IN-02
72176
P53

NASA Contractor Report 4422

Aerodynamic Roughness Measured in the Field and Simulated in a Wind Tunnel

Robert Sullivan and Ronald Greeley

COOPERATIVE AGREEMENT NCC2-346
FEBRUARY 1992

(NASA-CR-4422) AERODYNAMIC ROUGHNESS MEASURED IN THE FIELD AND SIMULATED IN A WIND TUNNEL (Arizona State Univ.) 53 p N92-19354
CSCL 01A Unclas
H1/02 0072176

NASA

NASA Contractor Report 4422

Aerodynamic Roughness Measured in the Field and Simulated in a Wind Tunnel

Robert Sullivan and Ronald Greeley
Arizona State University
Tempe, Arizona

Prepared for
NASA Office of Space Science and Applicatic
under Cooperative Agreement NCC2-346

NASA
National Aeronautics and
Space Administration
Office of Management
Scientific and Technical
Information Program
1992

Abstract

Aerodynamic surface roughness, z_o, is an essential parameter in the physics of wind-related geological processes. This report presents (1) wind velocity and temperature data from controlled field experiments in which aerodynamic roughness was measured over three arrays of non-erodible roughness elements, and (2) wind tunnel velocity data from 1/10 and 1/20 scale-model simulations of the field experiments. Detailed technical background describing the apparatus and techniques of data gathering for both the field experiments and the wind tunnel scale simulations are presented.

Introduction

The movement of sand and dust is influenced by many factors, including the supply of particles, wind speed and direction, characteristics of terrain, and roughness of the surface. Aerodynamic surface roughness, labelled z_o, is the height above the surface at which the wind velocity is essentially zero, as discussed by Prandtl (1936), Bagnold (1941), and others:

$$u = (u_*/k) \ln (z/z_o) \tag{1}$$

where u = wind speed, u_* = wind friction speed, k = von Karman's constant (usually assumed = 0.4), z = height, and z_o = aerodynamic surface roughness. Aerodynamic surface roughness is a function of many factors, including microtopography on a scale of meters, and the size of the grains on the surface. Because z_o influences the ability of wind to initiate sand and dust movement, as well as the amount of material transported, understanding aerodynamic roughness is critical in studies of processes related to wind.

This document presents data for evaluating how accurately z_o measured over scale models in wind tunnels correlates with actual values of z_o measured in the field. The study involved a field experiment and a wind tunnel simulation. The field experiment consisted of measuring aerodynamic roughness over three arrays of non-erodible roughness elements on a dry lake bed (Lucerne playa) in the Mojave desert, California, during the spring of 1987. Wind profiles over each of the roughness element arrays were measured with ten anemometers on a 15 m mast. Simultaneously, temperature was recorded with thermocouples at the top and near the bottom of the mast in order to evaluate the thermal stability of the atmospheric boundary layer. Later, the three roughness element arrays were simulated at 1/10 and 1/20 scale in an open-circuit boundary layer wind tunnel. Velocities within the wind tunnel were measured with a boundary-layer pitot-tube rake located in the same relative position in the scale model arrays as the anemometers were in the field arrays. Each array at each scale was sampled three times at five freestream velocities.

The original motivation for this work derives from the desire eventually to measure z_o (and ultimately u_*, the wind friction speed) at the Viking Lander sites on Mars through a comprehensive wind tunnel simulation. The present work evaluates, in a general case, how well scale model wind tunnel experiments can predict full-scale field values of z_o and u_*. However, the data presented here constitute two uniquely matched data sets that can be reduced, analyzed, and compared in numerous ways for many different purposes. To this end, this document makes available to the scientific community the data from both field and wind tunnel experiments, with appropriate technical background.

Field experiment

Four hundred eighty overturned commercial 12-qt. containers secured to the dry lake bed surface with steel rods served as removeable non-erodible roughness elements (Figure 1). In plan, the roughness arrays were sector shaped with the circumferential edge upwind and the anemometer stack located near the acute end (Figure 1). This plan shape is similar to that employed by Kutzbach (1961). Rings of roughness elements surrounded Kutzbach's primary anemometer mast to guard against edge effects disturbing the measured wind profiles. The plan shape of the arrays employed in this study is a modification of Kutzbach's method; in addition to roughness elements surrounding the anemometer stack, additional roughness elements fill in the margins of the arrays, desensitizing the wind profile from the possible effects of small wind directional fluctuations. The dimensions and roughness element spacing for the three roughness arrays (Figure 2) are summarized in Table 1.

Wind velocity was measured at ten heights by 3-cup, contact-type anemometers manufactured by C. F. Casella & Co., Ltd. (London). These instruments generate a small electric pulse for every 1/10 statue mile of wind-run. Pulses from each anemometer

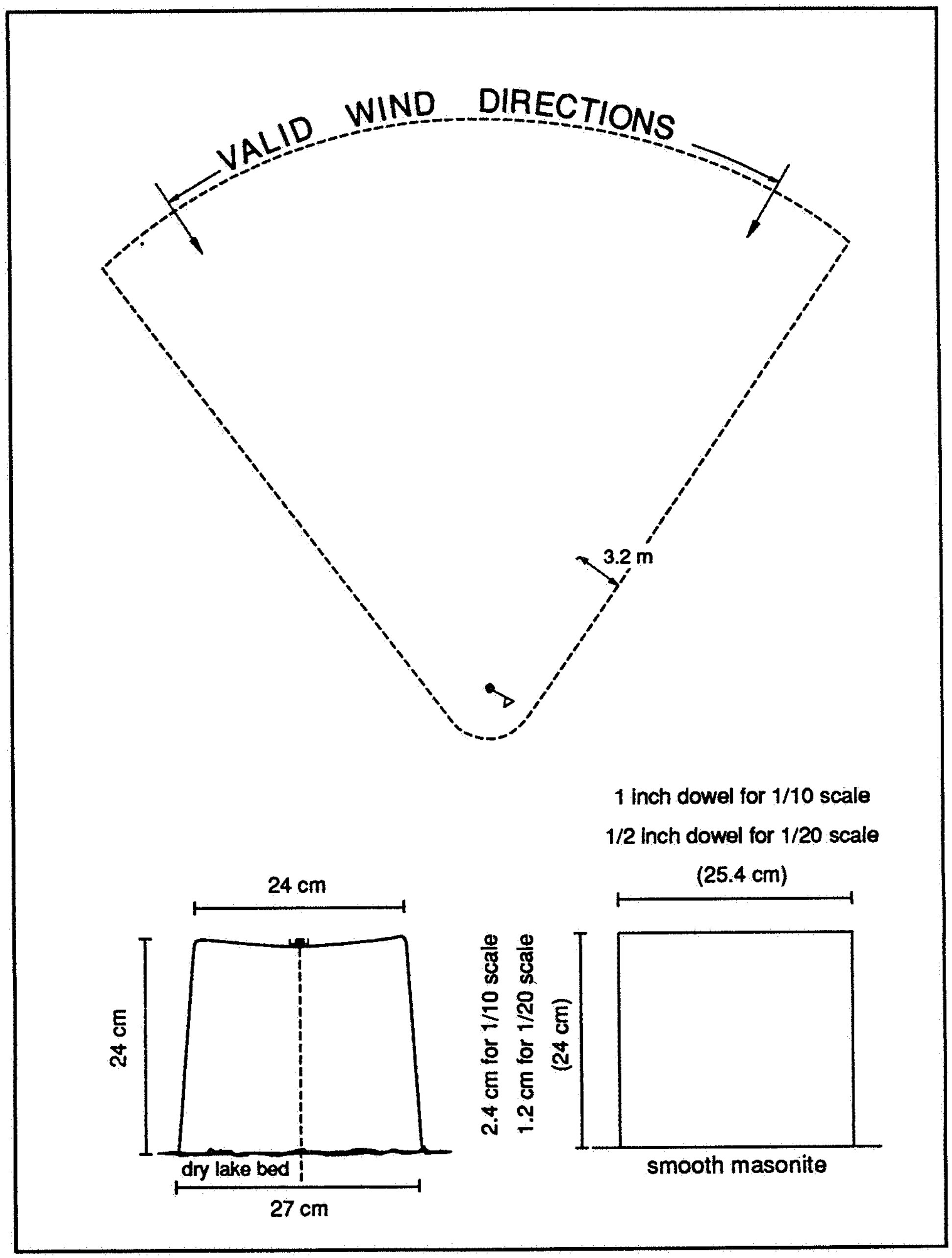


Figure 1 General plan of the roughness element arrays (map view), and roughness elements at full, 1/10, and 1/20 scales (cross-sectional view). Plan view of roughness element array shows valid wind directions, and the location of the anemometer stack (filled circle) and supporting tower (triangle). Example shown is array 2 (roughness array fetch = 40.0 m, spacing between roughness elements = 1.6 m).

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

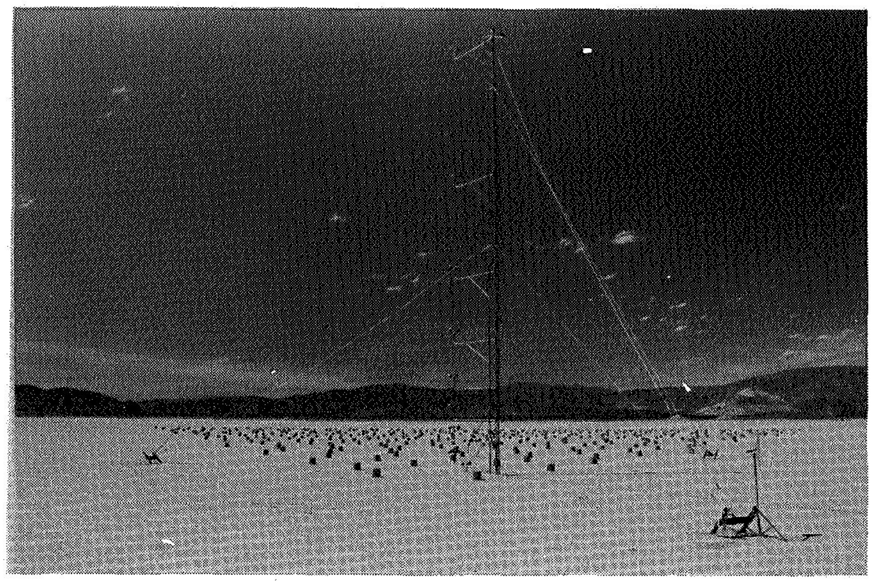


Figure 2. The full scale roughness element arrays on the eastern edge of Lucerne Dry Lake, California. (a) Array 1 looking into the prevailing wind direction (west). Upwind fetch = 89.6 m, roughness element spacing = 3.2 m. Mountains are 5-6 km distant.

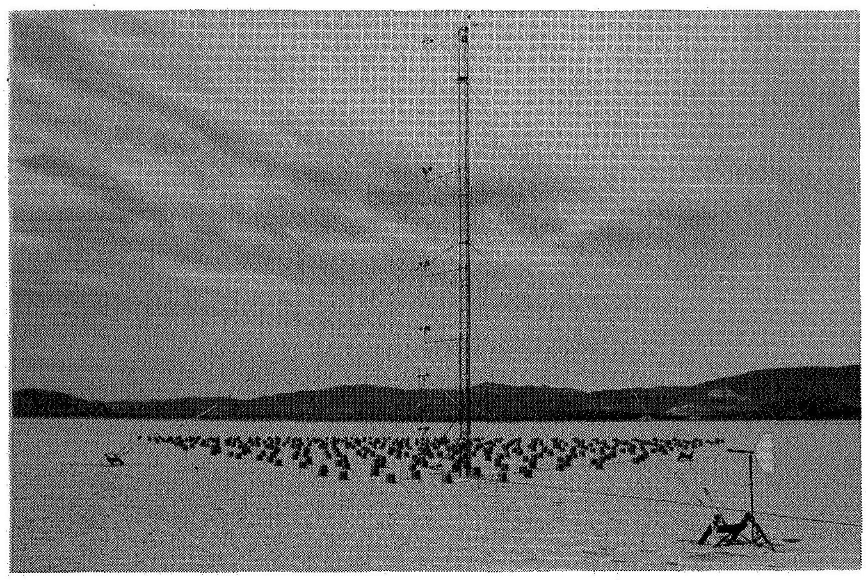


Figure 2 (continued) (b) Array 2 looking upwind. Fetch of array = 40.0 m; roughness element spacing = 1.6 m.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

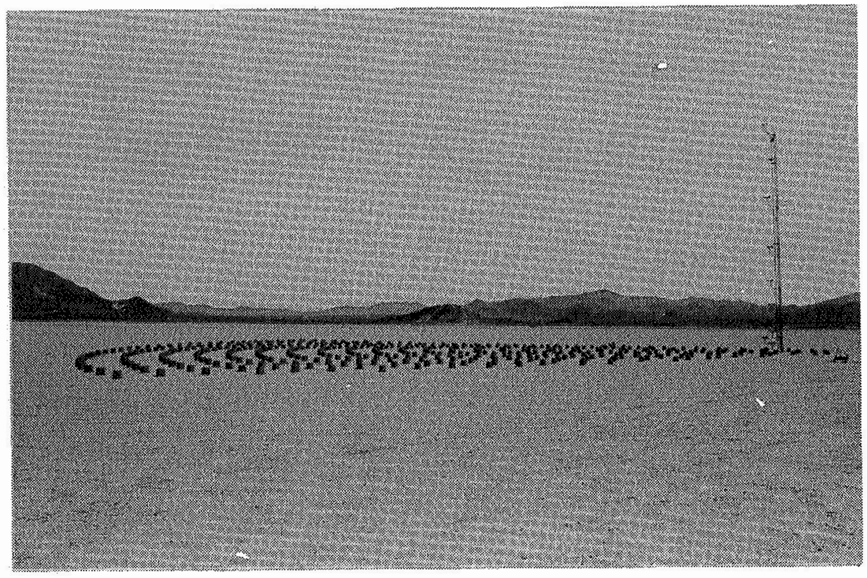


Figure 2 (continued) (c) Side view of array 2 looking north. Prevailing wind moves from left to right.

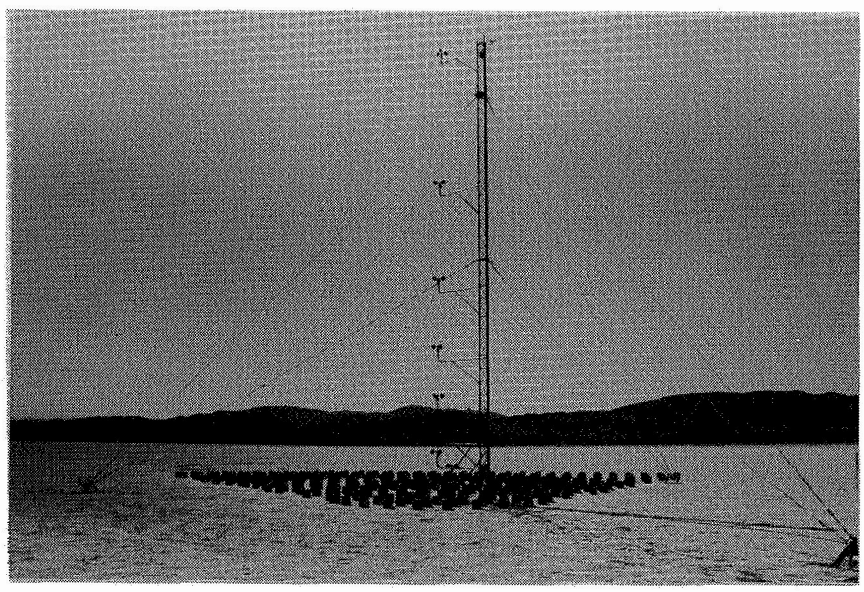
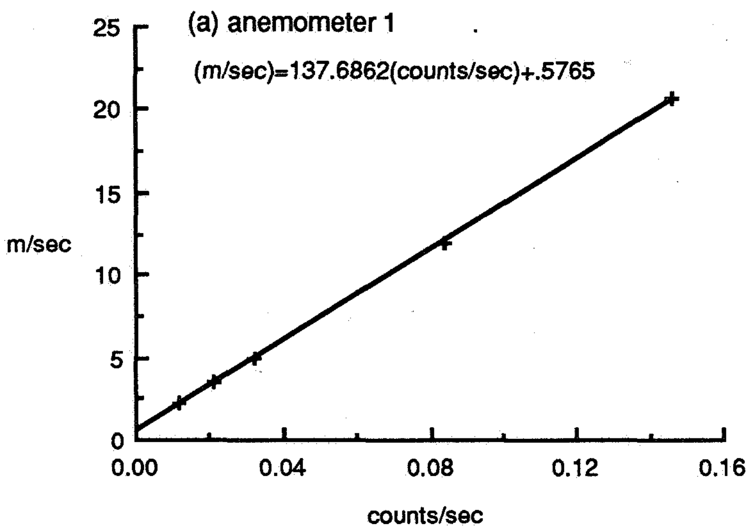


Figure 2 (continued) (d) Array 3 looking upwind. Fetch of array = 16.0 m; roughness element spacing = 0.8 m.



