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Minnesota 1973 Atmospheric Boundary Layer Experiment Data Report

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$2\omega \sin\phi = f = 1.09 \times 10^{-4}\ \text{sec}^{-1}$

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Preface

The primary objective of the Minnesota 1973 Atmospheric Boundary Layer Experiment was twofold: (1) To make measurements of the vertical fluxes of momentum and heat; and (2) to make measurements of profiles of wind velocity and temperature within the planetary boundary layer.

The following list of personnel participated in the field experiment:

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- Duane A. Haugen
- Yutaka Izumi
- J. Chandran Kaimal
- Robert A. Lynch
- MSgt Donald J. MacDonald
- Jim T. Newman
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Meteorological Research Unit, British Meteorological Office
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Preface

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1. INTRODUCTION

In late summer of 1973, the Boundary Layer Branch of the Meteorology Laboratory, Air Force Cambridge Research Laboratories (AFCRL), and the Meteorological Research Unit (MRU) of the British Meteorological Office, Royal Air Force, Cardington, England, conducted a joint field experiment for a study of the turbulent structure of the earth's planetary boundary layer in northwestern Minnesota. Measurements of vertical profiles of wind velocity and temperature and of vertical transport of momentum and heat from a 32-m tower were made by AFCRL. Simultaneous measurements of these parameters at five levels from 60 to 1220 m with probes attached to the tethering cable of a large kite balloon were made by MRU. The Aerospace Instrumentation Laboratory, AFCRL, operated and maintained the kite balloon used in the experiments. The 6th Weather Squadron, Air Weather Service, provided rawinsonde data at the site during each experimental period.

This joint effort in a full-scale planetary boundary layer experiment in Minnesota was preceded by two experiments to establish the compatibility of the AFCRL and MRU sensing techniques. The first comparison test was made in 1969 at Hanscom Air Force Base, Massachusetts, with the two probes mounted side by side on a 16-m tower. Despite the differences in sensor design and frequency response, the results show good agreement in the means, variances, and covariances

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involving the velocity components and temperature.[1] The second test was conducted in 1971 at Eglin Air Force Base, Florida, for a study of the effects of balloon and cable movements on the sensors. The AFCRL probes were mounted at heights of 150 and 305 m on a 370-m tower and the MRU probes were flown at similar heights on the tethering cable of a kite balloon. The results indicate overestimation of the horizontal wind speed by the MRU probes, but the errors in the measurements of momentum and heat fluxes were negligible.[2]

2. EXPERIMENTAL SITE

The site of the experiment was at the middle of the southern edge of an extremely flat, square-mile section of farm land in northwestern Minnesota. The section is located about 3 km east of the town of Donaldson on State Highway 11. The coordinates are 48° 34' N latitude and 96° 51' W longitude; the elevation is approximately 255 m above mean sea level.

An aerial photograph of the field site and cultivated fields to the north (Figure 1) shows the 32-m tower, trailers, granaries, balloon launch pad to the east-southeast

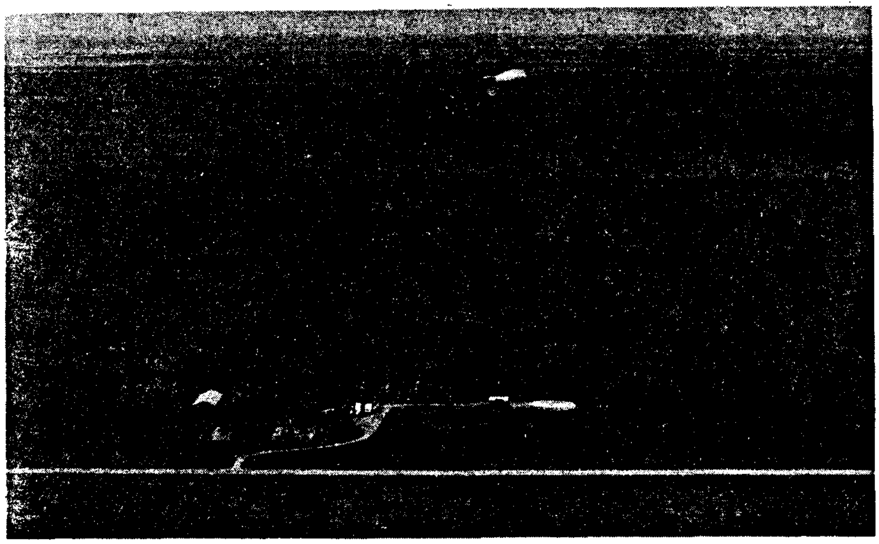

Figure 1. Aerial View of the Field Site

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[1] Readings, C.J. and Butler, H.E. (1972) The measurement of atmospheric turbulence from a captive balloon, Meteorol. Mag. 101:286-298.

