AN ESTIMATE OF THE ROUGHNESS LENGTH AND DISPLACEMENT HEIGHT OF SONORAN DESERT VEGETATION, SOUTH-CENTRAL ARIZONA

by Hans C. Claassen and Alan C. Riggs

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 92-4065

Denver, Colorado
1993

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

CONTENTS

PLATE

FIGURES

TABLES

CONVERSION FACTORS AND RELATED INFORMATION

Multiply	By	To obtain
meter (m)	3.28	foot
kilometer (km)	.64	mile
square meter (m^2)	10.76	square foot
meter per second (ms^{-1})	3.28	foot per second
watt per meter squared	4.18×10^4	gram-calorie per square
(watt m^{-2})		centimeter per second

To convert degree Celsius ($^{\circ}$C) to degree Kelvin (K) use the following formula:

$$K = {^{\circ}C} + 273 .$$

To convert degree Celsius ($^{\circ}$C) to degree Fahrenheit ($^{\circ}$F) use the following formula:

$${^{\circ}F} = 9/5({^{\circ}C}) + 32.$$

National Geodetic Vertical Datum of 1929 (NGVD of 1929):

A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

AN ESTIMATE OF THE ROUGHNESS LENGTH AND DISPLACEMENT HEIGHT OF SONORAN DESERT VEGETATION, SOUTH-CENTRAL ARIZONA

By Hans C. Claassen and Alan C. Riggs

ABSTRACT

A somewhat unconventional technique using a tethered balloon was used to estimate the roughness length for momentum (z_m) and displacement height (d) for typical Sonoran Desert vegetation. The results of $z_m = 0.15$ m and $d \approx 0$ are in reasonable agreement with expectation, given the nature and density of the vegetation present.

INTRODUCTION

It has been suggested (Businger, 1986) that measurements of the meteorological fluxes of momentum, sensible heat, and latent heat are best done at heights above ground level determined by either the roughness length (z_m) or the size and shape of vegetation (Raupach and others, 1980). Therefore, estimates of z_m and vegetation characteristics are a desirable prerequisite to developing a flux-measurement protocol. Because the literature contains little information on z_m for Sonoran Desert vegetation, it is desirable to measure z_m and the displacement height (d) associated with Sonoran Desert vegetation.

Purpose and Scope

This report presents the results of a study made to estimate z_m and d for Sonoran Desert vegetation in south-central Arizona. The technique used a tethered balloon alone to measure windspeed, wind direction, temperature, and relative humidity at a single height and thus constitutes a somewhat unconventional data-collection method. Because the objective was limited to a preliminary estimate of z_m to determine the height of a permanent meteorological tower, the inadequacies of the method were deemed to be compensated by the minimal instrumentation required. Future measurements that are made on the fully instrumented tower will yield more precise results.

DESCRIPTION OF STUDY AREA

The site chosen for measurements is located at the northern boundary of Organ Pipe Cactus National Monument, 1 km west of Arizona Highway 85 and about 150 km west of Tucson, Ariz. Site elevation is 533 m above NGVD of 1929. The site has a 10-km fetch for all headings except from 30° to 120°, where a 260-m ridge is 1.6 km distant. The measurement site in relation to the topography is shown on plate 1.

Sonoran Desert vegetation is characterized by a greater range of height among species than usually occurs in other desert plant communities. A detailed inventory of plant species and dimensions at the site is presented in table 1.

Table 1.--Vegetation inventory and derived characteristics, Sonoran Desert Site, Arizona

[m², meters squared; m, meters; s/S, s = silhouette area, S = average area occupied = 4,645/number of elements, where 4,645 is the total area inventoried]

Species	Number of plants	Total area covered (m²)	Percent of coverage	Average height (m)	Average diameter (m)	s/S
Larrea tridendata (creosote bush)	178	422.36	55.67	1.15	1.74	0.0767
Ambrosia deltoieda (bursage)	405	125.51	16.54	.38	.63	.0209
Ambrosia dumosa (bursage)	469	100.65	13.27	.35	.52	.0184
Cercidium spp	6	63.04	8.31	2.91	3.66	.0138
Krameria grayi	50	27.79	3.66	.39	.84	.0035
Fouqueria splendens (ocotillo)	5	6.03	.79	2.51	1.24	.0034
Not identified I	14	5.62	.74	.41	.71	.0009
Not identified II	2	6.81	.90	.47	2.08	.0004
Opuntia spp	2	.71	.09	.52	.67	.0002
Ferocactus wislizenii	1	.22	.03	.22	.48	.0000

MEASUREMENT TECHNIQUES

A single tethered balloon with one Atmospheric Instrumentation Research tether sonde was used for meteorologic measurements. The sonde measured windspeed using a low-threshold cup anemometer (threshold 0.1 ms⁻¹ accuracy ±0.25 ms⁻¹ from threshold to 10 ms⁻¹), air temperature and humidity using aspirated wet/dry bulb thermistors, and wind direction using a magnetic compass. Data were obtained at a rate of one measurement every 10 seconds. The sonde also included a fine-wire thermometer to determine sensible heat flux but did not function properly and supplied no useful data. Although synoptic ground-level measurements would have been desirable, the equip- ment was unavailable and an alternative protocol was followed. A description of this protocol follows.

Short-term values were averaged to estimate steady-state conditions. Data-recording intervals of 15 to 30 minutes at fixed heights were used. The initial sequence of heights was from near ground to the usual maximum height of 26 m or the reverse, in six logarithmically spaced heights. Later, a random-number generator was used to choose the altitude sequence. Two sets of measurements were made: one in September 1988 and the other in February 1989.

The height, diameter, and species of the 1,100-plus plants taller than 0.15 m were inventoried on a 4,645 m² plot at the site.

DATA REDUCTION

Mean windspeed was computed for each logging interval and the results were plotted versus logarithm of height (figs. 1-6). It was assumed that steady-state wind conditions prevailed during a suite of measurements when

Figure 1.--Wind-velocity profiles for September 15, 1988.