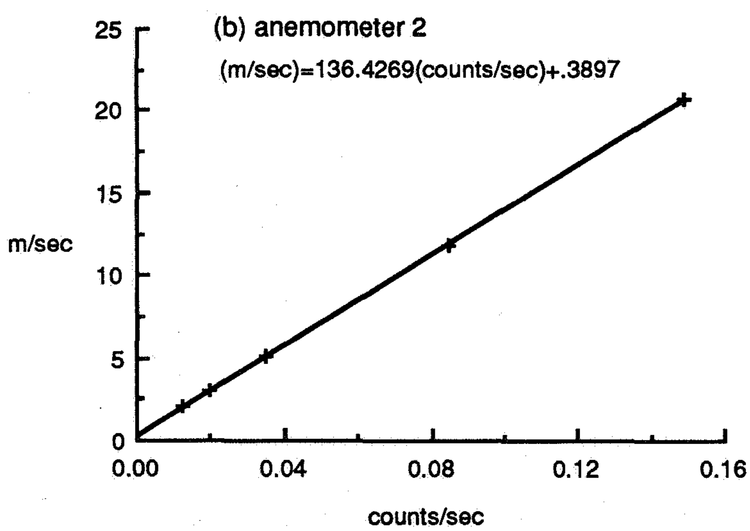
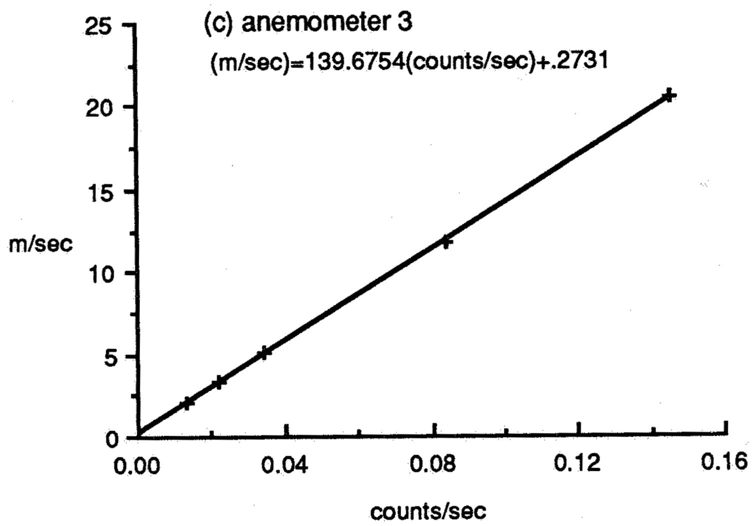


Figure 3. Anemometer calibrations. (a) anemometer 1; (b) anemometer 2; (c) anemometer 3; (d) anemometer 4; (e) anemometer 5; (f) anemometer 6; (g) anemometer 7; (h) anemometer 8; (i) anemometer 9; (j) anemometer 10.



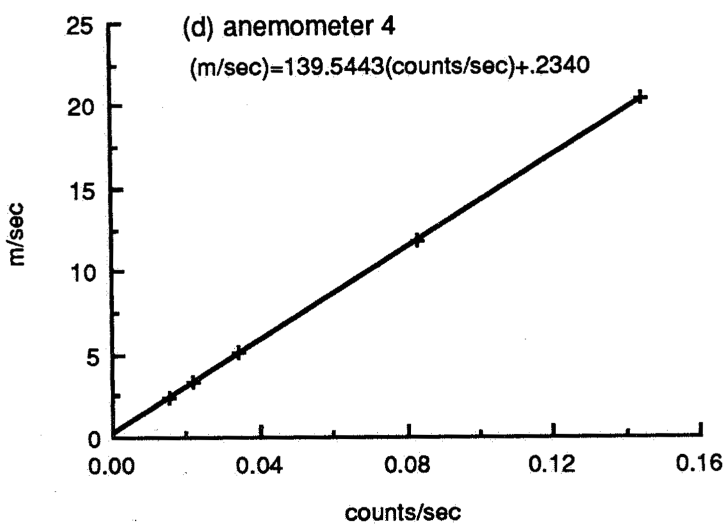
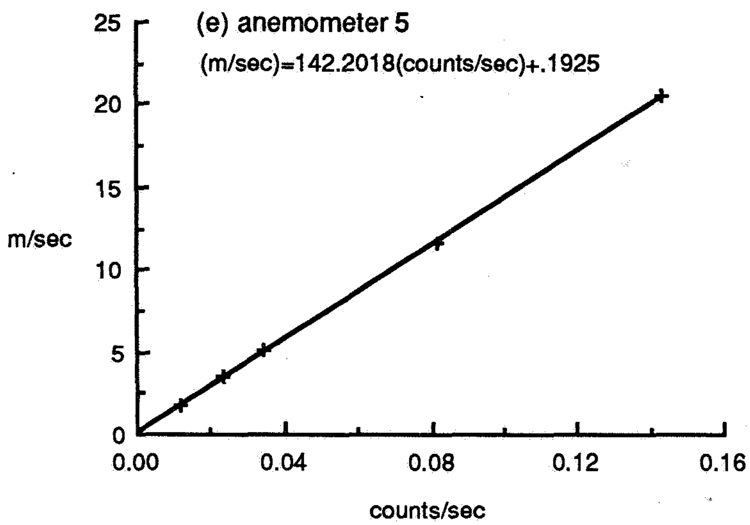


Figure 3 (continued).



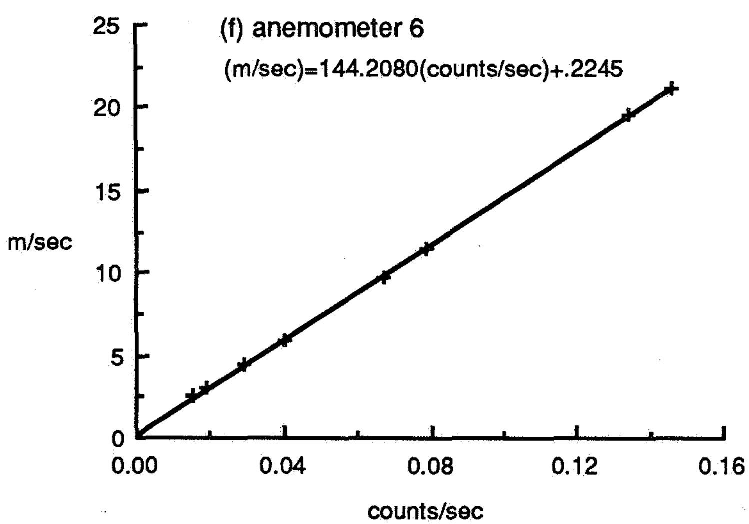
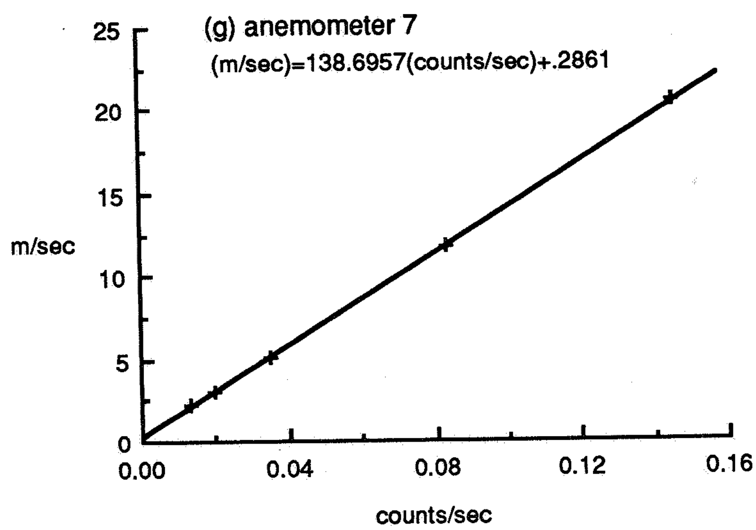


Figure 3 (continued).



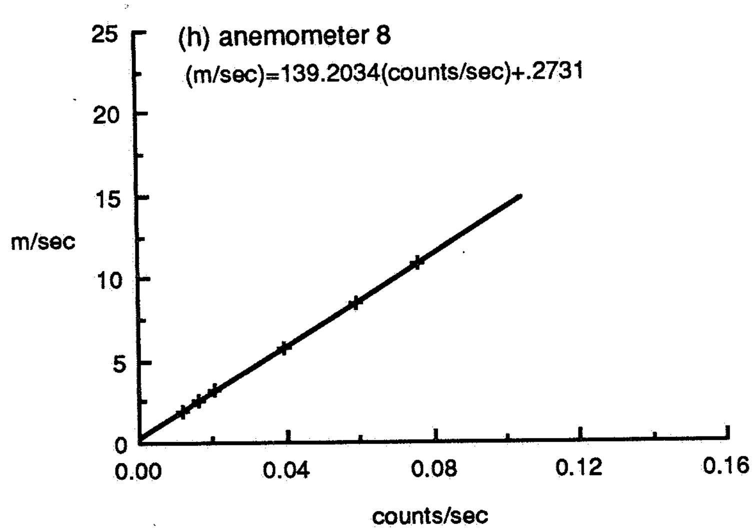
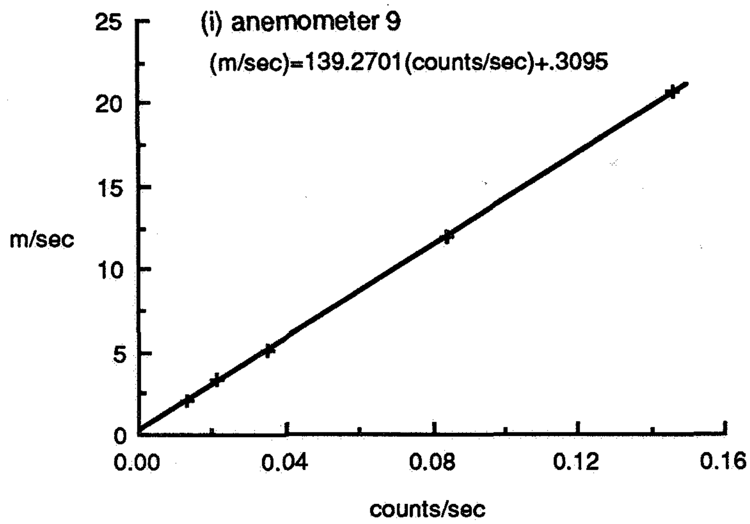


Figure 3 (continued).



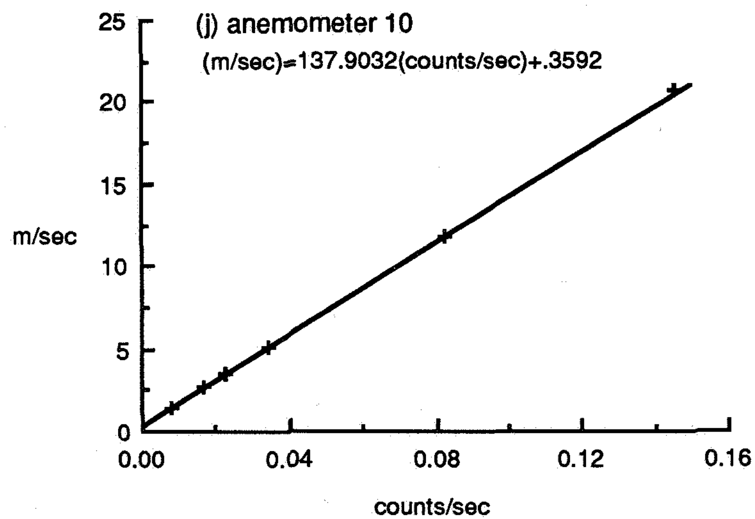


Figure 3 (continued).

register and accumulate on simple electrical counter boxes. Accumulated counts were recorded by hand at regular time intervals, thus supplying the necessary time component for computation of wind speed.

Each anemometer was calibrated at five or six velocities in a wind tunnel at Arizona State University. Each anemometer was placed in the wind tunnel with its three rotating cups located centrally within the wind tunnel's test section, immersed in the tunnel freestream and well away from the drag-induced boundary layers generated by the wind tunnel walls, ceiling, and floor. Each anemometer was monitored for 1 to 2 minutes at five or six wind tunnel velocities to give counts/s values for the anemometer which corresponded to meter/sec values measured by wind tunnel instruments. The results of these calibrations were straight-line equations relating counts/s to m/s velocity for each anemometer (Figure 3). These calibration equations were later employed in data reduction in which counts registered during time intervals (usually multiples of 15 minutes) were converted to counts/s and then to m/s wind speed. The raw anemometer data are presented in Table 2.

Temperature of the atmospheric boundary layer was monitored by iron-constantan thermocouples shaded from direct sunlight at heights of 1 m and 15 m. Temperatures at both heights were read from a single Omega 872 digital thermometer unit with a resolution of 0.1°C. Under conditions of thermal neutrality, any turbulent, vertical displacement of air particles is due to mechanical interactions only, such as deflection over surface roughness elements. Conditions of thermal neutrality in the wind data were identified by calculating the Richardson number, Ri, in time intervals from the temperature data:

$$Ri = (g/\theta)\ [(\theta_2-\theta_1)(z_2-z_1)\ /\ (u_2-u_1)^2] \qquad (2)$$

where g = acceleration of gravity (m/sec^2), θ = ambient potential temperature (°K), z_1 and z_2 are heights with $z_2>z_1$, and θ_1, θ_2 and u_1, u_2 are potential temperatures and wind speeds, respectively, measured at these heights. Potential temperature θ is defined as

$$\theta = T_z + gz/C_p \qquad (3)$$

where T_z is temperature (°K) measured at height z and C_p is the heat capacity of the atmosphere (e.g., Greeley and Iversen, 1985, p. 34). Ri = 0 indicates thermal neutrality. Increasingly positive and negative values of Ri indicate the turbulence is increasingly thermally dominated. Positive values of Ri indicate atmospheric conditions are thermally stable, while negative values of Ri indicate thermally unstable conditions. Unfortunately, thermally neutral atmospheric conditions are relatively rare, often occurring only in transience at dawn and dusk. The temperature data are presented in Table 3.

Wind tunnel experiment

The Arizona State University Planetary Geology Wind Tunnel was employed in this study. The wind tunnel is of the open-circuit type and has a test section of 0.99 m x 0.812 m. The ceiling of the wind tunnel is sloped in such a way to ensure constant static pressure in the vicinity of the test section. For this study, the boundary layer survey apparatus consisted of two sets of components linked by a Setra-systems pressure transducer: (1) air lines designed to route air pressure from specific locations inside the wind tunnel test section to the pressure transducer (where pressure is converted to a voltage); and (2) computer electronics for interpreting the transducer electronic signal as a wind velocity. Wind pressure was sensed using a 0.60 m high stationary boundary layer "rake" with 30 pitot tubes. Static (reference) pressure was sensed at right angles to the tunnel windstream on a separate pitot tube projecting 0.22 m from the side wall, approximately 2.2 m ahead of the boundary layer "rake." From under the floor of the tunnel at the base of the pitot-tube rake, 30 air lines (one for each pitot tube) carried air pressure to a scanivalve. The scanivalve delivered the air pressure of one pitot-tube/airline at a time into the pressure orifice of a Setra 239E pressure transducer. Another direct airline delivered static pressure from the side wall pitot-tube into the pressure transducer's static orifice. The pressure transducer sensed the difference between its static and pressure orifices, and assigned this relative pressure a voltage. Finally, the analog-to-digital converter and micro-computer system converted voltage from the pressure transducer to a calculated wind velocity. Daily or hourly variations in wind tunnel air temperature and outside barometric pressure are accounted for in these calculations.

