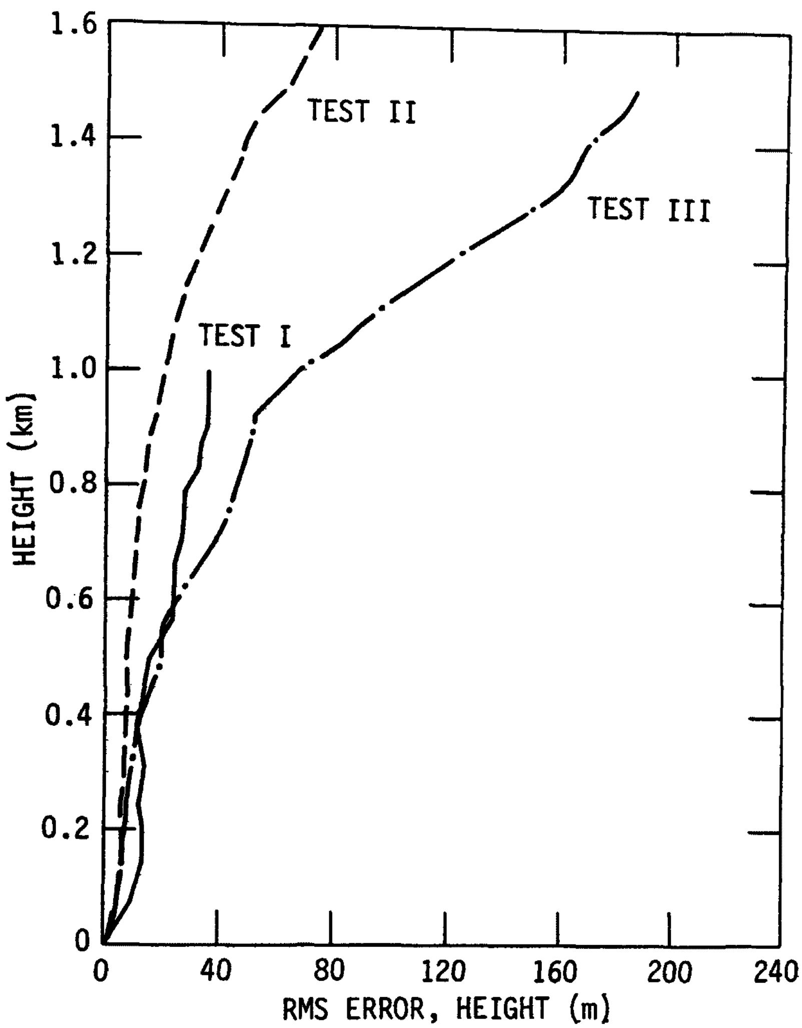


Figure B-7. Profile of the estimated error in the height of the measurement for the three tests of the accuracy of the double-theodolite wind measurement.

Although the computation using Thyer's technique does not fail when the crossing angle of the balloon path and the baseline is zero, it appears that errors tend to be amplified when this angle is small. It can be seen from Fig. B-2 that during Test III when the errors were largest, the wind was almost parallel to the baseline and therefore the balloon track was almost along the baseline. Thus the triangle to be solved was very oblique. On the other hand, during Test II when the errors were smallest, the wind in the lowest 500 m was about 90° to the baseline, and although it backed to a 20° relative angle at 1200 m, by that time the balloon had been carried out about 2 km perpendicular to the baseline so that the triangle to be solved was still very acute. The winds during Test I were about 45° to the baselines, and the indicated error remained fairly small.

Wind speed can affect accuracy in two ways. The stronger the wind, the more difficult it becomes to keep the balloon on the theodolite cross-hairs, both because of its more rapid movement and because in the PBL, strong winds are frequently more turbulent, causing the balloon to bounce around. In addition strong winds cause the range to the balloon to increase rapidly and although it is usually easier to track balloons when they are far away, small errors in angle readings result in large position errors.

In this set of tests, the "crossing" angle and wind speed are coupled in such a way that it is not possible to separate the effects of the factors discussed above, i.e., the lowest wind speed occurred on the day when the crossing angle was largest and strongest wind on the day the crossing angle was smallest. However, a close examination of the data indicates that the error in measurements of wind speed is probably more a function of the low-level wind direction (relative to the baseline) than the wind speed. This may be true also for the error in wind direction, although the increase in the error with height above a kilometer suggests that the range to the balloon may be a factor of some importance here.

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APPENDIX C

SURVEY POLICY REGARDING FURNISHING DATA TO OUTSIDE AGENCIES

In the course of conducting research or investigations the Survey may accumulate valuable, even unique, collections of data. These data may have been collected and processed into useful form either at State expense or in connection with grants or contracts.

It is expected that such data will be used initially and primarily for interpretive studies and publications by the Survey. However, the data may have values for studies of a related or quite unrelated nature by other organizations. Such outside use may produce further understanding of Illinois resources, represent valuable contributions to science, and enhance the scientific reputation of the Survey. However, reasonable care must be exercised that responsible organizations or individuals propose to make proper use of the data. It is also recognized that substantial personnel and machine time may be involved in responding to a data request.

This statement sets forth a policy under which such data may be furnished to other agencies.

1. Decisions regarding furnishing data to outside individuals or agencies shall be made by the Chief of the respective Survey.

2. Data are to be furnished only to responsible scientists and research or user agencies which establish a legitimate need for such data.

3. The requesting agency shall furnish a written description of the desired data and its proposed use.

4. Copies of published or unpublished reports containing results derived from the outside analyses are to be supplied to the Survey without charge.

5. Such requests from agencies of Illinois or agencies who participated in the funding of the data acquisition will be without charge. Requests from other individuals or agencies will be assessed a reasonable charge to cover the cost of making the data available. Such payment is to be deposited with the State of Illinois or with the Survey's Indirect Cost Account as the Chief considers appropriate.

December 8, 1970

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

A field program was carried out in the greater metropolitan area of St. Lous, MO during February and July of 1975 as part of the Regional Air Pollution Study (RAPS). The purpose of the program was to collect atmospheric measurements needed for future studies of the planetary boundary layer (PBL) over urban and industrial areas and surrounding rural areas. The overall goals of the PBL study are to (1) describe the thermodynamic, wind and turbulence fields over the region; (2) determine the magnitude and vertical variation of the vertical fluxes of heat, moisture and momentum as a function of land use; (3) obtain estimates of the exchange coefficients of these variables; and (4) determine the dependence of turbulence intensity on land use. Pilot-balloon stations provided simultaneous measurements of the wind profile with vertical resolution. Tethered-balloon sounding systems yielded thermodynamic and wind profiles. An airplane equipped with meteorological instruments provided measurements of the three components of wind velocity and of high frequency fluctuations in velocity, temperature and humidity.

Observational periods, or missions, were scheduled for 3-or 4-hour durations during field experiments. The objectives included (a) mapping missions to delineate the thermodynamic, wind and turbulent fields over the region, (b) flux missions to provide estimates of the true vertical fluxes of momentum, heat and moisture simultaneously with vertical profiles of these variables,and (c) nocturnal missions to provide information on the strength of the nocturanl heat island circulation.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air pollution	St. Louis, MO	13B
*Meteorological Data		04B
Measurement		20D
Boundary Layer		

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