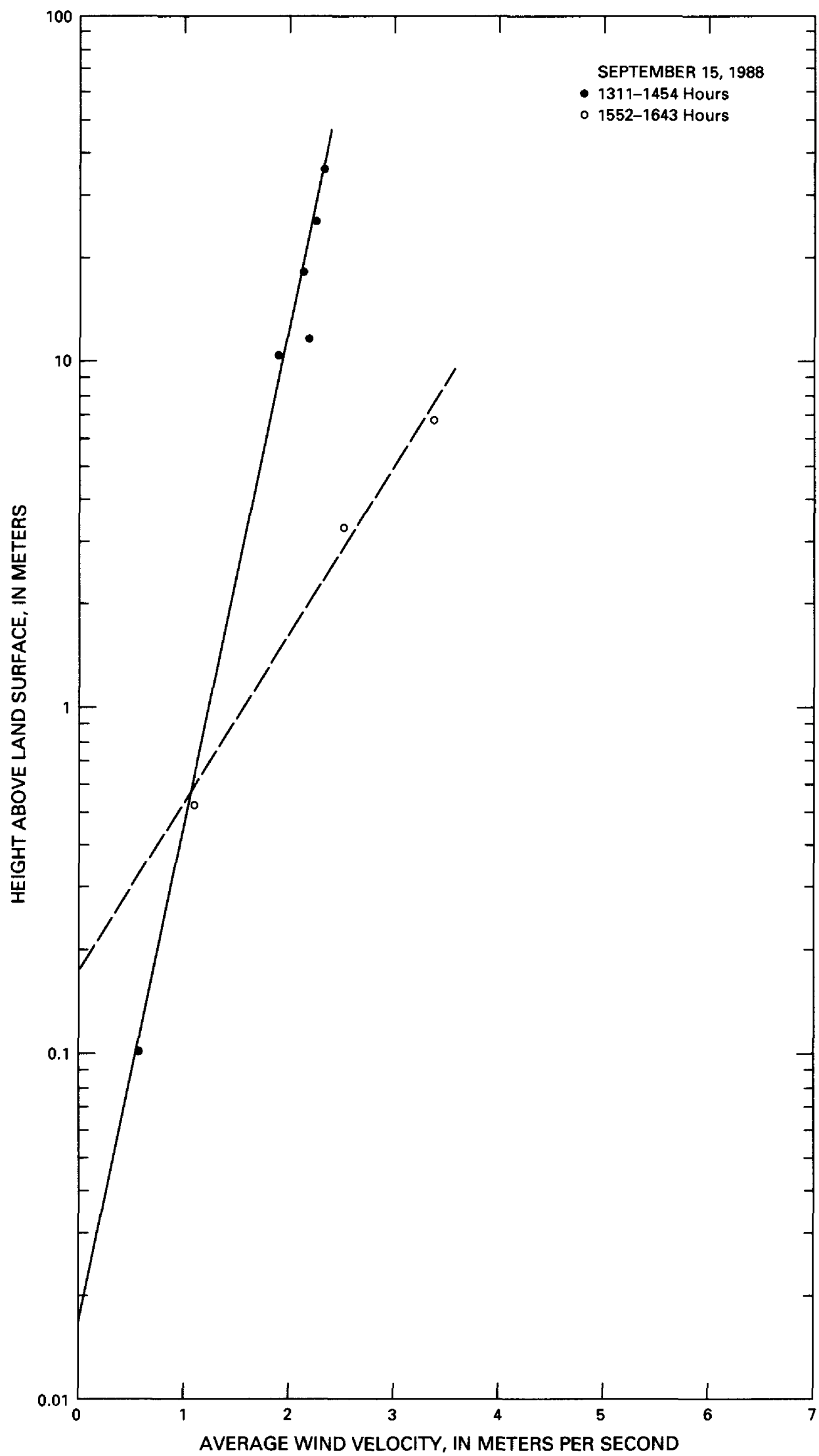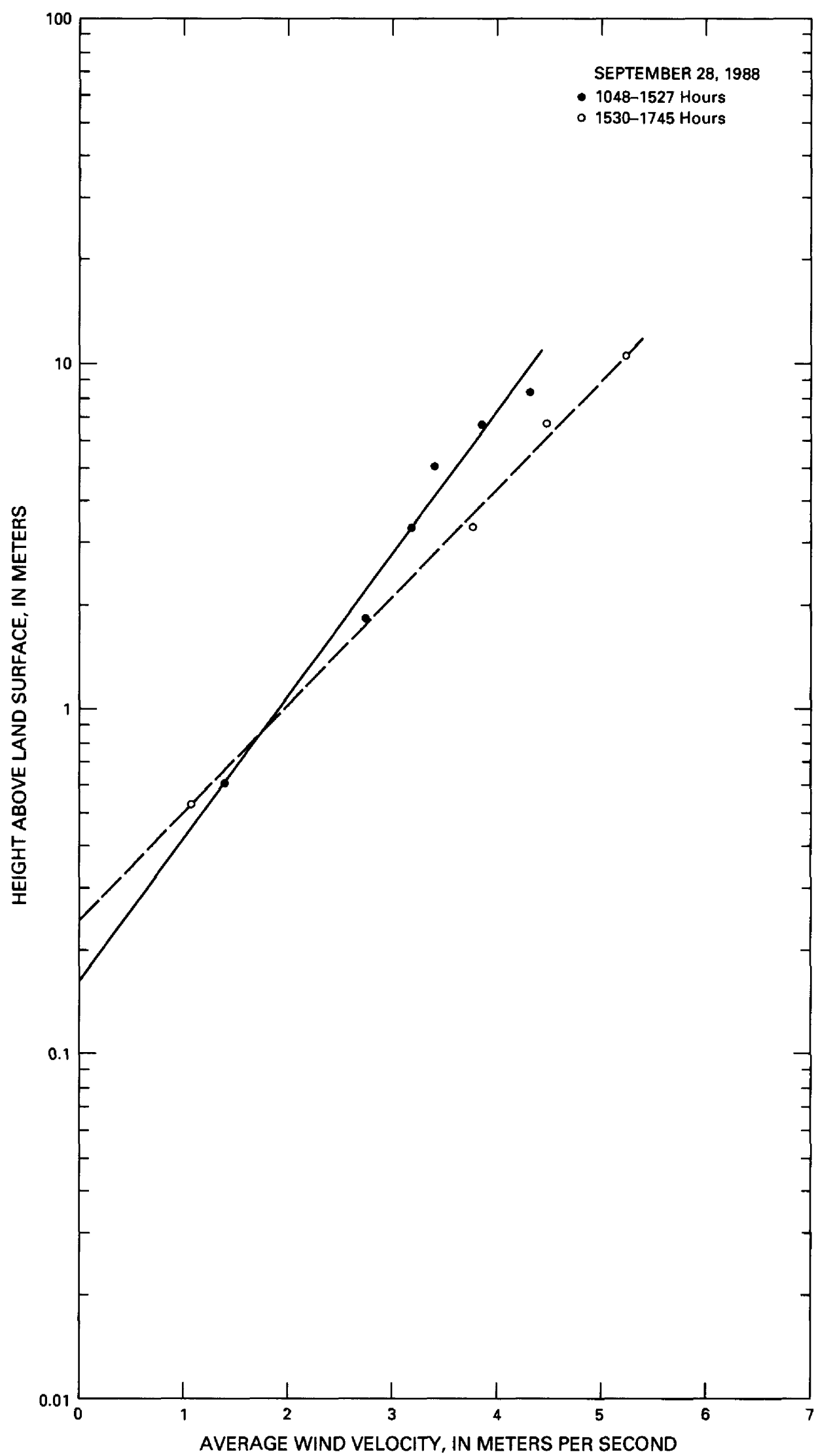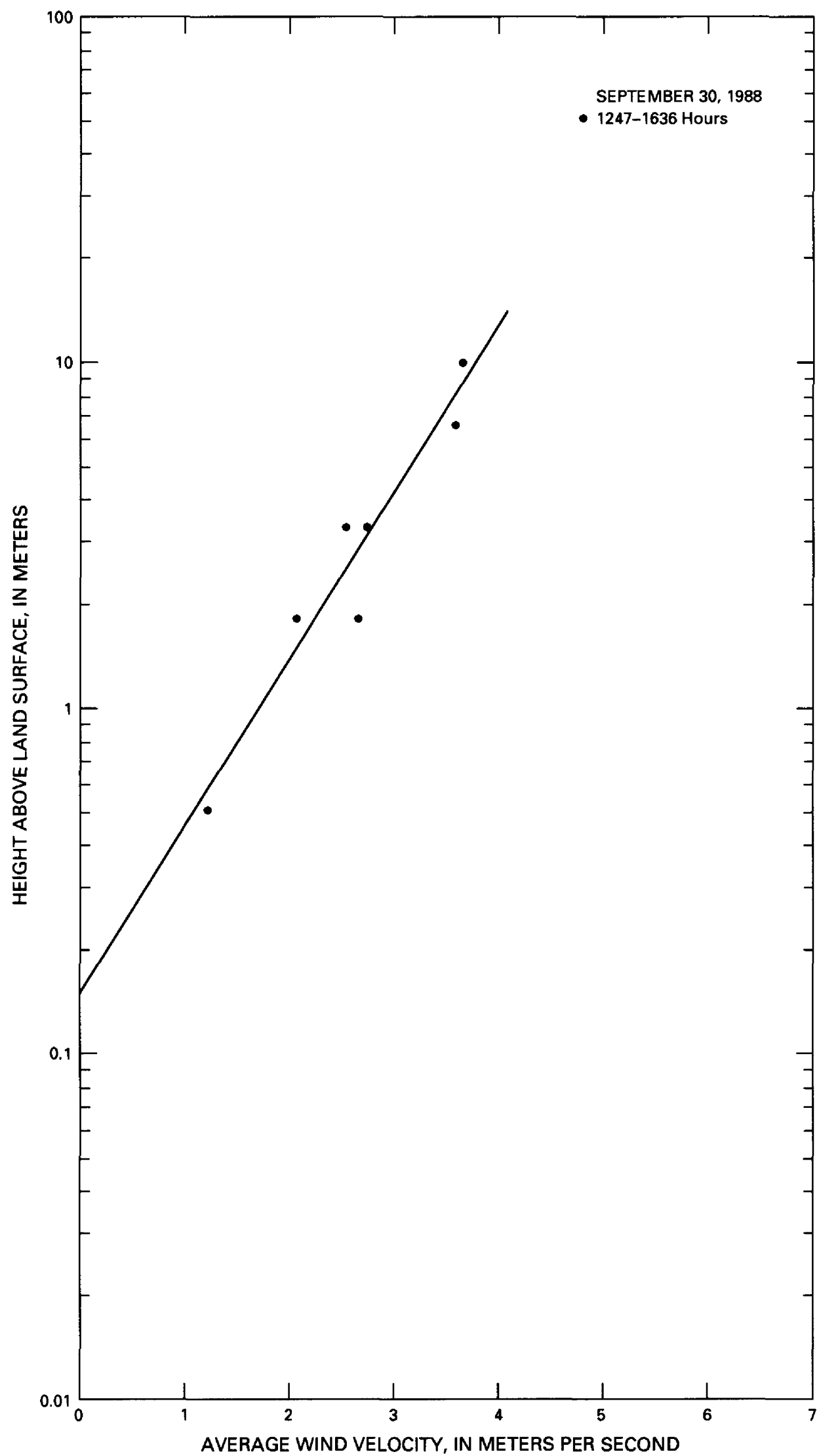Figure 2.--Wind-velocity profiles for September 28, 1988.