[2] Haugen, D.A., Kaimal, J.C., Readings, C.J. and Rayment, R. (1975) A comparison of balloon-borne and tower-mounted instrumentation for probing the atmospheric boundary layer, J. Appl. Meteorol. 14:540-545.

of the tower, and the moored balloon. It also shows the flat, featureless terrain that has no prominent obstacles for about 10 km to the north. The dark gray to black soil in this region, when saturated, becomes a very heavy, sticky mud. Only one-sixth of the section on the western side was planted with wheat that year. The crop was harvested before the experiments began, and that portion of the section left with wheat stubble. The barren five-sixths of the section that remained was harrowed before the experimental activities started. In addition, a strip of land, 100 m wide immediately north of the tower and running east to west, was dragged for further pulverizing and smoothing of the surface. This was to facilitate the installation of two drag plates used in an attempt to obtain direct measurements of the surface stress.

3. INSTRUMENTATION

Mean wind speeds and directions were measured with two-axis sonic anemometers, EG&G Model 198-2, shown in Figures 2 and 3. The sensors were mounted at the heights of 1, 2, 4, 8, 16 and 32 m on the north side of the tower. Mean temperatures were measured with Hewlett-Packard quartz thermometers. Figure 3 shows the aspirated radiation shield, R. M. Young Company Model 43404, which housed the temperature element. The sensors were mounted at the levels of 0.5, 1, 2, 4, 8, 16, 24 and 32 m on the northeast corner of the tower. The two-axis sonics and the quartz thermometers were each sampled once per second.