Aeolian processes typically occur in nature under atmospheric conditions of fully developed turbulence. Any simulation of turbulent atmospheric conditions in the wind tunnel should take place fully immersed within the wind tunnel's turbulent boundary layer, usually only in the lower fraction of a wind tunnel's windstream. A relatively long upwind fetch is normally required for the turbulent boundary layer to grow and develop into a useful fraction on the tunnel height by the time the windstream passes through the tunnel test section. Generation of this condition in the boundary layers of wind tunnels with relatively short upwind fetches requires the installation of artificial turbulence generators near the wind tunnel intake to "trip" the turbulent airflow within the tunnel, as was done in these experiments.

A measure of the turbulence of a boundary layer is the exponent of the velocity (normalized by the freestream velocity) vs. height (normalized by the height of the boundary layer):

$$(z/h) = (u/u_\infty)^\alpha \tag{4}$$

in which u =wind speed within the boundary layer, u_∞ = wind tunnel freestream speed, z = height within the boundary layer, and h = height of the top of the boundary layer (defined as where u = 99% u_∞). For completely laminar boundary layers $\alpha = 1$. Normally, $\alpha \cong 0.14$ is considered indicative of fully developed turbulence (Schlicting, 1979). For wind flow over a dry lake bed α ranges from 0.16 to 0.14 (Bruce White, personal communication). Roughness trippers (commercial hex nuts) were placed on the floor near the front of the wind tunnel and their configuration adjusted until values of α at the front and rear of the wind tunnel test section (7.53 m and 8.75 m fetch) approached those of a playa. The final configuration of roughness trippers is listed in Table 4. The resulting wind profiles and their best fitted values of α and h are shown if Figure 4. At the rear of the test section (8.75 m fetch) α decreases from 0.16 to 0.12 as u_∞ increases from 3.7 to 25.5 m/sec. Over the same range of u_∞, h increases from 0.16 m to 0.18 m. Similar results were obtained for profiles measured at the front of the test section (7.53 m fetch), although h averaged ~0.02 m less.

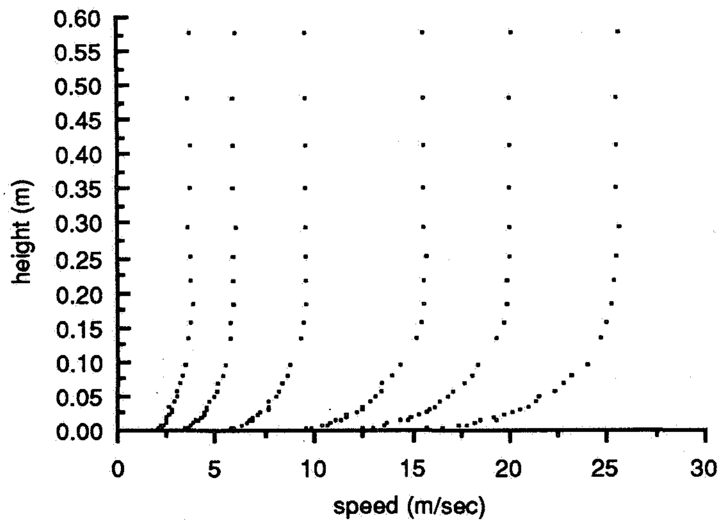


Figure 4. Boundary layer survey over smooth masonite; 8.75 m fetch profiles.

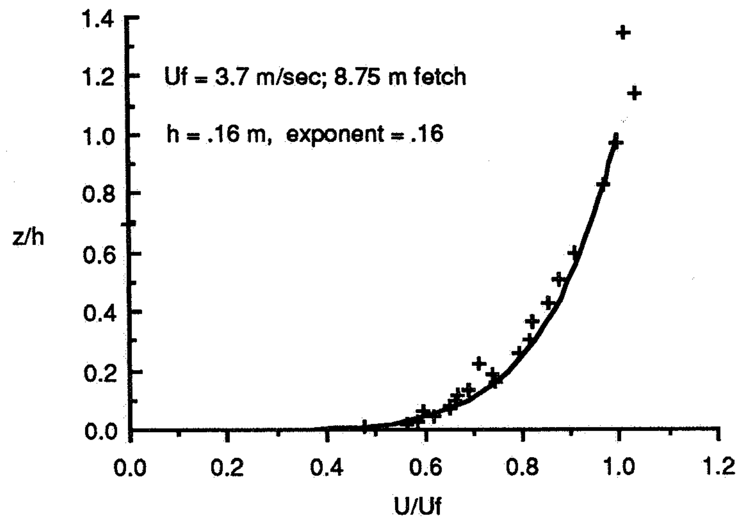


Figure 4 (continued). Boundary layer survey; best power-law fit to $u_\infty = 3.7$ m/sec (8.75 m fetch).

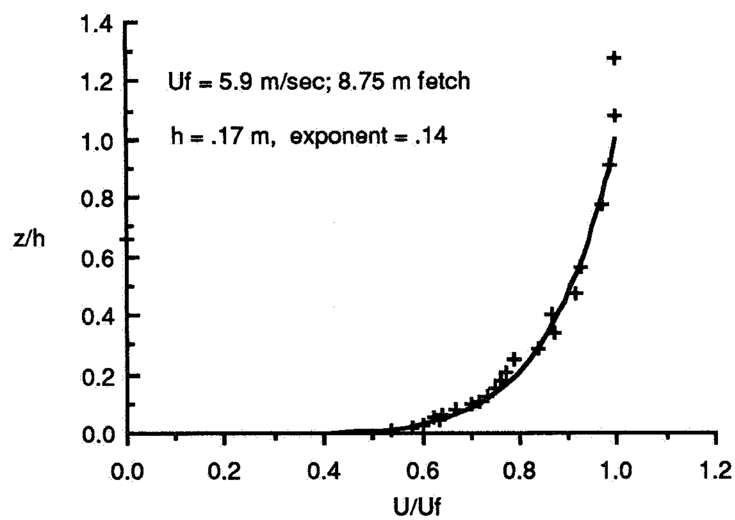


Figure 4 (continued). Boundary layer survey; best power-law fit to $u_\infty = 5.9$ m/sec (8.75 m fetch).

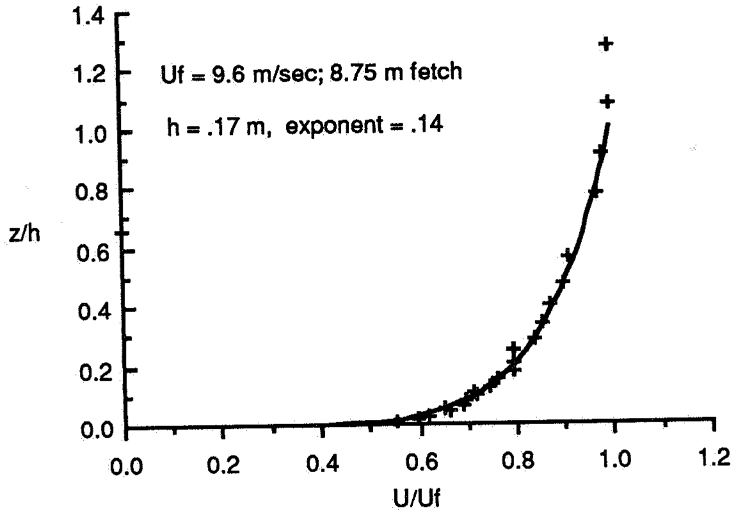


Figure 4 (continued). Boundary layer survey; best power-law fit to u_∞ = 9.6 m/sec (8.75 m fetch).

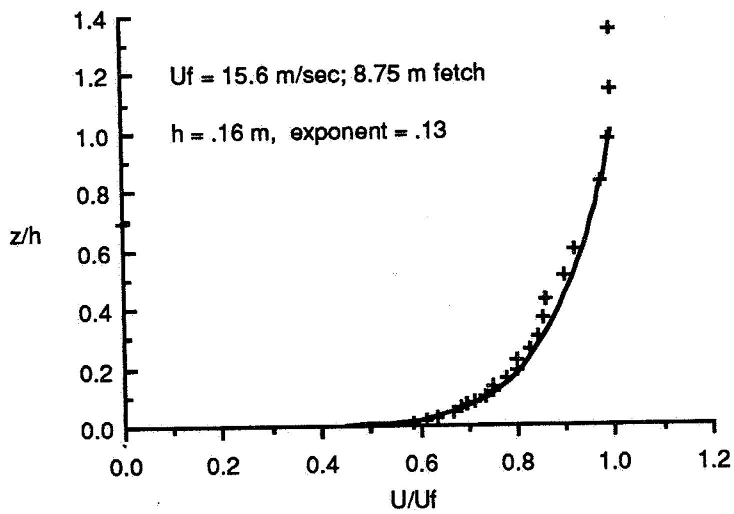


Figure 4 (continued). Boundary layer survey; best power-law fit to u_∞ = 15.6 m/sec (8.75 m fetch).

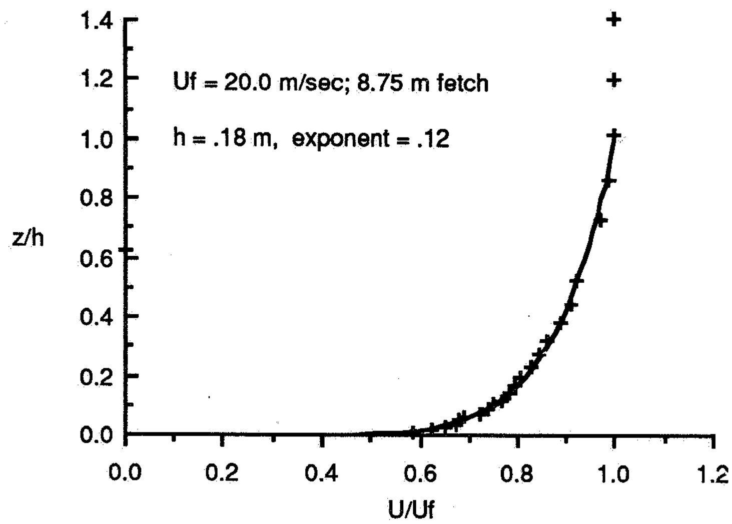


Figure 4 (continued). Boundary layer survey; best power-law fit to U_∞ = 20.0 m/sec (8.75 m fetch).

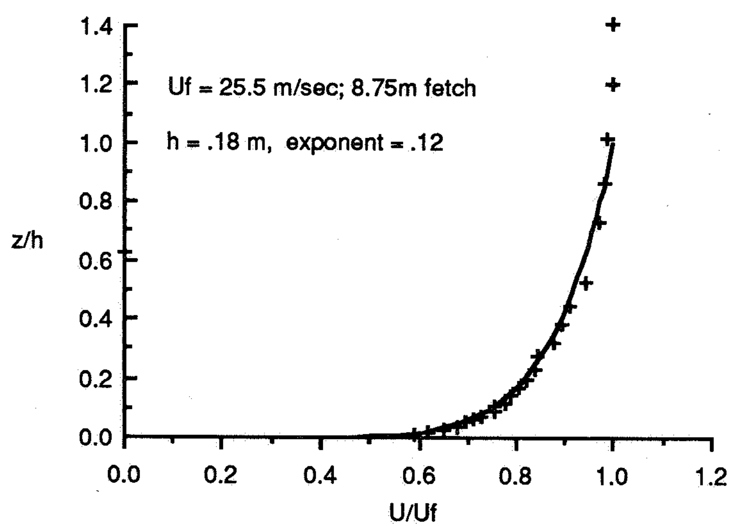


Figure 4 (continued). Boundary layer survey; best power-law fit to u_∞ = 25.5 m/sec (8.75 m fetch).

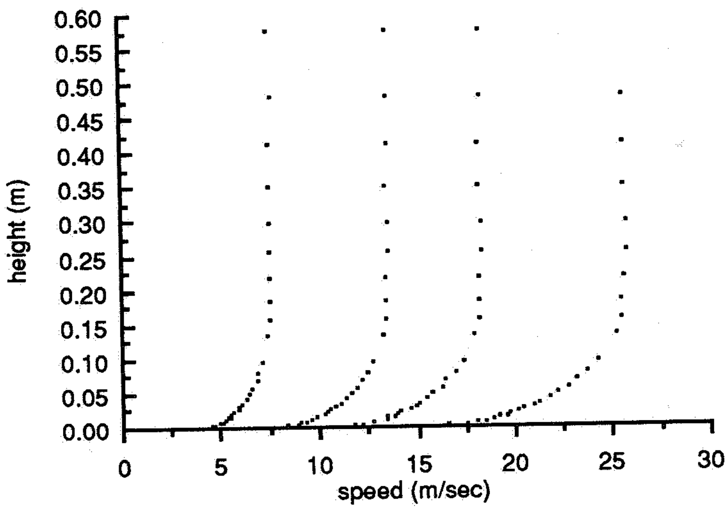


Figure 4 (continued). Boundary layer survey over smooth masonite; 7.53 m fetch profiles.

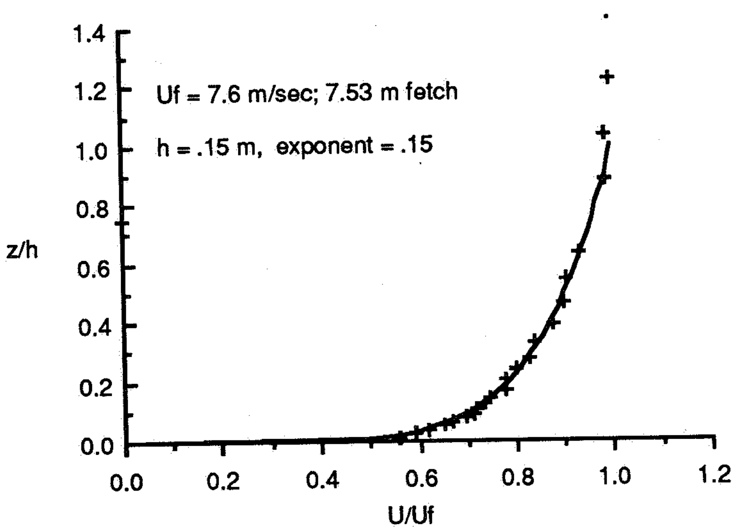


Figure 4 (continued). Boundary layer survey; best power-law fit to u_∞ = 7.6 m/sec (7.53 m fetch).

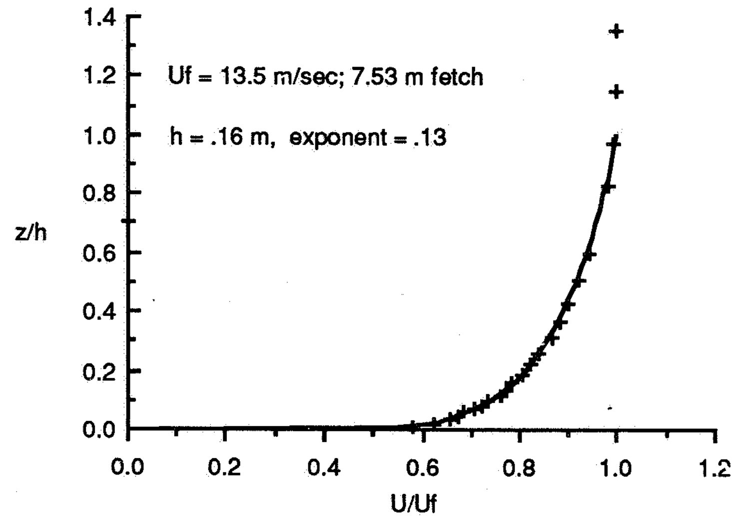


Figure 4 (continued). Boundary layer survey; best power-law fit to u_∞ = 13.5 m/sec (7.53 m fetch).