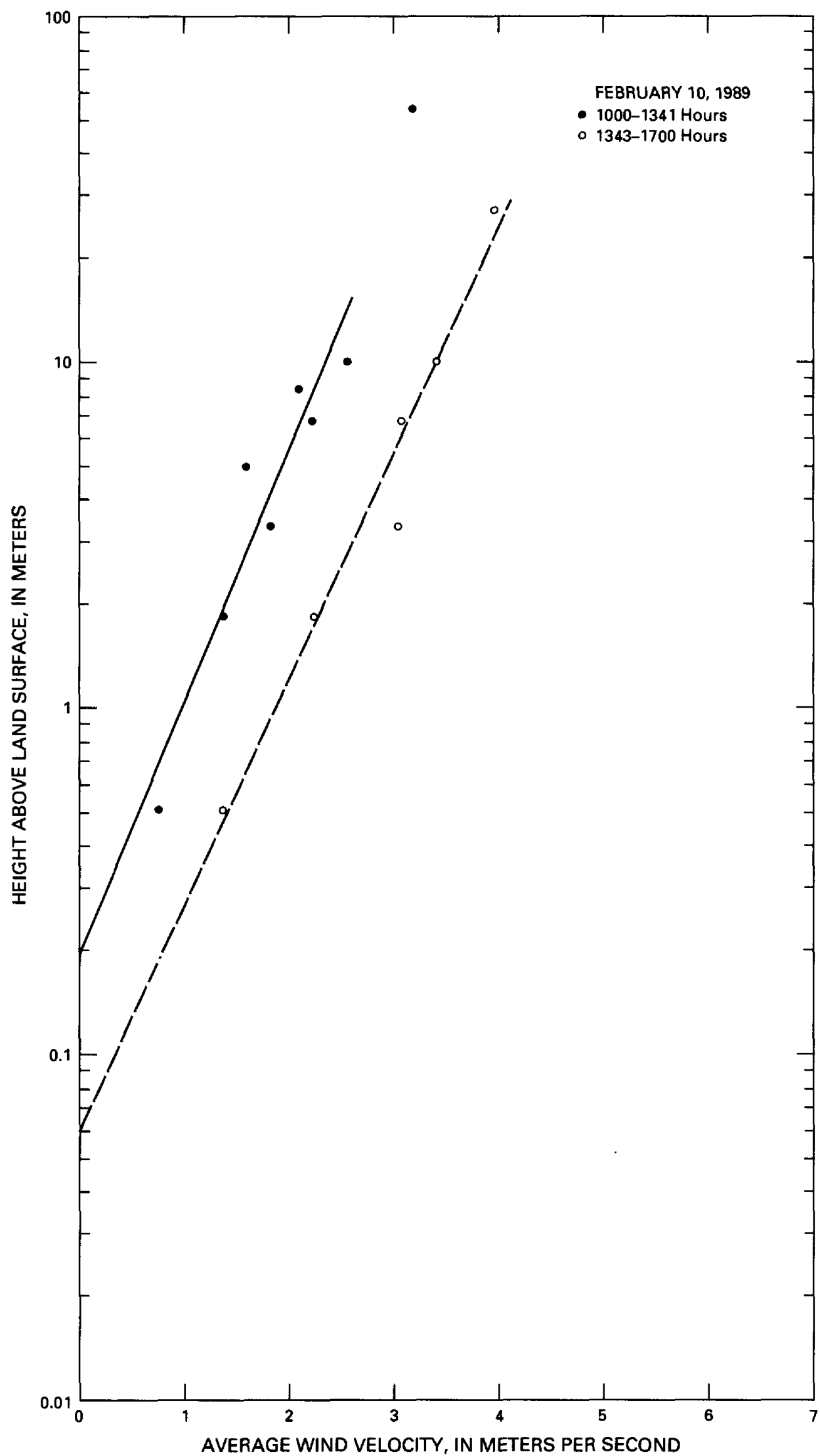Figure 3.--Wind-velocity profiles for September 30, 1988.