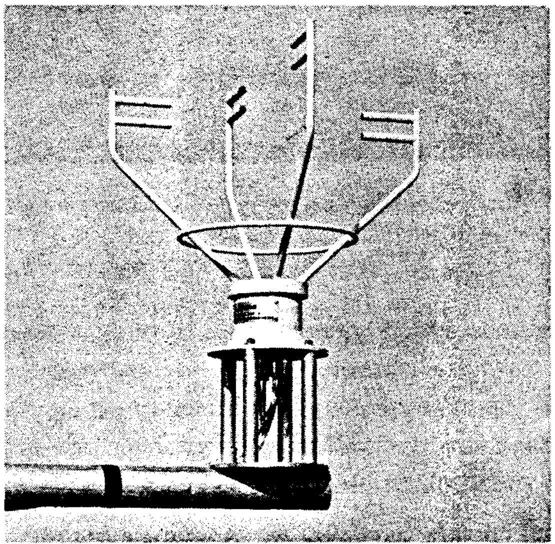

Figure 2. Two-axis Anemometer

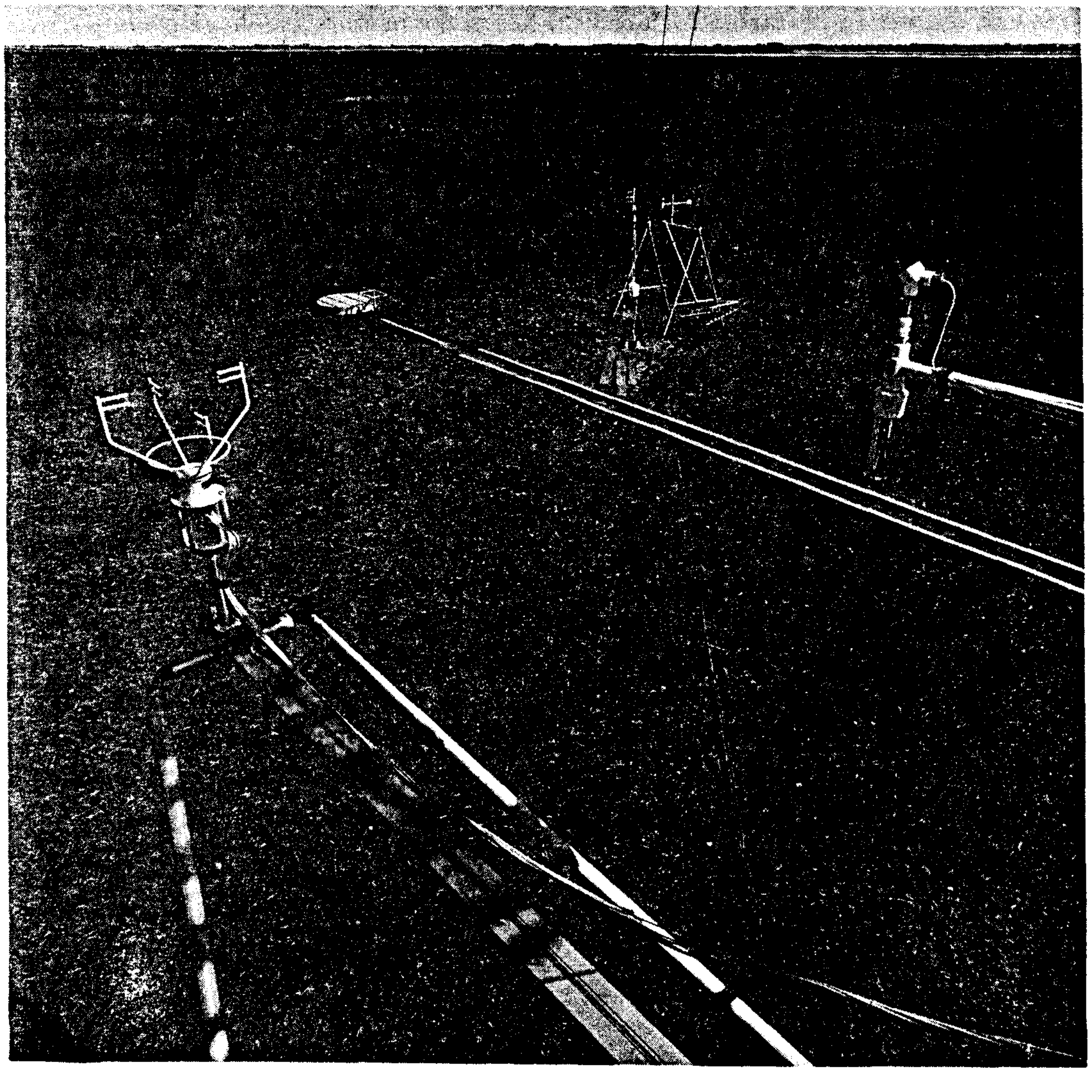

Figure 3. View from Tower Showing Tower-mounted Sensors, 4-m Mast and Drag Plate

Three-axis sonic anemometers (Figure 4) were used to measure fluctuating wind components.[3] A 25-μ diam platinum-wire resistance thermometer, EG&G Model 157, mounted on the rear frame of the three-axis sonic anemometer as shown in Figure 4, was used to measure fluctuating temperatures. These probes were mounted at the levels of 4 and 32 m on either the east or west side of the tower,

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[3] Kaimal, J.C., Newman, J.T., Bisberg, A., and Cole, K. (1974) An improved three-component sonic anemometer for investigation of atmospheric turbulence, Flow – Its Measurement and Control in Science and Industry, Vol. 1, Instr. Soc. Am., 349-359.

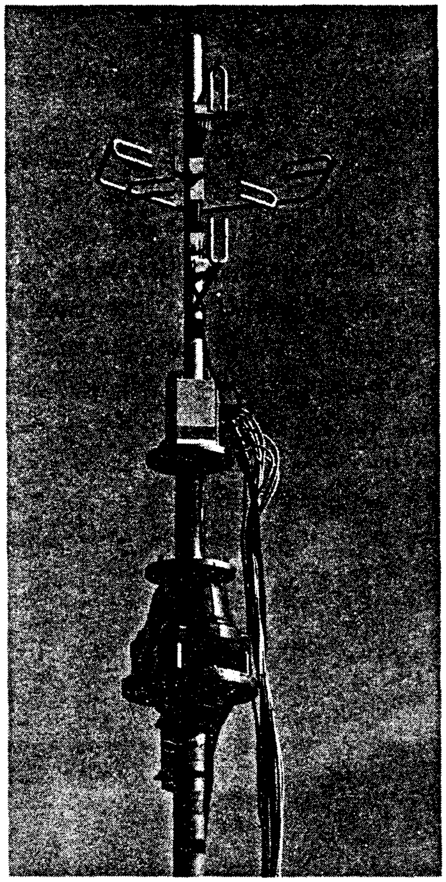

Figure 4. Three-axis Sonic Anemometer with Platinum-wire Resistance Thermometer

depending on the prevailing wind, for the experimental period. A third set of probes was mounted at 4 m on top of a mast located 40 m northeast of the tower, as shown in Figure 3. Before each observational run, the three-axis sonic probes were oriented into the mean wind by means of television antenna rotors controlled remotely from an instrumentation van. Reorientation was accomplished every 2.5 hours, as required. These fast-response sensors were each sampled 10 times a second.

4. DESCRIPTION OF THE MRU PROBE

The MRU turbulence probe consists basically of a set of sensors mounted on a vane (see Figure 5). This is attached to the tethering cable of a balloon so that it is free to rotate and hence can act to keep the sensors facing into wind. The temperature sensor consists of 180 cm of 26-μ diam platinum wire wound noninductively on a plastic former. A double V-shaped hot wire inclinometer mounted on a damped pendulum measures the inclination of the wind to the horizon while a second inclinometer, orientated at 90° to the first, measures the instantaneous horizontal wind direction relative to the vane direction. A magnetic flux value is used to obtain the vane direction relative to the earth's magnetic field. Wind speed is measured with a multislot photoelectric anemometer fitted with an eight-cup polystyrene rotor. Five probes were mounted on the tethering cable of a 1330-m^3 kite balloon (Lea Bridge Industries, England) at altitudes ranging from 61 to 1220 m. Four of the probes relayed information to the ground by radio telemetry and one by cable. Signals from the balloon-borne probes were each sampled at the rate of 10 times per second.

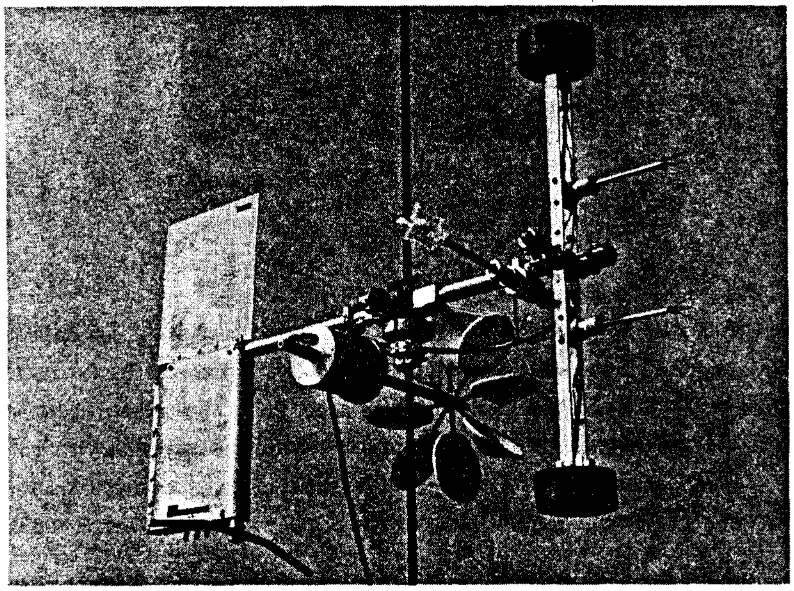

Figure 5. MRU Turbulence Probe

The outputs from all the instruments were sampled, digitized, and recorded on magnetic tape by the computer-controlled data acquisition system described by Kaimal et al.[4]

To supplement the tower and balloon observations, slow-ascent rawinsonde flights were made every two hours during the day and early evening and every three to four hours during the night. Pressure, temperature, humidity and wind velocity data were obtained to heights of about 3000 m.

5. EXPERIMENTAL PROCEDURES

Observational periods were begun only when the synoptic scale weather patterns indicated a prolonged period of winds with a northerly component. Before each observational period, ground comparison of the MRU probes was made with the three-axis sonic anemometer on the 4-m mast. These comparison runs were made to obtain relative calibration data for all the MRU sensors. Roughly three hours were required to complete the comparison observations.

The MRU probes were then prepared for flight and attached to the balloon cable in either a closely-spaced or a widely-spaced array. Observations were started after the balloon was positioned at the required altitude. The probe spacing and the balloon altitude decisions were based on the on-site rawinsonde observations and the expected synoptic conditions. It was necessary to retrieve the MRU sensors after approximately 10 hours of flight time in order to replace the batteries used with each probe. This operation takes approximately one hour, provided that no major problems develop. In addition, short breaks of about 10 min were introduced every 2.5 hours to check the orientation of the three-axis sonic anemometers and to mount a new magnetic tape for data recording. Normal practice was to have four 2.5-hour segments of data gathering per each flight time of the MRU sensors.

The height of the five balloon-borne instruments was measured once for each observational period by a double theodolite system. In addition, motion of the tethering cable was monitored by tracking a rawinsonde suspended 3 m above the top probe by the rawinsonde direction-finding receiving system. This information was obtained for two 10-min periods, one hour apart, at the beginning of an observational period.

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4. Kaimal, J.C., Haugen, D.A., and Newman, J.T. (1966) A computer-controlled mobile micrometeorological observation system, J. Appl. Meteorol. **5**:411-420.

6. DATA SET

The objective of these experiments was to obtain as much information as possible on the structure of convective, stable, and neutral boundary layers. Plans were to take measurements for 24 to 48 hours with interruptions only to change batteries for the balloon-borne probes and to reorient the sonics. In actual fact, nearly all the observations were made during the period from early or midafternoon to near midnight. All but one evening transition period exhibited rapid decrease in wind speed and intensity of turbulence in the surface layer followed by nighttime periods with nearly calm surface layer winds and virtually no turbulence throughout the levels of observation. This sequence of events was accompanied each time by the movement of the center of a high pressure system over the site followed by southerly winds the next morning as the pressure system moved on. As a result, extended observation periods were not realized. Indeed, only the data obtained during unstable periods appear reliable for detailed analyses. The criteria used to select the data were that the surface heat flux be positive and that the depth of the planetary boundary layer, as estimated from the rawinsonde data, remain fairly constant with time. For a detailed analysis of turbulent flow processes based on these data, see Kaimal et al.[5]

7. DESCRIPTION OF DATA

One of the first problems encountered in reducing boundary layer turbulence data is the selection of suitable filter techniques to remove long-term trends. Another is the selection of an averaging period that will provide statistically stable estimates of the various turbulence parameters. We have experimented with a number of different filter techniques, including linear detrending, moving averages, and recursive digital filtering. We eventually chose a recursive digital filter which consistently preserves fluctuations with frequencies greater than 0.001 Hz; that is, fluctuations with periods longer than roughly 16 min are severely damped. We then divided the 2.5-hour periods into two periods to obtain 75-min averages of the filtered data.

The computational steps are outlined as follows:

(1) Define a vector-mean horizontal wind for a 2.5-hour period such that the mean crosswind component is identically zero.