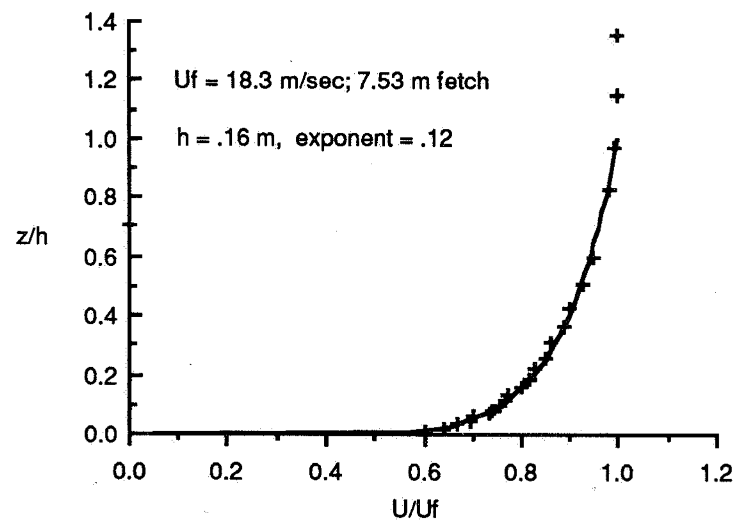


Figure 4 (continued). Boundary layer survey; best power-law fit to u_∞ = 18.3 m/sec (7.53 m fetch).

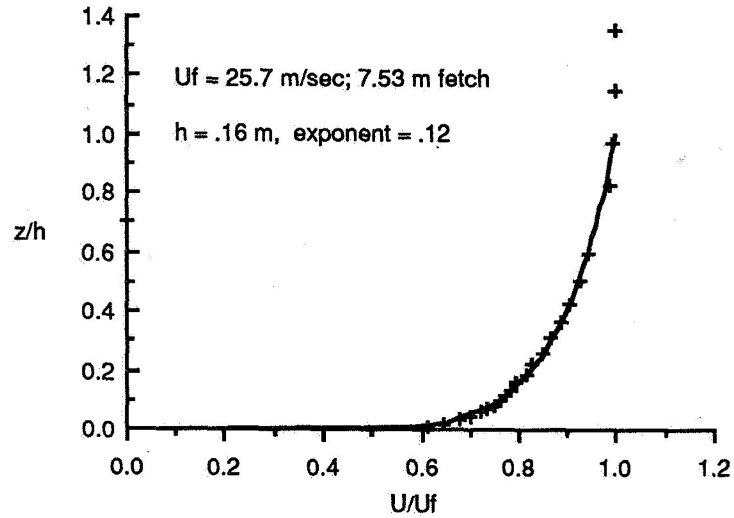


Figure 4 (continued). Boundary layer survey; best power-law fit to u_∞ = *25.7 m/sec (7.53 m fetch).*

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

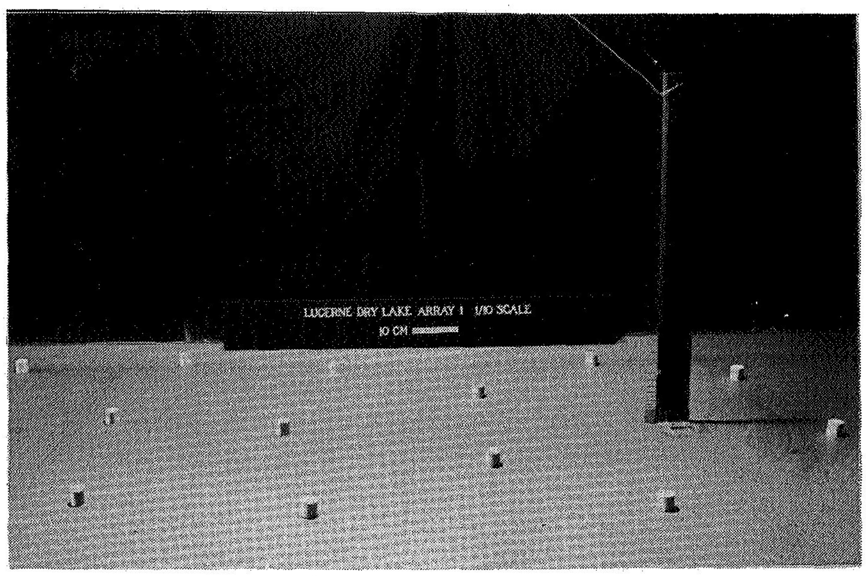


Figure 5. Scale model roughness element arrays in the wind tunnel. Wind moves from left to right, with boundary layer rake located at right in all photographs. (a) 1/10 scale array 1.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

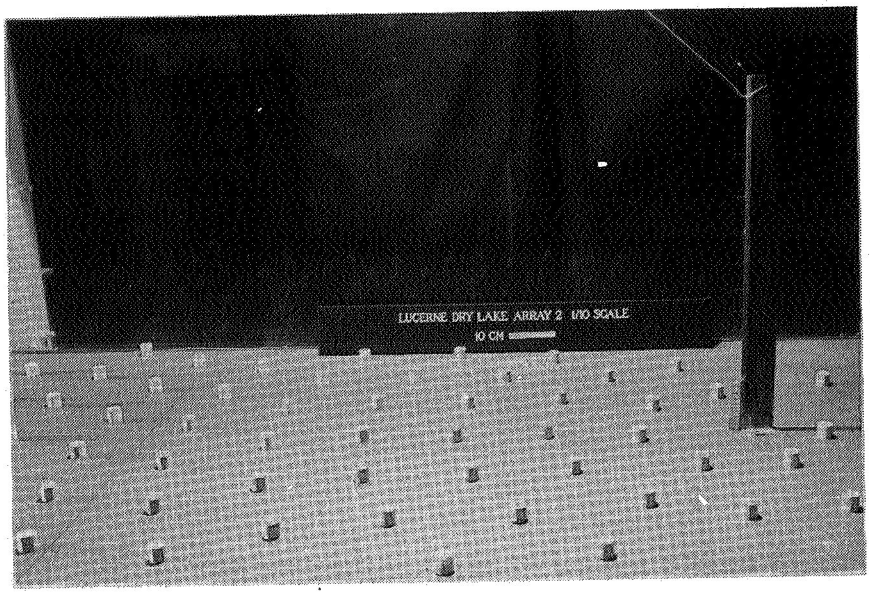


Figure 5 (continued) (b) 1/10 scale array 2.

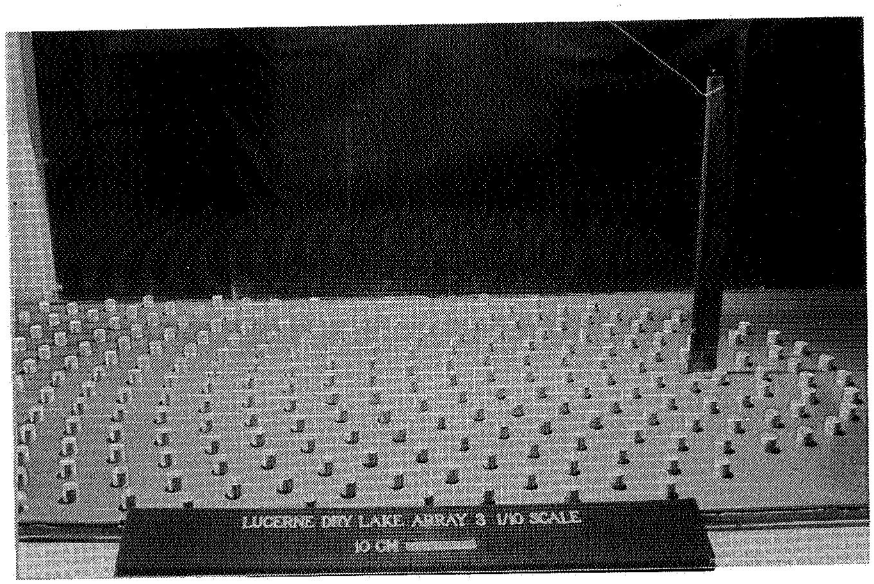


Figure 5 (continued) (c) 1/10 scale array 3.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

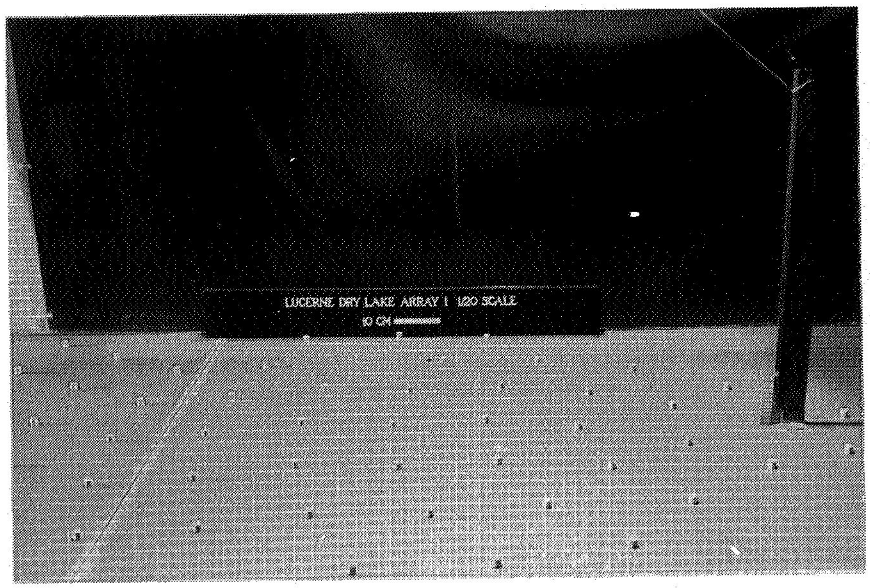


Figure 5 (continued) (d) 1/20 scale array 1.

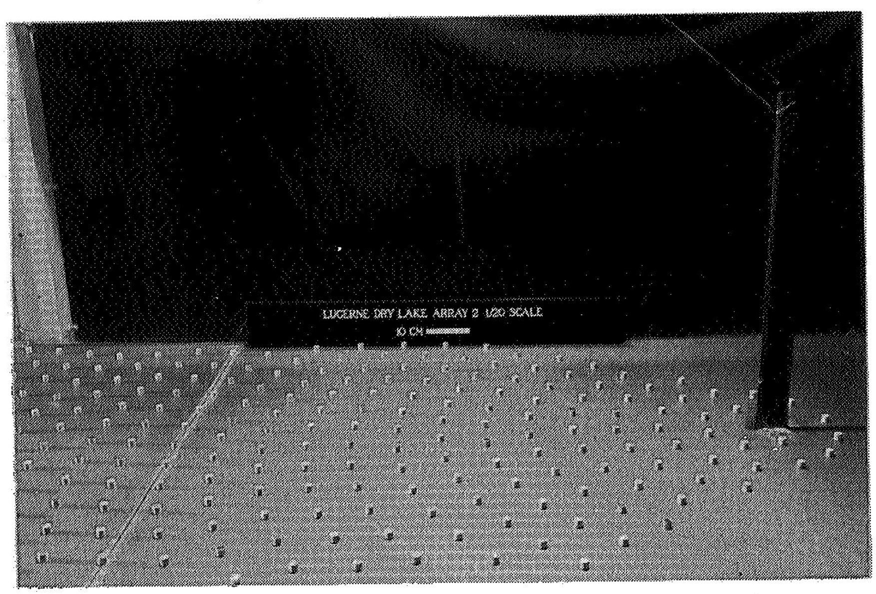


Figure 5 (continued) (e) 1/20 scale array 2.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

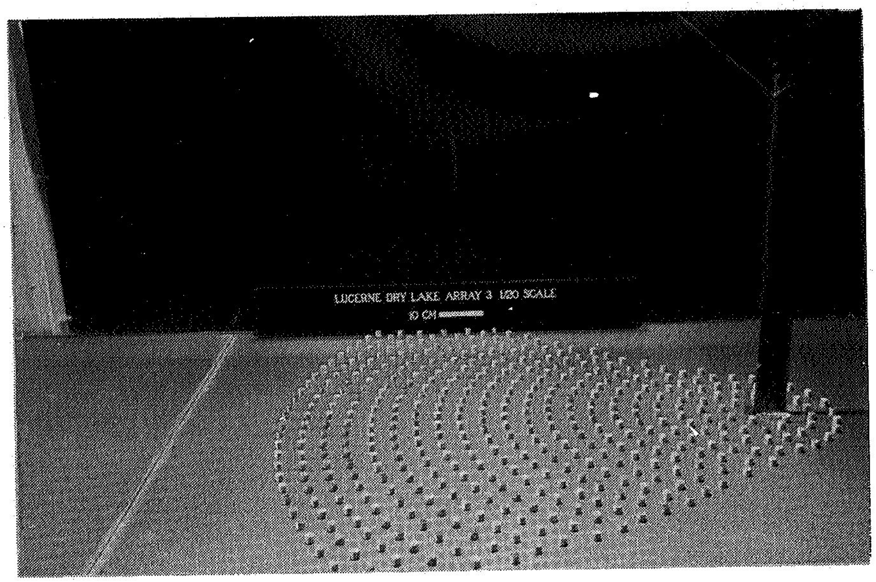


Figure 5 (continued) (f) 1/20 scale array 3.

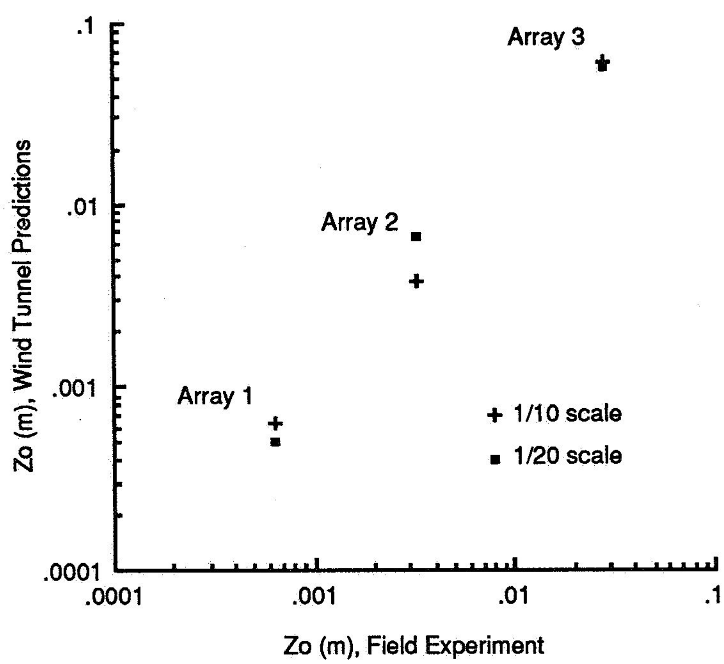


Figure 6. Correlations of z_o. Full-scale field values of z_o plotted against wind tunnel scale model predictions of z_o. Scale model predictions of z_o are obtained by multiplying wind tunnel values of z_o for each array by the inverse of its scale (10 or 20).

The smooth dry lake surface of the field experiment was simulated in the wind tunnel by installing sheet masonite flooring. The roughness elements of arrays 1, 2, and 3 were simulated at 1/10 and 1/20 scale by wood dowel cylinders cut to the appropriate lengths (Figure 1). In the field experiment, the sector shape of each array was focused on the anemometer "stack," as opposed to the (offset) supporting mast. For each of the model arrays in the wind tunnel the tips of the pitot tubes on the boundary layer rake occupied the same relative position within the scaled arrays as the anemometer "stack" did in the field arrays. A sector of roughness elements was required in the field to maximize the permitted wind directions for data collection. In no case was any scale model array narrow enough to fit completely within the wind tunnel walls; as much of the central section of each model array that would fit was simply installed while the internal geometry of field arrays was preserved. The entire fetch of array 1 at 1/10 scale (8.96 m) was too extensive to fit entirely within the fetch limits of the wind tunnel. Accordingly, this model's fetch was reduced 14% to 7.68 m. The matrix of experimental runs was 2 scales (1/10 and 1/20) x 3 arrays x 5 freestream velocities (u_∞ = 6.0, 9.0, 12.0, 18.0, and 24.0 m/s) x 3 trials each = 90 runs. For reasons cited in Sullivan and Greeley (1992), two modifications of 1/20 scale array 3 were also examined (10 additional runs). Each of the model roughness arrays is portrayed in Figure 5. The data for each set of three identical trials was averaged to give a single representative profile, and these data are presented in Table 5.