Figure 4.--Wind-velocity profiles for February 10, 1989.
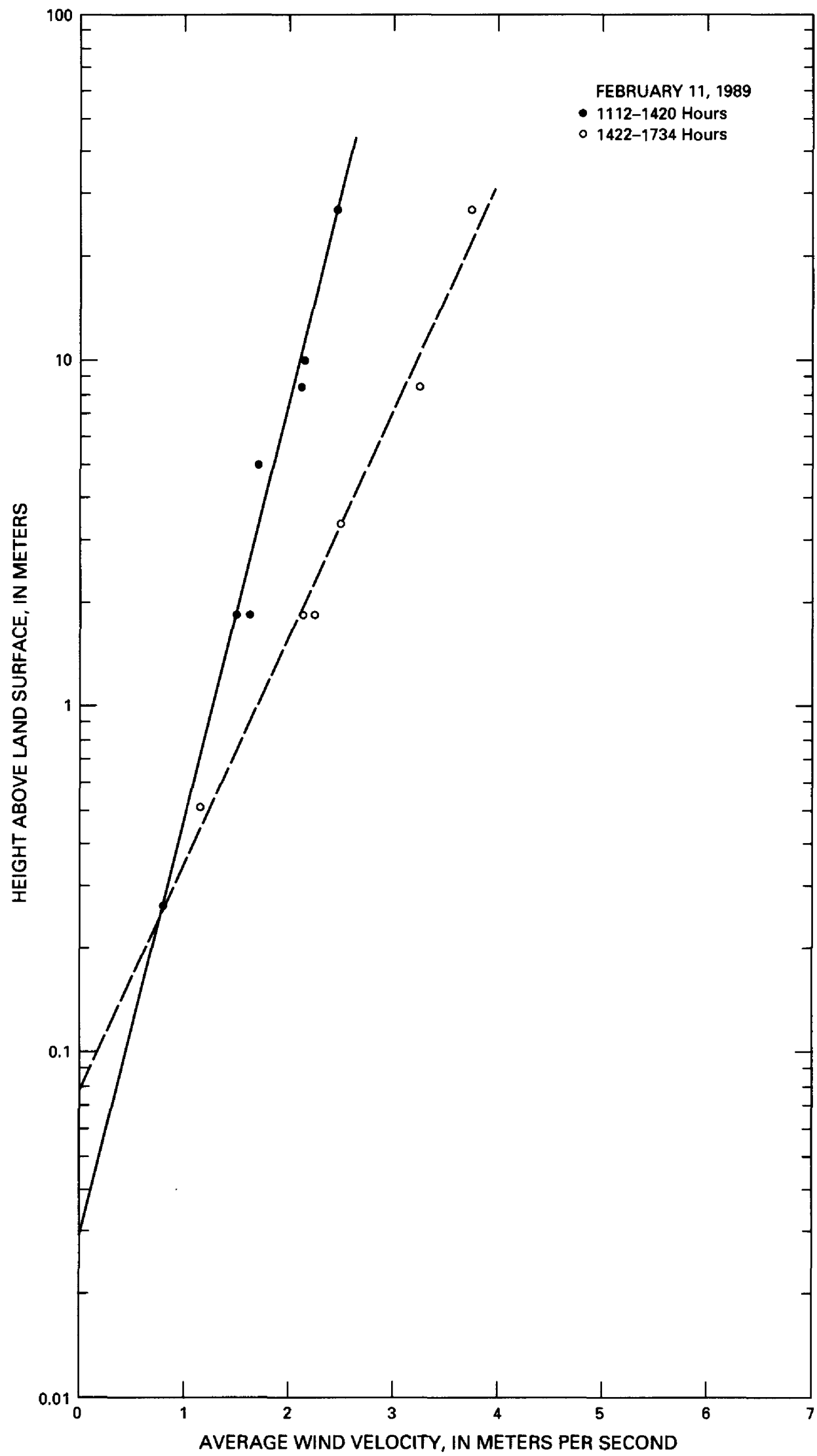
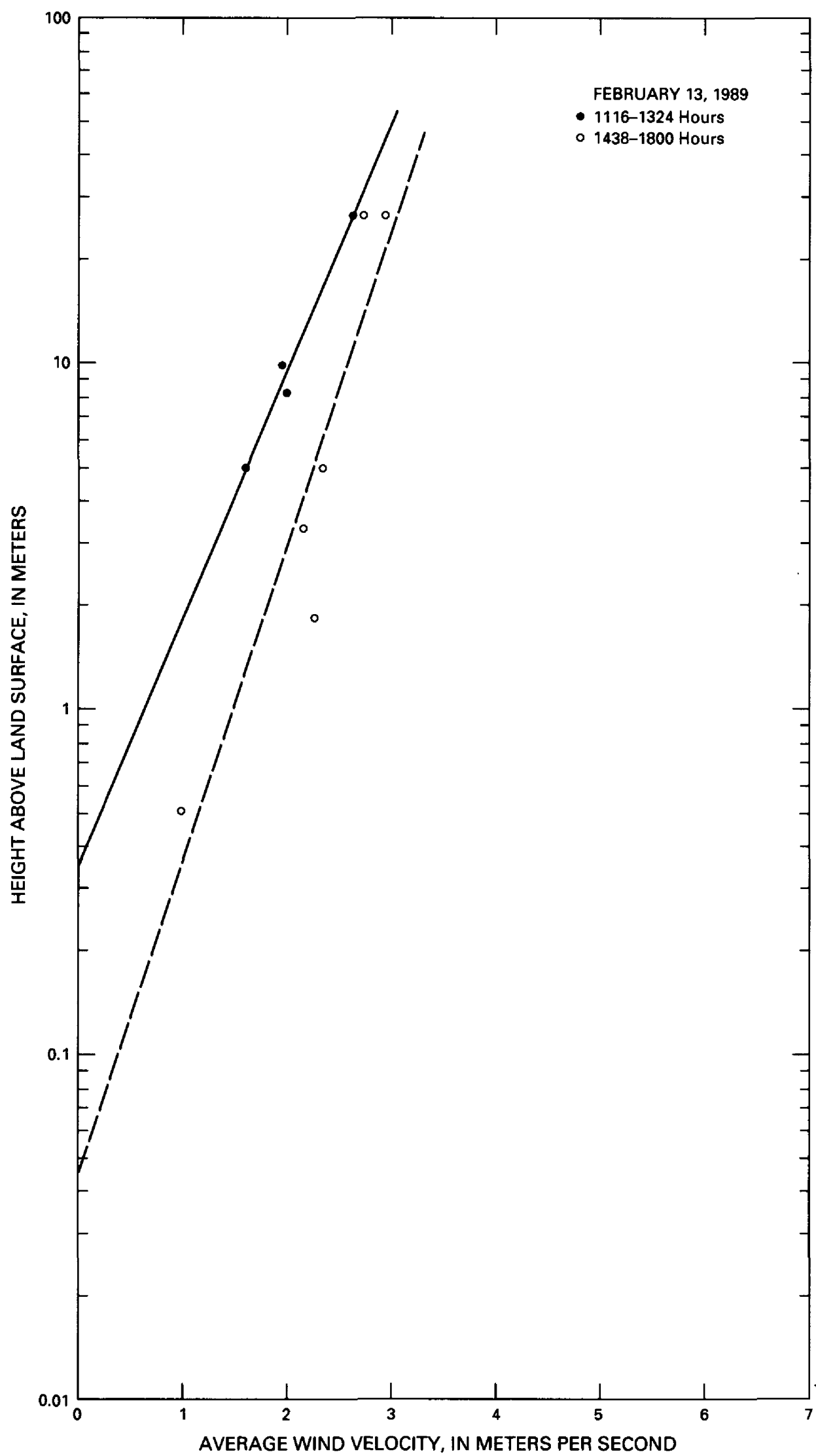Figure 5.--Wind-velocity profiles for February 11, 1989.

Figure 6.--Wind-velocity profiles for February 13, 1989.

AN ESTIMATE OF THE ROUGHNESS LENGTH AND DISPLACEMENT HEIGHT OF SONORAN DESERT VEGETATION, SOUTH-CENTRAL ARIZONA

plots of ln height versus windspeed yielded a straight line. A subset of these data, chosen for further analysis, is presented in table 2.

To minimize the effect of nonstationarity on computing vertical thermal gradients, temperature data were obtained 3 to 4 minutes prior to moving the sonde and 3 to 4 minutes after establishing a new measurement height. The absence of simultaneous measurements at different heights represents a potential source of error, of unknown magnitude, on the estimate of z_m, but it was hoped this error source was minimized by numerous measurements made under varying conditions. The horizontal windspeed, vertical windspeed- and temperature-gradient values computed from the raw data are presented in table 2. The vegetation inventory for census plot surrounding the launch site is presented in table 1. Also included in table 1 are average height (h) and diameter (D) and Lettau's s/S parameter (Lettau, 1969). Lettau's parameter: silhouette area/horizontal-occupancy area, is a measure of the effect of vegetation on the vertical wind-velocity profile, hereinafter called the wind profile. The wind profile commonly is used in estimating z_m.

$$\frac{s}{S} = \frac{Dh}{4,645/\text{no. of plants}} \quad (1)$$

Calculation of z_m

The equations that relate momentum and heat fluxes into and out of the vegetation canopy generally assume an idealized, dense canopy over which the wind blows. The distribution of roughness elements that make up the canopy displaces the wind profile upward by an amount d in addition to determining the slope of that profile (Thom, 1971). Therefore, the wind profile (neutral or adiabatic case) is described by:

$$u = A \ln \frac{z - d + z_m}{z_m}, \quad (2)$$

where A is a proportionality constant equal to the reciprocal of the slope of the logarithmic wind profile, and the other variables are as previously defined. It follows that

$$\frac{du}{dz} = \frac{\dfrac{A}{z - d + z_m}}{z_m} \left(\frac{1}{z_m} \quad (1) \right)$$

$$(3)$$

$$-\left(\frac{z - d + z_m}{z_m^2} (0) \right) = \frac{A}{z - d + z_m} \cdot$$

It generally is assumed that momentum flux (τ) in the surface layer is constant

$$\tau = \rho K_m \frac{du}{dz}, \quad (4)$$

where ρ is the air density (approximately constant with height) and K_m is the eddy diffusivity for momentum. Substituting equation 3 into equation 4

$$\tau = \frac{\rho K_m A}{(z - d + z_m)} \cdot \quad (5)$$

Solving for K_m

$$K_m = \frac{\tau (z - d + z_m)}{\rho A} \quad (6)$$

but $\qquad \dfrac{\tau}{\rho} \equiv u_*^2$ and $A \equiv \dfrac{u_*}{k}$, $\qquad (7, 8)$

u_* is the friction velocity and K is the Von Kármán constant (0.4).

Substituting equations 7 and 8 into equation 6

$$K_m = \frac{u_*^2 k (z - d + z_m)}{u_*}$$

$$= u_* k (z - d + z_m) \cdot \quad (9)$$

Table 2.--Summary of meteorological data and results of calculations

[m, meters; m s⁻¹, meters per second; s, second; K m⁻¹, degrees kelvin per meter; Watts m⁻², watts per square meter; $\bar{u}$, mean wind speed; u_*, friction velocity; du/dz, vertical windspeed gradient; dT/dz, vertical temperature gradient; $\bar{z}$, mean interval height; H, vertical heat flux; z_m, roughness length; ζ, stability; --, no values]

Date	Time	z (m)	$\bar{u}$ (m s⁻¹)	u_*	$\dfrac{du}{dz}$ (s⁻¹)	$\dfrac{dT}{dz}$ (K m⁻¹)	$\bar{z}$ (m)¹	H (Watts m⁻²)	z_m (m)	ζ	Weather conditions
9-15-88	(1552-1607)	6.71	3.373	--	--	--	--	--	--	--	Wind NW
	(1604-1611)	--	--	0.46	0.256	0.016	4.73	-15	0.54	0.01	
	(1608-1624)	3.34	2.509	--	--	--	--	--	--	--	
	(1621-1629)	--	--	.28	.509	-.374	1.305	76	.21	-.05	
	(1626-1643)	.51	1.068	--	--	--	--	--	--	--	
9-28-88	(1048-1118)	.61	1.40	--	--	--	--	--	--	--	Clear, wind N-NW
	(1115-1126)	--	--	.46	1.107	-.698	1.057	155	.17	-.018	
	(1123-1156)	1.83	2.75	--	--	--	--	--	--	--	
	(1234-1305)	5.02	3.38	--	--	--	--	--	--	--	
	(1302-1318)	--	--	.59	.274	.029	5.800	40	.57	.013	
	(1315-1345)	6.70	3.84	--	--	--	--	--	--	--	
9-30-88	(1318-1350)	1.83	2.08	--	--	--	--	--	--	--	Mostly clear, high, thin clouds, wind SW
	(1347-1356)	--	--	.28	.659	-.908	.966	141	.08	-.066	
	(1353-1423)	.51	1.21	--	--	--	--	--	--	--	
	(1420-1439)	--	--	.40	1.091	-.522	.966	90	.16	-.014	
	(1436-1508)	1.83	2.65	--	--	--	--	--	--	--	
	(1510-1540)	3.34	2.75	--	--	--	--	--	--	--	
	(1537-1544)	--	--	.52	.250	-.075	4.731	102	.42	-.038	
	(1541-1605)	6.70	3.59	--	--	--	--	--	--	--	

Table 2.—Summary of meteorological data and results of calculations—Continued

Date	Time	z (m)	$\bar{u}$ (m s⁻¹)	u_*	$\frac{du}{dz}$ (s⁻¹)	$\frac{dT}{dz}$ (K m⁻¹)	$\bar{z}$ (m)[1]	H (Watts m⁻²)	z_m (m)	ζ	Weather conditions
2-10-89	(1000-1030)	0.51	0.731	--	--	--	--	--	--	--	High scattered
	(1027-1034)	--	--	0.20	0.554	-0.144	0.966	10	0.24	-0.013	clouds, recent
	(1031-1101)	1.83	1.360	--	--	--	--	--	--	--	light rain,
	(1343-1413)	.51	1.358	--	--	--	--	--	--	--	wind N-NW
	(1410-1422)	--	--	.25	.213	-.104	2.265	40	.03	-.076	
	(1419-1449)	10.06	3.389	--	--	--	--	--	--	--	
2-11-89	(1422-1452)	3.34	2.488	--	--	--	--	--	--	--	Clear,
	(1449-1458)	--	--	.29	.474	-.326	1.305	137	.08	-.048	wind SW
	(1455-1525)	.51	1.146	--	--	--	--	--	--	--	
	(1522-1529)	--	--	.31	.761	-.790	.966	123	.08	.045	
	(1526-1556)	1.83	2.150	--	--	--	--	--	--	--	
	(1633-1703)	8.38	3.241	--	--	--	--	--	--	--	
	(1700-1707)	--	--	.24	.151	-.008	3.916	4	.04	-.012	
	(1704-1734)	1.83	2.251	--	--	--	--	--	--	--	
2-13-89	(1546-1616)	5.02	2.324	--	--	--	--	--	--	--	High, thin
	(1613-1628)	--	--	.25	.297	-.200	1.600	56	.07	-.077	clouds
	(1625-1654)	.51	.985	--	--	--	--	--	--	--	
	(1651-1658)	--	--	.26	.407	-.207	1.305	44	.08	-.042	
	(1655-1725)	3.34	2.136	--	--	--	--	--	--	--	

[1] $\bar{z}=e^{(1/2)(\ln z_u + \ln z_1)}$

For diabatic conditions (ζ, stability, $\neq 0$), the fluxes calculated using equations for neutral conditions must be modified by a flux corrector, ϕ. Thus:

$$\tau_{(\zeta = 0)} = \rho K_m \frac{du}{dz} \quad \text{and} \tag{10}$$

$$\tau_{(\zeta \neq 0)} = \rho \frac{K_m}{\phi_m} \frac{du}{dz} \tag{11}$$

$$H_{(\zeta = 0)} = -K_h \rho C_p \frac{dT}{dz} \tag{12}$$

$$H_{(\zeta \neq 0)} = \frac{-K_h}{\phi_h} \rho C_p \frac{dT}{dz} \tag{13}$$

$$E_{(\zeta = 0)} = -K_v \frac{dq}{dz} \quad \text{and} \tag{14}$$

$$E_{(\zeta \neq 0)} = \frac{-K_v}{\phi_v} \frac{dq}{dz} \, , \tag{15}$$

where

H is the heat flux ;
E is the water-vapor flux;
K_h is the eddy diffusivity for heat, and
K_v is the eddy diffusivity for water vapor;
dT/dz is the temperature density gradient; and
dq/dz is the vapor density gradient;
C_p is the heat capacity of the air at constant pressure; and
ϕ_m is the flux corrector for momentum;
ϕ_h is the flux corrector for heat; and
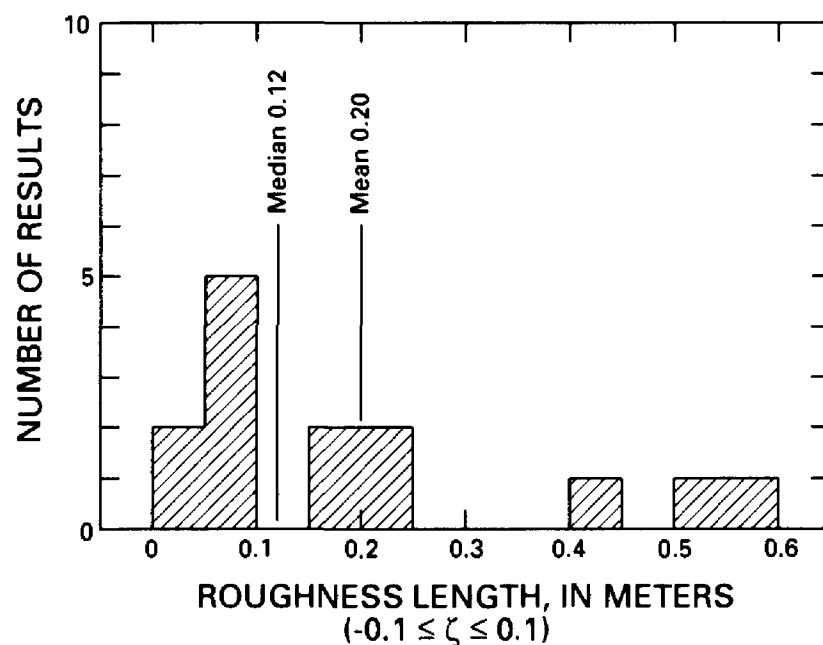ϕ_v is the flux corrector for water vapor.

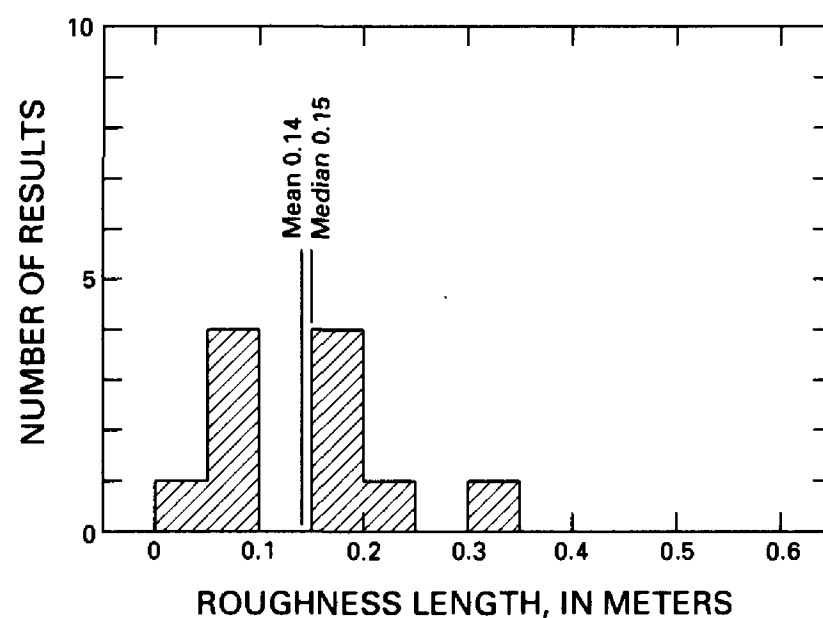Figure 7.--Frequency diagram summarizing z_m results from flux calculations ($-0.1 \leq \zeta \leq +0.1$).

Figure 8.--Frequency diagram summarizing z_m results from regression analysis.

The stability, ζ, is defined as the ratio of convective to mechanical production of turbulence (de Vries and Afgan, 1975)

$$\zeta = \frac{-k(z - d + z_m)gH}{\rho C_p T u_*^3} \qquad (16)$$

For $\quad \zeta > 0 \quad \phi_m = \phi_h = \phi_v = 1 + 5\zeta \qquad (17)$

$$\zeta = 0 \quad \phi_m = \phi_h = \phi_v = 1 \qquad (18)$$

$$\zeta < 0 \quad \phi_m = (1 - 16\zeta)^{-.25} \qquad (19)$$

$$\phi_h = \phi_v = (1 - 16\zeta)^{-.50} \qquad (20)$$

(Brutsaert, 1982).

Substituting equations 9 and 7 into equation 11, a diabatic influence expression for u_* results:

$$u_* = \frac{k}{\phi_m}(z - d + z_m)\frac{du}{dz} \ . \qquad (21)$$

Our computational method for estimating z_m is iterative and begins by estimating the following values:

z_m, estimated as the y intercept of the linear regressions of $\ln z$ versus $\bar{u}$,

u_* estimated as $0.2 \, \bar{u}$,

$\bar{u}$, the mean windspeed of the adjacent two logged heights,

$\dfrac{du}{dz}$, the windspeed gradient, determined as previously described, and

$\dfrac{dT}{dz}$, the temperature gradient, determined as previously described.

Equation 9 is used to estimate K_m (assumed to equal K_h), equation 13 estimates H, equation 16 estimates ζ, equations 17-20 estimate the diabatic correction factors, equation 21 estimates a new value for u_*. The process is repeated until no significant changes in H are obtained in successive iterations.

The diabatic profile equation is used to calculate z_m:

$$\bar{u} = \frac{u_*}{k}\left[\ln\frac{z + z_m - d}{z_m} + \psi_m\right]. \qquad (22)$$

ψ_m is the diabatic profile correction factor and is related to ζ by:

for $\zeta \geq 0$, $\quad -\bar{\psi}_m = -5\zeta \qquad (23)$

for $\zeta \leq 0$, $\quad -\psi_m = 2 \ln\left[\dfrac{1 + (1 - 16\zeta)^{.25}}{2}\right]$

$$+ \ln\left[\frac{1 + (1 - 16\zeta)^{.50}}{2}\right]$$

$$- 2 \arctan(1 - 16\zeta)^{.25} + \frac{\pi}{2} \qquad (24)$$

(Brutsaert, 1982). Equations 23 and 24 represent the integrated forms of the flux equations; for example, equations 7, 9, 11, and 17 combined and integrated to yield equations 22 and 23. Values of computed z_m are presented in table 2. A summary of the resulting computed z_m in the form of a bar graph is shown in figure 7. Those results for stability conditions $-0.1 \leq \zeta \leq +0.1$ (near-neutral) are included in figure 7. The median and mean values for both data sets are similar and indicate that $z_m \approx 0.16$ m.

The results from semilogarithmic regressions of the z versus $\bar{u}$ data are shown in figure 8. These results indicate that $z_m = 0.14$ m. Linear plots of z versus $\bar{u}$ (not shown) suggest $d \approx 0$.

DISCUSSION

Conventionally, onsite determinations of z_m are done in environments with dense vegetation having uniform height to more closely meet assumptions on which the micrometeorological models are based. For these circumstances, some general rules relating vegetation

height and density to z_m and d have been proposed.

Paeschke (1937):

$$z_m = \frac{h}{7.35} \; , \tag{25}$$

Sellers (1965):

$$ln \; z_m = \alpha + \beta \; ln \; h = 2.5 + ln \; h$$

for z_m, h in centimeters, $\tag{26}$

Stanhill (1969):

$$d = 0.64h \; , \tag{27}$$

Lettau (1969):

$$z_m = h \, (0.5 s/S) \; , \tag{28}$$

where

    s is the average vertical silhouette area of the roughness elements, and

    S is the average area occupied by an element.

Otterman and others (1988):

$$z_m = 0.5h \, [1 - e^{-s/S}] \; . \tag{29}$$

Although the quantity s/S is a simple geometric representation of roughness elements and, hence, contributes to drag force, the silhouette of a roughness element is only one factor that affects resistance to air flow produced by that element. For desert vegetation that has evolved to minimize transpiration, it would not be surprising if the resistance to flow were substantially different from tropical or temperate-zone vegetation of similar s/S. Typical drag coefficients for cylindrical, spherical, or hemispherical solid objects range from 0.2 to about 0.5 (Campbell, 1977). The use of 0.5 is evident in equations 28 and 29. One might expect these values to be representative values for vegetation elements composed of dense leaf and branchlets. Much desert vegetation is relatively open and generally is sparsely distributed; Otterman and McCumber (1986) estimate that s/S is less than 0.3 for even dense desert scrub, an estimate in agreement with our measurements (table 1). The observed nature of the predominant vegetation (*Larrea*, 56 percent; combined *Ambrosia* spp., 30 percent) would indicate that *Larrea* presents an open structure whereas *Ambrosia* approaches the idealized solid object because of a high density of leaves and branches. Thus, *Larrea* ($s/S = 0.0767$) would exert a different drag than combined *Ambrosia* spp. ($s/S = 0.0393$). In the results presented in table 3, it is assumed that all element types act independently and, therefore,

their s/S values may be summed. However, most species are relatively ineffective in contributing to the drag, primarily because of their scarcity. It is further assumed in the results in table 3 that the height of the canopy is the weighted (by area of coverage) mean of all species present.

**Table 3. Estimated values of roughness length (z_m) and displacement height (d)
[--, no values]**

	Method of Calculation					
Variable	Paeschke (1937)	Sellers (1965)	Stanhill (1969)	Lettau (1969)	Otterman and others (1988)	This study
^1z_m	0.12	0.07	--	0.05	0.05	
^1d			0.56			
^2z_m	.14	.08	--	.07	.07	
^2d			.66			
z_m						0.15
d						~0

[1]h is the mean, weighted according to area covered, of the two dominant species (0.876 m), and s/S is the sum of the three dominant species (0.1160).
[2]h is the mean, weighted according to area covered, of all species present (1.033 m), and s/S is the sum of all species, acting independently (0.1382).

It seems that the models of Sellers and Lettau underestimate z_m, and the model of Stanhill may substantially overestimate d. The reason for this disagreement may be because of the assumptions present in choice of 0.5 for the drag coefficient, or it may result from an incorrect conceptual model of the canopy. Seginer (1974) developed relations between the atmospheric parameters d and z_m, and the canopy parameters C_D, a ($= s/Sh$), and l_h (mixing length at top of the canopy) using Inoue's model (Inoue, 1963). These relations are expressed as follows:

$$\frac{d}{h} = 1 - \frac{l_h}{kh} \tag{30}$$

$$\frac{z_m}{h} = \frac{l_h}{kh} exp - \left(\frac{4k^3}{l_h C_D a}\right)^{\frac{1}{3}} \tag{31}$$

If we assume $d \approx 0$ and $z_m = 0.15$, $l_h = kh \approx 0.413$ for the weighted mean canopy height and

$$\frac{z_m}{h} = exp - \left(\frac{4.631}{C_D}\right)^{1/3} = \frac{0.15}{1.033} = 0.145$$

$$-1.930 = -\left(\frac{4.631}{C_D}\right)^{1/3}$$

$$C_D = 0.64 .$$

The above-estimated C_D is larger than expected for desert vegetation visualized as a collection of solid, right-circular cylinders ($C_D = 0.32$) (Campbell, 1977), but only slightly larger than the estimated value for dense canopies, 0.5 using generalized rules. That C_D is substantially larger than the idealized solid-form vegetation is not surprising (Brutsaert, 1982; Seginer, 1974), because the effect of the open structure of the most abundant species, *Larrea*, is expected to increase turbulence. However, it is surprising that the canopy in the Sonoran Desert seems to behave as if it were a borderline example of the dense, vertically homogeneous, canopy because only 16 percent of the horizontal area is occupied by plants taller than 0.15 m. Plotting our best estimate of z_m/h and $C_D ah$ (= $C_D s/S$) on graphs comparing Seginer's (Seginer, 1974, fig. 2) and Inoue's (Inoue, 1963) modeling results indicate reasonable agreement with both models. Because both models assume a vertically homogeneous canopy and, therefore, a value of l_h that is constant with height, it may be concluded that the vertical distribution of roughness elements in vegetation of the Sonoran Desert is sufficiently constant for the constant- mixing-length requirement to be appropriate. Seginer's numerical model (Seginer, 1974) attempts to describe the relation between z_m/h and $C_D s/S$ for sparse canopies where the stress on the ground is not zero. Our results are in reasonable agreement with Seginer's model as well, affirming that vegetation in the Sonoran Desert occupies a borderline position between dense and thin canopy, and may be modeled by using either concept.

SUMMARY AND CONCLUSIONS

Measurements of vertical wind profile and sensible heat flux estimates were made in Sonoran Desert vegetation using a tethered balloon. The objective was to estimate the roughness length and displacement height for design of a meteorological tower to study particulate and meteorological fluxes.

Although the method used is somewhat unconventional, the results $z_m = 0.15$ m $d = 0$ are in agreement with expectations. Comparison of results with various general estimation methods indicates that the assumptions made about the aerodynamic properties of vegetation elements may not be true for some Sonoran Desert species. Despite the foregoing, the results presented in this report are in reasonable agreement with both a model that views roughness elements as sparsely distributed and a model that views the roughness elements as homogeneous and densely distributed. Therefore, Sonoran Desert vegetation occupies a position that conceptually is between dense and sparse vegetation.

REFERENCES CITED

Businger, J.A., 1986, Evaluation of the accuracy with which dry deposition can be measured with current micrometeorological techniques: Journal of Climate and Applied Meteorology, no. 8, p. 1100-1124.

Brutsaert, W., 1982, Evaporation into the atmosphere: Boston, D. Reidel, 299 p.

Campbell, G.S., 1977, An introduction to environmental biophysics: New York, Springer-Verlag, 159 p.

de Vries, D.A., and Afgan, N.H., 1975, Aerodynamics of vegetated surfaces: New York, John Wiley, 453 p.

Inoue, E., 1963, On the turbulent structure of airflow within crop canopies: Journal of Meteorological Society of Japan, v. 41, p. 317-325.

Lettau, H., 1969, Note on aerodynamic roughness parameter estimation on the basis of roughness element description: Journal of Applied Meteorology, v. 8, p. 828-832.

Otterman, J., and McCumber, M., 1986, Parameterization of albedo, thermal inertia and surface roughness of desert scrub/sandy soil surface: Rome, Italy, International Satellite and Surface Climatology Project, [Proceedings], ESA SPO 248, p. 87-89.

Otterman, J., Staenz, K., Itten, K.I., and Kukla, G., 1988, Dependence of snow melting and surface-atmosphere interactions on the forest structure: Boundary-Layer Meterology, v. 45, p. 1-8.

Paeschke, W., 1937, Experimentelle Untersuchungen zum Rauhigkeits-und Stabilitäts problem in der bodennahen Luftschicht: Beiträge zur Physik der freien Atmosphaere, v. 24, p. 163-189.

Raupach, M.R., Thom, A.S., and Edwards, I., 1980, A wind tunnel study of turbulent flow close to regularly arrayed rough surfaces: Boundary-Layer Meteorology, v. 18, p. 373-398.

Seginer, I., 1974, Aerodynamic roughness of vegetated surfaces: Boundary-Layer Meteorology, v. 5, p. 383-393.

Sellers, W.D., 1965, Physical Climatology: University of Chicago Press., 272 p.

Stanhill, G., 1969, A simple instrument for the field measurement of turbulent diffusion flux: Journal of Applied Meteorology, v. 8, p. 509-513.

Thom, A.S., 1971, Momentum absorbed by vegetation: Quarterly Journal of the Royal Meteorological Society, v. 97, no. 414, p. 414-428.