(2) Define a Cartesian coordinate system for the layer based on the 4-m mean wind vector.

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[5] Kaimal, J.C., Wyngaard, J.C., Haugen, D.A., Cote, O.R., Izumi, Y., Caughey, J.S., and Readings, C.J., Turbulence Structure in the Convective Boundary Layer, to be published.

(3) Obtain the 2.5-hour scalar mean for the vertical wind component and the air temperature.

(4) Compute, from these means, the fluctuating or deviation quantities u, v, w, T, respectfully, as the longitudinal, transverse, and vertical turbulent wind components and the fluctuation temperature.

(5) Apply the recursive digital filter to these time series of fluctuation quantities. Compute the variances and covariances and the derived similarity parameters based on these moments over a 75-min averaging period.

This computational procedure was not followed for the mean profile data; namely, mean wind speed and direction and temperature versus height (see Table 2). The mean wind speed and direction were obtained from the five successive 15-min averages of the horizontal vector-mean winds to obtain the 75-min average values tabulated. Each 15-min vector mean was independently defined so that the 15-min mean cross-wind component was zero. The mean temperature is simply a 75-min average of the temperature data. Thus, although there is some slight filtering of the wind data by the above computational technique, the mean profile data presented include the effects of any long-term trends that may have existed during the observational periods.

There are eleven 75-min runs summarized in Tables 1 through 5. The units are given as follows: in meters for height z; in centimeters per second for wind components u, v, w, and windspeed U; in degrees azimuth from the true north for wind direction; and in degrees Celsius (°C) for temperature.

The eleven 75-min runs are identified in Table 1 by run number, start-end time of the 75-min period, and date. The height of the highest MRU probe is given as

Table 1. Run Summary

Run	Time (CDT)	Date (1973)	z_{max} (m)	u_* (cm sec^{-1})	Q_o (^oC cm sec^{-1})	T_* (^oC)	L (cm)	z_i (m)	$\frac{z_i}{L}$	w_* (cm sec^{-1})	θ_* (^oC)	$\frac{u_*}{fz_i}$
2A1	1217-1332	10 Sept	1219	45	19.58	-.43	-4166	1250	-30	200	.10	3.32
2A2	1332-1447	10 Sept	1219	45	20.94	-.46	-3804	1615	-42	223	.09	2.55
3A1	1510-1625	11 Sept	610	37	18.60	-.50	-2395	2310	-96	241	.08	1.47
3A2	1625-1740	11 Sept	610	32	11.62	-.36	-2430	2300	-95	206	.06	1.27
5A1	1622-1737	15 Sept	610	18	6.88	-.39	-711	1085	-153	135	.05	1.50
6A1	1401-1516	17 Sept	1219	24	20.97	-.88	-572	2095	-366	243	.09	1.04
6A2	1516-1631	17 Sept	1219	23	16.16	-.71	-643	2035	-316	221	.07	1.03
6B1	1652-1807	17 Sept	1219	26	7.16	-.27	-2270	2360	-104	177	.04	1.03
7C1	1415-1530	19 Sept	610	28	22.10	-.79	-878	1020	-116	195	.11	2.52
7C2	1530-1645	19 Sept	610	30	18.12	-.60	-1311	1140	-87	189	.10	2.41
7D1	1650-1805	19 Sept	610	25	9.89	-.40	-1352	1225	-91	158	.06	1.85

$0.1\,\bar{z}_i = 167.59\text{ m} \pm 54.95$

$\bar{z}_i = 1675.91\text{ m} \pm 549.47$

$-\bar{L} = 18.66\text{ m} \pm 12.59$

z_{max}. The remainder of the table contains various derived parameters pertinent to surface or planetary boundary layer similarity theories.

The friction velocity u_* is defined by

$$u_* = (-\overline{u\,w})_o^{1/2} \qquad \text{cm sec}^{-1} \tag{1}$$

where u and w are the fluctuating longitudinal and vertical wind components, respectively, and the subscript o denotes the value at the surface.

The surface heat flux Q_o is defined by

$$Q_o = (\overline{wT})_o \qquad {}^oC \text{ cm sec}^{-1} \tag{2}$$

where T is the fluctuating temperature. The friction velocity and the heat flux, obtained by averaging the 75-min filtered values of $\overline{uw}$ and $\overline{wT}$ at the 4-m levels on the tower and the mast, may be interpreted as the surface values of these parameters.

The scaling temperature T_* and the Obukhov length L are defined by

$$T_* = -Q_o/u_* \qquad {}^oC \tag{3}$$

$$L = -(u_*^3 T)/(kg\,Q_o) \qquad \text{cm} \tag{4}$$

where g is the acceleration of gravity, and k is von Karman's constant, equal to 0.35.

The height of the planetary boundary layer is given by z_i (in meters); it was estimated from the rawinsonde data as the height where the first temperature inversion was observed.

The ratio z_i/L is a nondimensional stability parameter, a measure of the convection intensity within the planetary boundary layer. Thus, we note for example that the convective turbulence and thermal driving forces are presumably much more dominant in Runs 6A1 and 6A2 than 2A1 and 2A2.