Summary

Wind speed and temperature data were collected in the field over four surfaces: a flat, smooth dry lake bed, and four arrays of non-erodible roughness elements of increasing roughness element surface density. The three field arrays were duplicated in the wind tunnel at 1/10 and 1/20 scale, and wind speed data for each were obtained at five freestream speeds. Many analyses of these data sets for many different purposes are possible. One analysis and comparison of these data sets is presented in Sullivan and Greeley (1992), who used the temperature data to identify periods of atmospheric thermal neutrality, and reduced the wind speed data for these intervals to yield values of z_0 for each roughness array. These results are summarized in Table 6. The wind speed data for the wind tunnel runs was reduced in a similar manner, yielding the values of z_0 presented in Table 7. A comparison of the field and wind tunnel results is presented in Figure 6. The correlation between field values of z_0 for each of the arrays and the wind tunnel values of

z_o (multiplied by their inverse scales) is approximately 1:1 for arrays 1 and 2, but is less predictable for array 3. A more accurate correlation for all the data is $z_{o\ field} = 0.2661 \cdot (z_{o\ model} \cdot scale^{-1})^{0.8159}$.

Acknowledgments

We thank Jonathan Fink and Michael Malin for fruitful discussions on this topic. Bruce White familiarized R.S. with the important concept of the internal boundary layer and its relevance to this work. The generous advice of James Iversen is also appreciated, especially with regard to the concept of potential temperature. The technical assistance and support of Gary Beardmore (field equipment and wind tunnel preparation), Nicholas Lancaster, Steven Williams, Robert Norton (field equipment preparation), Jeffrey Lee (wind tunnel preparation), Robert Levine (field equipment), Dan Ball (darkroom), and James Lien (computing) are also gratefully acknowledged. This work was supported by the NASA Office of Planetary Geology through Ames Research Center.

References

Bagnold, R. A., *The Physics of Blown Sand and Desert Dunes*, Chapman and Hall, London, 265 pp., 1941.

Greeley, R., and Iversen, J. D., *Wind as a Geological Process*, Cambridge University Press, Cambridge, 333 pp., 1985.

Kutzbach, J. E., Investigations of the modification of wind profiles by artificially controlled surface roughness *in: Studies of the Three-Dimensional Structure of the Planetary Boundary Layer*, Ann. Rep., Dept. Meteorol., Univ. Wisc.-Madison, pp. 71-113, 1961.

Prandtl, L., Uber die ausgebildete Turbulenz, *ZAMM, 5,* 136-139, 1925; and *Proc. 2nd. Intern. Congr. Appl. Mech.,* Zurich, 62-75, 1926; cited in *Schlichting*, 1979.

Schlichting, H., *Boundary Layer Theory*, McGraw-Hill, New York, 7th ed., pp. 578-595, 1979.

Sullivan, R., and Greeley, R., Comparison of aerodynamic roughness measured in a field experiment and in a wind tunnel simulation, submitted to *Journ. Wind Engin. Indus. Dynam.*, 1992.

Table 1. Summary of specifications of the field experiment.

	Array 0 (Bare playa)	Array 1	Array 2	Array 3
Roughness element spacing: distance between rows and elements in rows (m)	---	3.2	1.6	0.8
Roughness element spacing: roughness elements per m^2	---	.0977	.391	1.563
Distance from anemometer stack to upwind edge of array (m)	---	89.6	40.0	16.0
Distance from anemometer stack to downwind edge of array (m)	---	3.2	3.2	3.2
Amount of wind data collected (min)	525	840	750	540
Amount of thermally neutral wind data (min)	15	45	165	30

Table 2. Raw anemometer data from the field experiment.

Data are in raw form and are listed in counts accumulated at specific times, usually at 15 minute intervals. Formulae for converting accumulated counts to m/s are given in Figure 4. Data are listed chronologically starting with data for array 0 (bare playa), followed by data for array 1, array 2, array 3, and finally with additional data for array 0. Except for the initial array 0 data, all data have corresponding temperature data available (Table 3). Numbered columns refer to each anemometer, with anemometer 1 being highest. Between April 22 and May 2, 1987, the anemometers were in use at another location and were later reinstalled at the Lucerne site with a slightly different configuration. Heights of each anemometer for each period are as follows:

Anemometer number	height (m) March 13 - April 22 1987	height (m) May 2 - May 14 1987
1	15.15	15.15
2	10.25	10.25
3	6.94	6.94
4	4.72	4.71
5	3.18	3.18
6	2.17	2.17
7	1.451	1.448
8	1.005	1.005
9	0.654	0.652
10	0.242	0.246

Time	1	2	3	4	5	6	7	8	9	10
March 13 1987 Array 0										
730	0	0	0	0	0	0	0	0	0	0
745	41	40	38	37	36	35	34	32	31	27
800	94	92	88	86	83	80	78	73	70	61
815	147	144	138	135	130	125	121	114	111	95
830	200	196	188	185	178	171	167	157	153	132
845	256	250	241	238	228	219	214	202	197	169
900	313	306	295	290	279	268	262	249	243	208
915	368	360	348	343	329	317	310	293	288	246
930	427	419	405	398	383	369	351	342	336	287
945	485	475	459	451	434	418	409	388	381	325
1000	541	530	512	504	485	468	458	434	426	364
1015	606	594	574	565	544	525	514	487	479	409
1030	668	655	634	624	601	579	567	538	529	452
1045	735	720	697	687	662	638	625	593	583	499
1100	797	781	757	746	718	693	679	644	633	542
1115	862	845	819	807	777	749	735	697	686	587
1130	927	909	881	869	837	807	792	751	740	632
1145	996	977	947	934	900	868	852	803	796	680
1200	1063	1043	1011	998	961	927	909	863	850	727
1215	1126	1105	1072	1057	1019	983	965	916	902	771
1230	1195	1172	1137	1122	1081	1043	1024	972	957	819
1245	1265	1242	1205	1188	1145	1106	1086	1031	1014	868
1300	1329	1304	1266	1248	1203	1162	1141	1084	1066	913
1315	1394	1368	1328	1310	1263	1220	1197	1139	1119	959
1330	1458	1431	1389	1370	1321	1276	1253	1192	1170	1005
1345	1524	1496	1452	1433	1382	1335	1310	1248	1223	1052
1400	1594	1564	1518	1498	1446	1396	1371	1306	1280	1101
1415	1666	1635	1586	1565	1511	1459	1433	1365	1337	1151
1430	1724	1691	1640	1619	1563	1509	1482	1413	1382	1191
1445	1787	1753	1700	1678	1620	1565	1536	1465	1432	1234
1500	1844	1810	1755	1732	1672	1615	1585	1512	1478	1274
1515	1909	1873	1816	1792	1730	1671	1640	1565	1529	1319
1530	1966	1929	1870	1846	1782	1721	1690	1613	1574	1359
1545	2028	1990	1929	1904	1838	1775	1743	1663	1623	1402
1600	2086	2046	1983	1957	1889	1824	1790	1709	1667	1441
1615	2135	2094	2028	2001	1932	1866	1831	1748	1704	1474
1630	2192	2150	2082	2054	1983	1914	1879	1794	1748	1512
1645	2240	2196	2126	2098	2025	1955	1918	1831	1783	1544
1700	2295	2250	2178	2148	2073	2001	1963	1875	1826	1581
1715	2338	2292	2218	2187	2111	2037	1998	1903	1857	1608
1730	2387	2339	2264	2231	2153	2078	2037	1946	1893	1640
1745	2431	2382	2304	2271	2190	2113	2072	1979	1924	1667
1800	2467	2417	2337	2302	2220	2142	2100	2005	1949	1689
1815	2507	2455	2374	2338	2255	2175	2132	2035	1979	1714

Time	1	2	3	4	5	6	7	8	9	10
March 14 1987 Array 0										
830	0	0	0	0	0	0	0	0	0	0
845	55	55	54	53	51	49	48	45	44	39
900	113	112	109	108	104	100	98	93	91	79
915	171	170	165	163	157	152	149	141	138	119
945	306	303	294	290	280	271	266	252	247	213
1000	371	367	357	352	339	328	322	305	299	258
1015	429	424	413	407	393	380	373	353	347	299
1030	488	483	470	464	448	433	425	402	397	341
1045	548	542	527	521	503	486	477	452	447	382
1100	604	597	581	575	555	536	527	499	494	422
1115	648	642	625	617	596	577	567	537	532	455
1130	691	684	666	658	636	615	605	573	569	485
1145	738	731	712	703	680	657	647	613	609	519
1200	782	774	754	746	721	697	686	650	647	551
1215	830	823	802	793	766	741	729	691	687	586
1230	895	886	864	854	826	799	787	746	740	633
1245	963	953	929	918	888	859	846	802	796	680
1300	1036	1025	999	987	954	923	909	862	854	732
1315	1109	1097	1068	1056	1021	987	972	923	913	783
1330	1180	1166	1136	1123	1086	1050	1034	982	970	833
1345	1248	1233	1201	1187	1147	1110	1092	1038	1024	881
1400	1312	1296	1262	1247	1206	1167	1148	1092	1076	926
1415	1370	1353	1317	1302	1249	1218	1200	1140	1122	967
1430	1426	1403	1370	1355	1310	1268	1247	1187	1167	1006
1445	1485	1467	1427	1411	1365	1320	1298	1236	1214	1047
1500	1543	1524	1482	1465	1417	1370	1348	1283	1250	1087
1515	-	-	-	-	-	-	-	-	-	-
1530	1674	1652	1606	1587	1534	1484	1459	1380	1362	1176
1545	1738	1714	1666	1646	1591	1538	1512	1440	1411	1219
1600	1799	1777	1725	1704	1647	1593	1565	1491	1460	1261
1615	1852	1828	1776	1754	1696	1639	1611	1535	1502	1298
1630	1897	1872	1819	1797	1736	1679	1649	1571	1537	1328
1645	1949	1924	1869	1846	1784	1724	1693	1613	1578	1364
1700	2002	1975	1919	1895	1831	1770	1738	1656	1619	1399
1715	2043	2016	1958	1934	1868	1805	1773	1689	1652	1427
1730	2090	2063	2003	1978	1910	1846	1812	1726	1688	1458
1745	2144	2116	2054	2027	1958	1892	1857	1768	1729	1494
1800	2203	2174	2109	2081	2009	1942	1905	1815	1774	1532
April 1 1987 Array 1										
530	0	0	0	0	0	0	0	0	0	0
545	33	32	31	30	29	28	26	25	23	19
600	73	70	66	64	61	59	55	52	49	41
615	109	104	98	94	89	85	81	76	71	60
630	144	137	128	123	116	110	104	98	91	76
645	174	166	156	149	139	132	125	118	108	90
700	199	192	180	172	162	154	145	136	125	104

Time	1	2	3	4	5	6	7	8	9	10
April 2 1987 Array 1										
1530	0	0	0	0	0	0	0	0	0	0
1545	59	58	56	56	54	52	51	47	46	39
1600	125	122	118	118	114	109	106	101	97	83
1615	197	193	186	185	179	172	167	158	152	130
1630	264	259	250	248	240	230	224	210	202	174
1645	329	322	311	308	297	286	277	263	252	215
1700	391	382	369	365	352	339	329	311	299	255
1715	448	439	424	418	403	387	377	356	341	292
1730	501	490	473	466	449	432	419	397	380	324
1745	548	536	516	509	490	471	456	432	414	352
1800	589	574	553	544	523	502	486	460	440	373
April 2 1987 Array 1										
1815	0	0	0	0	0	0	0	0	0	0
1830	34	32	30	28	27	25	23	21	19	15
1845	66	62	58	54	50	47	44	40	36	28
1900	100	95	87	81	76	70	66	60	55	43
1915	133	125	115	106	99	92	86	79	71	56
1930	167	157	143	132	122	113	106	98	88	69
1945	203	190	174	161	149	138	129	119	107	84
2000	244	228	208	194	179	166	156	144	130	103
2015	288	270	247	230	213	198	186	173	157	125
1630	333	311	285	267	247	231	217	201	183	147
1645	376	353	324	303	282	263	248	230	210	169
1700	421	395	363	340	317	296	279	259	238	192
April 3 1987 Array 1										
600	0	0	0	0	0	0	0	0	0	0
617	73	71	68	67	64	61	58	55	53	45
630	125	121	116	114	109	104	100	94	90	77
645	174	170	162	159	152	145	140	132	125	107
April 3 1987 Array 1										
815	0	0	0	0	0	0	0	0	0	0
830	87	86	82	81	78	75	72	68	66	57
845	165	162	156	153	147	141	137	129	124	107
900	232	228	220	216	208	200	193	183	176	151
915	309	303	292	287	276	265	257	243	234	200
930	399	391	377	369	355	342	331	314	301	258
945	490	481	462	454	437	420	407	306	370	317
1000	579	568	546	537	517	497	482	457	439	376
1015	677	663	639	627	603	580	564	535	514	441
1030	767	752	725	713	686	659	641	608	584	501
1045	870	854	823	810	779	749	729	691	665	570
1100	966	948	913	899	865	832	809	767	739	633

Time	1	2	3	4	5	6	7	8	9	10
1115	1070	1051	1013	997	958	922	898	850	820	702
1130	1181	1159	1117	1090	1057	1017	980	938	905	775
1145	1280	1257	1212	1194	1147	1104	1074	1017	982	841
1200	1369	1345	1297	1278	1227	1182	1151	1089	1052	900

April 4 1987 Array 1

515	0	0	0	0	0	0	0	0	0	0
530	69	67	64	62	60	57	56	52	51	44
545	129	125	120	117	112	107	105	97	94	80
600	187	183	175	171	163	157	153	143	137	117
615	242	237	227	221	212	203	197	185	177	150
630	300	294	282	274	263	252	244	229	220	186
645	361	354	340	331	317	304	295	276	265	225
700	419	411	395	384	368	354	343	321	308	262
717	484	474	456	445	426	409	396	372	357	303
730	536	526	505	493	472	453	440	413	396	337
745	596	585	562	549	526	506	490	461	442	375
800	652	640	616	601	577	554	537	505	484	412
815	716	703	676	661	634	610	591	557	534	454
830	783	770	741	725	696	669	649	611	586	498
845	849	834	803	786	854	726	704	663	637	541
900	911	895	862	844	810	779	757	713	685	582
915	979	961	926	907	871	838	814	767	737	626
930	1044	1025	988	968	930	895	869	819	787	669
945	1113	1093	1054	1033	992	955	927	874	841	715
1000	1172	1151	1110	1089	1046	1007	978	922	887	754

April 10 1987 Array 2

915	0	0	0	0	0	0	0	0	0	0
930	60	57	53	51	48	47	44	41	38	29
945	112	106	98	94	88	85	80	74	69	52
1000	158	148	137	130	122	117	110	102	93	69
1015	202	189	173	163	153	145	137	126	114	84
1030	245	229	209	197	183	174	164	150	139	99
1045	282	264	241	226	210	198	186	171	153	111

April 11 1987 Array 2

545	0	0	0	0	0	0	0	0	0	0
600	76	74	71	68	66	63	61	57	53	43
615	147	143	137	133	127	122	117	108	101	81
630	205	200	193	188	179	172	165	152	142	112
645	253	248	238	232	222	212	204	188	175	137
700	321	315	304	296	282	271	260	240	224	175
715	395	383	374	365	348	334	321	296	276	217
730	453	444	429	419	400	383	368	339	317	248
745	499	490	474	462	442	425	408	375	350	274

