Wind and Temperature Profile Characteristics from Observations on a 1400 ft Tower[1,2]

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ABSTRACT

Profiles of mean wind speed obtained from a 1420-ft tower are analyzed on the basis of similarity theory to determine the relationship of profile shape to lapse rate structure. A total of 274 profiles representing four observation times (0600, 1000, 1400, and 1800 CST) are used in the analysis. Thirty minute averages of the wind speed are taken at eleven levels on the tower at these observation times. The wind speed values are normalized by means of the friction velocity as well as a reference height velocity computed at the lowest observation level, and profiles for these wind speeds are grouped according to profile shape characteristics. For each group, an average profile is computed and the vertical variation of mean wind speed is compared to a logarithmic or power law profile form.

Results of the study indicate that the mean wind profiles are dependent on the lapse rate structure and can be divided into "non-inversion" (lapse rates greater than isothermal) and "inversion" (lapse rates less than isothermal) profiles. For near adiabatic or slightly unstable lapse rates (mid-day non-inversion profiles), the logarithmic wind law represents the data well to a height of 300 to 400 ft. Above this height the wind speed is nearly constant. The more stable non-inversion wind profiles (lapse rates varying from about 2F to 5F per 1000 ft) generally show greater wind shears. These profiles are represented with a power law.

The wind profiles associated with lapse rates containing inversions are highly variable and depend on the nature of the inversion present. There appears to be an inter-dependence of vertical shear and inversion lapse rates for these profiles.

1. Introduction

In the last several decades, numerous studies have been conducted concerning the behavior of the mean wind and its variation with height in the friction layer. Measurements taken under carefully controlled conditions have shown that similarity theory is a useful tool for specifying the profile of mean wind speed in a shallow surface layer with a depth on the order of 50 meters. The bulk of precise experimentation has been confined to this shallow surface layer and many individual studies have been conducted under essentially controlled conditions of terrain roughness and stability. From these experiments have come several useful empirical and theoretical formulae descriptive of the wind profile.

Prior to 1960, however, few detailed observations of wind speed were available above the 50-meter level. In 1960 the Air Force Cambridge Research Laboratories established the Cedar Hill Meteorological Research Facility, a 1420-ft instrumented television tower located near Dallas, Tex. The tower is located in a terrain environment of gradually varying topography consisting of small orchards and open fields. The observations obtained from this facility provide continuous measurements of wind speed and temperature at eleven levels over the height range of 30 to 1420 ft.

It is the purpose of this paper to describe a study of the characteristics of the mean wind speed profiles associated with various kinds of stability stratification or lapse rate structure based on a sampling of a full year's data (1961) from the Cedar Hill tower. Analysis of the data was conducted from the standpoint of similarity theory with a view toward a simplified and practical description of wind profile behavior.

2. Description of data

As described in an unpublished paper by Captain D. W. Stephens[4] of the Geophysics Research Directorate, the data are obtained from an instrumented television tower located on a low ridge approximately 20 miles south-southwest of Dallas, Tex., at an altitude of 850 ft msl. The tower is triangular in cross section, 12 ft to a side, and rises without taper to a height of 1420 ft. Retractable booms which extend 12 ft from the tower structure are employed to mount instruments at twelve

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[4] Cedar Hill Meteorological Research Facility, Instrumentation for Geophysics and Astrophysics No. 18, AFCRL-632, June 1961.

levels on the tower: 30, 70, 150, 300, 450, 600, 750, 900, 1050, 1200, 1300 and 1420 ft above the base of the tower. Instrumentation consists of Bendix-Frieze Signal Corps type sine-cosine aerovanes and differentially connected copper-constantan thermocouples housed in Beckman and Whitley aspirated radiation shields. Wind speed and inter-level temperature differences are obtained continuously from the twelve sets of instruments. A detailed description of the data processing and meteorological equipment is provided by Gerhardt, Mitcham and Straiton (1962).

For the purpose of this investigation, the continuous record for the year 1961 was selectively sampled using measurements obtained during four months (February, April, August and November) for the daytime hours of 0600, 1000, 1400 and 1800 CST. In preparing the data, north-south and east-west wind components, as measured by the tower, are combined to obtain the scalar winds. The 5- and 10-min integrated values recorded by the tower system are averaged to provide 30-min mean readings centered about the four times cited above.

3. Similarity theory

In accordance with the hypothesis advanced by Monin and Obukhov (1954), the turbulence in the lower friction layer is completely dominated by the parameters $u^*=(\tau/\rho)^{\frac{1}{2}}$ and H/c_p, where τ is the surface stress, ρ the density, H the turbulent heat flux and c_p the specific heat at constant pressure. Application of dimensional considerations to this hypothesis leads to the conclusion that the surface layer is characterized by a single velocity scale, u^* and a single length scale L, defined by

$$L=-\frac{u^{*3}c_p\rho T}{kgH}, \tag{1}$$

where T is the absolute temperature, k is von Karman's constant, and g is the gravitational acceleration. For the surface layer, values of the two parameters u^* and L should be independent of height.

On the basis of this theory, it is possible to express the mean wind speed as a function of a dimensionless height $\zeta=z/L$, the expression taking the form

$$u=\frac{u^*}{k}\left[\varphi\left(\frac{z}{L}\right)-\varphi\left(\frac{z_0}{L}\right)\right], \tag{2}$$

where z_0 is a roughness parameter and, as pointed out by Monin and Obukhov (1954), $\varphi(\zeta)$ is a universal function. For small values of z/L, this universal function assumes the form

$$\varphi(\zeta)=\ln\frac{z}{z_0}+\frac{\alpha z}{L}, \tag{3}$$

and (2) becomes

$$u=\frac{u^*}{k}\left[\ln\frac{z}{z_0}+\frac{\alpha z}{L}\right]. \tag{4}$$

Eq (4) is referred to as the "log-linear" law and α is considered to be a universal constant. This generalization of the adiabatic profile law

$$u=\frac{u^*}{z}\ln\frac{z}{z_0} \tag{5}$$

was first introduced by Halstead (1943) without developing the similarity considerations.

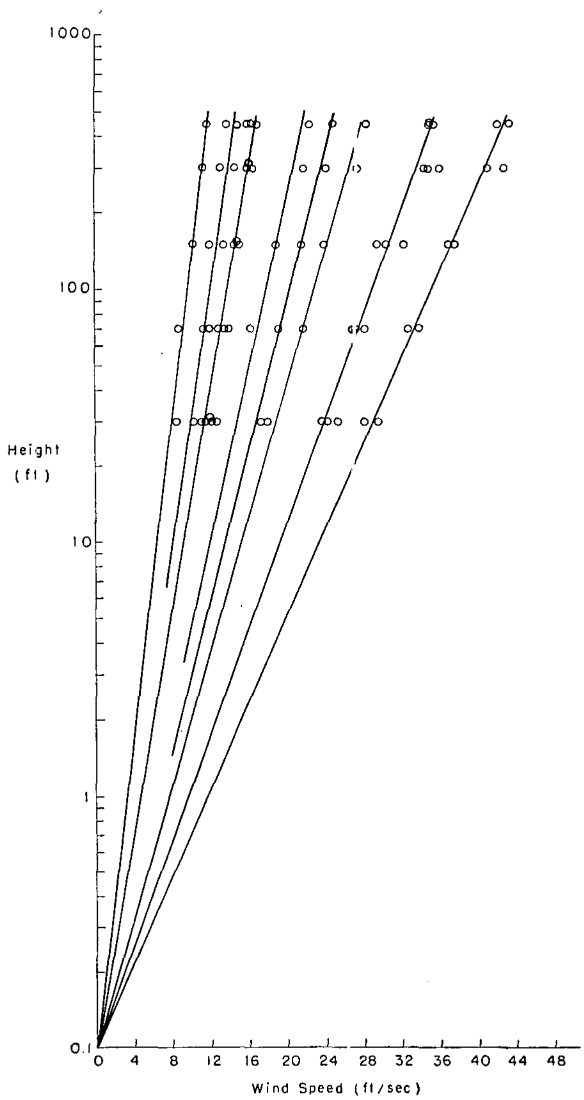


FIG. 1. Estimate of roughness length, z_0, based on 14 near-adiabatic profiles.

4. Analysis of data

With the assumption that u^* is independent of height in the surface layer for near adiabatic lapse rate conditions, (5) provides

$$u^* = \frac{k u_h}{\ln(h/z_0)}, \tag{6}$$

where u_h is the mean wind speed at level h, and z_0 must be evaluated for the observed wind data.

For the Cedar Hill tower site, z_0 was estimated on the basis of (5) from 14 profiles associated with near adiabatic lapse rates by plotting log z for five levels, as shown in Fig. 1, as a function of the mean wind speed. With a z_0 value of 0.1 ft (3 cm) and a k value of 0.4, (6) becomes

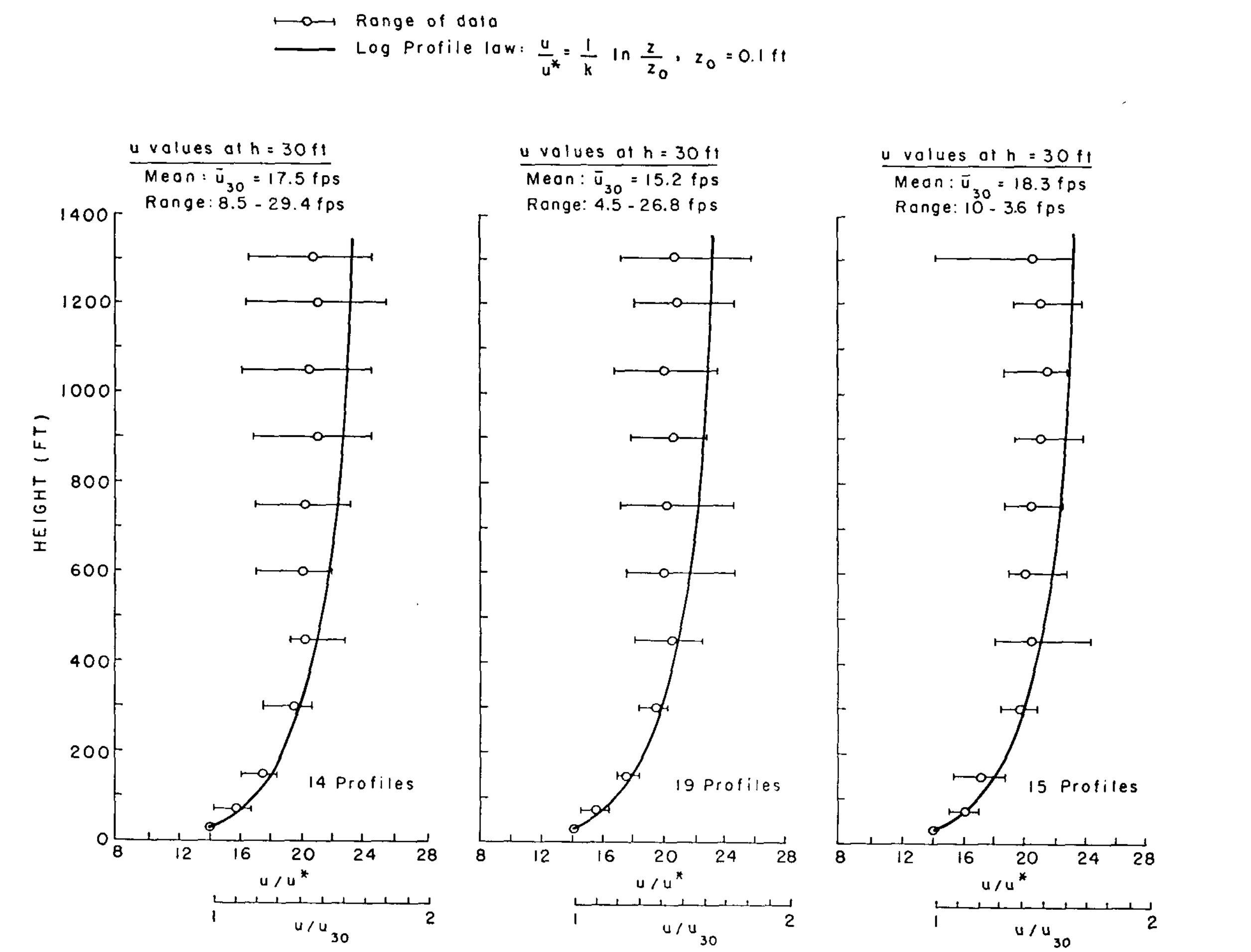
$$u^* = 0.07 u_{30}, \tag{7}$$

where u_{30} is the mean wind speed observed at the 30 ft level. The observed u values were divided by u^* and u_{30} and the resulting u/u^* (or u/u_{30}) profiles were examined in conjunction with the associated temperature structure.

Since the depth of the layer in which surface layer theory can be expected to hold is known to decrease with increasing stability, it is questionable whether the use of (7) to estimate u^* is valid under the more stable lapse rate conditions. In fact, even the lowest 30-ft tower level may not be within the surface layer under these conditions. For this reason, and because the ratio u/u_{30} is convenient for relating the winds to any given reference level, both u/u^* and u/u_{30} abscissae are included in the figures. It is of interest to note that for the lowest 10 m, or so, of the surface layer, Deacon (1949) found it possible to use a single z_0 value (obtained from adiabatic observations) in fitting an empirical expression of the form

$$\frac{du}{dz} = \frac{u^*}{k z_0}\left(\frac{z}{z_0}\right)^{-\beta} \tag{8}$$

to wind profiles over a wide range of stability conditions. In the expression (8), β is taken to be greater or less than



(a) Adiabatic [5°F<($T_{30}-T_{1050}$)<6°F] (b) Unstable [6°F<($T_{30}-T_{1050}$)<7°F] (c) Unstable [7°F<($T_{30}-T_{1050}$)<8°F]

FIG. 2. Average wind profiles compared to the logarithmic law for near adiabatic and unstable lapse rates.

unity in unstable or stable conditions, respectively. Deacon in his analysis assumed β to be independent of height, but observed that some variations with height occurred. Davidson and Barad (1956) in analyzing O'Neill data found that β varied systematically with height and stability for a height range of 0.4 m to 6.4 m.

5. Discussion of results

a Non-inversion data. Three basic forms of temperature structure, exclusive of inversion data, were observed in the analysis: (1) a uniform lapse rate in the near adiabatic to unstable range $[5F<(T_{30}-T_{1050})<8F]$, (2) a combined form consisting of an unstable lapse rate $[(T_{30}-T_{1050})<54F]$ in the lower half and a stable lapse rate $[0F<(T_{30}-T_{1050})<5F]$ in the upper half; and (3) a combined form consisting of an isothermal lapse rate from 30 to 150 ft, and a stable lapse rate above this level.

The average profiles of u/u^* and u/u_{30} associated with three ranges of the near adiabatic to unstable lapse conditions are shown in Figs. 2 and 3. As seen in the figures, the logarithmic formula (5) provides a generally good description of the data up to the 300–450-ft level. Fig. 3 shows that (5) is within 4 per cent of the average observed profile values up to the 450-ft level. Above this level the wind speed remains nearly constant with height. Scatter is seen to be fairly small in the logarithmic range and remains reasonably small through the highest level of observation.

The wind profile associated with a lapse rate structure of the unstable-stable form is shown in Fig. 4. The lower part of this profile is seen to exhibit a logarithmic form. The scatter of the observations for the lowest 450 ft, however, is quite a bit larger than for the other log profile cases, and this becomes even larger at the higher levels.

In the case of the combined isothermal-stable lapse rates, it is possible to distinguish three profile forms. The first, shown in Fig. 5, is associated with a stable lapse rate above the 150-ft level, that is on the average $\frac{3}{4}$ of the adiabatic lapse rate. The other two profiles, shown in Fig. 6, are associated with upper lapse rates which are equal to approximately $\frac{1}{2}$ and $\frac{1}{4}$ of the adiabatic condition.

Use of the logarithmic form (5) to represent these profile types proved unsuccessful as may be seen in Figs. 5 and 6. Panofsky, Blackadar and McVehil (1960) report attempts to use the Monin and Obukhov law (4) to fit stable wind profiles in the lower levels of the surface layer. This log plus linear law—where the linear term represents z/L or z/L'—was found generally unsatis-

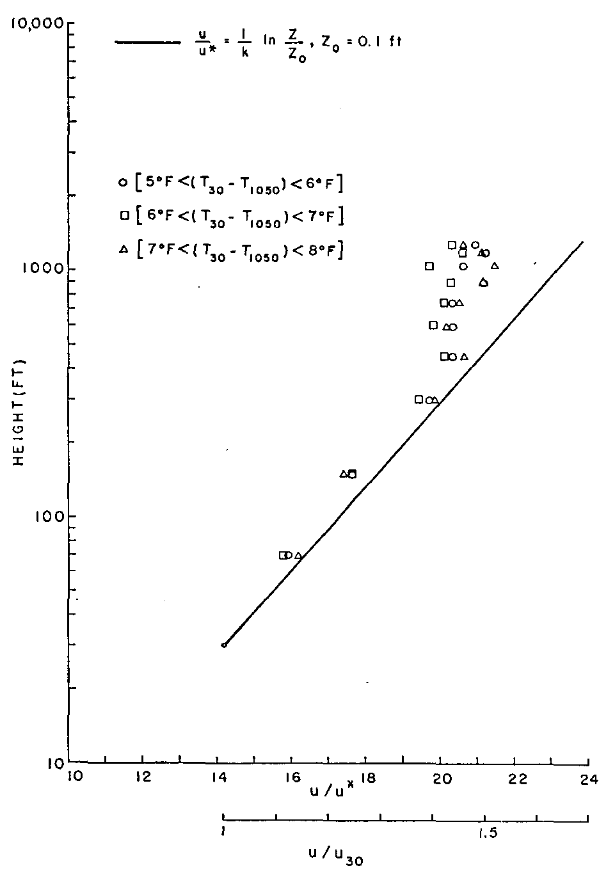


FIG. 3. Average wind profiles plotted as a logarithmic function of height.

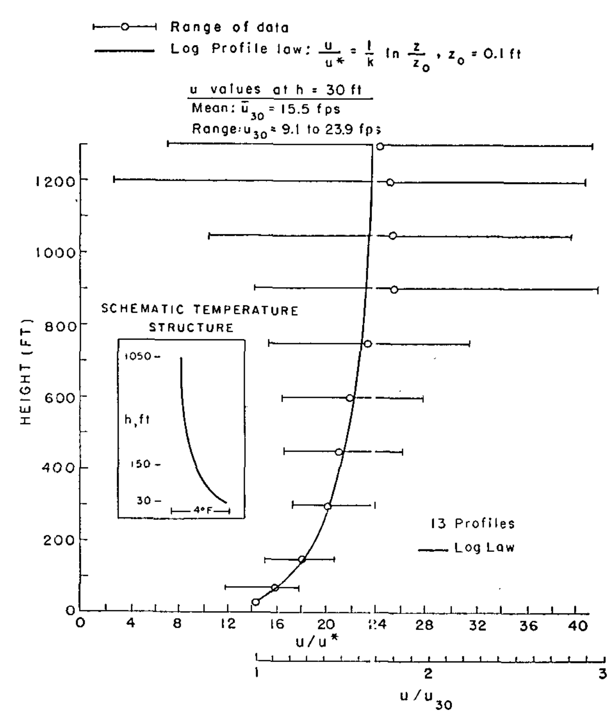


FIG. 4. Average wind profiles for a temperature structure varying with height from a superadiabatic to a near isothermal condition.

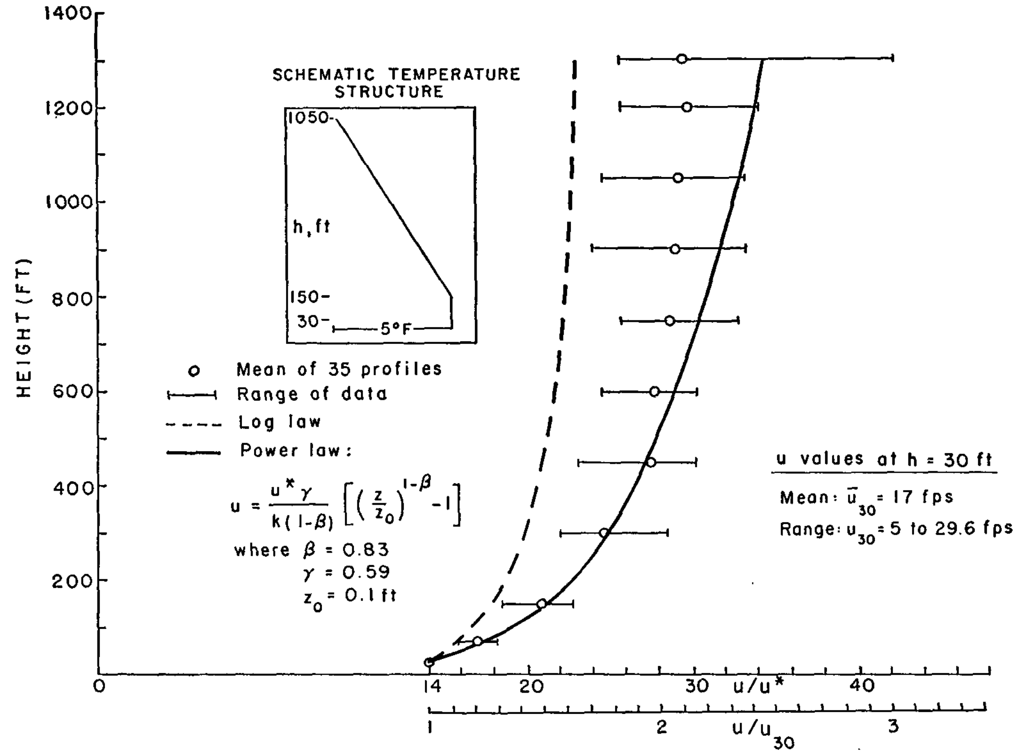


FIG. 5. Average wind profiles for a temperature stratification that is isothermal in the 30- to 150-ft layer and approximately $\frac{3}{4}$ of the adiabatic rate in the 150- to 1050-ft layer.

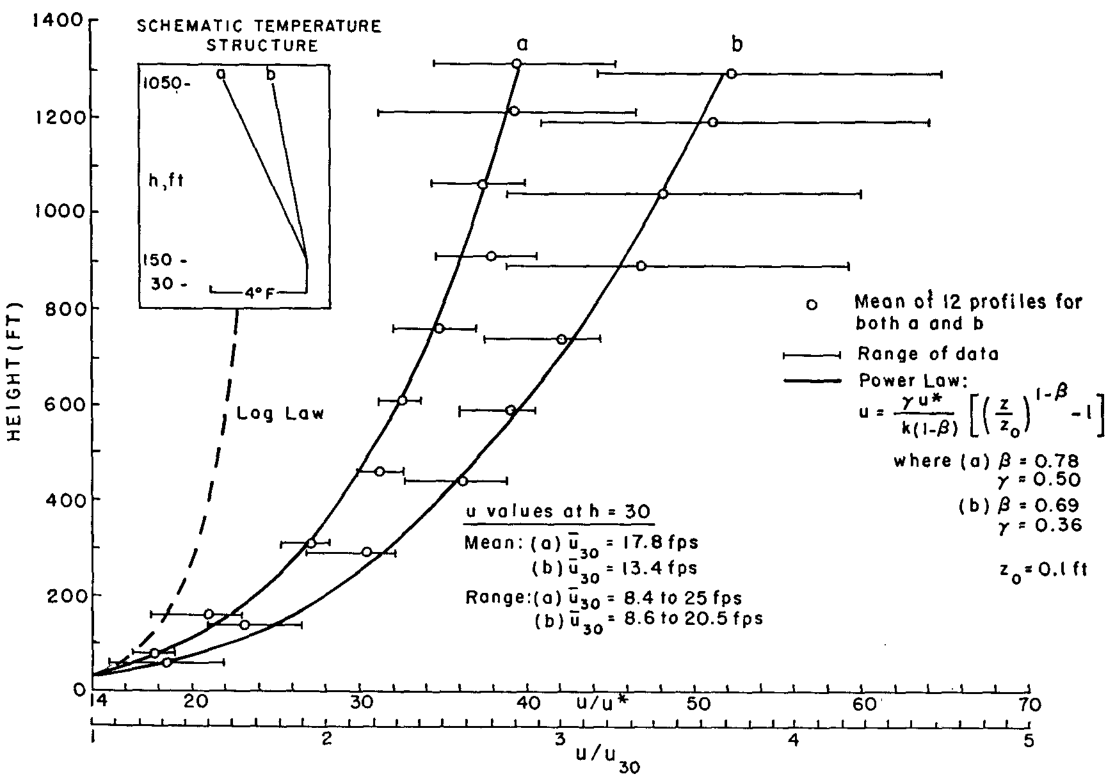


FIG. 6. Average wind profiles for a temperature stratification that is isothermal in the 30- to 150-ft layer and approximately $\frac{1}{2}$ and $\frac{1}{4}$ of the adiabatic rate in the 150- to 1050-ft layer.

Profile	Lapse Rate		No. of Cases	u values at h = 30 ft	
	Lower	Upper		$\bar{u}_{30}$ (fps)	Range (fps)
a □	Unstable	Inversion	4	16.0	10.1 - 20.9
b ●	Isothermal	Isothermal	12	12.1	7.1 - 17.6
c △	Inversion	Stable	17	9.6	2.9 - 17.1
d ■	Isothermal	Inversion	5	10.5	6.3 - 14.3
e ▽	Inversion	Isothermal	7	8.3	3.2 - 13.2

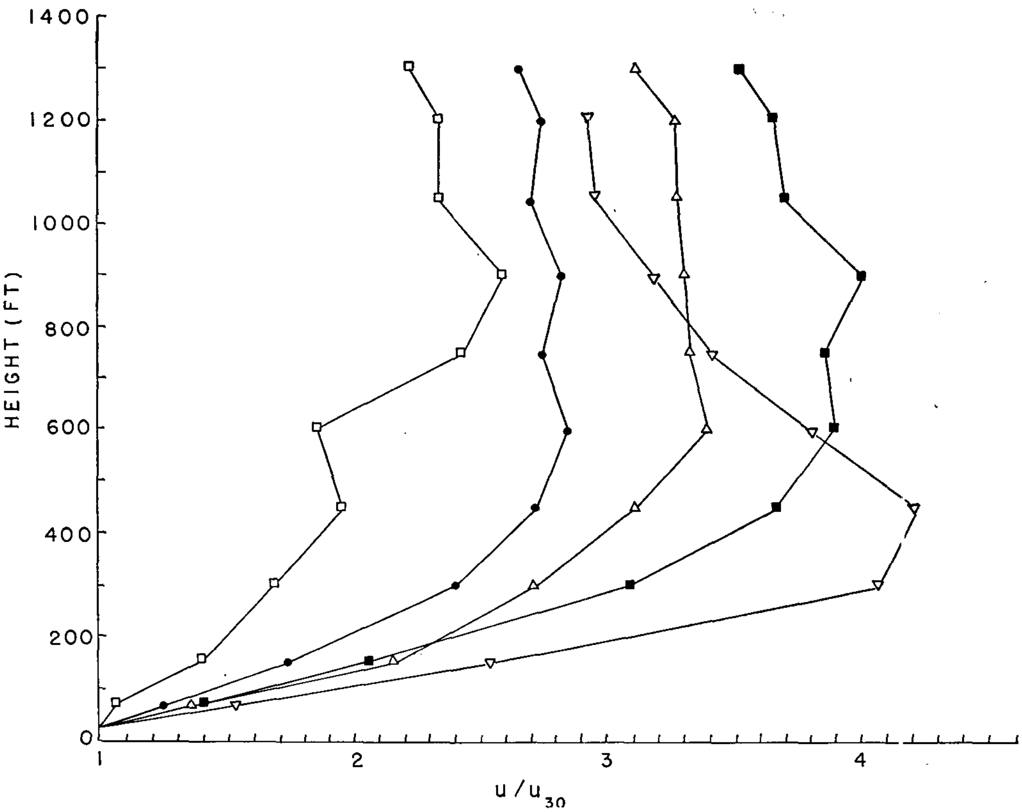


FIG. 7. Average wind profiles corresponding to various forms of inversion lapse rate structure.

factory by Panofsky *et al.*, for stable conditions, although some observed wind profiles were fitted with (4) by varying α as necessary. Takeuchi (1962) also found agreement of (4) for wider ranges of themal stability by varying α with stability. The need to vary α with place, time, and even height, suggests that some factors in addition to heat flux and surface stress are needed to provide a generalization of low level profiles under stable conditions.

As a matter of interest, an attempt was made to fit the stable profiles of Figs. 5 and 6 with a log-linear form at the lowest (30–450 ft) levels of the Cedar Hill tower. Since it was not possible to estimate z/L values due to a lack of accompanying heat flux data, arbitrary z/L values to provide a 'best' fit were used. On this basis, the log-linear form provided only fair agreement with the stable wind profiles observed in the 30 to 450 ft height range at the Cedar Hill tower.

By plotting the log of the wind speed as a function of log height, the data shown in Figs. 5 and 6 revealed the linear log-log behavior of a power law through substantial portions of the observations; therefore, the power law was chosen as the most suitable form with which to represent the tower data under stable conditions.

The power law form (8) of Deacon (1949) and Laikhtmann (1944) is widely cited in surface layer studies. By integrating (8) with the boundary condition $u=0$ at $z=z_0$, Deacon's generalized wind profile takes the form

$$\frac{u}{u^*}=\frac{1}{k(1-\beta)}\left[\left(\frac{z}{z_0}\right)^{1-\beta}-1\right]. \tag{9}$$

When $\beta=1$ (adiabatic case), (8) becomes the logarithmic profile form.

The power law profiles shown in Figs. 5 and 6 were obtained from (9) by selecting values of β to provide the 'best' fit to the averaged tower wind speed values at each level for the data of Fig. 6, and for the first 450 ft for the data of Fig. 5. To satisfy the condition

$$u/u^* = \frac{1}{k} \ln \frac{h}{z_0}$$

at the $h=30$ ft reference level for each of the three stable profiles, it is necessary to multiply (9) by the factor

$$\gamma = \frac{(1-\beta)\ln h/z_0}{(h/z_0)^{1-\beta}-1}. \tag{10}$$

Presenting the stable profiles in this manner, the abscissa can be represented by u/u^* and u/u_{30}.

The values of β found to provide reasonably good fits to the three stable profile classifications are, in order of increasing stability: 0.83, 0.78, and 0.69, respectively.

It may be seen from Fig. 5 that the representation of (9) is quite good through the lowest 450 ft in the case of the most stable profile, the wind becoming nearly constant with height above that level. Scatter is seen to be relatively small through the entire 1300-ft stratum. For the two other stable profiles (Fig. 6), (9) represents the data well for the entire height of the tower. Scatter remains fairly small through a substantial portion of both profiles.

b) Inversion data. The inversion data are the most difficult to describe. From the nearly continuous spectrum of profile forms observed in this grouping, at least five distinct forms of temperature stratification were noted. These are shown in Fig. 7. Davidson and Barad (1956), who observed similar profile behavior under inversion conditions, ascribed the variation to the influence of low level wind maxima commonly referred to as low level jets. (See also Blackadar, 1955). Although certain low level wind maxima appeared in the inversion data, attempts at correlating features of the wind maxima with the differences in profile shapes proved unsuccessful.

The general behavior of the wind profiles in Fig. 7 indicates a strong dependence on the temperature structure at the lower levels in the sense that the wind shear increases as the lapse rate becomes more stable. As seen in Fig. 7, however, the temperature stratification for the higher tower levels also influence the wind profile near the surface. For example, both profiles *b* and *d* have isothermal temperature gradients at the lower levels, but profile *d*, which has an inversion lapse rate above (while *b* remains isothermal), has wind shears that are nearly 50 per cent greater below the 600-ft level. Similarly, profiles *c* and *e* have inversion lapse rates for the lower part of the tower, but stable lapse rates higher up. Again, profile *e*, which has the more stable temperature structure overall, has the greater wind shear below the 450-ft level. Additional conclusions concerning the inversion profiles appear unwarranted because of the scatter of the observations and the sparsity of the data considered.

The five profile forms shown in Figs. 2 through 7 can be related roughly to diurnal changes. The logarithmic forms of Figs. 2 to 4 (1000 and 1400 CST data) are characteristic of midday profiles. The power law form with the nearly constant wind speed above 450 ft (Fig. 5) is characteristic of early evening profiles (1800 CST data). The remaining two power law forms (Fig. 6) occur predominantly in the early morning (0600 CST data); this is also true of the inversion data. A complete breakdown of the diurnal distributions is presented in Table 1 which includes an "erratic" classification for those profiles with irregular shapes and an "individual" classification for the more regular profiles for which no satisfactory description was found.

Table 1. Distribution of 274 observed mean wind speed profiles by type and time of day.

Temp. structure	Time (CST) 0600	1000	1400	1800	Total	Percentage (by type)
Adiabatic	0	3	11	0	14	5
Unstable	0	13	20	1	34	13
Unstable to isothermal	0	13	2	2	17	6
Isothermal to $\frac{3}{4}$ adiabatic	0	4*	5*	26	35	13
Isothermal to $\frac{1}{2}$ adiabatic	8	0	0	4	12	4
Isothermal to $\frac{1}{4}$ adiabatic	11	0	0	1	12	4
Inversion	48	6	4	13	71	26
Erratic	1	13	9	4	27	10
Individual	6	14	20	12	52	19
Total	75	66	70	63	274	100
Percentage (by time)	27	24	26	23	100	—

* Predominantly overcast sky conditions.

6. Summary and conclusions

In the analysis of the mean wind speed profiles for the 1420-ft Cedar Hill tower, it is found that the lapse rate structure together with a logarithmic or a power law expression provides a suitable description of the average wind speed profiles. Surface layer theory appears suitable for use in the lowest 300 to 400 ft as shown by the logarithmic structure of the near adiabatic and unstable profiles. Midday profiles conform to a logarithmic formulation while morning and evening profiles (exclusive of inversion data) are better suited to a power law representation. Inversion data show marked variation and there appears to be an inter-dependence of vertical shear and temperature inversion.

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