The vertical velocity scale w_* is defined by

$$w_* = \left[\frac{g}{T} Q_o z_i\right]^{1/3} \qquad \text{cm sec}^{-1} \tag{5}$$

and the temperature scale θ_* by

$$\theta_* = \left[\frac{Q_o^2}{\frac{g}{T}\, z_i}\right]^{1/3} \quad {}^{o}C \tag{6}$$

The ratio u_*/fz_i, where f is the Coriolis parameter, is a nondimensional parameter relating two commonly used planetary boundary layer scaling lengths, u_*/f and z_i.

Mean wind speed, wind direction, and temperature profile data are given in Table 2. The standard deviations of the three turbulent wind components and the temperature are given in Table 3. The values for the standard deviation of v, the cross-wind component, are probably too high by 10 to 20 percent due to lateral balloon movement.[2] The momentum fluxes, $\overline{uw}$ and $\overline{vw}$, are listed in Table 4; the vertical heat flux, $\overline{wT}$, and the horizontal heat flux, $\overline{uT}$, in Table 5.

Table 2. Profiles of Temperature, Wind Speed, and Wind Direction

	Run 2A1 1217-1332 (CDT) 10 Sept 1973			Run 2A2 1332-1447 (CDT) 10 Sept 1973			
z (m)	$\overline{T}$ (^oC)	$\overline{U}$ (cm sec^{-1})	$\overline{Az}$ (deg)	$\overline{T}$ (^oC)	$\overline{U}$ (cm sec^{-1})	$\overline{Az}$ (deg)	z (m)
1219	8.99	1214	331	9.61	1191	338	1219
914	11.66	1173	332	12.34	1180	329	914
610	14.43	1172	321	15.16	1177	318	610
305	17.16	1171	317	17.86	1170	314	305
61	19.54	1144	315	20.25	1142	313	61
32	20.03	1103	315	20.78	1125	312	32
16	20.34	1049	315	21.09	1070	312	16
8	20.72	994	314	21.49	1015	311	8
4	21.21	935	314	21.96	957	311	4
2	21.75	849	312	22.46	871	310	2
1	22.30	771	311	23.04	793	308	1
0.5	22.93			23.65			0.5

Table 2. Profiles of Temperature, Wind Speed, and Wind Direction (Continued)

	Run 3A1 1510-1625 (CDT) 11 Sept 1973			Run 3A2 1625-1740 (CDT) 11 Sept 1973			Run 5A1 1622-1737 (CDT) 15 Sept 1973			
z (m)	$\overline{T}$ (^{o}C)	$\overline{U}$ (cm sec^{-1})	$\overline{Az}$ (deg)	$\overline{T}$ (^{o}C)	$\overline{U}$ (cm sec^{-1})	$\overline{Az}$ (deg)	$\overline{T}$ (^{o}C)	$\overline{U}$ (cm sec^{-1})	$\overline{Az}$ (deg)	z (m)
610	14.56	999	328	14.65	908	332	3.93	568	007	610
457	16.02	977	332	16.13	891	335	5.33	543	015	457
305	17.55	957	330	17.68	873	333	6.86	521	021	305
152	19.12	942	330	19.22	863	332	8.38	488	025	152
61	20.10	906	328	20.21	823	332	9.27	463	031	61
32	20.60	878	330	20.67	808	332	9.61	444	033	32
16	20.97	833	332	21.01	760	334	9.87	427	033	16
8	21.33	790	331	21.30	720	332	10.07	404	033	8
4	21.75	739	331	21.63	677	332	10.34	380	033	4
2	22.21	681	330	21.94	624	331	10.53	354	035	2
1	22.76	610	329	22.36	560	330	10.80	319	036	1
0.5	23.42			22.88			11.21			0.5

Table 2. Profiles of Temperature, Wind Speed, and Wind Direction (Continued)

	Run 6A1 1401-1516 (CDT) 17 Sept 1973			Run 6A2 1516-1631 (CDT) 17 Sept 1973			Run 6B1 1652-1807 (CDT) 17 Sept 1973			
z (m)	$\overline{T}$ (^{o}C)	$\overline{U}$ (cm sec^{-1})	$\overline{Az}$ (deg)	$\overline{T}$ (^{o}C)	$\overline{U}$ (cm sec^{-1})	$\overline{Az}$ (deg)	$\overline{T}$ (^{o}C)	$\overline{U}$ (cm sec^{-1})	$\overline{Az}$ (deg)	z (m)
1219	4.72	744	296	5.24	762	297	5.81	771	302	1219
914	7.75	754	293	8.28	782	292	8.86	792	298	914
610	10.89	755	290	11.42	777	290	11.98	793	297	610
305	14.02	725	296	14.50	733	296	15.02	742	299	305
152	15.54	719	297	16.01	706	297	16.49	734	301	152
32	16.78	667	295	17.21	652	295	17.53	673	301	32
16	17.08	643	294	17.52	628	294	17.80	643	300	16
8	17.37	610	293	17.72	596	293	17.98	610	299	8
4	17.83	584	293	18.11	569	293	18.29	580	299	4
2	18.31	536	290	18.54	519	291	18.52	524	297	2
1	18.88	490	288	19.09	473	288	18.85	473	295	1
0.5	19.63			19.77			19.26			0.5