Time	1	2	3	4	5	6	7	8	9	10
April 11 1987 Array 2										
815	0	0	0	0	0	0	0	0	0	0
830	60	59	58	56	55	54	51	48	45	36
845	112	110	108	106	103	100	96	89	84	66
April 11 1987 Array 2										
1045	0	0	0	0	0	0	0	0	0	0
1100	61	60	58	58	55	55	52	48	46	37
1115	130	128	124	123	118	115	110	104	98	78
1130	203	199	194	191	184	179	172	163	153	122
1145	271	266	259	256	247	240	231	0	204	163
1200	332	326	317	313	303	294	283	0	250	200
1215	389	381	370	366	354	343	331	0	292	234
1230	456	447	434	429	415	402	388	0	342	274
1245	524	514	499	493	477	462	446	0	393	315
1300	596	584	567	560	542	525	507	0	447	358
April 11 1987 Array 2										
1330	0	0	0	0	0	0	0	0	0	0
1345	72	70	67	67	65	64	61	56	54	43
1400	137	133	129	128	124	121	116	109	103	83
1415	197	193	187	184	179	174	168	158	149	120
1430	258	253	245	242	235	229	220	207	195	156
1445	317	310	301	297	288	280	270	254	239	191
1500	374	367	356	351	341	331	320	0	282	226
1515	434	425	412	407	394	383	370	0	326	261
1530	489	479	465	459	445	432	417	0	367	293
April 11 1987 Array 2										
1815	0	0	0	0	0	0	0	0	0	0
1830	67	65	63	62	59	57	55	51	47	37
1845	135	131	127	125	119	116	111	103	96	75
1900	203	197	190	186	178	172	164	153	143	112
1915	268	260	250	245	234	226	216	201	188	147
1930	349	339	326	319	304	294	282	262	245	192
1945	438	425	408	399	380	366	351	326	306	242
2000	527	512	491	479	457	439	421	392	367	292
2015	605	587	562	549	523	504	483	448	421	334
2030	692	671	643	627	597	575	551	512	480	382
2045	764	741	710	693	660	635	608	565	530	421
2100	838	812	778	758	722	695	666	618	580	460
2115	919	890	851	830	791	761	729	676	635	503
2130	989	957	915	892	849	817	783	725	682	540
2145	1074	1039	992	967	921	886	849	786	740	587
2200	1156	1118	1067	1040	990	952	912	845	796	632
2215	1228	1183	1134	1105	1052	1011	969	898	845	672

Time	1	2	3	4	5	6	7	8	9	10
April 16 1987 Array 3										
2100	68	64	58	54	49	46	43	38	27	12
2115	110	103	93	87	80	74	70	62	45	23
2130	151	142	128	119	109	102	96	86	63	34
2145	193	182	164	153	141	133	125	112	83	47
2200	230	217	196	183	169	158	149	133	99	55
2215	272	256	231	215	199	186	176	157	117	66
2230	310	292	264	246	228	213	201	180	134	75
2245	351	330	298	278	257	241	228	204	152	86
April 17 1987 Array 3										
1900	0	0	0	0	0	0	0	0	0	0
1915	50	49	46	45	42	40	39	36	29	17
1930	99	96	90	87	83	79	70	76	57	33
1945	148	143	134	130	123	118	113	104	84	49
2000	201	196	183	177	168	161	154	142	115	66
April 17 1987 Array 3										
2015	0	0	0	0	0	0	0	0	0	0
2030	45	42	40	38	36	34	33	30	23	12
2045	87	82	76	72	68	65	62	57	43	23
2100	127	119	110	104	98	93	88	81	60	32
2115	174	163	150	141	133	126	120	110	83	45
2130	218	204	186	175	164	156	148	136	101	55
2145	266	249	227	214	200	189	180	165	125	68
2200	313	294	268	252	237	224	214	196	149	82
2215	362	340	310	293	275	261	249	228	174	97
2230	412	388	354	334	314	298	284	261	200	112
2245	458	432	395	373	351	333	318	292	224	127
2300	498	469	429	406	382	362	346	317	243	137
2315	545	514	470	445	419	397	379	349	268	151
2330	594	560	512	485	456	433	414	380	292	166
2345	631	595	543	514	484	459	438	402	308	175
2400	673	636	581	551	519	492	470	431	331	190
April 18 1987 Array 3										
915	0	0	0	0	0	0	0	0	0	0
930	79	78	74	73	70	69	67	61	55	39
945	149	149	143	140	135	131	127	117	104	74
1000	207	206	198	195	188	183	177	164	144	101
1015	263	263	253	249	240	233	226	209	183	128

Time	1	2	3	4	5	6	7	8	9	10
April 18 1987 Array 3										
1100	0	0	0	0	0	0	0	0	0	0
1115	57	56	55	55	53	51	50	47	40	28
1130	127	127	123	121	118	114	111	105	90	62
1145	196	195	189	187	181	175	171	161	138	96
1200	266	264	255	252	244	237	231	218	188	131
1215	339	337	325	321	311	302	294	278	239	166
1232	417	414	400	396	383	371	362	345	294	205
1245	473	470	454	449	434	422	411	392	334	231
1300	529	526	508	502	486	472	460	439	373	257
1315	600	596	575	569	550	535	521	502	423	287
1330	670	667	642	636	615	597	583	561	473	318
1345	744	740	713	706	683	663	647	625	525	351
1400	819	815	785	776	751	729	712	690	578	384
April 18 1987 Array 3										
1845	0	0	0	0	0	0	0	0	0	0
1900	65	63	60	59	57	55	53	49	42	25
1915	135	133	127	124	119	115	111	103	88	54
1930	207	205	195	191	183	177	171	159	136	85
1945	283	280	267	261	251	242	234	217	187	118
2000	362	358	340	333	319	308	299	276	239	149
2015	437	432	410	402	385	371	360	334	289	180
2030	517	511	485	475	455	438	425	394	341	214
2045	603	597	567	555	531	512	497	459	399	256
2100	691	684	649	636	608	587	569	525	456	297
May 2 1987 Array 0										
2115	0	0	0	0	0	0	0	0	0	0
2130	50	49	46	45	43	42	39	39	35	31
2145	106	103	97	94	91	87	83	81	74	65
2200	164	160	152	147	142	136	130	126	117	102
2215	221	215	205	198	192	183	176	170	158	138
2230	269	263	250	241	234	223	214	207	192	167
2245	312	305	290	279	270	258	247	239	221	193
2300	350	343	326	313	302	208	276	267	246	214
2315	377	370	352	338	326	310	298	287	262	228
2330	408	401	382	367	354	337	323	312	283	246
2345	438	432	412	395	381	362	347	334	302	263
2400	465	461	439	421	406	385	369	356	319	278
May 8 1987 Array 0										
1800	361	355	338	328	318	306	293	286	266	236
1815	412	404	384	372	361	348	333	325	302	268
1830	463	452	431	417	405	390	373	364	338	300
1845	503	491	468	453	439	422	405	395	366	324

Time	1	2	3	4	5	6	7	8	9	10
1900	533	520	495	477	463	445	426	415	384	340
May 9 1987 Array 3										
1730	0	0	0	0	0	0	0	0	0	0
1745	0	60	57	56	55	53	51	50	47	42
1800	0	116	112	110	108	103	100	97	92	82
1815	0	166	161	158	155	148	143	139	132	117
May 9 1987 Array 0										
1900	0	0	0	0	0	0	0	0	0	0
1915	0	24	23	23	23	21	21	21	19	16
1930	0	57	55	53	53	50	49	47	43	37
1945	0	87	83	80	78	74	72	70	64	55
2000	0	121	115	111	108	102	100	95	88	76
2015	0	159	152	145	141	133	130	124	114	99
2030	0	192	182	173	168	159	155	148	136	118
2045	0	221	209	199	193	183	177	170	155	134
May 10 1987 Array 0										
1645	0	0	0	0	0	0	0	0	0	0
1700	55	52	48	46	44	42	41	39	37	32
1715	88	84	78	75	73	69	67	63	60	52
May 10 1987 Array 0										
1945	0	0	0	0	0	0	0	0	0	0
2000	53	51	49	46	45	43	41	39	38	33
2015	119	113	108	103	100	952	92	87	85	73
2030	190	182	174	166	161	154	149	141	141	118
2045	261	249	238	227	220	210	204	193	191	162
2100	314	298	285	272	263	251	243	231	226	193

Table 3. Temperature data from the field experiment.

Raw data consists of temperatures measured at heights of 1 m and 15 m and the time of their measurement. Richardson numbers were calculated using equations (2,3) and the velocity data simultaneously gathered. "Ave. vel." (m/sec) are averages of anemometer 1 and anemometer 8 values for the appropriate 15 minute velocity data interval (see Table 2). Specific heat at constant pressure (Cp) for all calculations is 1004 J/kg°K. Temperatures listed are °C. "Thermal neutrality" is defined as when $-.010 \leq Ri \leq .010$ (e.g. Thom [1975]).

Time	Ave. vel.	1 m temp.	15 m temp.	Ri	Condition
April 1 1987 Array 1					
1737	4.88	22.3	22.2	.008	neutral
1747	5.57	21.3	21.3	.013	stable
1803	5.03	19.7	20.1	.057	stable
1809	5.03	19.2	19.7	.068	stable
1817	4.80	18.7	19.5	.086	stable
1828	4.80	18.1	19.5	.142	stable
1834	4.27	17.9	19.6	.267	extremely stable
1842	4.27	17.7	18.6	.151	stable
April 2 1987 Array 1					
1534	8.57	26.2	24.0	-.224	unstable
1540	8.57	26.0	24.2	-.180	unstable
1551	9.65	25.4	23.6	-.183	unstable
1557	9.65	25.1	23.4	-.172	unstable
1602	10.34	24.9	23.4	-.10	unstable
1618	9.57	24.1	22.9	-.078	unstable
1631	9.50	23.6	22.4	-.117	unstable
1647	8.88	22.9	21.9	-.072	unstable
1703	8.26	22.4	21.7	-.061	unstable
1718	7.65	21.3	21.1	-.007	neutral
1722	7.65	21.3	21.0	-.018	unstable
1727	7.65	21.1	20.9	-.007	neutral
1732	6.73	21.1	20.9	-.007	neutral
1742	6.73	20.8	20.8	.015	stable
1747	5.73	20.4	20.5	.022	stable
1752	5.73	20.1	20.4	.041	stable
April 2 1987 Array 1					
1819	4.65	18.9	20.1	.123	stable
1833	4.34	18.3	19.6	.132	stable
1835	4.34	18.4	19.7	.132	stable
1843	4.34	19.3	20.3	.104	stable
1847	4.57	18.7	19.8	.100	stable
1852	4.57	18.5	19.3	.076	stable
1902	4.42	17.7	19.1	.124	stable
1908	4.42	18.0	19.6	.140	stable
1917	4.49	17.8	19.2	.110	stable
1923	4.49	17.4	19.2	.138	stable

Time	Ave. vel.	1 m temp.	15 m temp.	Ri	Condition
1933	4.80	17.6	19.0	.110	stable
1939	4.80	17.6	18.8	.096	stable
1947	5.49	17.4	18.8	.099	stable
1955	5.49	17.1	18.3	.086	stable
2002	6.03	17.1	18.4	.104	stable
2018	6.03	16.7	18.0	.083	stable
2033	5.96	16.0	17.3	.118	stable
2042	5.96	16.9	17.9	.093	stable
2048	6.11	16.4	17.4	.074	stable

April 3 1987 Array 1

602	9.10	11.5	12.0	.044	Stable
610	9.10	11.4	11.7	.030	Stable
619	8.49	11.6	11.5	.003	Neutral
622	8.49	11.8	11.7	.003	Neutral
625	8.49	12.0	11.8	-.005	Neutral
632	7.11	12.4	12.1	-.021	Unstable
640	7.11	12.9	12.4	-.047	Unstable

April 3 1987 Array 1

817	12.34	12.5	13.6	.062	stable
824	12.34	12.9	11.7	-.053	unstable
828	12.34	12.7	11.7	-.049	unstable
832	11.11	12.6	11.5	-.059	unstable
838	11.11	12.1	10.9	-.065	unstable
847	9.73	12.2	10.7	-.136	unstable
852	9.73	12.0	10.9	-.096	unstable
902	10.95	12.1	10.6	-.084	unstable
911	10.95	11.6	9.9	-.096	unstable
917	12.8	11.0	10.1	-.039	unstable
922	12.8	11.8	10.0	-.084	unstable
932	12.95	12.6	10.3	-.109	unstable
941	12.95	13.5	10.6	-.139	unstable
947	12.72	13.5	10.1	-.182	unstable
954	12.72	14.2	11.4	-.148	unstable
1002	13.95	14.0	11.2	-.122	unstable
1013	13.95	13.4	10.7	-.118	unstable
1021	12.95	14.1	11.6	-.147	unstable
1032	14.72	13.9	11.4	-.109	unstable
1047	13.65	14.0	10.7	-.145	unstable
1103	14.8	14.1	10.5	-.146	unstable
1117	15.72	13.5	10.3	-.109	unstable
1135	14.11	14.7	11.4	-.145	unstable
1148	12.8	14.5	11.5	-.177	unstable
1202	12.8	15.8	12.4	-.201	unstable

Time	Ave. vel.	1 m temp.	15 m temp.	Ri	Condition
April 4 1987 Array 1					
518	9.72	6.7	6.9	.021	stable
533	8.49	6.7	6.8	.018	stable
538	8.49	6.8	7.0	.026	stable
547	8.42	6.8	6.9	.027	stable
553	8.42	6.9	7.0	.027	stable
602	7.88	7.0	7.0	.014	neutral
607	7.88	7.1	7.0	.004	neutral
611	7.88	7.3	7.2	.004	neutral
617	8.26	7.5	7.5	.012	stable
622	8.26	7.8	7.4	-.023	unstable
627	8.26	7.9	7.5	-.023	unstable
632	8.73	8.0	7.6	-.023	unstable
637	8.73	8.2	7.7	-.032	unstable
641	8.73	8.3	7.7	-.040	unstable
648	8.34	8.5	7.9	-.046	unstable
652	8.34	8.8	8.0	-.066	unstable
657	8.34	9.0	8.2	-.066	unstable
702	8.30	9.2	8.3	-.083	unstable
707	8.30	9.3	8.4	-.083	unstable
712	8.30	9.4	8.5	-.083	unstable
718	8.68	9.6	8.5	-.100	unstable
722	8.67	9.6	8.5	-.100	unstable
727	8.67	10.1	8.8	-.120	unstable
732	8.73	10.1	8.7	-.145	unstable
738	8.73	10.3	9.0	-.133	unstable
747	8.11	10.7	9.2	-.155	unstable
753	8.11	11.3	9.5	-.189	unstable
758	8.11	11.3	9.8	-.155	unstable
802	9.34	11.5	9.5	-.214	unstable
810	9.34	11.5	9.7	-.191	unstable
817	9.73	11.6	9.9	-.156	unstable
825	9.73	12.1	10.6	-.136	unstable
832	9.49	13.2	11.1	-.170	unstable
839	9.49	12.8	10.7	-.170	unstable
846	9.03	13.0	10.7	-.247	unstable
852	9.03	13.3	11.1	-.235	unstable
902	9.80	13.9	11.7	-.179	unstable
909	9.80	13.6	11.4	-.179	unstable
917	9.42	14.0	11.5	-.233	unstable
921	9.42	14.6	12.2	-.223	unstable
932	9.96	14.2	11.4	-.231	unstable
947	8.65	15.3	12.7	-.324	unstable
April 10 1987 Array 2					
1901	6.26	23.2	23.8	.059	stable
1904	6.26	23.1	23.6	.051	stable
1907	6.26	23.0	23.6	.060	stable
1910	6.26	22.7	23.3	.060	stable
1913	6.26	23.0	23.5	.051	stable

Time	Ave. vel.	1 m temp.	15 m temp.	Ri	Condition
April 10 1987 Array 2					
2118	8.19	19.4	20.3	.049	stable
2126	8.19	19.2	20.2	.054	stable
2133	6.95	19.1	20.2	.058	stable
2148	6.11	18.3	19.6	.074	stable
2203	5.65	17.8	19.7	.087	stable
2217	5.57	17.3	19.5	.109	stable
2233	4.88	17.0	19.3	.156	stable
April 11 1987 Array 2					
548	10.65	14.6	14.9	.021	stable
554	10.65	14.6	14.9	.021	stable
602	9.80	14.5	14.8	.019	stable
610	9.80	14.3	14.7	.024	stable
617	8.26	14.3	14.7	.046	stable
633	6.88	14.1	14.5	.059	stable
640	6.88	14.0	14.6	.081	stable
646	9.65	14.4	14.8	.036	stable
702	10.42	14.1	14.4	.024	stable
717	8.19	14.0	14.2	.025	stable
732	6.73	14.5	14.7	.051	stable
April 11 1987 Array 2					
817	8.73	16.5	15.2	-.130	unstable
824	8.73	16.8	15.3	-.153	unstable
832	7.57	17.2	15.5	-.202	unstable
840	7.57	17.4	15.7	-.201	unstable
April 11 1987 Array 2					
1046	8.80	24.0	20.9	-.281	unstable
1052	8.80	24.8	21.5	-.299	unstable
1102	10.03	23.4	20.6	-.256	unstable
1117	10.57	23.3	20.4	-.234	unstable
April 11 1987 Array 2					
1332	10.26	27.3	23.6	-.232	unstable
1347	9.50	27.0	23.4	-.379	unstable
1402	8.80	27.1	23.5	-.439	unstable
1417	8.88	28.1	24.7	-.353	unstable
1432	8.57	26.6	23.7	-.299	unstable

Time	Ave. vel.	1 m temp.	15 m temp.	Ri	Condition
April 11 1987 Array 2					
1631	7.80	22.1	20.7	-.138	unstable
April 11 1987 Array 2					
1816	9.49	20.3	19.5	-.044	unstable
1832	9.65	19.9	19.3	-.031	unstable
1840	9.65	19.4	18.9	-.024	unstable
1846	9.49	19.1	18.8	-.009	neutral
1851	9.49	18.8	18.4	-.014	unstable
1857	9.49	18.4	18.1	-.009	neutral
1901	9.11	18.3	18.0	-.010	neutral
1905	9.11	18.1	17.9	-.004	neutral
1910	9.11	17.9	17.8	.002	neutral
1914	9.11	17.6	17.4	-.004	neutral
1919	11.34	17.4	17.1	-.007	neutral
1921	11.34	17.2	17.0	-.003	neutral
1924	11.34	16.9	16.6	-.007	neutral
1927	11.34	16.8	16.5	-.007	neutral
1932	12.18	16.6	16.4	-.002	neutral
1936	12.18	16.5	16.3	-.002	neutral
1942	12.18	16.4	16.2	-.002	neutral
1946	12.34	16.2	16.0	-.002	neutral
1950	12.34	16.2	16.0	-.002	neutral
1953	12.34	16.1	15.9	-.002	neutral
1958	12.34	16.0	15.8	-.002	neutral
2003	10.72	15.8	15.7	.001	neutral
2008	10.72	15.7	15.6	.001	neutral
2013	10.72	15.6	15.5	.001	neutral
2017	12.03	15.3	15.2	.001	neutral
2022	12.03	15.2	15.1	.001	neutral
2028	12.03	15.0	14.9	.001	neutral
2033	10.03	14.9	14.8	.002	neutral
2038	10.03	14.9	14.8	.002	neutral
2042	10.03	14.9	14.9	.007	neutral
2048	10.18	14.9	14.8	.001	neutral
2052	10.18	14.8	14.8	.006	neutral
2058	10.18	14.6	14.6	.006	neutral
2103	11.11	14.6	14.5	.001	neutral
2108	11.11	14.6	14.6	.005	neutral
2114	11.11	14.5	14.4	.001	neutral
2119	9.57	14.4	14.5	.010	neutral
2124	9.57	14.3	14.4	.010	neutral
2129	9.57	14.2	14.3	.010	neutral
2133	11.64	14.4	14.5	.008	neutral
2138	11.64	14.3	14.4	.008	neutral
2143	11.64	14.3	14.5	.011	stable
2148	11.26	14.1	14.3	.012	stable
2154	11.26	14.0	14.0	.005	neutral
2202	10.03	14.0	14.2	.017	stable
2208	10.03	13.9	14.0	.012	stable

Time	Ave. vel.	1 m temp.	15 m temp.	Ri	Condition
April 16 1987 Array 3					
2102	5.49	23.2	25.1	.103	stable
2118	5.42	22.4	24.4	.121	stable
2132	5.65	22.6	24.5	.128	stable
2148	4.88	22.3	24.6	.153	stable
2203	5.49	21.7	23.4	.094	stable
2218	5.11	21.8	23.1	.102	stable
2233	5.42	21.1	22.6	.093	stable
April 17 1987 Array 3					
1016	7.35	30.2	27.6	-1.575	extr. unstable
1027	7.35	30.4	27.4	-1.830	extr. unstable
April 17 1987 Array 3					
1901	7.03	24.0	24.4	.044	stable
1905	7.03	23.7	24.0	.035	stable
1908	7.03	23.8	24.3	.052	stable
1911	7.03	23.3	23.7	.044	stable
1916	6.80	22.9	23.5	.053	stable
1920	6.80	23.0	23.6	.053	stable
1925	6.80	22.6	23.2	.053	stable
1931	6.80	22.7	23.2	.046	stable
1935	6.80	21.9	22.9	.082	stable
1939	6.80	22.4	23.2	.067	stable
1943	6.80	21.7	22.8	.089	stable
1947	7.42	21.8	22.8	.082	stable
1951	7.42	21.7	22.7	.082	stable
April 17 1987 Array 3					
2016	6.19	20.8	21.8	.082	stable
2033	5.73	20.2	21.4	.096	stable
2047	5.34	19.7	20.9	.085	stable
2103	6.26	19.5	21.4	.105	stable
2118	5.80	19.5	21.2	.095	stable
2133	6.34	19.1	20.6	.077	stable
2148	6.42	19.7	20.9	.086	stable
2202	6.65	19.4	20.6	.077	stable
2218	6.80	19.3	20.3	.066	stable
2233	6.34	19.1	19.9	.068	stable
2249	5.42	18.7	19.8	.089	stable
2303	6.42	18.6	19.6	.073	stable
2319	6.65	18.3	19.1	.054	stable
2333	4.96	17.8	18.7	.074	stable
2348	5.88	17.5	18.1	.069	stable

Time	Ave. vel.	1 m temp.	15 m temp.	Ri	Condition
April 18 1987 Array 3					
632	5.19	13.7	15.2	.106	stable
640	5.19	13.9	15.4	.106	stable
April 18 1987 Array 3					
916	11.19	18.8	16.7	-.106	unstable
931	10.11	18.6	16.5	-.168	unstable
947	8.50	19.8	17.2	-.319	unstable
952	8.50	19.2	17.4	-.215	unstable
1002	8.19	21.5	18.3	-.393	unstable
April 18 1987 Array 3					
1102	8.42	23.6	20.0	-.523	unstable
1117	10.26	23.1	19.6	-.376	unstable
1132	10.03	22.4	19.3	-.286	unstable
1147	10.19	23.8	20.7	-.285	unstable
1202	10.65	23.9	20.3	-.335	unstable
1218	10.26	23.5	20.1	-.532	unstable
1234	9.56	25.1	21.0	-.566	unstable
1248	8.34	24.7	22.2	-.426	unstable
1303	10.73	26.8	23.7	-.674	unstable
1319	10.34	25.8	22.7	-.384	unstable
1333	11.03	26.1	22.3	-.568	unstable
1347	11.19	27.6	23.4	-.628	unstable
April 18 1987 Array 3					
1846	9.19	17.3	16.9	-.017	unstable
1851	9.19	18.7	17.6	-.064	unstable
1901	9.96	18.6	17.1	-.091	unstable
1908	9.96	16.2	15.9	-.011	unstable
1912	9.96	16.0	15.7	-.011	unstable
1917	10.26	15.7	15.4	-.011	unstable
1923	10.26	15.3	15.1	-.004	neutral
1932	10.72	14.8	14.5	-.009	neutral
1940	10.72	14.6	15.1?	.035?	stable?
1947	11.03	14.4	14.1	-.007	neutral
2002	10.65	13.9	13.7	-.004	neutral
2017	11.18	13.5	13.2	-.007	neutral
2033	12.03	13.1	12.9	-.003	neutral
2048	12.26	12.5	12.3	-.002	neutral
2103	12.26	12.2	12.1	.002	neutral

Time	Ave. vel.	1 m temp.	15 m temp.	Ri	Condition
May 2 1987 Array 0 (Bare Playa)					
2116	7.27	17.8	18.2	.069	stable
2132	7.96	17.6	17.9	.037	stable
2147	8.34	17.0	17.2	.032	stable
2202	8.19	16.7	16.9	.032	stable
2217	6.96	16.4	16.7	.056	stable
2232	6.19	15.8	16.2	.068	stable
2247	5.50	15.6	16.0	.080	stable
2302	4.04	15.1	15.5	.142	stable
2318	4.73	14.7	15.5	.321	extremely stable
2333	4.42	14.4	15.0	.158	stable
2347	4.19	14.5	15.3	.419	extremely stable
May 8 1987 Array 0 (Bare Playa)					
1802	7.34	21.6	21.7	.026	stable
1817	7.34	22.2	22.0	-.007	neutral
1833	5.88	21.8	21.7	.006	neutral
1847	4.27	21.0	21.0	.020	stable
May 10 1987 Array 0 (Bare Playa)					
1651	7.65	22.4	23.0	.047	stable
1702	4.81	23.3	23.6	.075	stable
May 10 1987 Array 0 (Bare Playa)					
1947	7.49	23.0	23.8	.077	stable
2001	9.19	22.9	23.7	.049	stable
2017	10.03	22.4	22.9	.037	stable
2033	9.88	21.5	21.9	.026	stable
2048	7.42	20.8	21.1	.032	stable
2103	6.03	20.7	21.0	.041	stable

Table 4. **Configuration of wind tunnel turbulence generators.**

Row	Distance from flow straightener (m)	Hex nut diam. (in)	# in row
1	.07	5/8	10
2	.17	5/8	10
3	.28	1/2	10
4	.39	5/8	10
5	.51	1/2	13
6	.63	5/8	10
7	.77	5/8	10
8	.91	3/4	9

Table 5. Wind speed data from the wind tunnel experiments.

This table is divided into 1/10 scale and 1/20 scale sections. The first column in each section lists the heights of the pitot-tubes of the boundary layer rake above the floor of the tunnel. Note that port 11 was non-functional throughout this experiment. The remaining columns in each section represent an average profile data set of three identical runs at a particular freestream velocity over a particular model array at either 1/10 or 1/20 scale. For example, "Uf=6 ave." lists the average results of three wind tunnel runs with the wind tunnel freestream speed = 6.0 m/sec, and no model roughness element array present. "A1 1/10 6" lists the average results of three wind tunnel runs over the 1/10 scale model of array 1 with the wind tunnel freestream speed = 6.0 m/sec.

Lucerne 1/10

	height (m)	Uf=6 ave.	Uf=9 ave.	Uf=12 ave.	Uf= 18 ave.	Uf=24 ave.	A1 1/10 6	A1 1/10 9	A1 1/10 12
1	.575	6.050	9.077	12.060	17.937	24.103	6.033	9.053	11.983
2	.4815	5.947	8.943	11.920	17.793	23.797	5.993	9.023	11.993
3	.4105	6.010	8.957	11.960	17.913	23.893	5.983	8.953	11.950
4	.352	6.000	9.007	11.977	18.003	24.007	5.960	8.973	11.997
5	.299	5.997	9.047	12.040	18.087	24.070	5.977	9.010	12.037
6	.2535	6.010	9.063	12.073	18.130	24.090	6.007	9.013	12.037
7	.2155	6.000	9.023	12.047	18.070	24.023	5.960	8.990	11.983
8	.1825	6.017	9.017	12.003	18.003	23.987	5.950	8.943	11.937
9	.1545	5.913	8.913	11.907	17.770	23.667	5.887	8.807	11.783
10	.1315	5.843	8.813	11.680	17.530	23.380	5.710	8.600	11.513
11	.1115	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	.0945	5.520	8.413	11.143	16.820	22.413	5.457	8.187	10.910
13	.0805	5.417	8.123	10.863	16.433	21.893	5.287	7.907	10.627
14	.0685	5.260	7.913	10.543	16.087	21.490	5.043	7.793	10.390
15	.0575	5.077	7.763	10.340	15.657	20.993	4.873	7.517	10.090
16	.0495	4.997	7.567	10.057	15.133	20.590	4.790	7.367	9.907
17	.042	4.823	7.213	9.823	14.780	20.110	4.713	7.170	9.670
18	.0355	4.740	7.203	9.570	14.643	19.630	4.570	6.997	9.450
19	.03	4.527	6.977	9.420	14.430	19.157	4.483	6.793	9.223
20	.0255	4.510	6.707	9.180	13.987	18.877	4.380	6.673	9.007
21	.0215	4.357	6.627	8.913	13.790	18.507	4.250	6.533	8.830
22	.0185	4.267	6.487	8.840	13.363	18.017	4.173	6.403	8.697
23	.0165	4 230	6.297	8.637	13.247	17.737	4.080	6.293	8.553
24	.0135	4.060	6.197	8.360	13.030	17.340	4.030	6.160	8.383
25	.0115	4.033	6.063	8.127	12.673	17.100	3.850	6.030	8.257
26	.0095	3.917	6.007	8.027	12.460	16.823	3.863	5.943	8.030
27	.007	3.853	5.833	7.863	12.080	16.457	3.773	5.823	7.927
28	.005	3.597	5.587	7.487	11.760	15.653	3.663	5.640	7.677
29	.003	3.473	5.317	7.177	11.240	15.110	3.427	5.407	7.473
30	.001	3.230	4.960	6.727	10.450	14.273	3.257	5.120	6.967

Lucerne 1/10

	A1 1/10 18	A1 1/10 24	A2 1/10 6	A2 1/10 9	A2 1/10 12	A2 1/10 18	A2 1/10 24	A3 1/10 6	A3 1/10 9
1	17.923	24.017	6.010	9.030	11.977	17.947	24.057	6.013	9.027
2	18.043	24.023	5.993	9.030	12.017	18.010	23.947	5.993	8.987
3	17.960	23.937	5.963	8.967	11.967	17.967	23.933	6.007	8.990
4	18.007	23.960	6.010	8.977	11.970	18.017	23.997	5.963	9.013
5	18.053	24.017	6.023	9.023	11.993	18.043	24.060	6.017	9.067
6	18.073	24.033	6.073	9.030	11.973	18.047	24.033	5.970	9.040
7	17.983	23.910	6.000	9.013	11.950	17.960	23.967	6.010	8.983
8	17.907	23.780	6.017	8.990	11.927	17.873	23.877	5.957	8.950
9	17.660	23.470	5.850	8.837	11.673	17.557	23.540	5.850	8.823
10	17.383	23.100	5.643	8.593	11.310	17.107	22.990	5.720	8.590
11	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	16.623	22.010	5.150	7.770	10.193	15.590	21.000	5.143	7.803
13	16.157	21.413	4.847	7.313	9.700	14.750	20.130	4.843	7.223
14	15.670	20.923	4.657	7.090	9.327	14.333	19.423	4.377	6.597
15	15.387	20.437	4.443	6.777	8.973	13.863	18.623	4.120	6.090
16	14.987	19.937	4.283	6.523	8.677	13.380	18.007	3.667	5.640
17	14.707	19.547	4.197	6.353	8.457	13.003	17.537	3.307	5.047
18	14.313	19.150	4.110	6.147	8.223	12.543	17.070	3.010	4.593
19	13.943	18.603	3.843	5.950	7.933	12.070	16.387	2.753	4.117
20	13.790	18.323	3.670	5.730	7.723	11.723	15.873	2.523	3.813
21	13.463	17.993	3.563	5.437	7.317	11.213	15.310	2.033	3.363
22	13.200	17.640	3.253	5.183	7.050	10.800	14.647	1.930	3.053
23	12.970	17.290	3.317	5.063	6.883	10.507	14.160	1.787	2.740
24	12.710	17.010	3.163	4.833	6.477	10.177	13.770	1.623	2.490
25	12.607	16.817	2.947	4.720	6.430	9.740	13.373	1.543	2.487
26	12.403	16.603	2.900	4.547	6.180	9.520	12.940	1.317	2.213
27	12.173	16.353	2.823	4.433	6.073	9.313	12.710	1.353	2.183
28	11.890	15.853	2.637	4.270	5.760	8.963	12.297	1.147	1.910
29	11.287	15.330	2.517	4.103	5.583	8.670	11.770	0.807	1.487
30	10.793	14.503	2.393	3.843	5.293	8.233	11.317	0.630	1.213