Table 2. Profiles of Temperature, Wind Speed, and Wind Direction (Continued)

	Run 7C1 1415-1530 (CDT) 19 Sept 1973			Run 7C2 1530-1645 (CDT) 19 Sept 1973			Run 7D1 1650-1805 (CDT) 19 Sept 1973			
z (m)	$\overline{T}$ (^oC)	$\overline{U}$ (cm sec^{-1})	$\overline{Az}$ (deg)	$\overline{T}$ (^oC)	$\overline{U}$ (cm sec^{-1})	$\overline{Az}$ (deg)	$\overline{T}$ (^oC)	$\overline{U}$ (cm sec^{-1})	$\overline{Az}$ (deg)	z (m)
610	2.34	672	004	2.99	697	003	3.70	624	008	610
457	4.05	680	006	4.70	702	008	5.04	626	008	457
305	5.71	685	006	6.34	698	007	6.72	620	004	305
152	7.32	680	360	7.94	684	004	8.23	605	004	152
61	8.24	668	360	8.91	659	003	9.15	583	004	61
32	8.71	640	360	9.37	627	005	9.56	557	005	32
16	9.10	608	360	9.74	588	005	9.86	529	004	16
8	9.44	579	359	10.04	558	004	10.10	499	003	8
4	9.95	542	360	10.44	523	005	10.45	467	004	4
2	10.37	500	360	10.84	482	005	10.66	432	004	2
1	10.92	454	001	11.36	439	005	10.99	396	005	1
0.5	11.69			12.11			11.51			0.5

Table 3. Velocity Component and Temperature Standard Deviation Profiles

						Standard Deviation										
z (m)	Run 2A1	u	v (cm sec^{-1})	w	T (°C)	Run 2A2	u	v (cm sec^{-1})	w	T (°C)	Run	u	v (cm sec^{-1})	w	T (°C)
1219		122	166	122	.22		143	188	110	.19					
914		120	139	124	.17		139	192	129	.15					
610		119	160	106	.15		150	213	125	.14					
305		114	143	93	.18		140	166	103	.20					
61		180	217	82	.41		194	228	84	.39					
32		132	139	85	.48		123	132	86	.48					
4		141	143	59	.85		130	142	60	.87					
	3A1					3A2					5A1				
610		142	229	140	.11		127	184	124	.10		74	108	67	.06
457		147	208	144	.12		127	165	112	.10		75	83	67	.06
305		161	190	127	.13		142	148	99	.11		78	90	71	.07
152		177	222	122	.23		133	178	100	.17		71	81	73	.11
61		172	161	93	.35		116	120	77	.26		73	81	68	.16
32		152	150	84	.47		116	120	74	.36		69	75	56	.20
4		143	149	54	.84		116	123	49	.60		74	75	32	.44

Table 3. Velocity Component and Temperature Standard Deviation Profiles (Continued)

	Standard Deviation														
z	Run	u	v	w	T	Run	u	v	w	T	Run	u	v	w	T
(m)	6A1		(cm sec^{-1})		(°C)	6A2		(cm sec^{-1})		(°C)	6B1		(cm sec^{-1})		(°C)
1219		152	167	157	.15		123	176	151	.13		104	126	112	.16
914		138	130	163	.14		133	137	156	.14		95	106	114	.15
610		133	158	145	.15		111	157	125	.14		106	117	103	.13
305		144	134	123	.19		130	128	116	.18		106	111	101	.14
152		157	166	121	.25		142	152	113	.22		113	132	91	.16
32		142	135	80	.48		124	131	77	.40		103	109	62	.23
4		143	139	47	.96		130	137	43	.81		99	107	39	.46
	7C1					7C2					7D1				
610		98	101	134	.11		89	103	121	.10		81	59	122	.09
457		109	92	133	.12		92	94	129	.12		90	93	131	.10
305		118	93	117	.15		92	83	113	.14		86	88	110	.11
152		124	101	115	.26		105	102	123	.25		91	97	125	.16
61		133	110	98	.35		118	107	95	.37		100	101	73	.21
32		133	119	82	.51		113	122	77	.47		105	114	65	.33
4		136	126	49	1.05		122	123	48	.89		101	116	40	.58

$\overline{\sigma_w}$ (11m) ~ 6.1 m/sec

$\bar{u}$ (11m) ~ 6.9 m/sec

σ_q ~

Table 4. Momentum Flux Profiles
(cm^2 sec^{-2})

	z (m)	Run 2A1	Run 2A2	z (m)	Run 3A1	Run 3A2	z (m)	Run 5A1
$\overline{uw}$	1219	-2769	-3457	610	-1902	-1683	610	-137
	914	-4157	-6160	457	-3286	-3160	457	-622
	610	-3168	-6901	305	-4592	-3238	305	-262
	305	-3828	-6438	152	-2500	-909	152	-673
	61	-4687	-5780	61	-3105	-1121	61	-731
	32	-2074	-1819	32	-1418	-1622	32	-267
	4	-2057	-2024	4	-1374	-1014	4	-315
$\overline{vw}$	1219	6216	6949	610	8033	5271	610	-860
	914	5734	9998	457	9620	4772	457	-1034
	610	7603	12847	305	9321	5497	305	-833
	305	3898	4693	152	9333	6414	152	-1031
	61	2639	2908	61	3670	2061	61	-73
	32	496	383	32	120	292	32	-267
	4	527	367	4	20	135	4	208

Table 4. Momentum Flux Profiles (Continued)
(cm^2 sec^{-2})

	z (m)	Run 6A1	Run 6A2	Run 6B1	z (m)	Run 7C1	Run 7C2	Run 7D1
$\overline{uw}$	1219	-3199	-1314	-1229	610	-2763	546	-1670
	914	-5594	-4218	-1205	457	-4422	-2076	-2051
	610	-6244	-3063	-2095	305	-3405	-2046	-1311
	305	-6921	-4307	-4138	152	-3150	-3025	-994
	152	-4347	-3396	-3049	61	-1162	-1987	-374
	32	-1332	-1076	-1117	32	-1151	-1210	-416
	4	-573	-521	-702	4	-790	-904	-616
$\overline{vw}$	1219	8398	5756	1458	610	6326	2946	348
	914	4116	3112	933	457	2087	-138	-780
	610	7943	6230	2434	305	4684	1859	2631
	305	1758	1912	376	152	2055	561	-25
	152	3138	2794	1776	61	2616	979	926
	32	-145	-634	258	32	-166	-392	-295
	4	83	29	-14	4	82	-42	62

Table 5. Heat Flux Profiles
(°C cm sec^{-1})

	z (m)	Run 2A1	Run 2A2	z (m)	Run 3A1	Run 3A2	z (m)	Run 5A1
$\overline{wT}$	1219	-1.97	-2.79	610	3.02	3.44	610	.03
	914	4.31	1.73	457	5.51	3.40	457	.30
	610	3.70	6.62	305	5.17	4.39	305	1.42
	305	8.89	11.83	152	13.75	8.58	152	4.64
	61	17.94	18.06	61	17.49	10.88	61	6.51
	32	19.19	19.45	32	17.97	11.33	32	6.77
	4	19.58	20.94	4	18.60	11.62	4	6.88
$\overline{uT}$	1219	4.66	4.76	610	-.34	.72	610	.91
	914	2.94	.64	457	.61	-.45	457	.60
	610	1.08	-4.75	305	-2.30	-3.28	305	.79
	305	-5.57	-9.37	152	-4.87	-3.23	152	-.17
	61	-23.27	-23.28	61	-12.22	-4.62	61	-.69
	32	-16.50	-15.19	32	-1.24	-5.77	32	-.68
	4	-46.44	-47.60	4	-27.28	-22.19	4	-3.54

Table 5. Heat Flux Profiles (Continued)
(^{o}C cm sec^{-1})

	z (m)	Run 6A1	Run 6A2	Run 6B1	z (m)	Run 7C1	Run 7C2	Run 7D1
$\overline{wT}$	1219	-2.14	-.97	-4.80	610	6.22	5.66	5.33
	914	-2.50	1.13	-3.08	457	7.50	7.66	7.05
	610	1.10	3.25	.30	305	8.55	8.61	6.42
	305	10.79	9.31	5.20	152	16.62	16.70	8.10
	152	16.05	11.63	6.41	61	19.71	23.09	8.62
	32	20.54	14.83	6.98	32	21.42	20.48	9.72
	4	20.97	16.16	7.16	4	22.10	18.12	9.89
$\overline{uT}$	1219	-2.31	-3.23	-.76	610	-1.82	.38	.83
	914	.77	-1.16	-.58	457	-2.96	-.63	-.82
	610	-1.53	-1.63	-1.23	305	-5.99	-2.75	-.53
	305	-5.72	-6.25	-2.87	152	-10.99	-7.55	.46
	152	-5.27	-2.43	-3.41	61	-6.89	-8.53	-.55
	32	-2.68	-6.89	-5.23	32	-6.18	-7.41	-.52
	4	-15.43	-16.60	-13.57	4	-25.05	-23.12	-8.07

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A full-scale planetary boundary layer field experiment was conducted jointly by members of the Air Force Cambridge Research Laboratories, the Meteorological Research Unit, Royal Air Force, Cardington, England, and the Air Weather Service in late summer of 1973 in northwestern Minnesota. Direct measurements of vertical transport of momentum and heat, as well as vertical profiles of wind velocity and temperature, were obtained to altitudes of 1220 meters. Measurements were made from sensors mounted on a tower

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and on the cable of a barrage balloon. The data obtained for all the fully convective periods are presented in this report.