Lucerne 1/10

	A3 1/10 12	A3 1/10 18	A3 1/10 24	A0 (mas) all	A1 1/10 all	A2 1/10 all	A3 1/10 all
1	12.017	18.047	23.977	13.845	13.817	13.811	13.816
2	12.013	17.987	24.020	13.680	13.800	13.726	13.800
3	11.977	17.950	23.947	13.747	13.759	13.741	13.774
4	12.023	17.997	24.003	13.799	13.775	13.793	13.800
5	12.037	18.040	24.063	13.848	13.819	13.839	13.845
6	12.017	18.030	24.047	13.873	13.840	13.859	13.821
7	11.970	17.937	23.950	13.833	13.778	13.811	13.770
8	11.930	17.883	23.833	13.805	13.717	13.785	13.711
9	11.650	17.557	23.530	13.634	13.546	13.559	13.482
10	11.343	17.150	22.973	13.449	13.295	13.291	13.155
11	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	10.227	15.603	21.037	12.862	12.684	12.469	11.963
13	9.513	14.587	19.663	12.546	12.325	12.037	11.166
14	8.727	13.377	18.000	12.259	11.994	11.730	10.216
15	8.010	12.410	16.677	11.966	11.711	11.369	9.461
16	7.380	11.200	15.173	11.669	11.428	11.041	8.612
17	6.800	10.347	13.990	11.350	11.192	10.779	7.898
18	6.123	9.537	12.877	11.157	10.920	10.551	7.228
19	5.463	8.480	11.720	10.902	10.648	10.263	6.507
20	5.040	7.617	10.630	10.652	10.469	9.997	5.925
21	4.497	6.983	9.643	10.439	10.230	9.723	5.304
22	4.010	6.253	8.663	10.195	10.051	9.373	4.782
23	3.667	5.727	8.173	10.030	9.854	9.249	4.419
24	3.473	5.423	7.510	9.797	9.654	8.969	4.104
25	3.057	4.777	6.893	9.599	9.486	8.774	3.751
26	2.970	4.487	6.520	9.447	9.368	8.582	3.501
27	2.833	4.350	6.443	9.217	9.197	8.373	3.432
28	2.513	3.877	5.743	8.817	8.907	8.016	3.038
29	2.343	3.577	5.367	8.463	8.526	7.711	2.716
30	2.020	3.073	4.833	7.928	8.080	7.250	2.354

Lucerne 1/20

	height (m)	A1 1/20 6	A1 1/20 9	A1 1/20 12	A1 1/20 18	A1 1/20 24	A2 1/20 6	A2 1/20 9	A2 1/20 12
1	.575	5.940	8.947	12.027	17.800	23.737	6.040	9.050	11.947
2	.4815	6.050	9.033	12.037	18.030	24.043	6.003	8.960	12.007
3	.411	6.030	8.993	11.990	17.963	23.947	5.960	8.977	11.983
4	.3525	5.953	8.997	12.023	17.997	23.977	5.983	8.997	12.027
5	.299	5.960	9.000	12.033	18.030	23.997	5.980	9.007	12.023
6	.2535	6.020	9.047	12.080	18.067	24.063	6.050	9.057	12.047
7	.216	5.997	9.017	12.017	17.967	23.913	6.013	8.993	11.983
8	.1825	6.013	8.980	12.003	17.927	23.900	6.000	8.950	11.950
9	.155	5.903	8.887	11.847	17.750	23.667	5.923	8.880	11.763
10	.132	5.823	8.707	11.583	17.477	23.357	5.770	8.673	11.527
11	.112	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	.0945	5.493	8.183	10.993	16.557	22.293	5.520	8.273	10.923
13	.0805	5.353	8.027	10.640	16.147	21.683	5.273	7.973	10.590
14	.0685	5.263	7.817	10.413	15.797	21.170	5.067	7.730	10.270
15	.058	5.040	7.603	10.220	15.427	20.700	4.870	7.337	9.847
16	.0495	4.920	7.433	9.893	15.057	20.153	4.677	6.980	9.440
17	.0425	4.780	7.240	9.700	14.783	19.843	4.523	6.773	9.067
18	.0355	4.653	7.070	9.467	14.413	19.357	4.253	6.537	8.713
19	.03	4.537	6.883	9.247	14.090	18.977	4.183	6.207	8.327
20	.0255	4.413	6.817	9.077	13.823	18.600	3.930	6.037	7.973
21	.0215	4.383	6.587	8.797	13.563	18.247	3.793	5.810	7.743
22	.0185	4.163	6.497	8.680	13.160	17.800	3.580	5.523	7.420
23	.0165	4.030	6.327	8.443	12.907	17.507	3.567	5.457	7.360
24	.0135	3.980	6.190	8.333	12.710	17.133	3.437	5.343	7.093
25	.0115	3.903	5.970	8.083	12.417	16.723	3.353	5.140	6.853
26	.0095	3.897	5.877	7.957	12.263	16.380	3.243	4.987	6.647
27	.007	3.707	5.713	7.737	11.967	16.207	3.200	4.843	6.430
28	.005	3.687	5.597	7.510	11.607	15.707	3.073	4.647	6.207
29	.003	3.443	5.387	7.213	11.343	15.190	2.860	4.453	6.013
30	.001	3.260	5.020	6.910	10.767	14.557	2.803	4.223	5.690

Lucerne 1/20

	A2 1/20 18	A2 1/20 24	A1 1/20 all	A2 1/20 all	A3 1/20 6	A3 1/20 9	A3 1/20 12	A3 1/20 18	A3 1/20 24
1	17.907	23.917	13.690	13.751	6.023	8.930	11.883	17.960	23.803
2	18.007	24.017	13.839	13.803	5.987	9.043	12.030	18.023	24.037
3	17.940	23.943	13.785	13.765	6.027	9.010	11.973	17.967	23.940
4	17.993	24.000	13.789	13.801	5.973	8.967	11.987	17.990	24.000
5	18.010	24.017	13.804	13.811	5.990	8.997	12.023	18.017	24.027
6	18.057	24.027	13.855	13.850	6.017	9.030	12.060	18.077	24.037
7	17.960	23.943	13.782	13.780	6.007	8.993	11.990	17.977	23.913
8	17.910	23.880	13.765	13.741	6.010	8.990	11.960	17.910	23.863
9	17.680	23.630	13.611	13.589	5.930	8.883	11.780	17.653	23.513
10	17.377	23.287	13.389	13.347	5.780	8.733	11.510	17.313	23.123
11	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	16.547	22.077	12.704	12.670	5.513	8.233	10.937	16.493	22.027
13	16.050	21.567	12.370	12.310	5.370	7.920	10.670	16.090	21.477
14	15.670	20.910	12.092	11.955	5.197	7.680	10.377	15.687	20.867
15	14.967	20.117	11.798	11.520	4.960	7.490	10.017	15.083	20.207
16	14.367	19.140	11.491	11.059	4.767	7.230	9.510	14.360	19.167
17	13.727	18.583	11.269	10.746	4.500	6.697	9.017	13.633	18.053
18	13.320	17.780	10.992	10.339	4.180	6.327	8.407	12.733	16.840
19	12.757	17.110	10.747	9.983	3.777	5.827	7.790	11.640	15.657
20	12.430	16.593	10.546	9.671	3.507	5.437	7.210	11.030	14.510
21	11.883	16.073	10.315	9.396	3.373	4.887	6.763	9.953	13.297
22	11.660	15.467	10.060	9.030	3.077	4.623	6.077	9.200	12.400
23	11.300	15.077	9.843	8.874	2.883	4.153	5.717	8.853	11.643
24	10.967	14.677	9.669	8.652	2.730	3.953	5.283	8.173	10.770
25	10.600	14.393	9.419	8.431	2.450	3.590	4.817	7.703	10.157
26	10.293	13.890	9.275	8.206	2.200	3.403	4.383	7.043	9.347
27	9.940	13.563	9.066	8.001	2.053	2.973	4.077	6.533	8.780
28	9.640	13.073	8.822	7.721	1.770	2.690	3.770	5.790	7.923
29	9.233	12.567	8.515	7.447	1.727	2.360	3.307	5.190	6.987
30	8.930	12.173	8.103	7.131	1.497	2.020	2.870	4.487	6.260

Lucerne 1/20

	A3A 1/20 6	A3A 1/20 9	A3A 1/20 12	A3A 1/20 18	A3A 1/20 24	A3B 1/20 6	A3B 1/20 9	A3B 1/20 12	A3B 1/20 18
1	5.997	8.950	11.987	17.907	23.890	5.943	8.780	11.670	17.357
2	5.987	9.013	12.017	18.047	24.030	6.000	8.980	12.037	18.003
3	5.973	8.990	11.993	17.983	23.977	6.043	8.990	11.987	17.933
4	6.057	8.987	11.997	18.010	24.013	5.977	9.000	12.013	17.977
5	6.007	8.990	12.010	18.023	24.040	5.993	8.997	12.003	17.990
6	6.007	9.030	12.020	18.057	24.063	5.997	8.993	12.040	17.990
7	5.987	8.990	11.960	17.970	23.943	5.990	8.927	11.967	17.900
8	5.963	8.983	11.927	17.920	23.860	5.990	8.883	11.923	17.823
9	5.900	8.820	11.697	17.677	23.523	5.830	8.687	11.597	17.483
10	5.780	8.653	11.483	17.330	23.123	5.657	8.527	11.380	17.203
11	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	5.480	8.267	10.903	16.567	22.097	5.380	8.017	10.837	16.300
13	5.300	8.037	10.627	16.070	21.467	5.260	7.800	10.513	15.837
14	5.153	7.757	10.330	15.720	20.937	5.073	7.657	10.280	15.583
15	4.970	7.503	10.017	15.173	20.180	4.983	7.453	9.993	15.040
16	4.787	7.173	9.557	14.413	19.157	4.797	7.067	9.427	14.307
17	4.513	6.737	8.810	13.653	18.243	4.463	6.677	8.857	13.647
18	4.213	6.390	8.270	12.770	16.897	4.163	6.120	8.410	12.787
19	3.797	5.843	7.687	11.797	15.773	3.897	5.883	7.660	11.787
20	3.477	5.343	7.153	11.077	14.503	3.573	5.183	7.120	11.093
21	3.273	4.917	6.540	10.110	13.593	3.193	4.890	6.613	10.250
22	3.057	4.530	6.240	9.323	12.517	3.130	4.557	6.240	9.400
23	2.753	4.190	5.767	8.767	11.600	2.967	4.290	5.763	8.857
24	2.553	3.967	5.407	8.183	10.790	2.677	3.950	5.420	8.393
25	2.250	3.713	4.830	7.617	10.210	2.470	3.593	5.000	7.657
26	2.030	3.477	4.633	7.217	9.403	2.313	3.447	4.580	7.243
27	1.913	3.047	4.220	6.470	8.800	2.077	3.127	4.370	6.680
28	1.670	2.793	3.720	5.733	7.940	1.810	2.877	3.960	6.137
29	1.620	2.370	3.350	5.220	7.140	1.693	2.630	3.613	5.730
30	1.383	2.060	3.053	4.560	6.437	1.493	2.377	3.263	5.230

Lucerne 1/20

	A3B 1/20 24
1	23.287
2	24.050
3	23.960
4	23.980
5	24.043
6	24.043
7	23.890
8	23.813
9	23.393
10	23.033
11	0.000
12	21.860
13	21.400
14	20.907
15	20.163
16	19.340
17	18.223
18	17.073
19	15.827
20	14.717
21	13.643
22	12.657
23	11.927
24	11.197
25	10.380
26	9.633
27	9.167
28	8.547
29	7.940
30	7.053

Table 6. Summary of field experiment results.

	D (m)	z_o (m)
Bare playa, all anemometers (5/8/87, 15 min)	.00208	.000140
Bare playa, all anemometers (5/8/87, 15 min)	0	.000143
Array 1 internal boundary layer (4/3/87, 13 min)	-.197	.00397
Array 1 internal boundary layer (4/3/87, 13 min)	0	.000541
Array 1 internal boundary layer (4/4/87, 15 min)	.0421	.000441
Array 1 internal boundary layer (4/4/87, 15 min)	0	.000823
Array 2 internal boundary layer (4/11/87, 195 min)	-.0151	.00381
Array 2 internal boundary layer (4/11/87, 195 min)	0	.00324
Array 3 internal boundary layer (4/18/87, 15 min)	.0962	.0116
Array 3 internal boundary layer (4/18/87, 15 min)	0	.0313
Array 3 internal boundary layer (4/18/87, 85 min)	.0732	.0131
Array 3 internal boundary layer (4/18/87, 85 min)	0	.0271

Table 7. Aerodynamic roughness, z_o, from the wind tunnel experiment.

u_* (m/s) =	6.0	9.0	12.0	18.0	24.0	average
Array 1, 1/10 scale	.000037	.000106	.000077	.0000584	.0000507	.0000646
Array 2, 1/10 scale	.000568	.000394	.000274	.000323	.000331	.000378
Array 3, 1/10 scale	.00595	.00659	.00647	.00625	.00539	.00613
Array 1, 1/20 scale	.0000628	.0000198	.0000175	.0000154	.0000099	.0000251
Array 2, 1/20 scale	.000648	.000275	.000306	.000209	.00022	.000332
Array 3, 1/20 scale	.00271	.00314	.00293	.00276	.00280	.00287
Array 3A, 1/20 scale	.00327	.00311	.00243	.00276	.00279	.00287
Array 3B, 1/20 scale	.00256	.00260	.00211	.00251	.00255	.00247

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	February 1992	Contractor Report

4. TITLE AND SUBTITLE
Aerodynamic Roughness Measured in the Field and Simulated in a Wind Tunnel

5. FUNDING NUMBERS
NCC2-346

6. AUTHOR(S)
Robert Sullivan and Ronald Greeley

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Geology
Arizona State University
Tempe, AZ 85287

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Space Science and Applications
National Aeronautics and Space Administration
Washington, DC 20546

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR-4422

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited

Subject Category 02

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This study evaluates how well values of aerodynamic surface roughness, z_o, measured over scale models in wind tunnels correlate with values of z_o measured at full scale in the field. A field experiment was conducted in which values of z_o and u_* (wind friction speed) were measured over three arrays of non-erodible roughness elements on a dry lake bed. Wind profiles were measured by ten anemometers on a 15 m mast under thermally neutral atmospheric conditions. Values of z_o increased from .00014m (dry lake bed only) to .026m with increasing roughness element density. The three roughness element arrays were simulated at 1/10 and 1/20 scale in an open-circuit atmospheric boundary-layer wind tunnel. Velocities were measured with a boundary-layer pitot-tube rake from the same relative position within the scale model arrays as the anemometers were relative to the field arrays. Each array at each scale was sampled three times at five freestream velocities. Average values of z_o for each model array at each scale were compared with full-scale values of z_o obtained in the field. The field vs. wind tunnel correspondence of z_o is found to be $z_{o_{field}} = 0.2661 \cdot (z_{o_{model}} \cdot scale^{-1})^{.8159}$.

14. SUBJECT TERMS
wind engineering
aeolian processes
planetary geology
roughness
sedimentology
wind
wind tunnel

15. NUMBER OF PAGES
52

16. PRICE CODE
A04

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited