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The Structure and Simulation of Adiabatic Boundary Layers

by

J. Counihan

Part 1 ; The Structure of Adiabatic Boundary Layers.

("The wind is wild tonight there's battle in the air
The wind is from the West and it seems to blow from Clare"
E. Lawless)

A Thesis submitted for the degree of
Doctor of Philosophy
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ABSTRACT

It has been established that Industrial Aerodynamics wind tunnel tests should be carried out in flows which model atmospheric Adiabatic boundary layers . In order that the models being tested should be of an adequate size these boundary layers should be as deep as possible . Such a boundary layer can be produced naturally in a wind tunnel having a very long working section ; the object of this work has been to devise a system which would reproduce flows having the structure of Adiabatic boundary layers in a few boundary layer heights .

There are some conflicting opinions in the literature as to the nature of the boundary layer structure for various terrain types or , how the flow structure varies as a function of the terrain roughness . Consequently , the first part of this work was concerned with deriving the boundary layer structure appropriate to flow over various types of terrain . This was done by reviewing and analysing the available meteorological literature for the period 1880 - 1972 . The analysed data are finally presented as a function of the roughness lengths appropriate to various types of terrain and these data are considered to be the most representative available for adiabatic boundary layers .

Many methods of simulating such flows have been attempted; these have been briefly reviewed in the second part of the work and were generally found to produce flows which did not have all of therequired turbulence characteristics . The method described here produced all of the mean and turbulent flow properties required in a length of between three and four and one half boundary layer heights . In the first instance the flow appropriate to rural terrain was produced and subsequently , with the system for producing the flow partly modified , the flow characteristics of urban terrain were simulated . The structure of both of these boundary layers was consistent with that predicted by the analysed atmospheric data .

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1. INTRODUCTION .

At one time , in the field of Industrial Aerodynamics , a uniform airflow past a building or structural model in a wind tunnel was considered adequate for the determination of mean steady surface wind loads . However , with the advent of taller buildings , and larger buildings having complex external shapes, it was considered necessary to represent at least the velocity profile of the atmospheric boundary layer in such wind tunnel tests . Since economy is also of importance , these buildings tended to be lighter and more flexible in their structure . Consequently , it became apparent that it was not sufficient to measure the wind loads on a model building in just a shear flow , as under such conditions , the approximate mean wind loads only are obtained .

It has been found that it is also necessary to know the magnitude of the fluctuating load component which is superimposed on the mean loads . To determine such loads it follows that wind tunnel tests should be conducted in an air-flow that is fully representative of an atmospheric or rough wall boundary layer . This in turn implies correct simulation of the intensities and scales of the turbulent quantities of these boundary layer flows . Since the relevant wind-loading cases occur in high winds , which give rise to adiabatic equilibrium and where the turbulence is mechanical in origin , then the conditions of stable and unstable equilibrium in the Earth's boundary layer need not be considered here .

A rough wall boundary layer can be grown naturally , but this requires a prohibitive length of wind tunnel working section. The object of this project was to devise a system which would produce an accelerated rate of boundary layer growth and produce an equilibrium boundary layer , having the correct scales and intensities of turbulence , in a distance of three to four boundary layer heights . The system devised should also be flexible enough to produce the boundary layer flow appropriate to various types of terrain varying from say rural to urban .

As a consequence of this it became essential to have sufficient information available from which the various types of adiabatic boundary layers could be defined and from which some knowledge of the flow characteristics to be simulated could be derived . With this object in mind a limited amount of meteorological data was initially examined and sufficient data extracted from which the characteristics of "typical" rural and urban sites could be defined .

The prevailing general opinions , at least amongst non-meteorologists , suggested that there was "insufficient data available " from which to define adequately the atmospheric boundary layers of interest . In addition , there were widely varying opinions as to the correct application and analysis of the data presented in various meteorological journals . For these reasons it was decided that this was an appropriate time at which to review the meteorological data available on

adiabatic boundary layers ; in addition , such a review did not appear to have been attempted elsewhere . Consequently , as a result of the extensive literature found to exist on this subject it was decided , for practical reasons , to present the review and analysis on the structure of the boundary layer in one part (PART 1.) and the work on its simulation in a wind tunnel as a separate part (PART 2) . Both sections of the work support each other but can clearly be presented independently . As the review of the meterological data progressed it was seen that a simple mathematical representation of Adiabatic boundary layers might be deduced . This object was also acheived to some extent and is included in PART 1.

The meteorological literature for the period 1880 - 1959 was considered first in some detail and clearly established the similarity of the flow on the Earth's surface to that of a rough wall boundary layer . As a non-meteorologist , it was also considered necessary to consider the information in some detail, both from the point of view of becoming more familiar with this aspect of meteorology and of acquiring some capability in assessing the accuracy or validity of the material considered . In the latter context , various sources of error in this type of data were indicated and discussed and reasons given for some of the large amount of scatter present . Generally , the progress in acquiring experimental data and the production of empirical theories were seen to follow a logical sequence in this period.

The main advances and the more important quantitative data from this period were then summarised . Consequently , it became evident that a large amount of scatter existed in the meteorological measurements which originated from many sites , nominally of the same terrain type . Much of this scatter could be attributed to the fact that the types of terrain which could be classed as say , rural , varied widely with respect to the boundary layer characteristics which defined them . Therefore, although at this stage a "typical" rural terrain could be defined ,it was felt that the various grades of this terrain , and of the other types considered , should be defined more accurately . However in order to obtain such a definition additional quantitative data were needed . As a result , the literature of the 1960 - 1972 period was reviewed with the main object of obtaining the additional quantitative data required. Other significant advances in this period were also noted for completemess ; these were mainly of an empirical nature .

Finally , all of the atmospheric data is presented in a concise graphical form from which a simple mathematical model of the boundary layer structure for various types of terrain has been deduced . The information is presented in a form which is easy to use and has the advantage that if one quantity from a particular site is known , or can be measured , then the general boundary layer characteristics of that site can be readily deduced with a reasonable amount of accuracy .

All of the known available data has been assessed in some detail to derive the final figures which summarise the data . This approach would appear to be justified by considering just the number of recent papers which have presented inaccurate opinions on atmospheric data due purely to the fact of not assessing a sufficient amount of the available literature . On this basis , and the fact that all the available data needed to be put on record and analysed by one method , the work of this part of the thesis is presented .

2. DEFINING THE ADIABATIC BOUNDARY LAYER FROM THE METEOROLOGICAL DATA .

2.1. Initial Considerations .

The main object of this work is to devise a method of simulating in wind tunnels adiabatic atmospheric boundary layers appropriate to terrain varying from rural to urban . Since parts of the work will involve comparisons of data from atmospheric and flat - plate (or natural) boundary layers it is necessary to establish that there is some relationship between these two groups of boundary layer flow .

The laws governing an adiabatic atmosphere can be deduced as follows :-

Consider a vertical tube of air in the atmosphere of unit C.S.A. - the difference in pressure between h and h + dh :-

$$dp = w\,dh \qquad 1.$$

where: $w = \rho g = \frac{1}{V}$ = Spec. Weight. (wt. of 1 cu.ft. of air) 1.

From the characteristic gas equation : $pV = RT$

$$dh = -\frac{RT}{p}\,dp \qquad 2.$$

solution of which gives the pressure-height relationship required .

The relationships for adiabatic conditions are as follows :-

$$pV^{\gamma} = \text{Const.} \quad \text{or} \quad pV^{\gamma} = p_1 V_1^{\gamma}$$

From which is derived :-

$$p = p_1 \left(T_1/T\right)^{\gamma/1-\gamma} \qquad 3.$$

and

$$dp = -\frac{\gamma}{1-\gamma} p_1 T_1^{\frac{\gamma}{1-\gamma}} T^{-\frac{1}{1-\gamma}} dT \qquad 4.$$

Substituting for p and dp (from equations 3 and 4) in equation 2 :—

$$dh = \left(\frac{\gamma}{1-\gamma}\right) R\, dT$$

or :

$$\frac{dT}{dh} = \text{Lapse Rate} = -\left(\frac{\gamma-1}{\gamma}\right)\frac{1}{R}$$

which gives a lapse rate of $\simeq$ $0.030^{\circ}C$ / 100ft

or $\simeq$ $1^{\circ}C$ / 100 metres

(or exactly $0.98^{\circ}C$/100m)

It is more usual to define the atmosphere conditions prevailing with reference to what is called the potential temperature .

The potential temperature of dry air is defined as the temperature the air would attain if brought adiabatically to a standard pressure p_o from initial conditions having temperature T and pressure p .

If θ is the temperature corresponding to the standard pressure p_o then :-

θ = Potential temperature of the air.

From equation 3 :

$$\frac{T^{\gamma}}{p^{\gamma-1}} = \text{Const.} = \frac{\theta^{\gamma}}{p_o^{\gamma-1}}$$

Hence :

$$\theta = T\left(\frac{p_o}{p}\right)^{\frac{\gamma-1}{\gamma}} = T\left(\frac{p_o}{p}\right)^{0.288}$$

(In meteorology p_o is normally taken as 1000 mb.)

Therefore if the potential temperature θ remains constant with height the atmospheric boundary layer is in a state of neutral or adiabatic stability.

If the case shown in Fig. 1(a) is now considered i.e. when the temperature gradient is less than and greater than the adiabatic lapse rate . Consider the conditions for curve B to apply :-

If a particle of air is displaced upwards from P and its temperature varies as the gradient of curve A , then at any height its temperature will be greater than the prevailing temperature , therefore being less dense it has positive buoyancy and accelerates upwards . This corresponds to the unstable case i.e. the potential temperature decreases with height .

Curve C applies to the opposite case :-

that is , a particle moved upwards or downwards from P is subjected to a force that tends to restore it to position P . This corresponds to the stable case i.e. the potential temperature increases with height .

Curve A is clearly the equilibrium or neutral case and a particle displaced from point P will be in equilibrium in its new position.

These conditions can be summarised as follows :-

	A	B
	θ Constant with height	θ Decreases with height
Equilibrium :	Neutral or Adiabatic	Unstable

	C
	θ Increases with height
Equilibrium :	Stable

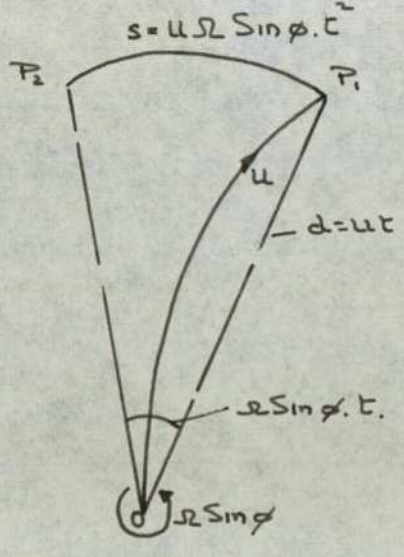
Therefore for the condition of neutral or adiabatic equilibrium thermal effects are absent and the turbulence in the atmospheric boundary layer is purely mechanical turbulence i.e. it is produced by surface roughness at ground level.

Therefore it can be seen that for this condition that atmospheric and natural boundary layers are comparable .

The Coriolis Force.

However there is one fundamental difference between these boundary layers and that is , the effect of the Coriolis Force , caused by the earth's rotation , on the vertical velocity gradient of the atmospheric boundary layer . This produces a change in the mean wind direction with increase of height from ground level to the top of the boundary layer.

The coriolis force acts as a result of the Earth's rotation Fig. 1(b) . As can be seen the angular velocity vector of the earth's rotation can be resolved into horizontal (Ω Cos ϕ) and vertical components (Ω Sin ϕ) . The important component is Ω Sinϕ which affects the winds .



If horizontal motion at a northern latitude ϕ is considered :-

Air moving towards P from O moves in a clockwise direction since the rotation of the earth is anti - clockwise .

In steady conditions the air moves a distance d at velocity u in a given time

i.e.

$$d = u.t$$

However due to the Earth's rotation P has moved from P_1 to P_2.

therefore: $s = ut \cdot \Omega \sin\phi . t$

$$= u\Omega \sin\phi . t^2$$

The air can be regarded as having been subjected to an acceleration 'a' or transverse force which gives it a curved path .

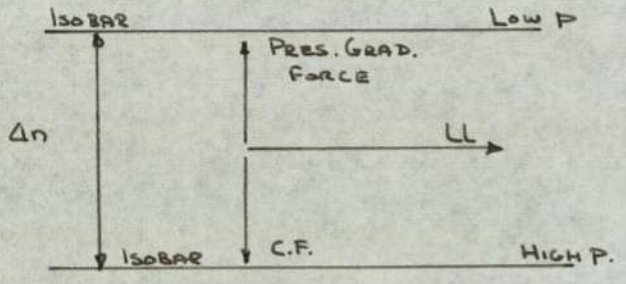
Comparing this equation with the standard equation

$s = \frac{1}{2} at^2$, since the initial velocity is zero

then :

$$a = 2\Omega \sin\phi . u$$

which is the side force / unit mass and is called the Coriolis Force . The Coriolis parameter (F) is the quantity $2\Omega \sin\phi$. The Coriolis Force (C. F.) always acting at right angles to the wind affects its direction but not its speed.



(Δn = DIST. BETWEEN ISOBARS.)

Now consider a flow in the Northern hemisphere where the pressure gradient force balances the Coriolis Force . The wind direction is perpendicular to both forces .

Therefore :

$$-\frac{1}{\rho}\frac{\partial p}{\partial n} + f U_G = 0$$

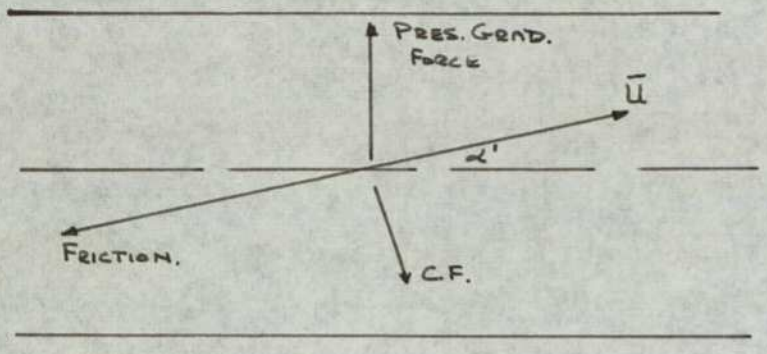
(f = CORIOLIS PARAMETER)

or

$$U_G = \frac{-1}{f\rho}\frac{\partial p}{\partial n}$$

(U_G = GEOSTROPHIC WIND.)

The effect of surface roughness.



The effect of surface roughness is to reduce the wind velocity and thus the Coriolis force . Hence the wind direction changes by an angle α' due to unbalance of the pressure gradient and Coriolis forces . The effect decreases as the distance from the ground increases until the wind reaches its geostrophic value at the top of the boundary layer . In effect the direction and magnitude of the mean wind is a function of height and the total angle through which it rotates is a function of the surface roughness . This provides the main difference between adiabatic atmospheric and flat - plate boundary layer flow. Neglecting this fact , pro tem., the boundary layer quantities to be considered can now be defined.

2.2. Quantities which define the boundary layer and its structure.

The following quantities are the turbulent boundary layer quantities considered on which data will be sought in the review of meteorological literature in Section 2.3. Such data includes their variation and magnitude in the adiabatic atmosphere boundary layer . The quantities of interest are as follows .

(a) The variation of the mean wind velocity in direction and magnitude with height

(b) The values of the roughness length and zero plane displacement which are functions of the surface roughness , for different types of terrain .

(c) The height of the Earth's boundary layer . It is necessary to know this quantity since if we are to produce its model we need to know the scale of that model .

(d) The Reynolds Stress and its variation with height. This stress is a function of the surface roughness and is of importance in producing the turbulent energy .

(e) The cospectrum of the Reynolds Stress . This provides knowledge of the frequency range over which these stresses are significant .

(f) The longitudinal , lateral and vertical fluctuating velocities and their variation with height i.e. the turbulence intensities .

(g) The power spectral densities of these fluctuating velocities and their variation with height i.e. the range of frequencies over which the fluctuations of these velocities are significant .

(h) The intermittency factor , or the ratio of turbulent to non - turbulent motion , and its variation with height .

(i) The correlations of the longitudinal fluctuating velocity for vertical and lateral separations , from which the length scales of turbulence vertically and laterally are obtained .

(j) The autocorrelation of the longitudinal fluctuating velocity i.e. its correlation as a function of time , from which the length scales of turbulence in the axial direction are obtained.

(k) The probability density distribution of the fluctuating velocities , i.e. determination of whether the distributions are Gaussian or not .

These quantities are now denoted by the symbols normally used :-

(a) The velocity gradient

$$\bar{u}/\bar{U}_{max.} \text{ or } \bar{u}/\bar{U}_o$$

$\bar{u}$ is the local mean velocity .

$\bar{U}_o$, $\bar{U}_{max.}$ is the mean free-stream or gradient velocity at the top of the boundary layer.

(b) The roughness length and zero plane displacement

are defined in the equation ;

$$\bar{u}/u_\tau = 1/k \log_e \frac{y-d}{y_o}$$

u_τ or u_* is the friction velocity

k is Von Karman's constant

y is distance measured vertically from the ground

y_o is the roughness length

d is the zero plane displacement

(c) The boundary layer height

defined by the symbol δ

(d) The Reynolds Stress

defined as, $\overline{u'v'}$

where, u' is the longitudinal fluctuating velocity

v' is the vertical fluctuating velocity .

This is usually normalised with respect to the free-stream velocity e.g. $\overline{u'v'}/\bar{U}_o^2$

(e) The Reynolds Stress Power Cospectral Density.

Denoted by-

$$S_{uv}(n)$$

This is usually presented as-

$$n\,S_{uv}(n) \text{ Vs. } n.$$

(f) The turbulence intensities.

The r.m.s. of the fluctuating longitudinal velocity is denoted by-

$$\sqrt{\overline{u'^2}}$$

From which the turbulence intensity is-

$$\sqrt{\overline{u'^2}}/\bar{u}$$

The lateral and vertical turbulence intensities are respectively-

$$\sqrt{\overline{w'^2}}/\bar{u} \quad , \quad \sqrt{\overline{v'^2}}/\bar{u}$$

(g) The Power Spectral Density.

Denoted by-

$$S_u(n),\ S_w(n),\ S_v(n)$$

for the longitudinal, lateral and vertical fluctuating velocities respectively.

(h) The intermittency factor

Defining the fraction of time , of the time period considered , for which the recorded signal was turbulent and denoted by :

$$\underline{\gamma_u} \ , \ \underline{\gamma_w} \ , \ \underline{\gamma_v}.$$

for the three fluctuating velocity components .

For example :-

$\gamma = 1.0$ in the lower section of the boundary layer

$\gamma \simeq 0$ at the top of the boundary layer .

(i) Space Correlations.

For the longitudinal fluctuating velocity the vertical scale of turbulence is denoted by ;

$$L_{uy} = \int R_u \, dy$$

and the lateral scale by ;

$$L_{uz} = \int R_u \, dz$$

where- $R_u = \dfrac{\overline{u'_a u'_b}}{\sqrt{\overline{u'^2_a}}\sqrt{\overline{u'^2_b}}}$ is the space correlation.

(j) Time Correlations.

For the longitudinal fluctuating velocity the longitudinal scale of turbulence is denoted by ;

$$L_{ux} = \bar{u} \int R_\tau \, d\tau.$$

where R_τ is the time correlation.

(The other symbols appearing in the review are defined where they occur in the text.)

2.3. Review of meteorological and micrometeorological data on the structure of the atmospheric boundary layer for the condition of neutral or adiabatic stability .

Since the beginning of this century information has started to become available about the Earth's boundary layer . A few papers are also available from the end of the previous century which are worthy of consideration . However , because of the development and improvement in measuring techniques in the last ten or twenty years the output of this type of information has increased considerably . Therefore there is some difficulty in deciding on the best method to adopt in reviewing and analysing the existing data .

It was assumed that the best way of doing this was in chronological order . This will necessarily result in some overlapping and repetition of comments or conclusions from time to time . However this should be counteracted by the fact that a more complete picture should emerge of the gradual build up in knowledge concerning the structure of the Earth's boundary layer . The various periods should also be indicated when fundamental facts were derived either by experimental or theoretical approaches .

Since natural or flat - plate boundary layer work was also progressing in the same period , reference will be made to data coming from this source in order to illustrate its similarity to the atmospheric boundary layer characteristics . The main concern is with the adiabatic

boundary layer , however where the variation of the quantities in question with stability is considered to be of interest , or relevant , this will be indicated in the text .

Where possible comments will be made on the accuracy or significance of the papers discussed . For clarity these comments will be made in the present tense . Comments and conclusions made by the authors of the papers considered will be recorded in the past tense .

The period considered initially covers from 1880 up to and including 1919 .

2.3.1. Review and assessment of meteorological data for the period 1880 to 1919 .

One of the main quantities of interest in the atmospheric boundary layer is the variation of the wind velocity with height . Some of the earliest measurements of this variation in the Earth's boundary layer were given in Stevenson (1880) . The wind velocity profiles were measured for conditions varying from light to strong winds over open ground and subsequently with corn 0.30 m. (1 ft.) and 1.07 m.(3.5 ft.) high on the ground . The data was analysed by presenting the velocity variation with height as a series of parabolic curves having their vertices at a point 22 m. (72 ft.) below the surface of the ground . By so doing the lower 6 to 9 m. (20 to 30 ft.) of the profiles were neglected , while at greater heights the measured variations fitted the parabolas .

From the present knowledge on boundary layer flow these measurements can now be analysed to give the roughness lengths y_o for the different terrain conditions specified above (Fig. 2) and the various wind speeds . It is deduced from the results that Reynolds Number effects are negligible for the range of wind speeds considered . The data derived is tabulated as follows .

Terrain :	Open ground	Corn 0.30m.(1 ft.) high	Corn 1.07 m. (3.5 ft.) high
y_0	0.137cm.(.54in.)	2.27 cm.(0.895 in.)	4.80 cm. (1.89 in.)

Since the degree of linearity of the results is very good the zero plane displacement is not taken into account (Fig.2) Therefore it can be assumed that this quantity is not large in these cases .

Again , assuming that the atmospheric boundary layer is of the order of 600 m. (2000 ft.) high and that the variation of the wind velocity with height follows a power law :-

$$y/\delta = \left(u/U_{max}\right)^{1/\alpha}$$

it can be established that the power index varies from about 1/7 to 1/6 for the terrain variations considered above .

Considering the sum of £50 which financed the project in 1880 , the amount of information to be gained from it is considerable .

From the results of his paper Stevenson presented the variation of wind velocity with height as a parabolic law as follows :-

$$\bar{u}_1 = \bar{u}_2 \sqrt{\frac{h_1+72}{h_2+72}}$$

$\bar{u}_1$ = VEL. AT h_1 ,

$\bar{u}_2$ = VEL. AT h_2 .

This type of data is generally regarded as being associated with short term meteorological phenomena , which is of interest , as opposed to long - term or large scale weather movements considered by Guildberg and Mohn (1883-85).

The work of Archibald (1885) is worthwhile mentioning in order to record the power law which he suggested to describe the variation of wind velocity with height :-

$$\bar{u}_1 = \bar{u}_2 \left(h_1/h_2\right)^{1/4}$$

Some of the later work of G. I. Taylor , on the variation of the wind velocity with height , was anticipated to some extent by Aberblows (1908) analysis of wind measurements made on the Eiffel Tower . However the arguments given by Taylor will be discussed later in this section , since he has considered the problem in more detail .

A third law for the variation of wind velocity with height was given by Shaw (1909) . This predicted a linear variation with height as follows :-

$$\bar{U}_h = \frac{H+a}{a}\,\bar{U}_{max.}$$

$(\bar{U}_{max} = U_{EL.\ AT\ H})$

where 'a' = Constant = a function of the ground roughness . The previous three papers will be referred to later in this section .

W. H. Dines (1913) considered the amount of energy required to convert the isothermal temperature gradient of the atmosphere into that required for an adiabatic lapse rate. It was pointed out that the mixing of the air between horizontal strata produced the adiabatic state . It is now known that the mixing is produced by strong winds generating turbulence from surface roughness .

This idea of mixing and the presence of eddies in the atmosphere was discussed by Rawson (1913) , based on observations made from aircraft flying at altitudes of 150 - 300 m. (500 - 1000ft.) e.g."typical wave motions , surgings and splashes can be clearly seen ....." . These observed motions were not always regular and could be described as non-periodic or turbulent , at least over the time periods considered . The same wind was seen to produce waves of different lengths and velocities , also, particles observed in the lower layers of the atmosphere were seen to travel with varying velocities .

So , from this paper , it is seen that the picture of a random , non - periodic , type of flow is being formed . A decrease of gustiness , or turbulence , with height was also observed in the surface layers .

Dobson , (1914) included extensive measurements of the variation of wind speed and direction with height over open country . From these it is deduced that the height of the atmospheric boundary layer lies at least in the range of 450 to 600 m. (1500 to 2000 ft.) for strong winds . If it is assumed that a power law having an index of 1/7th applies to the variation of velocity with height , then the velocity ratios ($\bar{u}/\bar{U}_{MAX.}$) can be estimated assuming boundary layer heights in the range quoted above . These can then be compared to Dobsons measured values at various heights . The assumption of a height of about 600 m. (2000 ft.) for the boundary layer height gives the best agreement between the measured and estimated velocity ratios . Dobson also showed that the variation of the

wind direction through the height of the boundary layer was 20 degrees .

A paper by Shaw (1914) distinguished between large scale atmospheric motions and fluctuations of the wind due to gusts (i.e. fluctuations having time periods of the order of 3 to 4 seconds) or localised flows in the atmosphere which were not great enough to be represented on the standard type of weather map . The horizontal scales of the wind recording charts were normally in one hour increments , however by expanding the scale to one minute increments a more realistic picture was obtained of the velocity fluctuations in a gust (Fig. 3) . It is seen that the gust fluctuations are in fact very similar to the output from a hot-wire anemometer in a shear turbulent flow .

Shaw went on to distinguish between gusts associated with flow from the sea and from the land i.e. the former being less gusty; he indicated the variation of the character of the gustiness with height and how gustiness was produced from local objects such as cliffs and buildings (Fig. 3). He also pointed out that for a given wind velocity the turbulence produced was dependent on the surface roughness. Finally he pointed out that temperature differences produced turbulence - "temperature differences cause convection and convection causes turbulence ."

G.I. Taylor (1915) on "Eddy motion in the Atmosphere" is considered in some detail since it was one of the first

papers, of a series , leading on to the formulation of the treatment of turbulence by statistical methods . Only those papers by Taylor dealing specifically with meteorological phenomena will be considered in this section .

Up to this point treatment of the observed eddy motions had been disregarded because of the mathematical difficulty in considering the behaviour of eddies individually rather than the average effect of a collection of eddies . This can be appreciated when the variety of motions described by authors of previous papers is considered and the variation of velocity in a gust as shown in Fig. 3.

This paper considered the effects of a system of eddies on the velocity of the wind in the vertical direction and its effects on the distribution of temperature and humidity in the atmosphere .

Taylor defined the average movement of an eddy in the vertical direction as :-

$$\bar{v}'(y_2 - y_1) = \tfrac{1}{2}(\bar{v}' d_1)$$

where : d_1 = the average height through which an eddy moves at an average eddy vertical velocity of $\bar{v}'$.

He considered the rate of transfer of streamwise momentum across a horizontal plane :-

$$x_{mom} = \iint \rho(\bar{u} + u')\, v'\, dx\, dy$$

and solved the equation for the rate at which the momentum was transferred . He showed that the effects of a disturbance was to reduce the $x_{mom.}$ of a layer δy thick at the rate :

$$\rho \frac{\partial^2 \bar{u}}{\partial y^2} \times \delta y \left[\text{Average Value of } \bar{v}'(y_2 - y_1)/\text{unit area} \right]$$

His main conclusions were :-

(a) "The same effect would be produced on a layer of thickness δy by a viscosity equal to $\rho \times \frac{1}{2}(\bar{v}' d_1)$ if the motion had not been disturbed ."

(b) The disturbed motion of layers of air can be accounted for by considering the eddies as introducing a coefficient of eddy viscosity :-

$$K = \tfrac{1}{2}(\bar{v}' d_1) = \mu/\rho$$

and

(c) The value of the viscosity obtained was the same as that that would have been obtained by assuming that - "the air in disturbed motion conserves the momentum of the layer from which it originated until it mixes with its new surroundings "

Since :

$$\mu/\rho = \tfrac{1}{2}(\bar{v}' d_1).$$

if μ could be measured from meteorological observations then the relation could be verified .

Taylor then went on to consider the relationship between the velocity , and its direction at any height , with the gradient velocity and its direction . He considered a horizontal 2-D. motion having no pressure gradient in the horizontal direction and represented the forces due to the Earth's rotation as :

$$X = -v\, 2\Omega \sin\phi$$

and

$$Y = u\, 2\Omega \sin\phi$$

where

ϕ = Latitude and Ω is the Earth's rotation $\simeq 0.000073$ rads /sec

The equations of motion were solved in terms of the following:-

$\bar{u}_s$ - The surface wind velocity

$\bar{U}_{max}$ - The gradient velocity

$\tan \alpha' - \left[\bar{v}/\bar{u}\right]_{y=0}$

Typical calculations were then compared with the full scale data of Dobson (1914) :-

	Light Wind	Medium Wind	Strong Wind
Full Scale $\bar{u}_s/\bar{U}_{max}$:	0.72	0.65	0.61
Full Scale α'° :	13	21½	20
Calculated α'° :	14	18	20

A comparison of the estimated and measured variations with height was presented (Fig. 4) .

From the above analysis Taylor also deduced :-

$$\mu/\rho = \frac{H^2 \Omega \sin\phi}{2.7^2}$$

where : (H = δ the height corresponding to the gradient velocity)

For a south of England latitude this reduces to :-

$$\mu/\rho = H^2(0.77 \times 10^{-5}) \qquad \text{c.g.s. units .}$$

From Dines (1912) , $\bar{v}'$ was derived as 25 cm/sec .

therefore; $\mu/\rho = 1/2\ (\bar{v}'\ d_1\ ) = 50 \times 10^3$ for H_1 = 800m

$$d_1 = 50 \times 10^3 \times \frac{2}{25} = 4 \times 10^3 \text{ cm.}$$

therefore d = 40m, (i.e. L_{wy})

This value is reasonably consistent with recent full scale data . From the same data the eddy size in the longitudinal direction was deduced as :

70 m . (ie L_{ux})

Taylor gave for winds varying from light to strong :-

$$30 \times 10^3 \leq \mu/\rho \leq 60 \times 10^3$$

(It is assumed that the above scale lengths are for heights of the order of 10 to 30 m.)

Taylor (1916) considered the relation between the skin friction or surface friction and the wind velocity . He assumed that the laws of dynamical similarity applied in the case of skin friction i.e. that a tract of land with roughness such as hedges , trees etc. was comparable to a rough plate ; in which case , the friction force per unit area was :-

$$F = C \rho \bar{u}_s^2 \qquad \text{where C = Constant}$$

Note: Such a form was derived for pipe flow by Stanton (1913) at the N.P.L.

i.e. $F = 0.002 \rho \bar{u}_m^2$

where:

$\bar{u}_m$ = The mean pipe flow velocity

the surface velocity $\bar{u}_s \simeq 0.5 \bar{U}_\infty$

and $\bar{u}_m \simeq 0.85 \bar{U}_\infty$

therefore $\bar{u}_s \simeq 0.70 \bar{u}_m$

therefore $F = 0.004 \rho \bar{U}_s^2$

Taylor quoted C of the order $0.002 \sim 0.003$ (based on $\bar{u}_s^2$) for Salisbury Plain . He assumed that the existence of skin friction implied the transfer of momentum from the atmosphere to the surface air layers so that the velocity profile there could be maintained (Taylor 1915).

The respective components of skin friction were defined as,

$$F_x = \mu \left(\frac{du}{dy}\right) y = 0 \quad , F_y = \mu \left(\frac{dw}{dy}\right) y = 0$$

and the total skin friction,

$$F = \sqrt{F_x^2 + Fy^2}$$

Taylor (1915) had previously defined $\left(\frac{du}{dy}\right) y = 0$ and $\left(\frac{dw}{dy}\right) y = 0$ in terms of:

$$\bar{U}_{MAX} \ , \ \bar{U}_S \ , \ H \text{ and } \alpha_1$$

hence he derived:

$$C = \frac{2\mu/\rho \ \sin\alpha' \ 3/4\pi + \alpha_1}{H} \ \frac{\bar{U}_{MAX}}{\bar{U}_S^2}$$

and knowing the eddy viscosity (μ/ρ) for moderate to strong winds the following was derived

$0.0032 \leq C \leq 0.0022$ for H of 800 ~ 900 m .

or $0.0048 \leq C \leq 0.0033$ for H of 600 m .

or $0.0020 \leq -\overline{u'v'}/\bar{U}_{max} \leq 0.0014$ for H = 600 m , $1/\alpha = 1/7$

since it is known that:

$$\frac{\text{F/unit area}}{\rho \ \bar{U}_S^2} = \frac{\overline{u'v'}}{\bar{U}_S^2} = C$$

hence an estimate of the Reynolds stresses for flat open country is given.

A further paper of Taylor's(1917) qualitatively assessed some full scale results based on the theory developed in his previous paper i.e. where coefficient of viscosity is defined as:

$$K = 1/2\ \bar{v}'\ d,$$

where d was taken as being approximately equal to the diameter of a circular eddy . From observations and measurements made on the Eiffel Tower at heights between (100 and 300 m) he deduced that the coefficient of eddy viscosity , which is proportional to the scale of turbulence , varied considerably with the time of year and distance above the ground .

For example in the Winter the temperature gradient up to about 300 m.(1000 ft.) was less than the adiabatic gradient and this resulted in :-

(a) the tendency to prevent the spontaneous formation of turbulence and

(b) it tended to suppress the turbulence formed by ground roughness .

In the Summer he suggested that the adiabatic gradient was formed fairly frequently and that this tended to encourage the spontaneous formation of turbulence . In the former case it is seen that this suppression of turbulence is caused by inversions .

It was also deduced by Taylor that the eddy size increased with increase of height above ground level , ... "because they have more room to grow ."

Near ground level the amount of turbulence was found to be independent of the temperature gradient and completely dependent on wind velocity . This is taken as implying that the roughness length y_o is independent of stability conditions , to some extent .

A comparison of the estimated values of the Eddy viscosity (K) from the Eiffel Tower and from measurements over Salisbury Plain indicated a higher level of turbulence over Paris .

The remainder of the paper was concerned with daily variations of the wind velocity and the only other relevant parts considered here are Taylor's theoretical calculations . These predicted a boundary layer thickness varying from 450m. to 600m. (1500 to 2000 ft.) for changes in the wind direction varying from 16 degrees to 20 degrees for strong wind conditions i.e. $\bar{U}_{MAX} > 15\text{m/sec}$ (48ft/sec)

A complete translation was not available for the paper by Schmidt (1918) ; however it indicated that the height of the atmospheric boundary layer was a function of the amount of angular change of wind direction with height . For a change of direction of 20 degrees a height of the order of 400 m. (1160 ft.) was suggested .

The paper of Douglas (1919) dealt generally with convective effects and what is now termed C.A.T. (Clear Air Turbulence) from the observations and analysis of various cloud formations .

However some points were made concerning the adiabatic lapse-rate condition and the development of the associated turbulence . He stated that the presence of waves or rolls of cloud was usually associated with a turbulent state of the atmosphere which could be associated with either convective or mechanical turbulence . It was considered that the change of temperature obtained at cloud level was brought about by eddies which were usually transmitted up from ground level .

He referred to and confirmed the point made in previous papers concerning the relation of an adiabatic lapse-rate to turbulent motion ; - " they appear to have a mutual action on each other , a high lapse rate being favourable to the upward transmission of eddies , and the turbulence thus tending to raise the lapse-rate below the clouds to the dry adiabatic rate ." It was also noted by his observations that for high winds it was only near the ground that extreme turbulence was met with i.e. above 600 m. to 900 m. (2000ft. to 3000ft.) turbulence was encountered only at intervals .

Finally , to conclude this period there was the paper of Chapman (1919) on " The variation of Wind Velocity with height ." It was made clear in his paper that the derived laws , up to that time , which gave the variation of wind velocity with height in the atmospheric boundary layer were very dependent on :-

(a) the prevailing wind speeds during the measurements i.e."light", "medium" or "strong" winds .

(b) the heights over which the measurements were made , and

(C) the number of heights (and observations / height) at which the velocity was measured within the height range considered .

The previously proposed formulae(i.e. of Stevenson , Archibald and Shaw) were shown to be limited in their application . Stevenson's elliptic representation was shown to be applicable between about 10 m. (30 ft.) and 15 m. (48 ft.) ; Shaw's linear law could not be applied unless different constants were used for different height ranges . The power law suggested by Archibald was used to calculate the velocity ratios ($\bar{u}/\bar{U}_{max}$) for a boundary layer of the order of 500 m. (1650 ft.) thick and these were compared with the observations of Dines (A.R.C.,R.and M92) for various wind conditions . Good agreement was obtained with "the average of Dines observations" . The agreement with specific data was best for conditions of strong winds.

FIG.5 shows the variation of the mean wind velocity with height above open grass land (from Annual Wind Summary of the Met. Office 1916). The points plotted on this figure are estimates assuming a power law with an index of 1/6 and the agreement is seen to be close .

Chapman however concluded from his review of measurements made from 30m. to 5000m. (98ft. to 16400ft.) that the measured observations were best represented by a log - law of the form,

$$\bar{u} = a \log. h + b$$

It is considered here that for heights of the order of the Earth's boundary layer say 600m. (2000 ft.) that a power law is no less accurate , as is also indicated for adiabatic conditions by Chapman . Whether a log - law or a power law provides a better representation over the full boundary layer height is thought to be a point of academic interest although it is felt that many professional meteorologists may not agree .

Boundary Layer Structure from 1880 to 1919 Meteorological data .

It can be concluded that in this period the atmospheric boundary layer flow was established as being non-periodic and random i.e. turbulent . The turbulence was established as being a function of the surface roughness and the height above the ground . The results of eddy motion were deduced to be comparable to the existence of of an eddy viscosity . The eddy sizes were shown to increase with increase of height above ground level .

A distinction was pointed out between turbulence due purely to roughness effects and turbulence due to convective effects i.e. thermal effects .

It is also reasonable to assume that is valid to apply a power law to the variation of the mean wind velocity with height in the boundary layer, from the data considered.

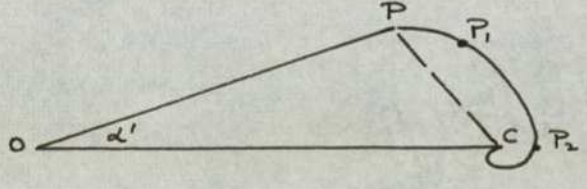
Therefore even from this early period some idea can be deduced of the structure of the boundary layer. Quantitative data from this period are included in Appendix 1.

2.3.2. Review and assessment of meteorological data for the period 1920 to 1929 .

It was seen in the preceding period that a picture of the boundary layer structure had begun to emerge as a result of observation , experiment and theory . The period from 1920 to 1929 is now considered in this section .

A paper of Richardson's (1920) was mainly theoretical and considered Taylor's equations for mixing in the atmosphere where the variables could represent potential temperature , pressure or horizontal velocity . These were modified so that problems involving considerable changes in density and diffusivity could be treated .

Whipple (1920) presented an interesting paper on the laws governing the approach of the wind to the geostrophic value . The spiral form presented by Whipple had however previously been suggested by Ekman (1905) and was , and is , known as the "Ekman Spiral" . This spiral form illustrated the variation of the wind direction and speed with height as follows :-



OP = Surface wind ; OC = geostrophic wind

$\angle OPC = 135^{\circ}$; PC = Relative wind

It can be seen from the diagram that:-

(a) When the wind speed equals the geostrophic wind speed (i.e. say OP_1) that the gradient direction has not been reached .

(b) The gradient direction is eventually reached ,(along OCP_2) passed , and then returned to again .

The gradient wind was defined here as previously :-

Pressure gradient $\perp r$ to isobars = $2\Omega \sin\phi \rho \bar{U}_G (\bar{U}_G = \bar{U}_{MAX})$

This form of presentation is seen to agree with the observations and theory of Dobson and Taylor respectively . Typically α' is of the order of 20° .

A paper by Richardson (1920) considered the supply of energy which was available to atmospheric eddies in the form of thermal energy , gravitational energy and convection effects . The section of interest here was that concerned with the production and dissipation of energy due to the eddy structure of the atmosphere .

The wind components of a gust were defined in terms of the mean and eddy velocities as follows :-

longitudinal	$U = \bar{u} + u'$
vertical	$V = \bar{v} + v'$
lateral	$W = \bar{w} + w'$

where e.g.

$\bar{U}$ = mean longitudinal velocity

u' = fluctuating (or eddy) longitudinal velocity.

Hence he defined the mean and eddying kinetic energy :-

$$\tfrac{1}{2}\rho(U^2 + V^2 + W^2) = \tfrac{1}{2}\rho(\bar{u}^2 + \bar{v}^2 + \bar{w}^2) + \tfrac{1}{2}\rho(u'^2 + v'^2 + w'^2)$$

or $$E = \bar{E} + E'$$

and showed that the " kinetic energy of eddying " was increased from the mean wind by the work done by the eddy stresses on the rate of mean strain :-

" the activity per volume " = $\rho\,\overline{u'v'}\,\partial\bar{u}/\partial y + \rho\,\overline{w'v'}\,\partial\bar{w}/\partial y$

which reduced to:

$$\rho\,\overline{u'v'}\,\partial\bar{u}/\partial y$$

This was defined as the rate at which the mean wind gave up energy to the eddies i.e. to the production of turbulence .

From the work of O.Reynolds , Richardson also defined the loss of energy by dissipation over a large volume as:

$$2\pi^2\mu\left\{\frac{1}{n_x^2} + \frac{1}{n_y^2} + \frac{1}{n_z^2}\right\}\frac{E'}{\rho} = \frac{\partial E'}{\partial t}$$

(the size of a cell containing an eddy was $n_x \times n_y \times n_z$)

or $$\frac{\partial E'}{\partial t} = \frac{2\mu\pi^2 E'}{\rho l^2}$$

where $\frac{1}{l^2} = \left(\frac{1}{n_x^2} + \frac{1}{n_y^2} + \frac{1}{n_z^2}\right)$

This can be stated as follows ; the action of the stresses on the velocity profile is approximately equal to the loss of energy by dissipation .

Taylor (1920) , on " Diffusion by continuous movements ", produced another step forward in the analysis of turbulence by statistical methods . The position to date was summarised by Taylor who stated that in the case of molecular diffusion most of the problems had been solved using the kinetic theory of gases . However , in the case of turbulent motion nothing was known concerning its diffusing power . This paper of Taylor's attempted to solve this problem . The paper as its title stated , was mainly concerned with diffusion , therefore only the points of interest relevant to turbulent boundary layers or measurements in them will be considered here .

By adopting an approach similar to that of a previous paper (Taylor 1915) , he considered the rate of heat transfer across a plane perpendicular to x ; this was stated to be a function of the average value of:-

$$\overline{u\,(x - a)}$$

which was written as

$$\overline{[u(x - a)]}$$

The transfer distance "a" was defined as a function of the particular turbulent motion considered .

Since $u = dx/dt$ and $(x - a) = \int_0^t u\,dt$

and putting $X = (x - a)$

- then :-

$$\underline{\left[u(x - a)\right] = \left[X\,dx/dt\right] = 1/2\left[dx^2/dt\right] = 1/2\,d/dt\left[X^2\right]}$$

This means that the heat transfer is dependent on the variation of the mean square value of the distance moved by a particle as a function of time .

Thus the concept of correlations was introduced into the subject by Taylor who stated that - " in a turbulent fluid , or any continuous motion , there is necessarily a correlation between the movement in any one short interval of time and the next . As the time period diminishes the correlation increases and tends to a limiting value of unity ." He defined the correlation coefficient of u' as R_ξ - this being the relation of the value of u' of a particle at any instant and the value of u' of the same particle after an interval of time ξ (i.e. a Langrangian correlation) so that :-

$$\int_0^t \left[u'_t\,u'_\xi\right] d\xi = \left[u'^2_t\right] \int_0^t R_{\xi - t}\,d\xi .$$

or :

$$\underline{\int_0^t R_{\xi - t}\,d\xi = \int_0^t \frac{\left[u'_t\,u'_\xi\right] d\xi}{\left[u'^2_t\right]} \quad \left(\text{or} = \int \frac{\overline{u'_t\,u'_\xi}\,d\xi}{\bar{u}'^2}\right)}$$

- which defined the correlation coefficient which equals 1 at $t = 0$.

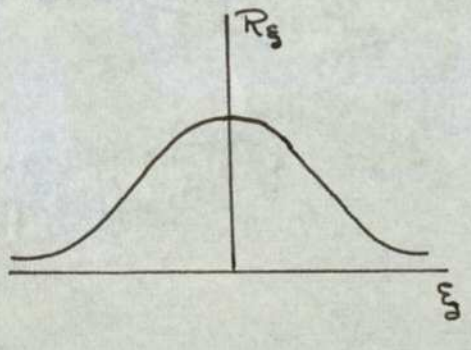
Taylor then went on to show that :-

$$[x^2] = 2[u'^2] \int_0^{T'} \int_0^{t} R_\xi \, d\xi \, dT'$$

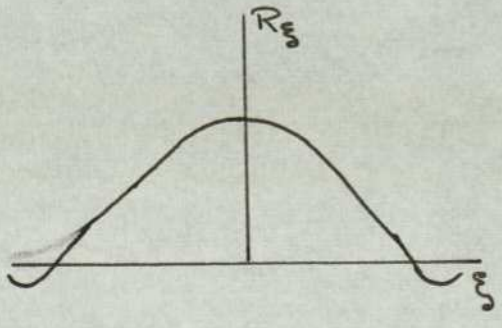
i.e. the problem of turbulent diffusion was reduced to the consideration of just one quantity - the correlation coefficient .

He went on to show that for small T' , i.e. $R_\xi \to 1$ that: $\sqrt{x^2} = T' \sqrt{u'^2}$

i.e. the standard deviation was proportional to T for small T. However as T' increased the standard deviation became proportional to $\sqrt{T}$ and the form of the R_ξ curve should be :-



In some cases it could be expected to become negative or to oscillate as follows :-



This type of correlation could be attributed to some sort of regularity in the eddies of which the turbulent motion consisted .

This paper of Taylor's , as his previous ones , represents a very important step forward in the formation of the principles which define turbulent motion , since no paper written at present , on such motion is complete without correlation measurements .

The paper by Goldie (1925) was mainly descriptive and considered the case of wind passing over a long stretch of sea . His introductory remark (originally in the Met. Glossary(1918) stated that - " whenever the wind passes over the ground , even smooth ground , the air near the ground is full of partially formed , rapidly disintigrating eddies - , the existence of these eddies is doubtless shown on an anemogram as gusts , but the axes of the eddies are so irregular that they have hitherto evaded classification."

His subsequent analysis of flow from the sea showed that this wind always showed a <u>regular pattern</u> in its mean velocities , but had a considerable and constant range of gusts . He suggested that these eddies could only be of the type that could be produced by the waves of the ocean . The majority of the remainder of the paper attempted to correlate the wave lengths and periodic times of the gusts and waves . Some of his data indicated a ratio of 1/3 for the ratio of the gust velocity to mean velocity which was independent of the mean wind speed . He associated a fall in gustiness with

the case where the mean velocity approached the velocity of propogation of the sea waves .

He went on to suggest that a similar occurrence was present when waves , arising from "surfaces" of discontinuity in the atmosphere , gave rise to variations in wind velocity at ground level . When the ratio of the wave amplitude to height tended to 1 he suggested that the eddy structure was distorted as in Fig. 6 , due to the presence of the ground . This is an interesting theory and shows that authors were aware of eddy distortion ; however the distortion shown in Fig. 6 is of the type which is now associated with inversion conditions .

A further paper on turbulence was presented by Taylor (1927) during this period . It consisted of , as Taylor suggested , a description of "turbulence without tears" and gave a very generalized , non-mathematical account of the main properties of turbulence known up to that time . He stated that no-one knew how turbulence occurred , although something was known about the conditions to be satisfied in order that a fluid may flow <u>without</u> turbulence .

It was known that the average effect of turbulence was to give a fluid the power of diffusing certain properites through it . Although a non-turbulent motion was capable of transmitting momentum through its layers by viscosity , the presence of turbulence increased its powers of transmission by several orders of magnitude . Taylor illustrated this point by using the experiment of Reynolds i.e.the injection

of dye into the water flowing in a pipe and observing the conditions under which the dye diffused i.e. the onset of turbulent motion .

He referred to the ability of an inversion to damp out turbulent motion in the atmosphere , that is the inability of the wind to diffuse momentum by lifting the heavy air near the ground and replacing it with lighter air from above . Under adiabatic conditions it was assumed that the friction of the wind at ground level was equal to the rate at which momentum was conveyed downwards . He also noted that under stratified conditions the lateral and longitudinal motions were reduced by the same ratio .

He went on to state that the lateral and vertical gust velocities were equal in magnitude ; it is assumed here that this implies that the relevant measurements were made and averaged over short time periods since the above conclusion suggests that the turbulence considered was isotropic .

Finally he pointed out that at distances of from 0.60 to 2.0 m (2 to 6 ft.) above ground level the lateral scales have been found to be elongated ; he attributed this to nearness of the ground and local roughness effects .

Summary of data on the structure of the boundary layer from the period 1920 to 1929 .

Although not many papers of interest appeared in this period , most of those referred to made some considerable advances concerning the structure of the boundary layer , especially on the theoretical side . For example the demonstration by Richardson that the rate of production of turbulence was proportional to the product of the eddy stresses and the mean wind shear gradient , followed by Taylor's classical paper defining and illustrating the importance of the correlation coefficient . Both papers are fundamental to any consideration of the production or analysis of turbulent motions .

The descriptive papers considered mainly illustrate the effects of stability on the eddy structure . They generally imply that the measurement of the temperature gradient should be an essential part of any full - scale measurements . It will be of interest to see if the data from the later periods to be considered confirms Taylor's observations concerning the turbulent motion in stratified conditions .

2.3.3. Review and assessment of meteorological data for the period 1930 to 1939 .

It has been shown that some notable theoretical papers were produced in the period 1920 to 1929 . Following this , it could be expected that these papers would provide an incentive towards obtaining more refined measurements in the Earth's boundary layer . It will be shown in the review of this period that this proved to be the case both in the number of papers written and the extent of detail in them .

The first paper of interest is that by Becker (1930) on " Investigation of the small - scale structure of the wind by means of a matrix of vanes " As the title suggests , the work was mainly concerned with short period events , however it was probably the first time that this experimental technique was used . The matrix consisted of vanes positioned in a vertical plane at right angles to the wind . Hence the instantaneous gust velocities could be recorded at a number of points and some assessment of the local wind structure obtained . The same technique was used in later papers by other authors with more sucess and these will be commented on in more detail in due course .

A paper by Scrase (1930) presented some of the most interesting full - scale atmospheric measurements in open country made up to this time . Previous to this , the available knowledge on atmospheric turbulence was based essentially on measurements of the eddy diffusivity K from

the work of Taylor . Although these methods gave values of K , relative to comparatively large -scale phenomenon , the mechanics of the processes involved were not made clear .

It was generally known that when air moved over surfaces of discontinuity (i.e. rough surfaces) that eddies were formed which usually originated at ground level . Therefore , since the diffusing power of turbulence was a function of the character of these eddies , examination of the eddy motion should yield some information on the mechanics of turbulence . Thus Scrase summarised the position and his paper presented a significant step towards defining some of the characteristics of the atmospheric boundary layer from experimental measurements . It is assumed that papers prior to this had given the author a good qualitative idea of the type of measurement needed , heights at which they should be made and the relevant gust periods . Since the paper was very detailed it is necessary to restrict a summary of it to noting the more important observations .

The relative magnitude of the three components of turbulence were measured and an attempt made to look at the structure of the different sized eddies . For example Fig. 7 shows typical measurements from which the lateral ($\bar{w}'/\bar{u}$) and vertical ($\bar{v}'/\bar{u}$) components were obtained for medium sized eddies .

Initially Scrase determined the variation of the gust velocities (or turbulence components) of the large size

eddies (i.e.1 hour averages) with mean wind speed , defining for example the longitudinal component as :-

$$\bar{u}'/\bar{u} = \left(\bar{u}_{MAX} - \bar{u}_{MIN.}\right) / \left(\bar{u}_{MAX} + \bar{u}_{MIN.}\right)$$

All three gust components were shown to increase slightly with wind speed up to about 5 m/sec (16.5 ft/sec.) . Above this speed at a height of 13.5 m. (45 ft.) they remained virtually constant with increase of wind speed . Most of the reduction of the gust velocities at low speeds was considered to be due to lack of intrument response for oscillations having time periods $<$ 5 secs. Scrase also showed , contrary to the assumptions of previous papers , that the <u>three components of turbulence were not equal</u> near ground level and quoted the following ratios :-

<u>Long : Lat.: Vert. = 1 : 0.73 : 0.46</u>

Subsequent to this , time periods of the order of $0.5 \leqslant t$ (mins) $\leqslant 8$ were considered and an assessment made of the relative sizes of the lateral and vertical turbulent components of "medium" sized eddies . It was found for time periods greater than 1 min . that the components were virtually independent of the averaging time , from which it was assumed that the majority of eddies have time periods of the order of a few seconds . The mean value of w'/u' was found to be

about 1.50 and independent of averaging time , for conditions of constant mean wind speed . The relative sizes of the lateral and vertical gust velocities were shown to be independent of the mean wind speed for the speed range considered i.e. $2 \leqslant \bar{u} \leqslant 7$ m/sec (6.5 ~ 23 ft/sec) . Their variation with height up to 20 m. (66ft) was also determined and approximately the same ratio was found (i.e. 1.50) to apply at all heights . The change in magnitude of the components between 5 and 20 m. (16.5 66 ft.) was not found to be very significant ; generally , the vertical component did not vary and the lateral component decreased slightly with increase of height . The above data on the three turbulent components compares very well with more recent measurements .

Finally,Scrase looked at the small scale turbulence by considering time periods of 60 secs. subdivided into intervals of 1/5 sec. , 3/5 sec. and 5 secs . It was shown that 1/5th sec. intervals were needed to define the smallest size eddies and it was assumed that a large number of eddies had periods of the order of a second . The ratio of the three turbulent components at two heights were found to be :-

1.5m (5ft) : Long. : Lat. : Vert. = 1 : 1.16 : 0.75 ; $\bar{w}/\bar{u}$ = 1.54

19m (62ft) : Long. : Lat. : Vert. = 1 : 0.73 : 0.56 ; $\bar{w}/\bar{u}$ = 1.30

It is assumed that the results at 1.5m. (5 ft.) are suspect since they are probably subject to local roughness effects . It is suprising that the results at 19 m. (62 ft.) agree so well with the previous data considering the shortness of the averaging period .

Scrase then considered the eddy shearing stresses . From traces of the gust velocity components (Fig. 8.) it was seen that a downward velocity could be associated with an increase of the longitudinal gust velocity . Hence the stress component $\rho\overline{u'w'}$ was found to be large whereas the components $\rho\overline{u'v'}$ and $\rho\overline{v'w'}$ were negligible .

From the relationship between the coefficient of viscosity and the shear stress :-

$$K = \mu/\rho = -\overline{u'v'} \Big/ \frac{d\bar{u}}{dy}$$

Scrase estimated the value of the Reynolds stress for open country as :-

$$-\overline{u'v'}/\bar{u}_{19}^2 \simeq 0.004 \quad \text{at } y = 19 \text{ m.}$$

or $$-\overline{u'v'}/\bar{U}_{MAX}^2 \simeq 0.0015$$ (assuming δ =600m and $1/\alpha$ =1/7)

This is a value consistent with previous measurements .

In this period a discussion was presented by Sutton (1932) with reference to a form for the variation of the velocity with height presented by Geiger (1927) . The law suggested was that :-

$$a = \log. \bar{u}_1 / \bar{u}_2 \;\div\; \log. h_1 / h_2$$

where $\bar{u}_1$ and $\bar{u}_2$ are the mean velocities at heights h_1 and h_2 respectively .

It was not a very practical representation due to the fact that as Sutton pointed out , 'a' was a function of both atmospheric stability and wind speed .

The same paper was discussed by Ali (1932) who showed that 'a' of the above expression had both daily and seasonal variations , the magnitude of the daily variation being dependent on the season . Presumably this seasonal effect is associated with the prevailing stability conditions for a given season . Hence the log - law in this form would not appear to be very satisfactory in practise without extensive knowledge of 'a' .

Giblett (1932) presented the results of extensive observations made at Cardington . These tests were initiated originally in connection with the design of the airship R 101. The report verified some of the findings of previous papers and extended the data available on the turbulent structure of the atmospheric boundary layer .

As the report contained a large amount of information, the following summary will be confined to the more important comments and conclusions drawn from observations concerning mainly , the structure of the wind for adiabatic conditions . The measurements were made over similar averaging periods as those used by Scrase (1930) e.g.

Normal run	$>$	1 hour
Quick run	$\simeq$	8 mins.
Ultra quick run	$\simeq$	42 secs. (subdivided into 5 sec. periods)

The main points made in the paper are as follows :-

1. It was indicated that there were different eddy structures associated with convective , adiabatic and inversion conditions respectively . The periodic times associated with adiabatic conditions were found to be considerably smaller than those associated with convective effects .

2. One of the characteristics noted concerning the adiabatic gusts was a rapid increase and a more gradual decrease in wind speed during the passing of individual gusts . This was investigated statistically using 5 second averages and the results were presented as probability density distributions (Fig. 9) . In all cases the distributions were skewed slightly to the negative velocities , which showed that rapid retardations are less frequent than rapid accelerations .

3. The observations showed that groups of gusts were carried along at approximately the mean wind speed at the height considered.

4. Reference was made to a paper of Taylor's (1917 ,Adv. Com. for Aero. Res. R and M no. 345 - new series) where the eddies were assumed to be circular in shape. However this paper , as well as that of Scrase , showed that this was not so , even at the height of 15 m.(50ft.) considered here . The ratio of the lateral to vertical scales of turbulence was found to be of the order of 2 or 3 to 1 for time periods of from 5 to 80 seconds .

However Giblett pointed out that eddies having fluctuations of shorter periods, and being distributed at random , could follow Taylor's assumption . It can be assumed that this would apply to the range of eddy dissipation (i.e. isotropic turbulence) of turbulence.

5. Giblett defined the characteristics of eddies which could be determined by correlating the eddy velocities at different spacial points at the same height . It is of interest to note the definitions which he used in order to relate the structure of the flow to the correlation characteristics observed (or vice versa):-

(i) The correlation of a velocity with itself at a point , at zero time interval is unity ; at other time intervals it is less .

(ii) If the velocity at a point rises and falls regularly , i.e. if the eddies are regular , then the correlation coefficient will decrease to negative values and then rise again to some positive maximum .

(iii) If the eddies are random then the correlations do not go negative .

(iv) Considering two points in line with the wind (A and B say) then if the structure of the wind is unchanged between the points , a correlation of unity is obtained at a time interval which is a function of both the wind speed and the distance between A and B (assuming that 3 above is correct)

(v) Considering two points across the wind , then the sign of the correlations will indicate whether both points are in the same stream of eddies , i.e. the lateral extent of the eddies .

Giblett concluded from his analysis of the measured correlations that the eddies , for the condition investigated, were of the "Cartwheel" type (i.e. axis across the flow) , having dimensions of 900 to 1200 m.(3000 to 4000 ft.) along-wind and 180 m.(600 ft.) across wind . It is assumed that this is the size of a typical eddy associated with convective effects . However using some of Giblett's data it is possible to estimate the eddy size , in a longitudinal direction , for adiabatic conditions using the definition

$$Lx = \bar{u} \int_0^T Rt \, dt$$

This gives a typical length scale (Lx) at a height of 15 m. (50 ft.) of 120 m. (400 ft.) which is in very good agreement with more recent full scale data .

6. It was indicated by Giblett that the effect of an inversion was to damp out the more irregular turbulent motions and make the eddies less elongated in shape . The damping effect was clearly illustrated by a comparison of recordings of the wind velocity variations during adiabatic and inversion conditions (Fig.10). No large eddies were observed during inversion conditions and in the extreme case the eddy structure should be completely suppressed .

7. Giblett defined the eddy energy as :-

$$\tfrac{1}{2}\rho t \leq (\bar{u}'^2 + \bar{v}'^2)$$

which represented the energy of eddies having time periods between t and T seconds and he assumed that , from this, a type of "energy spectrum" could be derived . Although nothing constructive was derived , in this paper , from this approach , the concept of describing the range of eddy sizes (or frequencies) by an energy spectrum is noteworthy .

Some ideas on the theoretical treatment of gusts by Durst were included in the paper . A brief reference was made here to the atmospheric boundary layer height being of the order of 450 m. to 600 m. (1500 to 2000 ft.) . Durst suggested that the slipping of air layers , at different velocities , on each other may result in the formation of "rolled up" eddies (i.e. with their axes across the stream) which would tend to break-up . It is suggested that such vortices , if they exist , would be likely to bend round into a horse - shoe shape and result in pairs of vortices with their axes along the wind direction . However reference was made to the work of Schmidt (Die Struktur des Windes , Wein , Sitzber . Ak. Wiss IIa , 138 , 1929) which had not shown the presence of the above "rolled" vortices .

Durst stated that eddies generated by obstacles - "will be of comparable size to the obstacles encountered "

and , as found by other authors , the eddies generated are also a function of the ground roughness .

Finally Durst determined the variation of the coefficient of viscosity (K) with wind speed for different values of the temperature gradient (Fig. 9) . This showed that the coefficient of viscosity , which is a measure of the turbulence in the atmosphere , remained constant for speeds above about 3.4 m/sec. (16 miles/hour i.e. 11 ft./sec.) . This is in fair agreement with the findings of Scrase (1930) et.al.

Further information on the structure of the wind was given by Sherlock and Stout (1932) . Here again the awareness of the time periods of typical gusts led to the design of instruments having response times of the order of 0.10 to 0.20 seconds . A study of the structure of the wind was initiated by having a row of such instruments across wind at a height of 15 m.(50 ft.) and a column of instruments on a 75 m. (250 ft.) high mast . The results were presented as contours of constant velocity (miles/hour) plotted on a time scale of 0.5 second intervals (Fig. 11) . The range of eddies considered here was the medium and small scale range as previously defined . The high degree of flow irregularity shown clearly indicated the need for a statistical approach and the need of instruments having response times of at least 0.5 seconds . The technique used was similar to that used by Becker (1930) and , as can be seen , illustrated "turbulence" far more distinctly than a written account could and is worthy of presentation just for this reason alone.

A paper on motion in the Earth's atmosphere was presented by Fujiwara (1932) which was mainly of interest due to the presentation of measurements of the mean vertical velocity as a function of height in the boundary layer . Typical examples of these measurements are given as follows :-

H (m)	160	300	500	700	900	1100	1300	1500	1700	1900	2100
$\bar{u}$(m/sec)	6.30	6.69	7.14	7.34	7.64	7.71	7.75	7.81	7.76	7.50	7.42
$\bar{v}$(m/sec)	0.80	0.30	0.24	0.13	0.03	-0.06	-0.17	-0.08	-0.18	-0.18	-0.07

where H was the height in the atmospheric boundary layer .

The above data gave the mean ratios :-

$\bar{v}/\bar{u} = 0.05$ for $0 \leq H \leq 900$ m

$\bar{v}/\bar{u} = 0.036$ for $0 \leq H \leq 5200$ m

For an unstable atmosphere a ratio of about 0.10 was suggested as being applicable .

A paper by Durst (1933) presented an expansion of his ideas on gust structure , some of which had previously been stated in Giblett (1932) . He suggested for the type of gust observed at Cardington , that those having periods of from 1 to 30 min. were convective cells , but that they had frictional cells or eddies mixed with them . He also noted the effects of an inversion in suppressing the eddy sizes , a point which has been mentioned in several of the previously considered papers and which has now been fairly well established .

Since the paper dealt generally with convective effects it is difficult to isolate the comments which apply purely to adiabatic conditions . This in fact was a fault in many papers of this and previous periods , namely , that data was presented for conditions which often are not clearly defined in terms of the prevailing temperature gradient . For example , Durst compared here tropical air - flow records (i.e. those having rapid fluctuations of uniform width) with those of polar air flow (i.e. having a saw - tooth appearance which was typical of convective effects) .

He went on to compare anemogram recordings over desert and urban areas and showed that the type of fluctuations which he associated with convective flow were present in the desert recordings but not in the urban case . However , in agreement with previous papers , he noted that the amplitude of oscillations in the urban case was greater and this he associated with the greater frictional influence of the city .

Some of the natural boundary layer theory of Prandtl and Von Karman was introduced and applied to meteorological problems by Sverdrup (1934) in a paper on the estimation of momentum exchange . Although most of the paper referred to stable atmospheric conditions some general facts relevant to adiabatic conditions emerged from the paper .
Prandtl's mixing length was defined as :-

$$\ell = k_o (y + y_o) \qquad (a)$$

where k_o = Von Karman's constant and y_o = roughness length.

The shear stress τ was defined:

$$\eta \, d\bar{u}/dy = \rho l^2 (du/dy)^2 \qquad (b)$$

where $\eta = \rho l^2 \, du/dy$ = the exchange coefficient .

From (a) and (b) Sverdrup defined :-

$$\bar{u} = \frac{1}{k_0} \sqrt{\tau/\rho} \log_e \frac{y+y_0}{y_0}$$

the log - law for the variation of the wind speed with height in a boundary layer . He emphasised that the above equations were valid only for a homogenous medium , consequently , in the atmosphere , they were only regarded as being applicable for adiabatic temperature distributions , a point which was verified in later papers . This is consistent with the discussions of Geigers (1927) paper on the application of the log-law , presented in this period , i.e. that the log-law had to be modified by a constant before it could be used for conditions other than adiabatic .

Sverdrup went on to state , however , that a power law of the form :

$$\bar{u}/\bar{u}_1 = (y/y_1)^{1/\alpha}$$

could be applied to most meteorological conditions .

He showed that the log - law could be applied up to a height of 10 m.(33 ft.) and quoted values of the roughness lengths derived from this law .

Terrain	y_o cm.
Short mown grass	0.54
Open Grassland	3.20
'Relatively' calm sea	3.90

which compare reasonably well with the data derived from Stevenson's (1880) results .

It is of interest to note that at this date there is still no definite adoption of either the log-law or power law to define the velocity profile , although it seems that the power law is more siutable for general application . The definition and use of the velocity gradient as a preliminary to the solution of many problems was very clearly illustrated in a paper by Sutton (1934) . Although some of the detail presented here from the paper may be irrelevant in the present context , it does serve to show the inter - relation between fluid - dynamics and meteorology in this period and the "manipulation" of various formulae in order to derive expressions applicable to the solution of practical problems . In effect this paper of Sutton's combined the previous theories on atmospheric phenomena , boundary layer theory and measurements in the atmosphere to produce laws for use in the estimation of evaporation rates . The sections of the paper applicable only to adiabatic conditions will be considered here .

Sutton used as a basis Taylor's (1915 and 1920) work on atmospheric and diffusion laws which defined the mean rate at which energy E was transferred to a unit horizontal area of thickness δy as follows :-

$$\frac{\partial}{\partial y}\left(\rho \overline{v'l} \frac{\partial \bar{E}}{\partial y}\right)\delta y$$

$\left[\overline{v'l} = v'(y-y_1) = \frac{1}{2}v'd \text{ as defined by Taylor}\right]$

i.e. v' is the vertical velocity that transfers $\bar{E}$ from y_1 to $y_1 + l$ (i.e. y)

The problem here , as stated by Sutton , was to find $\rho\overline{v'l}$ in terms of the mean motion and the height y .

It was shown by Taylor (1920) that :-

$$\overline{v'l} = \bar{v}'^2 \int_0^{t_0} R_\xi \, d\xi$$

which Sutton assumed could be written as :-

$$R_\xi = (\bar{u}\xi)^{-n}$$

(ξ being a time interval)

On the basis of Taylor (1927) and Scrase (1930) it was assumed that:-

$$\bar{v}'^2 \propto \bar{u}'^2$$

and the expression for the correlation was modified to :-

$$R_\xi = \left(\frac{\nu}{\nu + \overline{v'^2}\xi}\right)^{-n}$$

where $\overline{v'^2}\xi \gg \nu$ the kinematic viscosity and $n = 1/4$ for adiabatic conditions .

Substituting R_ξ in Taylor's expression and neglecting molecular forces in comparison to eddy forces Sutton obtained:-

$$\overline{v'l} = \frac{\nu^n}{1-n}\left(\overline{v'^2 t_0}\right)^{1-n} \qquad -1$$

Then to derive an expression for $\left(\overline{v'^2 t_0}\right)$ he considered first, from Prandtl :-

$$|\bar{v}'| = l\left|\frac{\partial \bar{u}}{\partial y}\right| \qquad , \; l = \text{mean path}$$

It was shown by Hesselberg and Bjorkdel (Beitr. Phys. fur Atmos Vol. 15 1929) that :-

$$\overline{v'^2} = \tfrac{1}{2}\pi\left(|\bar{v}'|\right)^2 = \tfrac{1}{2}\pi l^2\left|\frac{\partial \bar{u}}{\partial y}\right|^2$$

The time to move from y_1 to $y_1 + l$ was given by :-

$$t_0 = \int_{y_1}^{y_1+l} dy/v' = \frac{l}{|\bar{v}'|} = \left|\frac{\partial \bar{u}}{\partial y}\right|^{-1}$$

$$\therefore \quad \overline{v'^2 t_0} = \tfrac{1}{2}\pi l^2\left|\frac{\partial \bar{u}}{\partial y}\right| \qquad -2$$

It was shown by Von Karman , on the assumption that the eddy velocities at different points in the region were dynamically similar , that :-

$$l = k_0\,\frac{\left|\partial \bar{u}/\partial y\right|}{\left|\partial^2 \bar{u}/\partial y^2\right|} \qquad -3$$

Hence substituting 2 and 3 into equation 1 he obtained :-

$$A = \rho\overline{u'l} = \frac{(0.25l)^{1-n}}{1-n}\rho\nu^{n}\left\{\left(\left|\frac{\partial\bar{u}}{\partial y}\right|^{3}\right)\left(\left|\frac{\partial^{2}\bar{u}}{\partial y^{2}}\right|^{-2}\right)\right\}^{1-n}$$

Then on the assumption that :-

$$A(y)^{\partial\bar{u}/\partial y} = \text{Const.}$$

Sutton derived :-

$$\bar{u}/\bar{u}_{1} = \left(y/y_{1}\right)^{\frac{n}{2-n}}$$

He went on to point out that comparisons between pipe flows and natural winds had shown similarities between the flows (e.g. Prandtl and Tollmien(1925) and Bryant (1931)) from which it could be deduced that :-

$$\bar{u}/\bar{u}_{1} = \left(y/y_{1}\right)^{1/7}, \quad \text{or } n = 1/4 \text{ in above equation}$$

and this power law was assumed to apply in adiabatic conditions to flow over open country . Thus the relevance of the power law to the atmospheric boundary layer velocity profile is again illustrated and the index of 1/7th for adiabatic conditions .

Schmidt (1935) presented some general and particular data concerning turbulence in the atmosphere up to a height of about 6 m.(20 ft.) . The experimental method used was similar to that used by Becker (1930) . The measurements consisted of velocity measurements from which contours of

constant gust velocity were derived (Fig. 12) . This figure clearly shows the turbulent content of the flow in a vertical plane , produced by the increased surface roughness . Contours in a horizontal plane showed similar effects , although the results at the lowest level may be at a height of the same order of magnitude as the zero plane displacement , thus these results would not show typical contours .

Schmidt went on to make the interesting observation that turbulence may arise from jets of air moving horizontally and eventually vertically . If the present interpretation of these comments is correct , it is of interest to note that a similar explanation has recently been given concerning the diffusion of turbulence , namely , that it is in the form of long spanwise vortices at ground level which eventually eject into the upper parts of the boundary layer .

Correlation measurements were also made up to a height of 6m. (20 ft.) and for a distance of 12 m.(40 ft.) across wind . Generally the correlation increased with distance from the ground before becoming constant . The vertical scale can be estimated as being of the order of 15 m. (50 ft.) in the height range considered which is a reasonable value and consistent with more recent data . However this height range cannot be considered as adequate for accurate length scale determination ; also the effects of different time averages were not considered .

The "gust spectra" derived by Schmidt are of some interest as an introduction to data of this type .

These were derived from the analysis of a large amount of data (Fig. 13) . The results at HR 0.20 , 0.75 and 1.25 m. are fairly typical of the form of the high frequency ends of gust spectra . Clearly the greater degree of turbulence produced by the turnip field made it easier to define the spectrum shape from the measuring techniques used .

Schmidt finally distinguished between turbulence produced by dynamic action (i.e. roughness) as distinct from that produced by thermal effects . Concerning the strong vortices produced at ground level he again emphasised that these were spread upwards by some mechanism and gradually affected layers of air higher up in the boundary layer .

The work of Rossby and Montgomery (1935) attempted to relate changes in the mean wind direction and speed to changes in the roughness length y_o . This was derived from observed data and semi - empirical theory .

Prandtl defined the mixing length:-

$$\ell = \frac{k_o (y + y_o)}{} \quad , \qquad \text{where } k_o = \text{Von Karman's constant} .$$

and $\quad y_o = sh \quad , \quad s \text{ assumed} = 1/30 \text{ by Prandtl}$

h = roughness height

Hence :-

$$\tau = \rho l^2 \left(du/dy\right)^2 = \rho k_o^2 (y+y_o)^2 \left(du/dy\right)^2$$

which gives:-

$$\bar{u} = 1/k_o \sqrt{\tau_o/\rho} \log_e \frac{y+y_o}{y_o}$$

or:-

$$\tau_o = \rho \frac{k_o^2 \bar{u}}{\left(\log_e \frac{y+y_o}{y_o}\right)^2}$$

Hence from y_o and $\bar{u}$ at some reference height τ_o could be evaluated. This was assumed to apply to the lower layers of the boundary layer i.e. h < 50 to 100 m.(165 to 330 ft.) In the upper layer :-

$$l = \frac{0.065}{\sqrt{2}} (\delta - y)$$

i.e. in contrast to previous theories which assumed that the eddy viscosity (K) was constant with increase of height in the boundary layer , the mixing length (which is analogous to K)was made zero here when y = δ .

The Rossby and Montgomery data is presented in Fig.14 ; alternatively it can be given as:-

$$\frac{\bar{U}_{MAX}}{F y_o} \simeq f(\alpha')$$

where

$$\frac{\bar{U}_{MAX}}{F y_o} = \text{Rossby Number}$$

The data for open country derived from Fig. 14 were compared with the full - scale data of Jeffreys (1920):-

$\bar{U}_{MAX}$ (or $\bar{U}_G$) m/s	0 - 8	8.5 - 12	12.5 - 18	>18
α'° and Dobson (1914)	15.7	18.2	17.2	16.3
$\bar{U}_{Max}$ m/s	4.6.	9.1	15.6	
α'°	13.1	21.5	19.7	

and as can be seen good agreement was obtained . For latitudes greater than about 30 degrees , the change of direction of the wind (α'°) was found to be almost independent of latitude .

The authors then considered the Urban case (i.e. large roughness length) where the average height of buildings was taken as 30 m. (100 ft.) . The roughness length was taken as 1 m. (3.3 ft.) for a gradient wind speed of 12 m/sec. (40 ft/sec.) which gave a value of α' of 28 degrees . This was found to agree very well with data observed in adiabatic conditions by Van Everingdon (1909) :-

Location	De Bilt	Aachen	Potsdam	Berlin
α'°	21	31	30	27

More recent data would suggest that the above y_o of 1 m.(3.3 ft.) is lower than expected for the conditions quoted . However without knowing more detailed site

geometry (e.g. ratio of building to open area) it is not possible to give a more definite opinion . Regardless of this , it is worthwhile recording any data specifically relating to Urban conditions because of its scarcity , especially in the periods considered up to this point . Thus it will become possible to distinguish between Urban and Rural boundary layer characteristics .

The authors finally considered the value of the mean wind at any height h to be :-

$$\bar{u}(h) = \bar{U}_{max}\left(\cos\alpha' - \tfrac{1}{\sqrt{2}}\sin\alpha'\right); \bar{U}_{MAX} = \bar{U}_G = \text{Gradient Wind}$$

and derived :-

y_o (cm)	$\bar{u}_{30} / \bar{U}_{MAX}$
4	0.595
320	0.293

$\left(\bar{U}_{30} = \text{Mean velocity at 30 m.}\right)$

These values can be compared with those estimated by assuming power law applications having power indices of say 0.143 and 0.28 for the small and large roughness lengths respectively :-

$1/\alpha$	$\bar{u}_{30} / \bar{U}_{MAX}$
0.143	0.65
0.28	0.43

The agreement is seen to be reasonable in the case of the lower y_o value . Generally the remainder of the paper was concerned with stability effects and ocean currents .

A series of review papers were published by Pagon (1935) on the latest advances in aerodynamics and meteorology . They served as an introduction to the above subjects without going into too much detail .

He referred to the formation of turbulence at ground level and how the eddies were " projected into the body of the fluid" (see also Schmidt 1935) . Prandtl's assumption of a mixing length was shown and the fact that eddies , moving outwards from ground level , carried their original momentum with them (Taylor 1915) . He also considered the full scale measurements of Scrase (1930) . The various atmospheric equilibrium conditions were defined . It is of general interest to reproduce his copy of the Beaufort wind velocity scale (Simpson 1926) and table of gust loading allowances to be made in respect of wind loading on buildings :-

BEAUFORT'S WIND-VELOCITY SCALE

Beaufort No.	Explanation	Descriptive Conditions Marine	Descriptive Conditions Land	Statute M.P.H.	Weather Bureau Terminology
0	Calm		Smoke rises vertically	0-1	
1	Light air		Smoke drifts, weather-vanes quiet	1-3	light
2	Slight breeze	Sufficient wind for working ship	Felt on face, leaves rustle, vanes moved.	4-7	
3	Gentle breeze		Leaves and twigs in motion; extends light flag	8-12	Gentle
4	Moderate breeze	Most advantageous for sailing, leading wind, all sail	Raises dust and Paper; moves small branches	13-18	Moderate
5	Fresh breeze		Small trees in leaf sway, crested wavelets on inland waters	19-24	Fresh
6	Strong breeze	Reduction of sail necessary with leading wind	Large branches moved; wires sing umbrellas difficult to handle.	25-31	Strong
7	High Wind		Trees move inconvenient to walk.	32-38	

BEAUFORT'S WIND-VELOCITY SCALE

Beaufort No.	Explanation	Descriptive Conditions Marine	Descriptive Conditions Land	Statute M.P.H.	Weather Bureau Terminology
8	Gale	Considerable reduction of sail necessary with quartering wind	Breaks twigs. impedes progress generally.	39-46	Gale
9	Strong gale		Slight structural damage occurs	47-54	Gale
10	Whole gale	Close reefed sail running, or hove to under storm	Rare inland; trees uprooted considerable structural damage	55-63	Whole Gale
11	Storm		Rare; widespread damage.	64-75	
12	Hurricane	No sail can stand even running.		75	Hurricane

PROBABLE TRUE VELOCITIES AT BALTIMORE 5 MIN. PERIODS AND IN GUSTS (50%) AT ELEVATION 215 FT.

Y years	1	2	3	5	8	10	20	50	75	100
V m.p.h.5-min	42	46	49	51	55	56	60	66	68	70
V m.p.h.gusts	63	69	74	76	82	84	90	99	102	105
p,lb per sq.ft.	13.1	15.7	18.1	19.1	22.1	23.3	26.8	32.3	34.3	36.3

He briefly summarised the method of estimation used to derive the gradient velocity from the barometric pressure gradient :-

the pressure gradient $\frac{dp}{dn} = 2\rho\Omega \bar{U}_{max} \sin\phi = \rho l \bar{U}_{max}$.

The centrifugal force :- $\pm \rho \bar{U}_{max}^2 / r$

was also considered where r is the radius of the cyclone or anti - cyclone considered.

For example , in the Northern hemisphere cyclonic areas (a.c. wise) take the +ve sign and anti cyclonic areas (c. wise) take the -ve sign .

Hence the gradient velocity :-

$$\bar{U}_{max} = + \sqrt{\tfrac{1}{4} r^2 l^2 + r/\rho \, dp/dn} - \tfrac{1}{2} r l \quad , \text{ for cyclonic areas}$$

or :-

$$\bar{U}_{max} = - \sqrt{\tfrac{1}{4} r^2 l^2 - r/\rho \, dp/dn} + \tfrac{1}{2} r l \quad , \text{ for anticyclonic areas}$$

As an example these equations are applied as follows :-

dP/dn is expressed as 0.1 in. of mercury in N miles spacing of isobars .

ρ = .0738 ÷ 32.2 = 0.00229 ;

r = radius in miles ;

G = Gradient velocity in miles / hour and assumed to be reached at 1500 ft. at $\phi = 40^{\circ}$. Then :-

$$\bar{U}_{max} = 0.169r\left(\sqrt{1+\frac{49100}{Nr}} - 1\right)$$ for cyclonic areas

$$\bar{U}_{max} = -0.169r\left(\sqrt{1+\frac{49100}{Nr}} + 1\right)$$ for anti-cyclonic areas

This gives for a cyclonic area for N = 200 miles , r = 60 miles

$$\bar{U}_{MAX} = 13\ M/H \quad \text{(miles/hr.)}$$

A large section of the paper was concerned with a discussion of Taylor's work on determination of the change of wind velocity with height . Pagon then used Taylor's theory and assumed values for Taylor's eddy viscosity coefficient (K) for Rural and Urban conditions and also assumed the variation of the wind direction with height to be 20 degrees and 45 degrees for Rural and Urban sites respectively; he determined :-

	Rural		Urban	
Boundary Layer Height(δ)	Summer : 380m(1250ft)	Winter : 270m(885ft)	Summer : 620m(2020ft)	Winter : 430m(1420ft)
or ($\bar{\delta}$) :	325m(1068ft)		525m(1720ft)	

These figures are very similar to more recent values suggested for the above types of boundary layers i.e. 275m. (900 ft.) and 520 m. (1700 ft.) . However they were estimated from a theory which assumed the eddy viscosity to be constant with height which is incorrect .

Pagon then assumed that knowing the gradient wind and the height at which it occurred the velocity at any other height could be deduced as in the following table using the power law with a 0.157 index :-

TABLE II - WEIGHTED AVERAGE VELOCITY IN HEIGHT , y , IN PER CENT OF GRADIENT VELOCITY

		Open Country $\alpha' = 20^\circ$		Large Cities $\alpha' = 45^\circ$	
		Summer ;	Winter :	Summer ;	Winter
		K = 60,000	= 30,000 :	= 160,000 :	= 80,000
		δ = 1,250	= 885 :	= 2,020 :	= 1,420
y, ft	$y^{0.157}$	C = 0.284	= 0.300 :	= 0.265 :	= 0.277
100	2.06	59	62	55	57
200	2.30	65	69	61	64
300	2.44	69	73	65	69
400	2.56	73	77	68	72
500	2.65	76	79	70	74
600	2.72	77	81	72	76
700	2.79	79	83	74	78
800	2.86	81	85	76	80
900	2.90	82	87	77	81
1000	2.96	84	89	79	83

- the average weighted velocity is defined :-

$$\bar{u} / \bar{U}_{MAX} = C\, y^{0.157} \qquad \text{where } C = \left(\frac{1}{1.145y} \right)^{0.157}$$

see above table .

This paper defines another difference between Urban and Rural terrain , however its validity is open to doubt due to the reasons quoted above . Previous papers considered have also indicated Rural boundary layer heights much higher than the 300 m. (1000 ft.) estimated here .

A further paper was presented by Best (1935) which gave detailed experimental measurements and was comparable to the papers of Scrase and Giblett previously considered . The height up to which measurements were taken was of the order of 5 m. (16.5 ft.) and the terrain was flat open ground . Hot - wire anemometers were used to obtain the measurements close to the ground and averaging periods of 10 minutes were adopted .

The effects of various degrees of equilibrium on the mean velocity at a height of 2 m. (6.5 ft.) were shown (Fig. 15).If it is assumed that a power law can be applied to conditions other than adiabatic then these results show that the power index would be higher for stable conditions and lower for unstable conditions , a result which is consistent with more recent measurements . If it is also assumed that the atmosphere tends to the adiabatic state as $\bar{u}_{2m}$ tends to be independent of stability (i.e. as it tends to a constant value , for these test results) , this clearly occurs at a velocity of about 5m/sec. (16.5 ft./sec.) and agrees with the findings of Scrase . He measured an increase of turbulence intensity with increase of mean wind speed up to the same speed (i.e. 5m/sec.) and it is assumed

that such data could have been obtained during a change from inversion to adiabatic conditions . However a part of the decrease of turbulence at lower speeds may be attributed to lack of intrument response and partly to Reynolds Number effects . Such effects are considered in more detail in later periods .

Best then established the variation of the velocity with height (up to 5 m.(16.5 ft.)) as:-

$$\text{Velocity} = \text{Constant} \times \log_e {}^{y}/_{y_o} \qquad \text{(Fig. 16)}$$

Although Prandtl at this time had established y_o for sand roughness as being 1/30th. of the diameter of a sand grain , Best here assumed y_o to be equal to the height of the grass i.e. 1cm. (hence he plotted log (y-1)) . He then checked the validity of using a power law (Fig.16) and found that it was valid for heights above about 1m.(3 ft.) i.e. it tended to be constant with a power index of 0.13 as y increased up to the height of 4 m. (13 ft.) considered (Fig. 16) .

Best also presented some of the first measurements of the order of magnitude of the turbulence intensity , this being defined as

$$\bar{g} = 100 \, {}^{\bar{u}'}/_{\bar{u}}$$

and was averaged over 10 min. periods at approximately adiabatic conditions

$$\bar{g} \simeq 15 \text{ to } 16\%$$

at heights between ground level and a height of 2m (6.5ft.), a result which is in excellent agreement with recent measurements.

Up to a height of about 0.1 m. the turbulence intensity was found to be independent of temperature gradient i.e. surface roughness effects were predominant . At greater heights and for velocities less than 4m./sec. (13.0 ft./sec.) he measured a decrease of turbulence intensity as the temperature gradient changed from that of lapse to inversion conditions (see also Scrase 1930) .

Best also investigated the lateral and vertical gustiness using the method used by Scrase (1930) . The results were summarised as shown in Fig. 17 , where D_z and D_y were the lateral and vertical eddy sizes respectively and were consistent with the findings of previous papers . The mean value of D_z / D_y was found to be about 1.80 (Cf to 1.6 as measured by Scrase) .

As the height above the ground increased to about 5 m. (16.5 ft.) the lateral gustiness was found to decrease very slowly and the vertical component to increase . At a height of 5 m.(16.5 ft.) the vertical component was found to be still less than the lateral component . Best pointed out that these results agreed very well with the pipe flow measurements of Fage and Townend (1932) .

He also confirmed the findings of Scrase that , provided the duration of the records exceeded 1 minute there was no effect on the conclusions reached . This paper is particularly significant in as much as it begins to define stability effects more clearly than they have been shown in previous papers .

The laws describing the variation of the wind velocity with height were again considered in a paper by Sutton (1936) i.e.

$$\frac{\bar{u}_{y_1}}{\bar{u}_{y_2}} = \left(\frac{y_1}{y_2}\right)^{1/\alpha}$$

and

$$\frac{\bar{u}_{y_1}}{\bar{u}_{y_2}} = \log_e(a\, y_1/y_2 + 1) \Big/ \log_e(a+1)$$

By using available measurements he showed that though the log law may provide a better fit to these measurements , that use of the power law made the mathematical solution of problems much easier . In the log law the constant 'a' indicated the amount of turbulence present , this being indicated by the index $1/\alpha$ in the power law . Sutton generally concluded that the application of either equation was only valid for heights less than 50 m. (165 ft.) .

An interesting paper by Paeschke (1935) presented tabulated values of the power law power indices and the roughness length y_o for various types of terrain . However, since a complete translation of this paper is not available discussion of it is necessarily limited . Generally the paper showed that the application of either a power law or log law to describe the mean velocity variation with height was equally valid . With regard to the power law , he tabulated the power indices appropriate to various types of terrain as follows :-

Type of Terrain:	Beet Fields	Cereals	Grassland High	Grassland Low	Fallow Land	Airport	Snow Surface
Exponent - α : (own data)	3.0	3.5	3.6	3.85	4.0	4.3	5.0
Exponent - α : (Schmidt)	2.4			5.3	4.2	4.2	5.2

where α was defined as in the following

$$\bar{u} / \bar{u}_1 = \left(y / y_1 \right)^{1/\alpha}$$

He also quoted , from measurements between 15 and 150 m. (50 and 500 ft.) over houses in Strasburg

$$\alpha = 2.8 \text{ (or } 1/\alpha = .358 \text{) i.e. Urban Conditions .}$$

In the majority of previous papers the exponent α for rural areas has generally fallen in the range of 6 or 7 from which it is seen that all of the above values are lower than expected . The fact that α for an urban area and beet fields are comparable in order of magnitude is not plausible . Apart from other factors affecting the value of α which will be considered later , it seems likely that some of the error may be due to the restricted height range in which some of the measurements were made .

The data considered plotted equally well when a log law was used (Fig. 18a) . The data of this figure when plotted against log $(y - y_o) / h$ - where h was the roughness height - collapsed onto one straight line .

From such plots Paeschke derived the roughness lengths as follows:-

Type of terrain.	y_o (cm.)	d (cm)
Flat; snow covered.	0.50	3.0
Gottingen Airport.	1.73	10.0
Fallow land.	2.14	10.0
Low grassland.	3.20	20.0
High grassland.	3.95	30.0
Cereals.	5.0	130.0
Beet fields.	6.50	45.0

Typical velocity profiles for the above roughness conditions were presented (Fig. 18b.). These values generally appear to agree with the data of Sverdrup and of Rossby and Montgomery who give about 3~4 cm. (1.2~1.6 in.) and 1 ~ 3m. (3.3 ~ 10ft.) for grassland and urban sites respectively. The paper is particularly worthy of note being one of the first to apply some sort of order to data to allow for the variation and effects of different types of roughness ; also in considering and determining the magnitude of the zero-plane displacement 'd'.

A paper by Reichardt (1938) is of interest mainly since it contained some typical turbulence and shear stress measurements made in a naturally grown boundary layer (Fig. 18 c) (see also Fage and Townend 1932) . For example , in the lower section of the boundary layer , this gives the ratio $\sqrt{\overline{v'^2}}/\sqrt{\overline{u'^2}} \simeq 0.5$ which compares very well with the measurements by Scrase in the atmospheric boundary layer ; there is also the point that the variation of $\sqrt{\overline{v'^2}}$ with height was shown to be much less than that of $\sqrt{\overline{u'^2}}$ with height (cf. with Scrase's comments) .

Taylor (1938) defined the spectrum of turbulence and its relation to the correlation coefficients and verified the validity of the theory from experimental measurements . His theory can be briefly summarised as follows :-

If u' is the longitudinal turbulent velocity , Taylor suggested that it could be resolved into harmonic components. Then its mean value ($\overline{u'^2}$) could be regarded as being the sum of contributions from all frequencies (n) . If $\overline{u'^2} S(n)\,dn$ was the contribution from frequencies between n and (n + dn) then :-

$$\int_0^\infty S(n)\,dn = 1$$

He defined :-

$$\overline{u'^2} = 2\pi^2 \int_0^\infty \lim_{T \to \infty} \left(\frac{I_1^2 + I_2^2}{T} \right) dn .$$

where :

$$2\pi^2 \lim_{T \to \infty} \left(\frac{I_1^2 + I_2^2}{T} \right) = S(n)$$

is the contribution to $\overline{u'^2}$ which arises from frequencies between n and (n + dn).

He then defined two qualities of correlation curves for flows where (a) small eddies were predominant

and (b) large eddies were present .

Firstly , the spectrum for (b) will show greater values of for small 'n' than for the case (a) . Secondly , for flow (b) the correlation R(x) as x increases , will intially decrease more slowly than when the eddies are small .

He then defined the correlation coefficient as :-

$$R(x) = \int_0^\infty S(n) \cos \frac{2\pi n x}{\bar{u}} \, dn. \qquad - 1$$

(where $\bar{u}$ = mean velocity)

and,

$$S(n) = \frac{4}{\bar{u}} \int_0^\infty R(x) \cos \frac{2\pi n x}{\bar{u}} \, dx. \qquad - 2$$

where these equations are Fourier Transforms of each other i.e. if $S(n)$ is measured then $R(x)$ may be calculated from 1 or vice versa .

He also defined the curvature of the $R(x)$ curve at its vertex as :-

$$1/\lambda = 4\pi^2 \int_0^\infty \frac{n^2}{\bar{u}^2} S(n) \, dn.$$

where λ is the curvature and was defined as a measure of the smallest scaleof turbulence.

A measure of the mean largest eddy size could be obtained by putting x = o in Equation 2 :-

$$\therefore \quad \bar{u}\left[S(n)\right]_{n=0} = 4\int_0^\infty R(x)\,dx.$$

This paper was significant in that it produced a definite relationship between spectrum and correlation measurements , at least for isotropic turbulence , which was confirmed by experimental measurements (Fig. 19). The wider application of this theory will be made apparent in later papers .

Finally , in this period , Calder (1939) demonstrated that the turbulent shear stress could be regarded as being constant (to within about 6 %) from ground level up to about 30 m.(100 ft.) , in which range the variation of wind direction was also found to be negligible . This result was also found by Giblett (1932) up to a height of about 45 m. (150 ft.) .

Summary of data on the structure of the atmospheric boundary layer from the period 1930 to 1939 .

A considerable amount of qualitative and quantitative data can be derived from the papers published during this period . Probably the most significant fact , as far as this work is concerned , was the similarity shown to exist between atmospheric and flat plate boundary layers . The main points which have emerged from the review of this period are summarised in the following text .

It was generally recognized that detailed examination of the eddy motion should yield information on the mechanics of turbulence . In this context several suggestions were made regarding the possible form of these eddies . It was suggested that they were formed by layers of air rolling up and again that jets of air moving horizontally eventually spread upwards thus creating and diffusing turbulence upwards . It was shown that groups of such eddies are carried along at the mean wind speed and that their structure was dependent on the prevailing temperature gradient .

Contrary to previous opinions , it was established that turbulent eddies were not circular in shape and it was shown that the variation of the turbulence components with height agreed very well with measurements made in natural turbulent boundary layers . The ratios of the three turbulent components to each other were derived and similarly shown to be comparable with natural boundary layer data .

The highly random and irregular motion of turbulent flow was clearly shown . Measurement of the turbulent components of such flow for various averaging periods led to the suggestion of using an energy spectrum as a means of representing the energy in eddies having various time scales i.e. frequencies . Although some attempt was made to reproduce the high frequency end of such a spectrum , the most significant advance was made by Taylor who defined the spectrum and its relationship with correlation measurements .

For the first time quantitative data was derived on the value of the longitudinal turbulence intensity for a Rural terrain site . Additionally some measurements of turbulence scales became available and further values for the shear stress for Rural sites .

It is significant also that in this period more attention was given not only to defining the temperature gradient prevailing during test runs but also the variation of the turbulent quantities with atmospheric stability . Similarly, the dependence of the roughness parameter and power index of the velocity profile power law on the terrain type was more clearly defined and established .

Some data also emerged appropriate to urban sites . General application of the power law to describe the variation of the mean wind speed with height was shown to be acceptable and 1/2.8 was suggested as a power index for urban flow .

In many instances , since it had been shown that a similarity existed between atmospheric and natural boundary layers , experimental results and theory from both sources were combined in the solution of practical problems.

The quantitative data from this period are tabulated in Appendix 1. Thus it can be seen that sufficient measurements are now available from which to establish the atmospheric flow as being of the boundary layer type.However there is still a lack of data for urban sites and on , for example, the variation of turbulence scales with height, and the form of the energy spectrum.

Review and assessment of

2.6. Meteorological data for the period 1940 to 1949 .

Many of the papers produced in this period are mainly concerned with collating the various contributions to the statistical theory of turbulence which apply to both atmospheric and natural boundary layers , and comparing the theoretical predictions with measurements made in isotropic turbulent flows . Other contributions deal with manipulation of the mixing length laws to derive surface shear stresses and values for the roughness parameter , z_o , and derivation of a law to define the turbulence spectrum . In contrast with the previous period many of the papers tend to be semi-theoretical .

Some of the papers produced original contributions to turbulence theory . Amongst those was the paper by Kolmogoroff (1940) concerning the structure of turbulence at large Reynolds Numbers . He stated that the eddy motions of turbulent flow were characterised by a wide range of length scales and that energy passed from the large to the small eddies whose energy was dissipated into heat by the action of viscosity . He assumed that a range of small eddies existed with properties common to all types of turbulence and that such eddies were isotropic .

The hypothesis of Kolmogoroff may be stated as follows

(a) The small - scale components of the motion depend only on the viscosity (ν) and the mean rate of dissipation of energy (ε)

(b) In the sub - range of small eddies the mean properties depend only on the mean rate of dissipation of energy (ε).

The law for the inertial sub - range of the spectrum can be written as :-

$$S(k) \propto \varepsilon^{2/3} k^{-5/3}$$

i.e. the slope of the spectrum in the above range should be - 5/3 . This has now been adequately proved to apply in the case of atmospheric turbulence spectra .

Dryden (1943) presented a comprehensive review paper on turbulence theory which included comparisons with measured data . Most of the contributions relevant to atmospheric turbulence however have been noted in the previous text .

For example he summarised the definitions of length scales :-

$$l_1 = \sqrt{\overline{w^2}} \cdot \int_0^\infty Rt \, dt.$$

(w is the veloc. component transverse to the main flow.)

- this being the Lagrangian method of describing the flow in diffusion problems . (Ref. Taylor)

The Eulerian description , by considering the stream--lines existing in space at any instant , was defined as

$$Ly = \int_0^\infty Ry.dy \quad - \text{(Vert)} \qquad 2$$

or

$$Lx = \int_0^\infty Rx.dx \quad - \text{(Long)} \qquad 3$$

where L is a definition of the average size of the eddies in the flow .

He pointed out the use of the concept of isotropic turbulence theory for comparison with experimental data since this type of turbulence could be produced by screens and grids of bars in wind tunnels . Most of the studies of this type were mainly concerned with the rates of decay of the tubelence produced .

He redefined the spectrum and correlation expressions of Taylor in terms of the length scale Lx as follows :-

$$\frac{L_x^2}{\lambda^2} = 4\pi^2 \int_0^\infty \left(\frac{n L_x}{\bar{u}}\right) \frac{\bar{u} F(n)}{L_x} \, d\left(\frac{n L_x}{\bar{u}}\right)$$

where :

$$\frac{1}{\lambda^2} = 2 \lim_{x \to 0} (1 - R_x) / x^2$$

λ being a measure of the smallest eddies or dissipating eddies and :-

$$\frac{\bar{u} F(n)}{L_x} = 4 \int_0^\infty R_x \cos \frac{2\pi n L_x}{\bar{u}} \cdot \frac{x}{L_x} \, d\left(\frac{x}{L_x}\right)$$

integration of which gives :-

$$\frac{\bar{u} F(n)}{L_x} = \frac{4}{1 + 4\pi^2 n^2 L_x / \bar{u}^2}$$

This expression for the spectrum was compared with measured spectra (Fig. 20) and reasonable agreement obtained . However the inertial range does not have the slope of -5/3 proposed by Kolmogoroff . This form for the spectrum was

later modified by Von Karman (1949) in the period being considered .

The remainder of the relevant parts of this paper have previously been discussed .

Meatham (1945) presented a paper which dealt mainly with pollution and dispersion studies . The part that turbulence plays in reducing the levels of pollution by upward diffusion of smoke etc. was indicated. However no turbulence measurements were made in the urban environment considered .

Some typical values of the roughness parameter , y_o , were derived in a paper by Frost (1946) from a consideration of the mixing length expressed as a function of the height above the Earth's surface . He pointed out that the classical theories of Taylor and Richardson had incorrectly assumed that the coefficient of diffusion (K) was constant in the Earth's boundary layer . In fact it can vary from about 10^{-1} cm^2/sec near ground level to about $10^4 \sim 10^5$ cm^2/sec at 300 ~ 500 m.(1000 -1650 ft.) above the ground . His expression for the mixing length was used to express K as a function of the ground roughness and height above ground level . This was subsequently used to solve evaporation and diffusion problems . Derivation of the equations is briefly shown in the following text :-

- from Prandtl's development of Taylor's theory:-

$$K = l^2 \left(\partial \bar{u} / \partial y \right)$$

and the shear stress :-

$$\tau = \rho l^2 \left(\partial \bar{u} / \partial y \right)^2$$

- where l is the mixing length .

From the work of Rossby and Montgomery for an adiabatic atmosphere -

$$l = f_n (y + y_o)$$

which Frost modified to :-

$$l = y^{1-m} y_o^m$$

where m lies between 1 ~ 0

Hence :-

$$K = y^{2-2m} y_o^{2m} \partial \bar{u} / \partial y \qquad 1$$

and

$$\tau = \rho y^{2-2m} y_o^{2m} \left(\partial \bar{u} / \partial y \right) \qquad 2.$$

It has been shown in previous papers that τ/ρ was constant in the lower parts of the boundary layer . Therefore taking the square root of equation 2 and integrating -

$$\bar{u} = \frac{1}{m}\sqrt{\frac{\tau}{\rho}}\left(\frac{y}{y_o}\right)^m$$

and if $\bar{u}_h$ is the velocity at height h , then :-

$$\bar{u} = \bar{u}_h \left(\frac{y}{h}\right)^m$$

Papers previously discussed had indicated the applicability of such a power law where the index 'm' was taken as 1/7 for strong wind conditions . Therefore by substituting in equations land 2 Frost derived :-

$$K = m y^{1-m} y_o^{2m} \bar{u}_h h^{-m} \qquad 3$$

and,

$$\tau = \rho m^2 y_o^{2m} \bar{u}_h^2 h^{-2m} \qquad 4$$

He then determined the roughness length y_o -

using, $\tau = 2.6 \times 10^{-3} \rho \bar{u}_h^2$, from Rossby for h = 15m (50 ft.)

and equation 4,

y_o = 1cm. for strong wind over the sea .

using, $\tau = 2.7 \times 10^{-3} \rho \bar{u}_h^2$, from Taylor for h = 30m (100 ft.)

and equation 4

y_o = 2.6 cm. for strong wind over open countryside.

Sverdrup (1936) also indicated that K obeyed the same power laws satisfactorily . Frost's derived y_o's fall within the range of acceptable values for flow over flat terrain . The remainder of his paper was concerned with the application of the above expressions to diffusion problems .

Some further work on the roughness lengths for short grass was presented by Sheppard (1946) which is worthwhile noting . Equations were presented relating Von Karman's constant , the roughness length and the surface drag coefficient C_D . Some measurements of the above quantities were presented and compared with the values presented by Paeschke (1938) . Sheppard's measurements were made up to a height of about 2 m.(6.5. ft.) . His expressions were derived as follows :-

The shear stress,

$$\tau = -\rho \overline{u'v'} \qquad 1.$$

From Prandtl,

$$u' = l' \partial\bar{u}/\partial y \quad ,$$

where l' is the mixing length for a particular turbulent element .

and taking , $v' \propto u'$

then,

$$\tau = \rho l^2 \left(\partial\bar{u}/\partial y\right)^2 \qquad 2.$$

Using 2 and the relation,

$$l = k \frac{\left|\partial \bar{u}/\partial y\right|}{\left|\partial^2 \bar{u}/\partial y^2\right|} \qquad 3.$$

(from Von Karman)

k = Von Karman's constant

Sheppard derived :-

$$\bar{u} = \frac{1}{k}\sqrt{\frac{\tau}{\rho}}\ \log_e \frac{y+y_o}{y_o} \qquad 4.$$

or if $y_o << y$ and if $\bar{u} = \bar{u}_1$ at a reference height y_1 then,

$$k = \sqrt{\frac{\tau_o}{\rho}}\ \frac{\log_e y_1/y}{\bar{u}_1 - \bar{u}} \qquad 5.$$

Introducing a drag coefficient :

$$\tau_o = \tfrac{1}{2} C_D \rho \bar{u}_1^2$$

A drag coefficient of the following form can also be derived:-

$$K_o = \frac{\tau_o}{\rho \bar{u}_1^2} = \frac{\overline{u'v'}}{\bar{u}_1^2}$$

From 2 and 4 above the mixing length was defined :

$$l = k\,(y + y_o)$$

The results of Sheppard's measurements are presented in the following table :-

TABLE 1. VALUES OF C_D AS FUNCTION OF $\bar{u}_{2m}/\bar{u}_{1m}$ OR OF y_o IN CONDITIONS OF NEUTRAL EQUILIBRIUM .

1/α	(1) u_{2m}/u_{1m}	(2) y_o (cm.)	(3) type of surface giving values shown in (1) and (2) *	(4) drag coefficient C_D (using vel. at 2m as reference velocity)
-	1.06	0.0009	one with rather smooth appearance , e.g. ice or smooth snow	2.11×10^{-3}
1/7	1.10	0.10	lawn grass up to 1cm.long	5.54×10^{-3}
1/5	1.14	0.72	downland ; thin grass up to about 10 cm.	1.01×10^{-2}
1/4	1.18	2.3	thick grass up to about 10cm.	1.60×10^{-2}
-	1.22	5.0	thin grass up to about 50cm.	2.32×10^{-2}
1/3	1.26	8.9	thick grass up to about 50 cm. thin wheat etc. up to about 100 cm.	3.21×10^{-2}
-	1.30	13.9	fully grown root crops	4.28×10^{-2}

* The notes in column (3) are based on Paeschke (1938) and unpublished observations by the author .

Hence, assuming the applicability of a 1/7th power law velocity profile the Reynolds Stresses are derived for rural conditions :-

$$0.0016 \leqslant \frac{\overline{u'v'}}{\bar{U}^2_{max.}} \leqslant 0.0043$$

which gives us the order of magnitude of the ground shear stress for rural terrain .

The power indices are also estimated assuming a boundary layer height of 600 m.(2000 ft.) and shows the errors involved by using data from very low heights .

Sheppard also deduced that Von Karman's constant , k , was approximately 0.40 for conditions of neutral stability .

Some of the main expressions defining turbulence were summarised in a paper by Sutton (1947) with particular application to diffusion problems . For example , the scatter of particles was defined by the standard deviation σ :-

$$\sigma^2 = 2\bar{u}^2 \int_0^T \int_0^t R_\xi \, d\xi \, dt. \qquad \text{(Taylor 1920)}$$

or using the mixing length approach , the diffusion coefficient :-

$$K = \overline{v'l} = l^2 \left(\partial\bar{u}/\partial y\right)^2$$

Then the vertical eddy diffusion coefficient was defined as:-

$$K = \overline{v'l} = v' \int_0^t v'(\xi) \, d\xi = \overline{v'^2} \int_0^t R_\xi \, d\xi.$$

i.e. a knowledge of R_ξ determines K .

However a point more of interest to this review was the assumption by Sutton of the applicability of a power law for representation of the Boundary Layer velocity profile having a power index of 1/7th . It has already been noted in the

previous text that these conditions fit many sets of measurements except perhaps in the lowest few metres . He defined values for the lateral and vertical turbulence intensities from the work of Scrase (1930) as :-

$$\frac{\overline{w'^2}}{\overline{u}^2} = 0.226 \quad , \quad \frac{\overline{v'^2}}{\overline{u}^2} = 0.055 \quad \text{(based on local velocities)}$$

It is noted that although these values have the correct relative magnitude , they are more representative of extreme gustiness values than average values . The paper of Best (1935) also quoted values for these components which were not considered and which similarly were extreme cases . The remainder of this paper was concerned with diffusion problems .

A further paper on velocity profile measurements was presented by Frost (1947) which again confirmed the applicability of a power law for unstable to stable atmospheric conditions and the increase of the power index with increasing stability . His measured power indices gave values ranging from 0.145 to 0.77 and quoted 0.30 for the neutral case . At the same site Giblett (1932) had previously measured an index of 0.143 (i.e. 1/7th.) for neutral conditions . Frost attributed the large discrepancy to " differences in exposures " for the two test series . However no details of the differences were given in the text .

Some of the first detailed measurements applicable to urban areas were presented in a series of papers by

Yamamoto and Shiotani (1948) . The papers were concerned with turbulence in the atmosphere for rural conditions and over a large city . Their measurements of mean velocity in the former case were not very informative , since for example a negligible change of velocity was obtained between heights of 38 and 50 metres (125 to 165 ft.) . These measurements were made up to a height of 50 m. (165 ft.) near Maebashi broadcasting station .

It is assumed from their results that near adiabatic conditions were probably only obtained for one run i.e. where the mean velocity was greater than 5m/sec. During this run a mean value of $\sqrt{\overline{u^2}}/\bar{u}$ % (based on local velocity) of about 13% was measured which is of the right order of magnitude for open country conditions . However the range of turbulence intensities measured varied from 12% to 39% which is attributed to conditions other than adiabatic prevailing and, in some cases, the interference effects of the nearby broadcasting building .

Their measurements of the frequency distributions (Fig. 21) showed a slight positive skew (see also Giblett 1932) , otherwise they are regarded as being reasonably normal . The exception to this was the run of 19th, 16h12m which also gave a length scale in the streamwise direction of 107 metres 350 ft.) . The test observations do not indicate the prevailing stability conditions for this run . The correlation curve (La Grangian) for this run (Fig.21) showed different trends to the other curves which it is thought could be attributed to

the presence of the nearby buildings . For the case that is assumed to be adiabatic a length scale of 75m.(250ft.) was obtained which is low for the heights being considered .

The authors also attempted to measure the scales of turbulence in the vertical direction , by vertical spacing of the instruments . No useful data was obtained due to their restricted working heights of 12 metres (40 ft.) . It is known from recent work that vertical separations for such measurements should be of the order of hundreds of metres .

Their investigations of these quantities as a function of averaging period (i.e. 10 ,60 and 300 seconds) showed that for averaging periods greater than 60 seconds the measured turbulence intensities did not change considerably , as also found by other authors . However the longitudinal scales of turbulence were found to vary for :-

$$10 \leq t \leq 300 \quad \text{secs.}$$

from $$4.3 \leq Lx \leq 75 \text{ m.} \quad (14 \sim 250 \text{ ft.})$$

The final paper in the series was concerned with turbulence measurements outside Tokyo and gave results which are regarded as being typical of an Urban environment . The mean velocity measurements were analysed using the log law to give the roughness length y_o . Previously Prandtl had quoted

$$\underline{y_o = h/30} \quad \text{for sand roughness (h = roughness height.)}$$

and Paeschke (1937),

$$\underline{y_o = h/7 \text{ to } h/8} \quad \text{for open countryside.}$$

The present authors assumed from their measurements

$$\underline{y_o = h/3} \qquad \text{for urban conditions}$$

This can be taken as a very rough guide . Their results gave mean roughness lengths of the order of 4 m. (13 ft.) for conditions where building heights vary from about 10 to 20 m. (33 to 66 ft.) and probably near adiabatic stability prevails.

It was noted that the turbulence measurements at , or slightly above , roof level e.g. say 25 m. (80)ft.) , showed a considerable degree of irregularity , which is attributed to the local building effects . Neglecting these measurements the turbulence intensities based on local velocities fall in the range of 20% to 30% . For rural areas they can be accepted as being in the range of 10% to 20% .

The correlation measurements did not give smooth curves of the type shown in Figure 21 . Pronounced increases in the correlation coefficient were shown for time intervals between 30 and 60 seconds . These are associated with the presence in the flow of secondary dominant eddies and it is assumed that these are produced by the adjacent buildings . From Taylor's (1935) relationship between correlations and power spectra it is to be expected that some effect of this would be evident if the spectra were measured . Neglecting extreme cases , the longitudinal length scale was determined as being of the order of 100 m. (330 ft.) for heights between 30 and 60 metres (100 to 200 ft.) .

The authors attempted to estimate the power spectra from the correlation measurements . However the scatter was found to be considerable and the results mainly showed that the lower frequency eddies contained the greater part of the turbulent energy , which agrees with theoretical predictions.

These papers are of considerable interest in giving some of the first detailed figures for comparisons of urban and rural flow characteristics . Although the different stability conditions prevailing during the tests were not measured , and some of the above quantities are stability dependent to some extent , the results still serve as a useful guide to urban characteristics .

Deacon (1948) presented a paper concerning velocity profiles and the roughness parameter y_o , which although regarded as being complementary to Sheppard's (1947) paper , also indicates other relevant points .

The relationship :-

$$\bar{u}/u_* = \tfrac{1}{k} \log_e y/y_o \qquad (\text{where } u_* = \sqrt{\tau_o/\rho})$$

was taken as being applicable in the constant shear stress layer near the ground , and a drag coefficient defined (see also Sheppard 1947) :-

$$C_D = \tau_o / \tfrac{1}{2}\rho \bar{u}^2 = 2\left(u_*/\bar{u}\right)^2$$

Deacon pointed out here that this coefficient was dependent only on the roughness parameter y_o , which in turn was

dependent on " the form and distribution of the roughness elements " . The above expressions were considered to be applicable to fully developed rough flow . It was also generally accepted by Deacon that these expressions were applicable for conditions of neutral stability and that Von Karman's constant k , could be taken as 0.40 . He also pointed out the necessity of making a"zero point correction " to find the point of zero velocity when dealing with such roughness as long (60cm) grass (see also Paeschke 1937) .

In relation to the above points Deacon presented a useful table of roughness lengths (Fig.22) which also shows the velocities which it was necessary to exceed (at a height of 1 m. (3.3 ft.)) in order to achieve turbulent flow . The figures for these velocities were based on Schlichting's suggestions about Nikuradses criteria for roughness . These criteria were derived from experiments with sand and Schlichting suggests that they are approximately applicable to surfaces having roughness elements of " differing form " . The criterion for turbulent flow being that :-

$$\frac{u_* y_o}{\nu} > 2.5$$

It is noted that this allows for the " form " of the roughness but its " distribution " was not considered although its importance was indicated in the preceding text . However it is fair enough to assume that for small roughness elements the distribution may not be too important .

Deacon then considered the effects of stability on the velocity profile near ground level . Some of the results are shown in Fig. 22 for a short grass type of surface . Assuming a boundary layer height of 600 m.(2000 ft.) for the case of adiabatic stability this gives a power index of 1/6.6 on the assumption of the applicability of a power law to the velocity distribution in the Boundary Layer . This value for the index is reasonably consistent with that derived from previous papers .

The final point that Deacon considered which was relevant to our work was the dependence of y_o on stability conditions . It was made clear in previous papers that near ground level friction forces predominate and this effect increases with increasing wind velocity . Hence the author assumed that it may not be necessary to derive a variation of the roughness parameter with stability . The remainder of the paper was concerned with diffusion calculations .

A paper by Von Karman (1948) was considered next since the author derived an expression for describing the power spectral density curve which has been found to be also applicable to atmospheric data .

He used different notation to express the spectrum than that used by Taylor (1938) i.e.

$\underline{F(K_1)}$ was used instead of $S(n)$

where K_1 is the wave number $= \frac{2\pi n}{\bar{u}}$ measured in the x_1 - direction .

Von Karman stated that the main aim of that particular period was to find laws describing either the correlation or the spectral functions , and in this paper he derived :-

$$\mathcal{F}(K_1/K_0) \propto \frac{1}{[1+(K_1/K_0)^2]^{5/6}}$$

which was shown compared with the observed form of the spectrum in Fig. 23 . This also shows the application of Kolmogoroffs - 5/3 law in the inertial sub - range of the spectrum .

A further paper was presented by Von Karman and Lin (1949) on the theoretical treatment of turbulence . It was concerned with the analysis of the spectrum during the process of decay of turbulent energy . The case was considered where the inertial Reynolds Number of turbulence was very large .

It was generally agreed at this period that greater part of the turbulent energy was contained at low frequencies, while the energy in the viscous dissipation range was negligible . Energy was transferred by inertial forces to the high frequencies where it is changed to heat , (Kolmogoroff 1940).

The authors proposed division of the spectrum into three regions :-

(a) The low frequency range or fixed range where it was suggested that the spectrum form was :-

$$\propto K^4$$

(b) An intermediate range , which has not necessarily the similarity characteristics of the high range but is significantly influenced by dissipation ε but not directly by viscosity ν .

(c) A high frequency range which follows Kolmogoroff's law .

It was assumed that the low frequency range of eddies was produced by some natural or artificial mechanism which produced individual eddies . In this range it was assumed that the form of the spectral functions was fixed or independent of time . With regard to the higher frequency ranges , sufficient experimental evidence was available to show that the similarity prevailing at the highest range extended to the medium range . Thus the laws applying to the spectrum and its proposed shape are shown in Fig. 23. How ever the lack of experimental data over sufficiently long periods of time did not make a complete comparison of proposed and measured spectra possible over the full range of spectral frequencies .

Lettau's (1949) paper on isotropic and non-isotropic turbulence in the atmospheric boundary layer was mainly theoretical and mostly concerned with the effect of stability on heat flow . However he made the following points relevant to adiabatic atmospheres .

In the development of his theory and discussions on thermal stratification he used " Adiabatic turbulence " as a basis . The variation of the mixing lengths with stability was derived (Fig.24) and following this , the schematic representation of turbulence as shown in Figure 24 . It can be seen from this that Lettau assumed that the turbulence in an adiabatic atmosphere was isotropic (i.e. that the longitudinal and vertical turbulent velocities in particular were equal in magnitude) and therefore that the effect of stability variations from the adiabatic case was to produce non-isotropic turbulence . This assumption however cannot be considered to be applicable to heights greater than about 2 to 3 metres (6.5 to 10 feet) above ground level , since turbulence components vary rapidly with increase of height above ground level .

Another conclusion made , which has some relevance to this work , was that the roughness parameter y_o was a constant, regardless of the prevailing stability conditions . Lettau attributed the wide variation in measured y_o 's, for comparable sites , to the fact that various authors had forced a fit to their measured velocity profiles , presupposing Yo to be a function of stability . Deacon's (1948) paper reached similar conclusions on this point . This conclusion seems reasonable but it is considered that there may be exceptions to it for extreme stability conditions and in the case of very large roughness .

Pasquill (1949) related the velocity distribution log-law to a momentum diffusion coefficient Km as follows :-

$$\tau = \rho K_m \partial\bar{u}/\partial y .$$

using this expression and the log-law he obtained,

$$K_m = \frac{\bar{u}_1 k^2 y}{\log_e y_1/y_0}$$

From his work on the effects of varying stability conditions on the roughness parameter , he concluded that for marked stability conditions the assumption of a constant roughness parameter is involved , (see Deacon (1948)) .

A monograph published by Sutton (1949) serves as a useful summary concerning some of the main developments in turbulent flows . Since most of the references quoted by Sutton have been referred to in the previous text , the more important points from the text will only be recorded here .

The usefulness of the mean velocity gradient as an indicator of turbulence intensities was pointed out and the importance of the Reynolds Stresses in transporting momentum across a fluid surface . The correlation between the velocity components of the Reynolds stress was defined :

$$R = \frac{\overline{u'v'}}{\sqrt{\overline{u'^2}}\sqrt{\overline{v'^2}}}$$

so that the correlation depends not only on the respective

magnitudes of the two velocity components but also on the degree of correlation between them . For example , horizontal gusts (+ve u') are usually associated with downward currents (-ve v') and vice versa . Therefore there is a correlation between u' and v' and the corresponding Reynolds Stress $-\rho\overline{u'v'}$ will have a value (see also Scrase 1930) . On the other hand there are no systematic variations between w' and v' and the corresponding stresses are small or near zero .

Sutton pointed out the significance of the adiabatic lapse-rate which was defined

$$\Gamma = gA/C_p \approx 1^{\circ}C/100m.$$

where :

g = accn. due to gravity ; A is the reciprocal of the mech. equiv. of heat .

C_p = Spec. heat of air at constant pressure .

The result of mixing in the atmosphere was to tend to produce an adiabatic lapse-rate , and this was the equilibrium state to which the atmosphere was always trying to return . Following this a " potential temperature " was defined as the temperature attained by a mass of air which is brought to a standard pressure adiabatically . Hence , an atmosphere was in a stable , unstable or neutral equilibrium condition according to whether the potential temperature increases , decreases or is constant with height (Fig. 1)

In considering the velocity profile of the atmospheric Boundary Layer , Sutton confirmed the application of a power law having a power index of 1/7th. for adiabatic stability and over rural terrain . He also pointed out that at moderate or high latitudes the geostrophic or gradient wind was assumed to occur at a height of about 500 metres . However where the surface was rough the log law must be used in order to define the degree of roughness i.e.

$$u/u_* = 1/k \log_e y/y_o$$

where y_o is the roughness length and k (Von Karman's constant) is taken as 0.40 .

He briefly referred to some typical turbulence measurements e.g. $\overline{v'}/\overline{w'} \simeq 0.70$ (Cf. flat plate measurements of 0.72). Most of the turbulence measurements and their limitations have been mentioned in the previous text .

He pointed out that although Taylor's K (diffusion coefficient) assumed to be constant through the Boundary Layer , was useful in indicating the general form of solutions , in this height range , it was not accurate in its predictions of near ground level conditions . When allowance was made for the variation of K with height the angle of the gradient wind relative to the surface wind was found to be about 29° for a 1/7th power law in neutral conditions .

The main problem in turbulence , as Sutton stated , was to express the Reynold's Stress (τ) as a function of height in the Boundary Layer . Prandtl , by considering the movement of an eddy "which conserves its momentum on moving a distance l " arrived at:-

$$\tau = -\rho\overline{u'v'} = -\rho l^2 \left(\frac{d\bar{u}}{dy}\right)\left|\frac{d\bar{u}}{dy}\right|$$

which was taken to be comparable to the mean free path in the Kinetic Theory of gasses .

By considering the " mean transfer of momentum " Taylor (1916) obtained :-

$$\tau = -\rho l \sqrt{\bar{v}^2}\ \frac{d\bar{E}}{dy}$$

where E can be momentum , heat or matter .

By adoption of the concept of the mixing length l many problems became amenable to solution .

When considering rough surfaces , Sutton pointed out the necessity of considering the quantity d i.e. the " zero-plane displacement " in order to provide a datum level above which turbulent interchange commences - in which case the modified log-law becomes :-

$$\frac{\bar{u}}{u_*} = \frac{1}{k} \log_e \frac{y-d}{y_0}$$

This law has been found to apply up to a height of about 13 metres " provided y_o and d are chosen independently to give the best fit " . Sutton pointed out that most writers agree regarding the order of magnitude of y_o but that there was considerable spread in the actual values obtained .

Sutton also reviewed the main points emerging from the statistical treatment of turbulence most of which have been considered in the previous text .

Summary of data on the structure of the atmospheric boundary layer for the period 1940 to 1949 .

Some of the more important advances in this period were made concerning the spectrum of the turbulence . The theory of universality of the turbulence in the inertial sub-range made it possible to define the slope of the spectrum in this range . A law defining the spectrum was presented and its form defined throughout the various frequency ranges . However , at this time , sufficient experimental data was not available in order to check the latter .

The values of the power index were estimated from some of the presented experimental data (assuming δ = 600 m. (2000 ft.)) however it is considered that the indices are over-estimated due to consideration of too small a height range . In other words , near ground level the log - law strictly applies and estimates of a power index from measurements in this region (since du/dy is less than it should be for the power law which should apply over most of the boundary layer height) results in an over - estimate of the power index (e.g. an index of say 1/5th may be deduced instead of say 1/7th. which would be applicable over at least 95 % of δ).

Rural turbulence intensity measurements were presented which agreed with data from a previous period and similar data were measured in an urban area . Turbulence length scales and y_o 's were also derived for Rural and Urban terrain.

The main details lacking , in the case of the Urban terrain, are those of the site geometry from which it would be possible to determine whether the data was typical of an Urban area or was dominated by local effects .

Regarding the roughness length y_o, attention was drawn to the fact that it was a function of both the form and the distribution of the roughness elements . The necessity of making a correction for the zero - plane displacement (d), when dealing with large roughness elements was indicated and the modified log-law allowing for this factor (d) presented . It was also generally agreed that y_o was independent of stability conditions , at least for moderate departures from the adiabatic state .

Quantitative values of the boundary layer characteristics derived from this period are tabulated in Appendix 1.

2.3.5. Review and assessment of meteorological data for the period 1950 to 1959 .

During this period , and up to the present day , the number of relevant meteorological papers published increased considerably as they did in the case of most other technical subjects . For this reason it will be necessary to be less detailed in dealing with the papers considered . For example , Webb (1955) presented a neat summary of data on the variation of the turbulent length scale with height in the atmospheric boundary layer . Therefore , although the other papers from which the data was derived will be included in the bibliography , they will not otherwise be specifically mentioned unless they contain other data which is either revised or , additional to that quoted in the periods previously considered.

On considering the amount of data presented from previous periods , and the extent of detail , this is justifiable ; also , since the main concern should now be to establish more refined and extensive measurements of the quantities already considered . It has been adequately shown that compatibility exists between the flow over the Earth's surface and flow in natural (or flat-plate) boundary layers . The basic structure of both rural and urban boundary layers has emerged , or begun to emerge , from the literature already considered . The basic laws defining the relationship between mean velocity , shear stress , surface roughness etc. have been noted and the manner in which they can be applied .

However , some gaps still remain to be filled in on some aspects of the information ,required e.g. measurements of the power spectra of the fluctuating velocities in the atmospheric boundary layer . More detailed measurements of the space and time correlations , and their variation with height , would also be of interest . It is suggested that some deductions could be made as to how these eddy sizes vary with height , by adopting one of the suggested forms of the structure of the boundary layer eddy system given in some of the papers previously considered . In addition , more exact information is desirable on the variation of the mean and fluctuating velocities with height , especially in urban areas , as well as more accurate measurements of roughness parameters for such terrain . On this basis the relevant papers presented in the period 1950 - 1959 are now considered .

The first papers of interest in this period are those of Laufer (1950) and Lettau (1950) . The former presented some typical measurements in a natural boundary layer (e.g. FIG.25) which shows the variation of the longitudinal turbulence intensity through the full depth of the layer (see also FIG.18 , Reichardt 1938) . It is noted that in the lower 10% of the boundary layer turbulence intensities (based on local velocity) lie between 0.10 and 0.18 .

The correlation :-

$$\frac{\overline{u'v'}}{\sqrt{\overline{u^2}}\ \sqrt{\overline{v^2}}}$$

was measured and was found to lie in the range 0.40 ~ 0.60 - more recent data gives 0.30 . A value of 0.60 for the ratio

$$\sqrt{\overline{w^2}}/\sqrt{\overline{u^2}}$$

was obtained which does not agree very well with either past or recent values of the order of 0.73~0.75 ; this suggests that the accuracy of some of the results may be in some doubt . Using the appropriate scaling factors the following data on the length scale of the longitudinal turbulence can also be deduced :-

y/δ	L_{uu}/δ
0.10	0.30
0.40	0.50

- the length scale seems to increase with height up to y/δ of about 0.40 ~ 0.60 .

Similarly , the paper of Lettau's presented mean-wind velocity measurements made through the full boundary layer depth . They were in fact the classical measurements made by Mildner (1932) in Leipzig . They were not presented in the relevant period due to non - availability of translation of the original paper . The data is very frequently referred to in the meteorological literature . The measurements are shown in FIG. 26a for near

neutral conditions and the mean velocity data can be represented by a power law having an index of the order 0.21~0.26

e.g. for $1/\alpha = 0.21$,

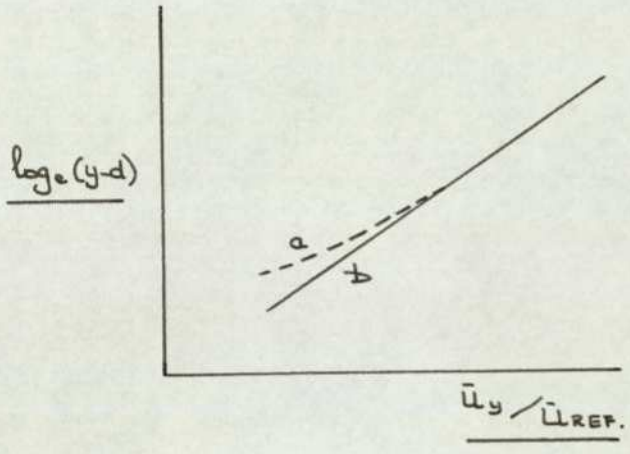
y/δ	$\bar{u}/\bar{U}_{MAX}$ (THEOR.)	$\bar{u}/\bar{U}_{MAX}$ (MEASURED)
0.170	0.690	0.674
0.340	0.797	0.807
0.455	0.848	0.871

Since the measurements weremade outside Leipzig with the wind blowing from the city , suburban flow can be defined as having the above index ; the value quoted for α' of 26° also agrees very well with previously quoted values for flow over towns (cf. rural areas $\alpha' \simeq 20^{\circ}$) .

Pasquill (1950) analysed measurements made in grass between 1 and 15 cm. (0.39 to 5.9 in.) in height in conditions approximating to adiabatic . He assumed that the following law applied :-

$$\bar{u}_y/u_* = 1/k \log_e\left(\frac{y-d}{y_o}\right)$$

and illustrated the importance of determining the value of the zero - plane displacement d .



e.g. curve 'a' represents the actual measurements and various values of 'd' are assumed until a straight line plot is derived 'b' - the intercept of this line on the vertical axis then gives y_o .
The following data were derived:-

h (cm.)	y_o (cm.)	d (cm.)	$\overline{u'v'}/\bar{U}^2_{MAX.}$
15 (5.9 in.)	0.66 (.26 in.)	8 (3.2 in.)	0.0010

and the shear stress data agree with previous examples:-

	Concrete (Sheppard '47)	Downland (Scrase 1930)
$\overline{u'v'}/\bar{U}^2_{MAX}$:	0.00043	0.00168

The importance of allowing for 'd' had previously been stated by Deacon (1949) . The above analysis illustrates that previous measurements of y_o should be treated with some caution ; although they may be correct as regards order of magnitude , clearly they could be subject to large errors . It is also worth noting that the importance of 'd' becomes more relevant as the order of magnitude of the roughness height and density of the roughness increases .

The work of Shiotani has previously been referred to ; Shiotani (1950) continued on the same line of investigation and presented further measurements made in a rural boundary layer under adiabatic conditions . Measurements were made up to a height of 16 m. (53 ft.) in terrain covered by grass and vegetables of height 30 to 40 cm. (12 to 16 in.) . The measured roughness length varied between 1.5 to 5.5 cm. (0.6 to 2.2 in.) . Typical length scales (L_{ux}) were of the order 60 m. (200ft.) and turbulence intensities as follows :-
(also see FIG. 26b)

y (m)	$\sqrt{\overline{u^2}}/\bar{u}$	$\sqrt{\overline{v^2}}/\bar{u}$	$\overline{u'v'}/\sqrt{\overline{u^2}}\sqrt{\overline{v^2}}$	$\overline{u'v'}/\bar{U}_{max.}$
1	0.14	0.09	0.243	.0024
3	0.10	0.08	0.258	

Probability density distributions of the fluctuating longitudinal velocity also tended to be normal (FIG. 26c)

The longitudinal turbulence measurements fall in the range previously indicated for rural terrain . Some turbulence measurements made in the suburbs of Tokyo were also presented:-

$\bar{u}$ (m/sec.)	$\sqrt{\overline{u^2}}/\bar{u}$	$\sqrt{\overline{v^2}}/\bar{u}$
0.58	0.42	0.30
3.03	0.48	0.31
5.05	0.36	0.18

The first set of data is not considered to be accurate due to the very low reference velocity . The other measurements of the longitudinal turbulence are excessively high but they may be extreme values and not mean values for the site considered . The author indicated that the turbulence intensity decreased as stability increased but that near-ground level conditions were invariably dominated by roughness effects .

The work of Obukhoff and Yaglom (1951) was mainly theoretical . However they re - stated in more precise terms the original similarity laws of Kolmogoroff - " the motion of all vortices whose scales are considerably less than L (the scale of the largest vortices) must be subject to certain statistical laws which do not depend on the geometry of the flow and the properties of the mean flow . The establishment of these laws, which have a wide range of applicability , constitutes the theory of local isotropic turbulence " . The original work of Taylor in this field has previously been considered .

In this type of flow there are only two relevant magnitudes:-

1. The mean dissipation of energy / unit time / unit mass of fluid ε , - this determines the intensity of the energy flow transferred along a cascade of vortices of different scales , and

2. The kinematic viscosity ν which plays an essential role in the process of dissipation -

dimentionally these are :-

$$\varepsilon = L^2 T^{-3}$$

$$\nu = L^2 T^{-1}$$

or combined give :-

$$\eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$$

where η determines an internal scale which is characteristic of the local turbulence structure .

Although many authors had attempted to give some explanations of the flow processes in the flow near the Earth's surface Townsend (1951) was one of the first to do so , for a flat - plate boundary layer , by a consideration of the turbulent energy .

The sum of the equations for the turbulent energy balance is :-

$$\overline{u'v'}\,\partial\bar{u}/\partial y$$

$$+\tfrac{1}{2}\partial(\overline{u'^2v'}+\overline{v'^3}+\overline{v'w'^2})/\partial y$$

$$+\tfrac{1}{2}U\partial(\overline{u'^2}+\overline{v'^2}+\overline{w'^2})/\partial x$$

$$+\tfrac{1}{2}V\partial(\overline{u'^2}+\overline{v'^2}+\overline{w'^2})/\partial y$$

$$=-\tfrac{1}{\rho}\partial(\overline{pv'})/\partial y$$

$$+\nu\left[\overline{u'\left(\frac{\partial u'}{\partial x}\right)^2}+\overline{v'\left(\frac{\partial v'}{\partial x}\right)^2}+\overline{w'\left(\frac{\partial w'}{\partial x}\right)^2}\right]$$

where 1. Production of turbulent energy

2. Diffusion of turbulent energy

3 & 4. Convection of energy by the mean flow

5. Flow of energy under the action of a pressure gradient

6. Viscous dissipation of turbulent energy .

At high Reynolds numbers (as proposed by Kolmogoroff) the viscous range of eddies contain little or no energy and has been defined previously (Taylor) by an independent scale λ . In this range it was assumed that -

$$\overline{\left(\frac{\partial u'}{\partial x}\right)^2}=\frac{1}{2}\overline{\left(\frac{\partial v'}{\partial x}\right)^2}=\frac{1}{2}\overline{\left(\frac{\partial w'}{\partial x}\right)^2}$$

(although this was not completely verified by Townsend) and the energy dissipation can be written :-

$$\varepsilon=15\rho\nu\overline{\left(\frac{\partial u'}{\partial x}\right)^2}$$

From his measurements to determine the energy balance FIG.27a Townsend deduced that the flow in the boundary layer could be divided into an inner and an outer layer .

In the outer layer non-turbulent fluid was entrained by large eddies and the flow was similar to free turbulent wake flow; Kolmogoroff's hypothesis of eddy "cascade" flow also applied .

In the inner region there was a large flow of energy towards the wall and energy dissipation occurred partly by turbulent friction and partly by viscosity at the wall . The turbulent energy and scales of turbulence were created in this region . Townsend suggested that the flow basically consisted of long cylindrical eddies with their axes parallel to the flow direction .

Probability distributions and turbulent length scales were measured by Cramer (1952) in the height range 0 to 12 m.(0-39ft.) However the surrounding terrain was very variable e.g. from sand covered to trees , bushes etc. Hence the results are variable on this account as well as from various atmospheric stability or instability conditions . The longitudinal turbulence varied from 0.12 to 0.33 (the lower value representing stable conditions) and the mean value quoted of 0.25 can be associated with the large roughness of the area ; the measurements were made at a height of 2.5 m. (8 ft.) . The probability distributions were generally near - Gaussian (FIG. 27b) and found to be independent of the equilibrium conditions of the atmosphere . Some distributions

for stable conditions tended to be more peaked which is to be expected , however the measurements are probably made too near to the ground to be greatly influenced by a stable atmosphere . The lateral scales of turbulence were found to increase (i.e. L_{u_3}) with increase of stability (FIG.27c) . For a near - neutral condition L_{u_3} is approximately 6 m. (20 ft.) and Cramer suggested :-

$$L_{u_x} \approx 2 \sim 3 \times L_{u_3}$$
$$\approx \underline{12 \sim 18 \text{ m}} \ (40 \sim 60 \text{ ft.}) \quad \text{for } y = 2.5 \text{m} \ (8 \text{ ft.})$$

Previous measurements in the atmosphere had indicated an angle of deviation of about 20° between the mean wind direction at ground level and the top of the boundary layer in rural terrain. In contrast , the measurements of Gordon (1952) , based on ocean weather ship observations , indicated , for adiabatic conditions an angle of 7° between ground level and 600 m. (2000 ft.) . The angle of deviation increased as the degree of stability increased . A possible explanation for this discrepancy is given later in this section .

The main information to be abstacted from Priestley (1952) is :-

$$\underline{L_{u_x} \approx 15 \sim 20 \text{m.}} \ (50 \sim 66 \text{ ft.}) \quad , y = 2 \text{m} \ (6.6 \text{ ft.})$$

which appears to be slightly smaller than would be expected .

Most of the relevant points previously reviewed were included in Priestley and Sheppard (1952) and they consider mainly heat transfer processes . They provided some additional data on the surface drag coefficient :-

$$C_D = \tau_0 / \rho \bar{u}_y \quad , \quad \bar{u}_y = \text{VEL. AT ht. } y.$$

and since :

$$\bar{u}/u_* = 1/k \log_e y/y_0$$

$$\therefore \quad C_D = k^2 / (\log_e y/y_0)^2$$

then for :

$$y_{REF} = 10\,m,$$

$$0.5 \leq y_0 (cm.) \leq 10\,cm.$$

they obtained :-

$$0.0028 \leq C_D \leq 0.008$$

which agrees with:- $0.003 \leq C_D \leq 0.006$

for rural terrain (based on $\bar{u}$ local) . They also presented Laufer's data as being typical of boundary layer characteristics (FIG.28a) and showed diagramatically how energy is transferred through the range of frequencies represented in power spectra (FIG.28b)

A further measurement of the longitudinal length scale (L_{ux}) can be derived from Sheppard (1952) as follows :-

y (m.)	L_{ux} (m)	$\sqrt{\bar{u}^2}/\bar{u}$ %
2	12	19.0

Further data on flow over water (Lough Neagh) were quoted as:-

δ(m.)	$1/\alpha$	$\overline{u'v'}/\tilde{U}_{MAX.}$
500	0.122	0.0011

Many previous authors (e.g.Priestley and Sheppard 1952) had pointed out the lack of reliable data on shear stress measurements over sea . Sheppard et. al.(1952) attempted to investigate this point and obtain a value of the shear stress from the following expression :-

$$\tau_x(y) - \tau_x(0) = F\int_0^y \rho(v_j - v)\,dy$$

where y is the height at which $\partial\bar{u}/\partial y = 0$.

and $\tau_x(y) = 0$

F = coriolis parameter and ρ = density.

v_j and v are the wind components of the geostrophic and actual wind normal to the surface direction .

Clearly for the above expression to apply the height at which $\partial\bar{u}/\partial y = 0$ must be obtained i.e. the top of the boundary layer . In these investigations this height was not clearly defined , hence the surface stress was not determined . However the change of wind direction with height was shown to be of the order of 3.6° in a height of 300m. (1000ft.) (Cf. Gordon 1952)

An interesting result derived was the frequency distribution of the variation of the mean wind direction in various height ranges for averaging periods of 10 mins. (FIG.28c) . However it should be noted that the data was obtained for a condition where an unusual meteorological state prevailed . Some measurements of the longitudinal turbulence were also made which ranged between 13 - 20% at surface level for unspecified equilibrium conditions.

A further investigation on the same topic , but at a different site , was made by Sheppard and Omar (1952) . In this case the top of the boundary layer was determined for various degrees of atmospheric equilibrium as being of the order 450 - 600 m. (1500 - 2000 ft.) , and using the same expression as Sheppard et al (1952) they derived :-

$$C_D \simeq 1.3 \times 10^{-3}$$

where $C_D = \tau_0 / \rho \bar{u}_s^2$, $\bar{u}_s$ = surface wind

This value of the drag coefficient was shown to be of the same order of magnitude for conditions varying from stable to unstable and to be independent of wind speed .

The velocity variation in a typical gust was examined by Sherlock (1952) and was shown to follow a 1/7th. power law in the height range at which the measurements were made . In the analysis , the type of velocity distribution obtained by assuming application of the Ekman spiral was shown (FIG.29a) . It was also shown that this flow agreed fairly well with a 1/7th. power law velocity distribution , at least up to a height

of 300 m. (1000ft.) , on the assumption of a variation of the mean wind direction with height of 17° (i.e. α') FIG.29b .

The problem of the variation of the roughness parameter or drag coefficient for grass of different lengths was investigated in some detail by Deacon (1953) (FIG.30a) by making measurements up to a height of about 10m. (33 ft.) on an open grassland site . The temperature gradients were also measured in order to relate the measured drags to the prevailing atmospheric conditions . For the condition of meutral of adiabatic equilibrium the log-law was shown to apply . The author also deduced that Nikuradses criterion for rough flow i.e.

$$u_* y_o / \nu > 2.5$$

was only applicable to certain types of roughness . The investigation of the variation of the roughness parameter with wind speed showed it to be constant with increase of speed for short grass and to decrease in the case of long grass . In the latter case this may not be a representative result since , as the wind speed increases , the grass bends and presents an effectively smoother surface . In addition the author does not appear to have allowed for the zero plane displacement . FIG.30c includes various other measurements of y_o in tabulated form . The variation of the vertical gustiness i.e. $\bar{w}'/\bar{u}$ (where $\bar{w}'$ is the mean extreme vertical component) with

equilibrium was also determined (FIG.30b) . The main point of interest here is the rapid suppression of vertical motion very close to the ground as the stability increases . However the author still assumes , in agreement with work from different sources , that y_o is reasonably independent of equilibrium conditions It is also clear from the results that y_o/h varies considerably for the range of grass heights (h) considered .

From extensive tests at Round Hill U.S. Friedman (1953) presented some measurements of the lateral turbulence intensity for various equilibrium conditions :-

taking $\bar{u}/\bar{u}_1 = (y/y_1)^{\frac{n}{2-n}}$ he first derived n :-

Equilibrium	Round Hill	Suttons data
Large lapse	-	0.20
Near neutral	0.28(afternoon)	0.25
Mod. Inversion	0.38(sunset)	0.33
Large inversion	0.68(evening)	0.50

For the near neutral state this gives a 1/7th. for the power index . Hence the lateral turbulence data were tabulated for various atmospheric states :-

y(m)	Afternoon	Sunset	Evening
1.4 (4.6ft.)	0.306	0.205	-
2.7 (8.9ft.)	0.233	0.194	0.042
5.5 (18ft.)	0.198	0.157	0.047
11.0 (36 ft.)	0.185	0.135	0.051
22.0 (72 ft.)	0.185	0.148	0.095
44.0(144 ft.)	0.149	0.123	0.059

It is noted that the results for the near neutral state are of the order of magnitude expected at a referace height of say 30m. (100 ft.) . For example if the extreme value of the longitudinal turbulence at ground level (say y/δ = 0.05) is taken as 20% , then the corresponding lateral turbulence should be about 15% based on the local velocity - which it is approximately from these measurements .

Some investigations were carried out on atmospheric turbulence the initial results of which were reported on by MacCready (1953 a,b) . Measurements were made up to a height of 2.40m. in flat country . The probability density distributions of the longitudinal and vertical velocity components were established as being Gaussian and the effects of stability on length scales e.g.

	h(m.)	L_{u_x}(m.)	$\sqrt{\bar{u}^2}/\bar{u}$
Moderately unstable :	2.4 (7.9 ft.)	90(295ft.)	-
Slightly stable :	146 (480 ft.)	420(1380ft.)	0.05 (Other Source)

Further data on longitudinal and vertical turbulence intensities was also given :-

y (m)	$\bar{u}$ (m/sec.)	$\sqrt{\overline{u^2}}$	$\sqrt{\overline{u^2}}/\bar{u}$	$\sqrt{\overline{w^2}}$	$\sqrt{\overline{w^2}}/\bar{u}$
0.15 (.50 ft.)	3.16	0.92	0.291	0.36	.114
0.70 (2.3 ft.)	4.96	1.23	0.248	0.60	.121
2.40 (7.9 ft.)	4.86	1.26	0.259	0.70	.144

Again the results are typical of those obtained over rural terrain as were the data given by Robinson (1953) from measurements at a height of 1.30 m. (4.3 ft.) at Kew and a mean velocity of 4.42m/sec These are tabulated as follows :-

$\sqrt{\overline{u^2}}/\bar{u}$ %	$\sqrt{\overline{w^2}}/\bar{u}$ %	$\sqrt{\overline{w^2}}/\sqrt{\overline{u^2}}$	L_{ux} (m)
21.0	15.5	0.74	12 (39ft.)

Shiotani (1953) presented additional data on correlation measurements and deduced that the auto correlation coefficient distribution followed the law :-

$$R_t = 1 - (t/T_o)^{2/3}$$ (for isotropic turbulence only)

where T_o = Time for largest eddy to pass measuring point . and it was deduced that $T_o \propto y$. The results applied to adiabatic conditions over snow fields . Regarding the structure of the flow he stated that for isotropic flow the turbulent

eddies were spheres and for shear flow were oblate spheroids having their major axis in a streamwise direction and the minor axis vertical . Typical data on turbulence intensities and scales is tabulated as follows :-

y (m.)	$\sqrt{\overline{u^2}}/U\%$	$\sqrt{\overline{v^2}}/U\%$	L_{ux} (m.)
0.4 (1.3 ft.)	12.4	4.2	-
0.6 (2 ft.)	12.8	5.2	-
0.9 (3 ft.)	8.9	4.3	-
1.5 (4.9 ft.)	10.0	4.9	-
7.5 (25 ft.)	15.6	-	-
11 (36 ft.)	12.0	6.1	30 (100 ft.)
75 (250 ft.)	6.3	-	90 (295 ft.)

As predicted by previous authors, $\sqrt{\overline{v^2}}/\sqrt{\overline{u^2}} \approx 0.5$.

A fairly comprehensive review was produced by Sutton (1953) dealing with most aspects of meteorology concerned with the Earth's boundary layer . Since most of the relevant points have previously been considered in the previous text it will suffice just to note here some of the more important points emphasised by Sutton .

1. The top of the boundary layer is reached at heights in excess of 500 m. (1640 ft.) and power indices for the various equilibrium conditions are :-

Large lapse rate	Adiabatic	Large inversion
1/4	1/7	1/6

Alternatively use : $d\bar{u}/dy = a y^{-\beta}$

For : Adiabatic , $\beta = 1$

Unstable , $\beta > 1$ or $R_i < 0$

Stable , $\beta < 1$ or $R_i > 0$

2. Examples of allowing for the zero plane displacement :-

Surface	y_o(cm)	d(cm)
Thin grass - height up to 10cm.(4 in.)	0.7 (.28in.)	-
Thick grass - height up to 10cm.(4 in.)	2.3 (0.9in.)	-
Thin grass - up to 50 cm. (20 in.)	5 (2 in.)	-
Thick grass - up to 50 cm.	9 (3.5in.)	-

'd' estimated :-

Grass 1 - 3 cm.(0.39 - 1.2 in.)	0.5 (0.2in.)	0
Grass 60 - 70 cm.(24 - 28 in.)	3 (1.2 in.)	30(12in.)

3. The velocity profile log - law was taken to be applicable up to a height of 10 m. (33 ft.) and only for adiabatic conditions .

The boundary layer characteristics of flow over the sea had not been very clearly defined up to this date and large variations existed in the measured data . The work of Hay (1954) is considered to give the most reliable results on this topic since every precaution was taken to define and allow for all sources of error . A mean set of values for flow over calm sea have been

noted for adiabatic conditions :-

y_o (cm.)	$u_*/\bar{U}_{MAX}$	$\overline{u'v'}/\bar{U}^2_{MAX}$	$\sqrt{\overline{u^2}}/\bar{U}$ %	$\bar{U}_{2m}$ (m/s.)
0.1(0.04 in.)	0.024	0.0006	3.50	6.5

Marshall (1954) presented data of mean velocity measurements from several sites averaged over a period of a year . From these the appropriate power law indices for the various sites can be deduced :-

Wind from:	Stornaway land	Blackrock land	Scilly sea	Kew land(trees locally)
	1/6	1/7	1/8.5	1/3.2

It was generally assumed here that the ratios of surface to gradient wind were as follows :-

	$\bar{U}_2/\bar{U}_{MAX}$	α'
Inland :	1/3	30^o
Sea :	2/3	10^o

Although conditions other than adiabatic are not being considered in detail here , the significant paper of Monin and Obikhov (1954) defining a velocity profile law which is widely used to cover various equilibrium conditions cannot be omitted . The relevant quantities assumed by the authors were :-

(a) $u_*/\bar{U}_{MAX} = 0.05$ for rural terrain.

(b) The height of the ground layer , assuming a maximum variation of $\pm$ 10% in $u_*/\bar{U}_{MAX}$ in this layer , is 50 m.(164 ft.) - i.e. the "Constant"stress layer.

Having defined the log - law,

$$\bar{u}/u_* = 1/k \log_e \left(\frac{y-d}{y_o}\right)$$

they went on to define the Monin Obikhov length L as :-

$$L = -u_*^3 \Big/ k \cdot g/T_o \cdot q/C_p\rho$$

where q = turbulent heat flux , C_p = Spec. heat at const.pressure

The three quantities involved -

$$g/T_o \; , \; u_* \; , \; q/C_p\rho$$

are stated to be the " definitive characteristics of turbulence in the ground layer " , and for :-

Neutral ,		$L = 0$	
Unstable,	$q > 0$	$\therefore L < 0$	(or $R_i < 0$)
Stable	$q < 0$	$\therefore L > 0$	(or $R_i > 0$)

The Richardson no. was defined in terms of L :-

$$R_i = y/L \cdot 1/\phi(y/L)$$

and the velocity profile as :-

$$\bar{u}/u_* = 1/k \left[\log_e y/y_o + \beta(y/L) \right]$$

β is a universal constant and L, the "Monin Obikhov length" is the height of the substrate of dynamic turbulence .

Up to this time very much progress had not been made on the power spectral densities . The paper by Panofsky and McCormick (1954) defined some general characteristics of spectra measured at Brookhaven up to a height of 125m. (410 ft.) . They were as follows :-

(a) At low frequencies the spectral energy of $u' > v'$ and at high frequencies they are equal , i.e. in the range where Kolmogoroff's similarity law applies and the energy is proportional to $k^{-5/3}$.

(b) The ratio of the turbulent to mean energy is greater for overland than oversea passages , however the spectral shapes are similar .

(c) The frequency at which the peak energy occurs in the vertical spectrum decreases with increase of height i.e. implies an increase of the eddy size with increase of height .

(d) Stable stratification suppresses energy at low frequencies, while unstable conditions increases the low frequency energy.

As will be seen later these points define some of the very different characteristics of the u' and v' spectra e.g. the eddy sizes associated with the longitudinal component being greater than those of the vertical component and the fact that spectral shapes are independent of terrain roughness .

The work of Rider (1954) merely added to existing knowledge of the Cardington site (i.e. mown grass surface) .. By making measurements up to a height of 2m. (6.6 ft.) he defined the following,

y_o (cm.)	$\overline{u'v'}/\overline{U}^2_{max}$
0.32 (0.12 in.)	0.00083

which agrees fairly well with other authors data e.g. Sutton (1953) gives y_o = 0.10 cm. (0.04 in.)

One of the few theoretical papers presented in this period was that of Businger (1955) and this was mainly concerned with modifications to Lettau's (1949) work on isotropic and non - isotropic turbulence and how it is affected by various degrees of stability and instability .

It has been indicated by previous authors that y_o is independent of atmospheric conditions over rural terrain . It was also shown to be independent of fetch by Charnock (1955) in the case of flow over water . However no results were quoted hence the accuracy of the conclusions being considered doubtful cannot be assessed ; as indicated previously such measurements over water are particularly prone to many sources of error . It was stated that early results implied an increase of the shear stress with decrease of wind speed , which was thought to be in error , however it is considered that this may possibly be a Reynolds Number effect i.e. change of flow from turbulent to laminar as

speed decreases . This point cannot be checked from the paper but (see Deacon(1957) later)

Additional data on the applicability of the power law was given in Collins (1955) :-

Terrain	$1/\alpha$	Reference
Brookhaven (U.S.A.)	0.25	Singer and Smith (1950)
Typical City Site	0.33	Hellerman (1953)
Various	0.10-0.40	

Similar detailed data to that given by Collins was included in Deacon (1955) and is tabulated here :-

Terrain	$1/\alpha$	Reference
Sale : Gently rolling, grazing	0.16	Deacon (1955)
Cardington : Short grass	0.17	Frost (1947)
Leafield : Fields, low stone walls , hedges	0.17	Heywood (1931)
Quicklom : Level meadows , hedges trees	0.23	Franckenberger , Rudloff (1949)
Upton : Scrub oak , scrub pine , h = 10m.(33 ft.)	0.26	Panofsky (1953)
Akron : Rolling country,bushes,small trees	0.22	Huss & Portman (1948)

Deacon in fact investigated the "Maximum" gust in given periods in this work whereas the values of interest in this review are

the r.m.s. values , however he made some general comments on gust structure . Although a few gusts had a vertical scale of at least 150m.(490 ft.) , the majority were less than this ; also the stronger the gust the less the variation of gust speed with height . The latter point has been confirmed by many authors. Deacon suggested it followed the law :-

$$\bar{u}/u_c = \left(y/10\right)^{0.085}$$

where u_c is the maximum gust in a given period .
The main point shown from the summarised data of this paper is the almost universal adoption of the power law to define the velocity profiles of the Earth's boundary layer .

There were a few points of interest in a further paper by Deacon (1955b) who defined the total rate of turbulent energy production as :-

$$\tau\left(\partial\bar{u}/\partial y\right) + Hg/C_pT$$

(H = vertical eddy flux of heat)

which is $\propto$ $R_i + R_i'$

these being dynamical and thermal turbulence terms respectively.

Then he defined :—

$$\frac{R_i}{R_i'} = \frac{K_m}{K_h} = \frac{\text{Eddy viscosity}}{\text{Eddy conductivity}}$$

and,

$$K_m^* = \frac{K_m}{u_* y} = u_* / y \frac{\partial \bar{u}}{\partial y} = f(R_{iy}, y)$$

for neutral conditions $R_{iy} = 0$ and

$$K_m^* = k$$ — Von Karmans Constant

which he established as being of the order 0.38 .

Some doubt still remained regarding the time that measurements should be averaged over in order to obtain statistically representative results . Deacon showed here that longer times were needed than previously anticipated :-

Component	y(m)	t(mins)
u'	1.5	10
u'	28	20
v'	1.5	5
v'	28	5

i.e. the variation of u' with distance from the ground is much greater than that of v' , a fact which is consistent with the variation of these quantities with height in a boundary layer .

In support of this he quoted , for adiabatic conditions :-

$$u'_{28}/u'_{1.75} \simeq 0.5 \quad ; \quad v'_{28}/v'_{1.5} \simeq 1.0$$

and $\left(u'/v'\right)_{28} \simeq 1.5$ and $\left(u'/v'\right)_{1.75} \simeq 2.5$

Finally , concerning the transport of energy , he concluded that there was considerable upward transport of small scale eddy energy and downward transport of large scale eddy energy . Regarding the energy of the $u'v'$ cospectrum (FIG.31a) it was shown that there was little energy for $ny/\bar{u} > 1.0$ or < 0.01 , a point which is verified adequately by more recent data ; this in fact represents some of the earliest data on the properties of this cospectrum .

To add to the previous data on defining indices for the power laws for various types of terrain there is the work of Kamei(1955) . The velocity profiles were measured up to heights of about 30m. (100 ft.) in several urban areas and at a coastal site . The data may be summarised as follows :-

Terrain	$1/\alpha$
Coastal	1/5
Urban	1/3

However , due to the low height range considered for the urban cases it is felt that some of the measurements could have been influenced by local effects . It is also considered , from assessment of some of the previous data , that even in the case of rural or coastal sites measurements should be made upto a

height of at least 50m. (164 ft.) and greater to determine the power index accurately . He also listed the following roughness lengths but the sources of measurements and other details are not evident :-

Nature of surface	y_o (cm)
Field	33.2 (13 in.)
Plain	8.0 (3.2 in.)
Tokio	150 (60 in.)
Nauen	500 (197 in.)

(e.g. Nauen was quoted by Deacon 1955a as being less rough than Quicklom , Quickborn being a 'rough' rural area - hence y_o = 500cm. for Nauen seems doubtful !)

The most interesting data to date on the power spectra were given by Panofsky and Van Der Hoven (1955) . Initially the main points from Panofsky and McCormick (1954) were summarised . The main fact from the present paper is shown in FIG. 31b,c which represents the power spectral measurements extending from the micrometeorological range through to the mesometeorological range i.e. the range of large scale weather movements . The authors showed the presence of a spectral gap at K = 0.10 which in fact corresponds to a one hourly period . This gap provides a convenient separation of mean and turbulent motions in atmospheric movements i.e. it suggests that mean motions should be averaged over periods of about one hour .

This in fact provides the reason for discrepancies in measurements made by previous workers as also pointed out in Deacon (1955a) and as such makes a significant contribution in the field of meteorological measurements . The complete spectrum was presented later by Van Der Hoven (1957).

The relevant point from Swinbank (1955) was $\frac{1}{2} \propto \frac{1}{7}$ for flat terrain lacking large obstructions . The measurements were made from a height of 8m.(26 ft.) to 30m. (100 ft.) . Taylor (1955) provided further measurements of the length scales (L_{ux}) . However since most of the data was obtained in conditions of unstable equilibrium the estimated length scales will be somewhat greater than those applicable to adiabatic conditions . The only other point of interest was that the condition of local isotropy was shown to apply over a wider range of frequencies than previously thought ; this agrees with the findings of authors previously considered . The derived length scales are as follows :-

y(m)	L_{ux} (m)
1.5 (4.9 ft.)	24(78 ft.)
28 (92 ft.)	40 - 110 (130 - 360 ft.)

The work of Webb (1955) was one of the first attempts to define the variation of the length scale with height . Typical measurements from his data are,

y(m)	L_{ux} (m)	L_{vx} (m)
1.9 (62 ft.)	-	3.3 (10.8 ft.)
29 (95 ft.)	84(280 ft.)	12 (39 ft.)

The correlated data is shown in FIG.32 where he suggested,

$$L_{u_x} \propto y^{1/2} \quad , \qquad \text{for } y < 100\text{m.}(330\text{ft.})$$

Although this seems plausible on the results quoted , more recent data suggests that it may be valid in the surface layer but not above it . This point will be summarised in more detail later when more data has been accumulated . Considerable data was also presented for unstable and stable conditions and is also shown in FIG.32 . It is of interest to note that in the unstable cases L_{u_x} only increases up to moderately unstable conditions and then rapidly decreases as the degree of instability increases further . It can also be seen that the small scale of the vertical component indicates that it has not got much energy at low frequencies in comparison to that of the longitudinal component . This also agrees with conclusions of papers considered previously . The vertical spectra also indicated the energy spread over a wide range of frequencies , whereas the longitudinal spectra had well defined peaks . He also concluded that Kolmogoroff's -5/3 range applied to eddies having scales of the order of 30 - 60 m.(100 - 200 ft.) where " it is certainly believed isotropy does not extend ".

Ellison (1956) presented a very condensed review on atmospheric turbulence most of which has previously been considered here . The topics of interest are discussed generally without

the introduction of new data . Some of the main points which he emphasised are noted here . When considering large roughness elements he made the point of taking the point of origin for velocity data near the top of the roughness elements i.e. the zero plane displacement was not considered ! With regard to determination of y_o for the sea he indicated that an error of 5 cm. (2 in.) in the height above the sea measurements would lead to an error of 30% in y_o . The use of the power law to represent the velocity profile through the boundary layer was recommended for adiabatic conditions , for other conditions the law suggested by Deacon (1948) was recommended i.e.

$$\bar{u}/u_* = \frac{1}{k(1-\beta)} \left[(y/y_o)^{1-\beta} - 1 \right]$$

where k = Von Karman's constant and β = 1 for adiabatic conditions . A typical value of the shear stress of 0.0013 was quoted for open country ; this was assumed to be reasonably independent of atmospheric equilibrium . He showed that determination of the shear stress over sea areas by use of the expression,

$$\rho \int_o^y F (u_j - u) \, dy$$

(Cf Sheppard et al 1952)

was rarely possible due to baroclinic atmospheric conditions . In a baroclinic atmosphere a horizontal temperature gradient exists which can be at right angles to the flow direction such that , for example :-

A horizontal temperature gradient of $1^{o}C$ /100 km. can cause a vertical gradient in the geostrophic wind of about,

3m./ sec./ km.

This can either reduce or increase the variation of the wind direction with height resulting from the Coriolis force . However , for the case of strong winds , the friction effect becomes dominant , except perhaps in the case where y_o is very small . Therefore when the wind is blowing over land its effect should , fortunately , not be too significant .

A paper on the climate of towns by Landsberg (1956) , although not a technical paper , made the observation that changes in climatic conditions due to the presence of buildings was recognised as early as the beginning of the 19th. century and pointed out the difficulty in obtaining representative data from such sites without these being influenced by local topographic effects . He defined the main effects resulting from buildings as ,

(a) a change of the aerodynamic surface roughness
(b) a change of the local heat output , and
(c) the addition of chemicals which polluted the atmosphere .

The problem of the wide range of shear stresses measured in what could be considered as being the same type of terrain was treated by Deacon (1957) ; some indication of it had also been

given in Deacon (1948) . On the assumption that it was indepen--dent of atmospheric equilibrium he showed that some of the variation could be attributed , in the case of rural terrain , to a Reynolds number effect (FIG.33a) below a speed of about 2m./sec. at a reference height of 15cm.(6 in.). The increase of the stress with decrease of speed below 2m./sec. is analogous to the increase of a cylinder drag coefficient as its Reynolds number is reduced . Nikuradse's criterion for rough flow i.e.

$$\frac{u_* y_0}{\nu} > 2.5 \qquad \text{(for sand roughness)}$$

was shown not to apply to grass and

$$\frac{u_* y_0}{\nu} > 40$$

was suggested as being more applicable . This is an agreement with the conclusions made by previous authors . Above 2m/sec the shear stress tends to a constant value of $\overline{u'v'} / \bar{U}^2_{max} \simeq 0.0022$, which is generally in agreement with previous data .

A comparison was made by Deland and Panofsky (1957) of the measurements from O'Neill , Nebraska , and Brookhaven whose roughness lengths were 1.0cm (0.39 in.) and 1m.(39 in.) respectively , from which some general conclusions were drawn on roughness effects . In both cases the turbulence got more isotropic as the wave length decreased , also , large eddies , in adiabatic flows , tended to be orientated in vertical planes parallel to the wind direction - a point which does not agree with the findings of Townsend . The spectral shapes were found

to be similar in both cases . The longitudinal velocity spectra were found to be reasonably invarient with height but the peak of the $nS(n)$ curve of the vertical spectra moved to a lower frequency with increase of height . This is consistent with suppression of the low frequencies at or near ground level . Similarly in the case of the cospectra , generally , there was an increase of energy at the low frequencies and a decrease at the high frequencies as the height was increased above ground level . They also concluded that the variances and stresses were increased by the following factors for the above change of roughness :-

Longitudinal	Lateral	Vertical	Reynolds Stress
Factor: 3	2	6	10

However , it is considered that these values are probably for extreme cases and that more representative values would tend to be somewhat lower . The authors suggested that the vertical spectrum shape could be represented by :-

$$\frac{f S_v(f)}{(C = \text{Const.})} = \frac{c.f}{(1+4f^{5/6})^2}$$

where $f = ny/\bar{u}$ i.e. the spectrum is height dependent . There is a considerable amount of data in this paper on the effects of the state of atmospheric equilibrium on the turbulent properties of the boundary layer which makes it of value as a reference paper .

Notess (1957) contained the results of many flights over different types of terrain . However the main analysis was contained in Notess (1959) . The main points indicated in the present anaysis were a reduction of turbulence on flying from land to sea and very little turbulence measured above an altitude of 600 m.(2000 ft.) . For heights greater than 215 m.(700 ft.) the spectra of all three components of turbulence were found to be similar .

The turbulence in the atmosphere was considered by Press (1957) as it was applied in relation to a/c gust loading . Results were quoted for altitudes where the turbulence is generally isotropic i.e. $y >$ 300m.(1000 ft.) and this was verified by the date presented . The point of interest shown here was that the probability density distributions can be regarded as Gaussian up to moderate values of the standard deviation (see FIG.33b , for u- component), however at extreme values , the measurements vary from that predicted by the Gaussian distribution.

Townsend's work on the structure of boundary layer flow was further developed in Townsend (1957) . His main conclusions were that measurements in the inner or constant stress layer were consistent with the occurrence of two-dimensional jets in the flow which were directed outwards from the viscous layer and were long in the flow direction . In the outer layer the large scale motions appeared to be jets of turbulent fluid . Townsend assumed that the large eddies were an essential part of turbulent shear flows . The type of motion deduced for the outer layer is shown

in FIG.34a,b where the eddies were assumed to be of comparable size to the boundary layer depth . The type of flow deduced for the inner layer is also shown in FIG.34a , it was assumed to consist of two-dimensional jets aligned with the mean flow . Up to this time this was the only attempt made to describe the flow structure based on the results of a detailed experimental investigation . However at later dates other detailed investig--ations suggest other types of flow structure in flat plate boundary layers .

The work of Van der Hoven (1957) is an essential part of any paper which refers to the Earth's boundary layer . In this paper the complete spectrum for the mesometeorological and micrometeorological ranges were presented (FIG.34c) . Two distinct peaks were indicated on the spectrum , one at a four day period and the second at one minute . The former was associated with movements of large pressure systems and the latter with the peak of the spectrum produced by mechanical turbulence . The gap between the two spectra occurs at a period of about one hour and it was assumed that this was due to the lack of physical processes in the atmosphere which could support eddy energy at this frequency range . The main contributions to this spectrum lie in the frequency range of :-

$$1 \times 10^{-3} \leq Hz \leq 3 \times 10^{-1}$$

However it can be seen from the spectrum that for most purposes an averaging time of from 15 to 30 minutes would be sufficient

in order to obtain representative mean values . These measurements give the first complete data on the power spectrum of the longitudinal velocity . Also of interest was the fact that the experimental data suggested that the spectral gap occured at a higher frequency in flows over rougher terrain . This implies that in the case of , say , an urban area that there is a reduction in the streamwise scale of longitudinal turbulence , a point to be borne in mind for future reference .

The results of a considerable programme of work carried out at O'Neill, Nebraska were edited and presented by Lettau and Davidson (1957) . The detailed data for the neutral equilibrium case will only be recorded here :-

Range of y_o(cm) : 1.73 , 0.51 , 0.34 , 0.44 (0.68 ~ 0.13in)

Range of $\frac{1}{\alpha}$: Lapse - 1/6 ~ 1/10 , Neutral 1/5 ~ 1/7, Inversion 1/4 ~ 1/2

$\overline{u'v'}/\bar{U}^2_{max}$: 0.0016 ~ 0.0018

y(m)	$\sqrt{\overline{u^2}}/\bar{u}$	$\sqrt{\overline{w^2}}/\bar{u}$	$\sqrt{\overline{v^2}}/\bar{u}$
1.5	0.219	0.143	0.079
3	0.198	0.113	0.065
6	0.168	0.096	0.058
12	0.155	0.096	0.063

For near-ground level the following can also be deduced :-

$\sqrt{\overline{u^2}}/u_*$	$\sqrt{\overline{w^2}}/u_*$	$\sqrt{\overline{v^2}}/u_*$
2.7	1.6	1.1

The growth of a boundary layer over a change of surface roughness was considered by Elliott(1958) . This is of relevance with regard to measurements of the roughness length y_o . Although most authors of previous papers choose sites of homogenous roughness for such measurements , there are , no doubt , cases where errors occured due to flow not being in equilibrium at the measuring position i.e. due to the terrain fetch being insufficiently long . However such errors may not be any more significant than those arising from instrumentation . Elliott's work predicted the height of the growing boundary layer as :-

$$y = 0.86 x^{0.8} y_o^{0.2}$$

Therefore if y_o is known and the mean roughness height h the following can be determined :-

(a) The boundary layer height appropriate to the new surface and ,

(b) Whether sufficient fetch is available for near equilibrium conditions to be attained (i.e. by assuming that it takes a distance of N x h to attain equilibrium)

Additional data was presented by Ely (1958) from the O'Neill, Nebraska site :-

y (m)	$\bar{u}$ (m/sec)	y_o (cm.)	$\sqrt{\bar{u}^2}/\bar{u}$ %
3	2~9	1.0	19~20

The scatter of the data generally increased above a wind - speed of about 6m./second , this may be associated with the onset of adiabatic conditions producing mechanical turbulence . From a spectral analysis he also concluded that,

(a) Thermally generated turbulence occurred at lower frequencies than mechanical turbulence i.e. it reduces the spectral "gap"

(b) 39% of energy between 0.001 and 0.5 cps was of solar origin and decreased with increase of wind speed i.e. production of adiabatic conditions .

No indication was given of what stable or unstable condition applied for (b) above , otherwise , these conclusions agree with the findings of other authors .

Jensen (1958) gave additional measurements of velocity profile indices for rural and urban (Copenhagen) sites . However the Copenhagen data are not considered to be very representative due to the restricted height range of the measurements and the fact that more local than mean effects could have been measured .

Type	Site	$\frac{1}{\alpha}$	y_o(cm)	y(m)
Urban	: Copenhagen (h = 15m)	0.36	750 (296in)	35~80 (118~260ft.)
(Cultivated area)	: Nøesgard	0.27	4.5(1.8in)	.50~3.0 (1.6~10ft.)
"	: Albertslund	0.187	0.95(0.37in)	1.0~6.0(3.3~20ft.)
"	: Freslev	0.152	.30(0.12in)	.70~8.5(2.3~28ft.)
(Very Smooth)	: Højir	0.11	0.018(.007in)	.50~2.0(1.6~6.6ft.)

Johnson's (1958) paper provided another illustration of the results of basing a velocity profile index on measurements too close to the ground for rural terrain and adiabatic equilibrium ,

e.g. $\frac{\bar{u}_{40m}}{\bar{u}_{1000m}}$ gives $1/\alpha = 1/6.3$

and $\frac{\bar{u}_{2m}}{\bar{u}_{1000m}}$ gives $1/\alpha = 1/4.36$

He also gave the power indices for other equilibrium conditions , from measurements at 40m. (130 ft.) and 1000m.(3300 ft.)

	Inversion	Lapse
$1/\alpha$:		
:	1/3.5	1/8.7
$1/\alpha$:	1/3.0	1/9.0 (cf.Friedman 1953)

The change of wind direction with height (α') was quoted as 33° from 40m.(130 ft.) to 1000 m. (3300 ft.) .

A comprehensive set of correlation measurements was presented by Grant (1958) from flat-plate boundary work . From these it can be seen that the length scales of turbulence increase with increase of distance from the ground ; at about half the boundary layer height the rate of increase becomes less noticeable. Also it can be seen that :—

$$L_{ux} > L_{uy} > L_{uz}$$

These measurements are of importance since they verify the type of variation proposed , and to some extent measured , in the adiabatic atmospheric boundary layer .

Taylor's hypothesis concerning turbulent eddies , i.e. that they are carried along at the same speed as the local mean wind speed was verified by Panofsky et al.(1958) . The hypothesis was shown to apply up to a height of at least 90 m.(295 ft.) and for turbulence intensities up to 0.26 . Thus if the autocorrelation is measured and its integral multiplied by the local mean velocity the local mean eddy size is obtained . The conclusions were based on the analysis of some of the O'Neill data .

Deacon (1959) , on the basis of available data , assumed that the length scale of turbulence increased with height from the ground and that near the ground the production and dissipation of turbulent energy could be assumed equal . Once again the applicability of the power law and the relevant power indices was reviewed by De Marrais (1959) . The main results were summarised in tabular form (FIG.35a) . An index of 0.29 was suggested by the author as being applicable to the Brookhaven site in neutral conditions . This was based on measured velocity ratios at 11 and 125 m. (36 and 410 ft.) ; 46 and 125 m.(150 and 410 ft.) and 11 and 46 m. (36 and 150 ft.) . However this value is considered to be too high for this site since recent papers show that the power index does not vary considerably from lapse to neutral conditions . This is also shown to be the case for the other data tabulated by the author (Fig.35a) . The second table (FIG.35b) also shows that determination of a power index from readings too close to the ground tends to give above average values , due to the fact that the log-law is more applicable near

ground level . The height below which velocity readings should be neglected is clearly dependent on the prevailing ground roughness . On the above basis a value of the order of 0.22~0.23 would be expected for the Brookhaven site .

Some further information on length scales was given by Hay and Pasquill (1959) . They assumed that the length scale can be determined by the product of the mean wind speed and the time taken for the auto - correlation curve to fall to a value of $1/e$ i.e. assuming that the curve goes asymptotically to zero . Hence the length scale (L_{ux}) over downland at a height of 2m.(6.6 ft.) were deduced to be of the order 20~40m.(66 130ft.).

Johnson (1959) concluded that the velocity variation with height could be more consistently described by a power law than a log-law and quoted the following data :-

Terrain	$1/\alpha$	Reference
Snow	0.165 ~ 0.149	Frost (1948)
O'Neill	0.17	

He also quoted some turbulence intensity measurements made over a snow surface but it is not possible to interpolate data for neutral conditions from the unstable and stable data quoted .

An attempt was made by Lettau (1959) to correlate the ground shear stress or surface drag coefficient $C_a \left[= \left(\tau_o/\rho\right)^{1/2} / \bar{U}_{MAX}\right]$ with the roughness length which was used as the characteristic length in the Rossby Number $\left(\bar{U}_{MAX} / y_o F\right)$. This work was based on the fact that in fluid dynamics the drag coefficient of smooth and rough walls could be correlated against Reynolds Number . The variation derived by Lettau is shown in FIG.36a , which also includes additional data on the roughness length of various sites . It is suggested that the data could perhaps be equally well represented by a straight line .

From flight measurements (Henry 1959) established Taylor's hypothesis and that the longitudinal and vertical velocity spectra had slopes of -5/3 at the high frequency ends . The standard spectral form was given as :-

$$S(\Omega) = \frac{q\,\mathrm{Tanh.}(p\Omega)}{(p\Omega)^{5/3}} \quad ; \Omega = \frac{\omega}{\bar{u}} \quad = \text{wave number}$$

where p and q are empirical constants .
The following forms were proposed for the middle and high frequency ranges for adiabatic equilibrium :-

$$S_v(\Omega) = 0.179\, \frac{\bar{u}^{-5/3}\,\mathrm{Tanh.}(2.42\,\frac{y\Omega}{\bar{u}})}{y^{2/3}\left(\omega/\bar{u}\right)^{5/3}}$$

and,

$$S_u(\Omega) = 0.139\, \frac{\bar{u}^{-5/3}\,\mathrm{Tanh.}(20.8\,\frac{y\Omega}{\bar{u}})}{y^{2/3}\,\Omega^{5/3}}$$

Further expressions from aircraft theoretical work were given by Lappe et al (1959) for the spectra as follows :-

$$S_v(\Omega) = \frac{1}{\pi} \sigma^2 L \left[\frac{1 + 3\Omega^2 L^2}{(1 + \Omega^2 L^2)^2} \right]$$

and,

$$S_u(\Omega) = \frac{2}{\pi} \sigma^2 L \left[\frac{1}{1 + \Omega^2 L^2} \right]$$

where σ^2 = Total variance and L = Characteristic turbulence scale .

The above forms however were not verified by flight test results. However the results provided further verification of Taylor's hypothesis . The flight tests were carried out over different types of terrain and it was shown that there was an increase of low frequency energy with increase of terrain roughness i.e. an increase of the length scale of turbulence ; this point , at first glance , is contrary to thatdeduced from previous papers . However the roughness in this case consists of the large topographical irregularities of the Peakskill site . It seems reasonable to assume that such irregularities cannot be assumed to have the same effect as the change of roughness encountered by flow going from a rural to suburban or urban area . Such a change of roughness is taken to produce a reduction in the low frequency energy or length scale of turbulence .

A further analysis of the same flight test data was presented by Notess (1959) . For the expressions presented above Laffe et al (1959) , L was taken as 300m.(1000 ft.) in

order to fit the proposed spectral shapes to the measured data . The slopes of the spectra were found to vary between - 1.5 and - 2.0 at the high frequency end , where isotropy of all three turbulent components was also shown to be true . The energy content of the spectra was shown to be a function of ground roughness (y_o) . Considering the vertical velocity component , the low frequency energy was shown to decrease for $y < 180$m. (600 ft.) and also shown to decrease as the ground roughness decreased . The probability density distributions of the fluctuating velocities were also assumed from the data to be Gaussian , however the author points out that this may not necessarily be true at very low altitudes . It is assumed that this applies to heights which are low enough to be influenced by local effects. The author's derived length scales are shown in FIG.36b ; Flight 109 being the near adiabatic case . Flight 112 data represent a gradient of - 1.5°C /100 m.

Panofsky and Deland (1959) was mostly a review of data previously presented by Panofsky and others . In agreement with many other authors (e.g. McCready 1956 , Jones 1957) the applicability of the -5/3 law at the high frequency end of spectra was confirmed . In this range also the spectral energy of the various turbulence components was found to be similar . With increase of surface roughness the energy of all components increased e.g. cf. O'Neill site whose $y_o \simeq 0.7$ cm. (0.28 in.) and Brookhaven having $y_o = 1$ m.(39 in.) (see Deland and Panofsky 1957).

It was suggested here that the change of spectral density due to roughness could be represented by :-

$$S/S' = \left[\log_e y/y'_o \;/\; \log_e y/y_o\right]^2$$

With regard to the vertical velocity spectrum , this was found to be similar at all heights but to move to a lower frequency with increase of height above ground level . The lack of energy in this spectrum at low frequencies (cf. to the longitudinal spectrum) is shown in FIG.35c ; there is not a great deal of energy below a frequency of about 0.004 c.p.s. whereas the longitudinal spectrum contains appreciable energy down to frequencies of at least the order of 0.001 c.ps. This effect was also illustrated in the $\overline{uv}$ spectrum (FIG.35c) by the rapid decrease of its energy content in the frequency range where there is little or no energy in the vertical spectrum . It follows that the maxima of the cospectra would be expected to move to lower frequencies with increase of height .

Singer and Smith (1959) summarised the results of long term investigations at Brookhaven aimed at determining the variation of the power index $1/\alpha$ with various meteorological parameters . It is assumed from the extensive data that the correct value of the index for neutral conditions at this site is 0.21 which is obtained by neglecting the velocity measurements at the lowest test height of 11.3 m. (37 ft.) . This is considered to be justifiable since the height of the surrounding roughness

(i.e. trees) is of the order of 9m.(30 ft.) . However it is noted that recent literature tends to take a 0.28 index for this site , which is here considered to be an over-estimate . This point will be considered again later in the text .

Vinogradova (1959) gave the results of fairly comprehensive measurements of the stress over water surfaces . From hot-wire measurements it can be deduced that at a height of 2m. (6.6 ft.)

$$u_* \diagup \bar{u}_{2m} \approx 0.05$$

or $$\frac{u_*}{\bar{U}_{MAX}} = 0.0221 \quad , \text{ for } \delta = 600\text{m.}$$

$$\therefore \frac{\overline{u'v'}}{\bar{U}^2_{MAX}} = 0.0005.$$

Summary of data on the structure of the atmospheric boundary layer for the period 1950 - 1959 .

There is no doubt that in this period there was a great increase in the amount of measurements made at various sites in the atmospheric boundary layer . These data have been included in App. 1 with those from the preceding periods . The most complete measurements are those of the Leipzig site re-analysed by Lettau (1950) and the extensive measurements from the O'Neill site presented by Lettau and Davidson (1957) The many measurements by Shiotani of turbulence length scales and intensities also provided a valuable contribution in this period , as did the tabulated data of Deacon (1955) of the power indices of various types of terrain . Webb's (1955) analysis of the variation of the length scale with height is also significant and provides a useful basis by which to correlate other data of this type .

The work of Van Der Hoven (1957) produced the complete spectrum of the longitudinal turbulent velocity and established the existence of the spectral gap , thus giving a time over which data should be recorded in order to provide representative mean values . The work of Townsend (1951 and 1957) also went some way towards describing the structure of flat - plate boundary layers which , it has been assumed , are similar to adiabatic atmospheric boundary layers .

The most noteworthy theoretical contribution is that of Monin and Obukhov (1954) by which the Monin-Obukhov length was established .

Since the amount of data available is now fairly extensive it is proposed to make an interim assessment in order to establish the general characteristics of the various types of terrain of interest . These will then be refined to a more definite form by the additional quantitative data to be derived from the 1960 - 1969 period .

2.4. INTERIM ASSESSMENT OF DATA FROM THE PERIOD 1880 - 1959 .

In the preceding review of the meteorological literature sufficient data have been presented from which the orders of magnitude of most of the boundary layer quantites of interest can be broadly determined . The form of the review to date has, in fact , made it possible to "converge on" the orders of magnitude of some of the quantities by indicating from the extensive literature survey the cases which can be taken as giving extreme or inaccurate data .

Although the manner of the variation of some of the quantities with the roughness length is now evident , for a final analysis it will be considered essential to describe the variation of this quantity as a function of , say , the power index and turbulence intensity in more detail . As a preliminary to this , it is considered that this is an appropriate point at which to briefly summarise the information presented in the previous text for the following reasons . It is clear that the majority of the main points that needed to be emphasised,or illustrated , concerning the characteristics of the atmospheric boundary layer or the significance of the acquired data , have been made in the preceding text . Hence it is assumed that the 1960 - 1969 period can be assessed by tabulating the remaining data required and only commenting where comments are considered necessary , on either their originality , accuracy or applicability . The extensive data from this period necessitates this form of presentation both from the point of view of conciseness and the avoidance of considerable repetition .

Therefore , in the following summary , the status of the various quantities needs to be established , consistent with the amount of data available , from the 1880 - 1959 period so that it can be merely refined or added to by the information from the final period to be considered . The objective is to present the data finally in a concise graphical form .

The boundary layer quantities of main interest will be considered individually in the following text .

2.4.1. The flow structure .

Up to the end of the period ending in 1959 comparitively little was known concerning the detailed flow structure of the atmospheric boundary layer or its flow patterns . In this period, as in the following period , the greatest progress in this field was made by investigations in flat-plate boundary layer flow . It is assumed that a similar type of flow will exist in adiabatic atmospheric boundary layers .

Originally , most ideas on the structure of the flow were derived from observations of cloud and particle movements made from low flying aircraft . Rawson (1913) , for example , commented on the presence of "typical wave motions , surgings and splashes ..." and motions which could be described as non-periodic or turbulent . It was generally indicated that such motions , or turbulence , decreased in intensity with increase

of height . Shaw (1914) showed how the character of gustiness changed as it encountered large obstructions such as trees and buildings and his anemogram recordings clearly showed its degree of randomness .

Eventually this type of flow was described on a theoretical basis by Taylor (1915) who considered the "average" effect of a collection of eddies rather than the complex mathematical problem of individual eddies . The eddies were considered as introducing a "coefficient of eddy viscosity " and were assumed to be circular . It was later shown , also theoretically, that the "kinetic energy of eddying " was increased from the mean wind by the work done by eddy stresses on the rate of mean strain (Richardson , 1920) . This increase of kinetic energy can also be defined as the rate at which the mean wind gives up energy to these eddies in the production of turbulence .

The analysis of turbulence by statistical methods was later further expanded by Taylor (1920) . He introduced the concept of describing and deducing the structure of a flow by correlation measurements of the time history of a particle . It was assumed that the average effect of turbulence was to give a fluid the power of diffusing certain properties through it ; therefore , by the above work of Taylor , the problem of turbulent diffusion was reduced to the consideration of one quantity , namely the correlation coefficient . Further observations (Goldie , 1925) showed that the air near the ground

consisted of partially formed rapidly disintegrating eddies and it was initially thought that the eddy velocities were equal in all directions .

Investigations of this concept were carried out by Becker (1930) , Sherlock and Stout (1932) and Giblett (1932) ; the recordings of Giblett showed , additionally , the random motion of the air and that its structure was a function of the atmospheric equilibrium . It was suggested by Durst at this time (see Giblett 1932) that the shear in the flow resulted in the formation of "rolled up" eddies having their axes across the stream which would tend to break up ; To date other investigators had not detected such motions . However , with regard to the relative magnitude ot the eddies it was adequately shown by Best (1935) that the longitudinal , lateral and vertical eddy velocities were not the same in magnitude . He also investigated the effects of averaging the measured quantities over various periods of time and thus illustrated the fact that the flow consisted of eddies of various sizes .

In the case of the adiabatic atmosphere the production of turbulence is a maximum at ground level and its magnitude , or intensity , was recognised as being a function of the ground roughness . It was suggested by Schmidt (1935) that this turbulence , in the form of vortices at ground level , was spread upwards in the boundary layer by some mechanism or other.

It was subsequently assumed that these vortices were in fact "projected" into the main flow above the ground , thus distributing the turbulence created at ground level into the upper part of the boundary layer (see also Pagon 1935) . This was one of the first attempts to describe the physics of a shear turbulent flow .

The use of a power spectrum had been suggested as a method of analysing the flow structure by indicating the energy content of the various ranges of eddy sizes (Schmidt 1935) . The basic theory relating the power spectrum to the correlations was subsequently derived by Taylor (1938) . In this context the hypothesis of Kolmogoroff (1941) showed the similarity of the structure of turbulence at high Reynolds numbers i.e. the similarity of the small scale turbulent eddies associated with the high frequency end of the spectrum . It was generally agreed, at this time , that the eddy sizes represented in the spectrum could be described by three separate bands as follows :-

(a) A low frequency range where the greater part of the turbulent energy was contained ; this energy being transferred by inertial forces to the higher frequencies ,

(b) An intermediate range which had not necessarily the similarity characteristics of the higher range and which was significantly influenced by dissipation , but not directly by viscosity , and

(c) a high frequency range which followed Kolmogoroff's law of similarity .

The next important contribution was that of Townsend (1951) from work on flat-plate boundary layers . He suggested that the large eddies in the flow were of the same order of magnitude as the boundary layer height , and described and determined the various contributions towards the balance of the turbulent energy equations . It wasalso proposed that the boundary layer could be divided into an outer and an inner layer . In the outer layer non-turbulent fluid was entrained from the mean flow by the large eddies ; in the inner layer turbulent energy and scales of turbulence were created .

Priestley and Sheppard (1952) illustrated how energy was transferred through the different frequency ranges of a power spectrum and Panofsky and McCormick (1954) showed that generally the spectral shapes were independent of terrain roughness . However this implies that the flow structure is not affected by large roughness elements which seems unlikely . It was also shown that the structure of the longitudinal turbulence differed to that of the vertical turbulence i.e. its length scales , or eddy sizes , were greater than those of the vertical turbulence. Again , the existence of eddies of various sizes was shown by Deacon (1955a) , who also confirmed the existence of a downward transport of large scale energy in the boundary layer .

Enlarging on his previous analysis Townsend (1957) suggested that there existed , in boundary layer flows , contra - rotating vortex pairs moving with the flow and having their axes parallel to the flow direction . Sets of large eddies were assumed to exist both in the inner , or constant shear stress layer , and the outer section of the boundary layer . Extensive measurements in flat-plate boundary layer flow by Grant (1958) showed the existence of large eddies in the flow and the increase of eddy size with increase of distance from the wall.

Panofsky et al (1958) verified Taylor's hypothesis concerning the transport of eddies at the same speed as the local mean wind speed . At the end of this period it was generally accepted that turbulent length scales increased with increase of distance above the ground and that close to the ground the production and dissipation of turbulent energy could be assumed equal . It can be assumed also that although a broad picture has emerged of the flow structure its detailed flow patterns were not known up to this time .

2.4.2. The mean velocity profile and the boundary layer height .

During the course of investigations into the structure of flow in the Earth's boundary layer many forms for the law governing the variation of the mean velocity with height have been suggested . One of the earliest was that of Stevenson (1880)

who proposed a parabolic law ,

$$\frac{\bar{u}_1}{\bar{u}_2} = \sqrt{\frac{y_1 + 72}{y_2 + 72}}$$

where $\bar{u}_1$ and $\bar{u}_2$ are the mean velocities at arbitrary heights y_1 and y_2 respectively . To apply a parabolic law Stevenson neglected the lower 10m. (33 ft.) of the measured velocity profiles . By assuming the application of a power law , power indices of between 1/6 and 1/7 can be deduced from Stephenson's results for the various terrain conditions considered .

Other laws suggested were that of Archibald (1885) in the form of a power law ,

$$\frac{\bar{u}_1}{\bar{u}_2} = \left(y_1/y_2\right)^{1/4}$$

and that of Shaw (1909) , for example , which predicted a linear variation with height ,

$$\frac{\bar{u}_1}{\bar{U}_{MAX}} = \frac{\delta + C}{C}$$

where 'C' is a function of the ground roughness .

The results of Dobson (1914) showed that the boundary layer height was of the order 450 - 600 m. (1500 - 2000 ft.) and the assumption of a power index of a 1/7th gave the best fit to his measured velocities . Generally , from other observations , little turbulence was found to exist above a height of about 600m. (2000 ft.) . This height range of 450 - 600 m. (1500 - 2000 ft.) was also predicted by Taylor (1917) and 400 m. (1300ft.) by Schmidt (1918) .

The main problems involved in the derivation and measurement of mean velocity profiles were adequately assessed by Chapman (1919) . Although he concluded that most of the measurements could best be represented by a log - law , i.e.

$$\bar{u} = a \log y + b$$

there is no doubt that a power law provides just as adequate a fit to most of the data considered , particularly in the case of high winds . Other variations of the log law were suggested later but these were generally not adopted as they involved constants which were functions of both wind speed and atmospheric stability e.g. Geiger (1927) , Sutton (1932) and Ali (1932) . A further reference to a boundary layer height of the order 450 - 600 m. (1500 - 2000 ft.) is contained in Giblett (1932) .

By utilizing the flat plate boundary layer theory of Prandtl and Von Karman a more refined version of the log-law was produced by Sverdrup (1934) ,

$$\bar{u} = \tfrac{1}{k}\sqrt{\tfrac{E}{\rho}} \log_e y/y_o$$

This was assumed to be applicable for the conditions of

(a) Adiabatic equilibrium , and

(b) Up to a height of about 10 m.

and provided a method of determining the relative roughness of the terrain considered . However Sverdrup also pointed out that a law of the form ,

$$\bar{u}_1/\bar{u}_2 = \left(y_1/y_2\right)^{1/\alpha}$$

(i.e. a power law)

could be applied equally well to most meteorological conditions. Since the power law could be mathematically manipulated more easily than the log-law it tended to be used more often than the log-law in meteorological problems ; $1/\alpha$ being taken as an indication of the amount of turbulence present . A value for the index of a 1/7th was regarded as being applicable to rural terrain e.g. Sutton (1934) , Rossby and Montgomery (1935) and Pagon (1935) and 1/3 for greater roughness .

Pagon (1935) derived values for rural and urban boundary layer heights of 325 m. (1068 ft.) and 525m. (1720 ft.) respectively by assuming an eddy viscosity which was constant

with height . Paeschke (1937) quoted extensive data on the power index values for flows over many types of terrain . However these are mostly over estimated due to considering measurements made at heights which are too close to the ground . This type of over estimate is in fact common to many , even more recent papers , especially in the analysis of measurements of mean velocities from urban areas . Further values of an index of a 1/7th for rural areas were quoted by Frost (1947) and Sheppard (1947) .

The most important later modification to the above laws was indicated by Sutton (1949) as ,

$$\bar{u}/u_* = 1/k \log_e \frac{y-d}{y_o}$$

which took into account the zero plane displacement (d) when considering large roughness elements (see also Paeschke 1937)

The index which applies to flow over water was given as 0.122 by Sheppard (1952) who also quoted a boundary layer height of 500m. (1650 ft.) and Sheppard and Omar gave a height of the order of 450 - 600 m. (1500 - 2000 ft.) . The values of a 1/7th and 600m (2000 ft.) were quoted extensively in the period 1950 - 1959 for the power index and boundary layer height respectively ; the lower layer in which the log-law was taken to be more applicable , was assumed to be of the order of 30 - 50 m. (100 - 165 ft.) in height . The most relevant data was included

in Collins (1955) , Deacon (1955a) and Kamai (1955) with more detailed data from one site included in Lettau and Davidson (1957) .

An example of an overestimate of the power index for the Brookhaven site can be deduced from De Marrais (1959) and Singer and Smith (1959) . Although a value of 0.28 is presently taken to represent this site , a closer examination of the data would suggest a power index having a value of 0.20 - 0.23 as being more applicable . The site consists of woodland having trees up to about 10m. (33 ft.) in height .

It can be assumed at this stage that the choice is arbitrary as to whether the mean velocity profile is represented by a log-law or a power law . The lower 30 - 50 m.(100 - 165 ft.) of the boundary layer seems to be represented better by a log-law and it is certainly incorrect to try to deduce a power law index from measurements made in this height range . However the power law seems to give a better fit to most of the data over a greater height range and for the high wind conditions which lead to adiabatic equilibrium . Hence it was decided to define the mean velocity profiles of rural and urban flows by power laws .

It can be readily deduced from the preceding text that the power index for flow over rural terrains lies in the range of 1/6 to 1/7th ; a value of 1/7 (0.143) can be taken as the value occurring most often in the literature and therefore the most likely value for typical rural terrain .

At this stage of the review the choice of a power index to represent flow over an urban area is more difficult for the following reasons . In the first instance there is a scarcity of results for such conditions and secondly, and more important, there is the fact that many of the available results will include local topographical effects rather than be representative mean values of particular urban areas .

Some of the data included in this context are the often quoted measurements near Leipzig by Mildner (1932) . They are here assumed to be typical of a suburban site and a power exponent in the range of 0.22 - 0.25 provides a good fit to the data . The urban case referred to by Rossby and Montgomery (1935) is best represented by an index of 0.40 . Additionally , values of 0.36 for Strasburg and 0.40 for Tokio were suggested by Paeschke (1935) and Shiotani and Yamamoto (1948) , respectively. The sources of these measurements , however , lack sufficient detail , with respect to the situation of the measuring positions relative to the local topography , for a reliable assessment to be made of them .

Hellermann (1953) suggested a value of 0.33 for a typical city site and Kaimei (1955) the same value for Japanese towns . In the latter case the measurements appear to be influenced by the local effects of nearby buildings . The same statement applies to the Copenhagen measurements of Jensen (1958) from which a power index in the range of 0.34 - 0.35 can be deduced

for the city centre . The Brookhaven site which has local obstructions of up to 10m. (33 ft.) in height can be regarded, for present purposes , as being representative of a suburban site and be represented by a power index of 0.21 (Singer and Smith 1959) .

It can be seen that it is by no means clear what the power index should be for an urban area , from the data of this period, except that it is probably in the range 0.21 - 0.40 .

With regard to the boundary layer height , the majority of the relevant data inevitably suggests a value in the range of 450 - 600m. (1500 - 2000 ft.) with most of the quoted values suggesting 600m. (2000ft.) . This value has been assumed when determining $\bar{u}/\bar{U}_{max}$ from the power law in order to normalise the data from various sources ; this has produced a reasonable degree of consistency in the measurements so treated.

2.4.3. The Roughness Length .

The magnitude of the roughness length can be defined from the log-law,

$$\bar{u}/u_* = 1/k \log_e \frac{y-d}{y_o}$$

either by computation or graphically . Reliable estimates are

difficult to obtain since the roughness length is a function of stability (to some extent) , fetch and wind speed unless in the latter case :-

$$\frac{u_* y_o}{\nu} > 2.5$$

However , there is some evidence that this criterion is a function of the "type" of roughness being considered and therefore it cannot be taken as a definite guide .

Generally there is sufficient data available from which typical average values can be obtained for the cases required; this is especially true of more recent data when the points mentioned above were taken into account . On the other hand it is possible to deduce typical rural values from even the measurements of Stephenson (1880) as follows ,

TERRAIN	: "Open ground"	: Corn (h = 30cm.)	: Corn(h = 1m.)
y_o(cm)	: 0.137	: 2.27	: 4.80 480

which values are independent of wind speed in the speed range considered . These can be compared with values derived by Sverdrup (1934) which , although the terrain description is not very explicit , have the same order of magnitude as those shown above ;

TERRAIN	: Short mown grass	: Open grassland	: "Relatively" Calm sea
y_o(cm)	: 0.54	: 3.20	: 3.90

In the case of urban terrain one of the first values quoted was that of 1m. by Rossby and Montgomery (1935) ; they also suggested a value of 3.2m. (10.5 ft.) for "large roughness" . The extensive data presented by Paeschke (1937) has already been indicated as being significant since it allows for the effect of the zero-plane displacement in estimating the roughness lengths. The author quotes,

$$0.5 \leq y_o\,(cm.) \leq 6.5$$

for terrain varying from snow-covered to beet and cereal crops . Frost (1947) quoted values of 1.0 cm. (0.39 in.) and 2.6cm. (1.02 in.) for sea and open country respectively . Sheppard (1947) and Deacon (1948) summarised most of the available data on roughness parameters from which the range of values applicable to rural terrain can be deduced as ,

$$1.0 \leq y_o\,(cm.) \leq 13.5$$

A further value for urban terrain was also quoted at this time by Shiotani and Yamamoto (1948) i.e. a value of 4m.(13ft.) for Tokio . They suggested that for urban areas,

$$y_o = h/3$$

A further example of allowing for the zero plane displacement was given by Pasquill (1950) who determined a y_o of 0.66cm. (0.25 in.) for grass 15 cm. (5.9 in.) tall. Shiotani (1950) stated values for the roughness length of terrain covered by grass and vegetables as ,

$$1.5 \leq y_o\,(cm) \leq 5.5$$

Additional data was quoted by Deacon (1953) and Sutton (1953) which lies in the range of values already quoted . From the work of this period it became possible to start correlating roughness lengths for particular sites e.g.

	Cardington	Brookhaven	O'Neill
y_o(cm.) :	0.32	100	1.0

for which the power law indices are also known .

The paper of Kamei (1955) included another value of 1.5 m. (4.9 ft.) for the roughness length of Tokio ; a value of 4 m. (13 ft.) had previously been suggested .

In relation to the roughness length of grass , Deacon (1957) suggested that Nikuradse's criterion should be modified to,

$$\frac{u_* y_o}{\nu} > 40$$

Some other y_o data was presented by Lettau (1959) which again agrees with the previously quoted values .

Therefore it can be assumed at this stage that y_o for rural areas should fall in the broad range of ,

$$1.0 \leqslant y_o(\text{cm}) \leqslant 15$$

and as a very rough guide for urban areas , that it should lie in the range,

$$1.0 \leqslant y_o(\text{m}) \leqslant 4.0$$

Clearly the variation of this quantity with type of terrain (or say $1/\alpha$) will eventually need to be defined more precisely.

2.4.4. The Reynolds Stresses .

If the roughness lengths of the terrains considered are known then it is not strictly necessary to define appropriate values of the Reynolds stresses . However , if it is assumed that its variation through the boundary layer is similar to that of a flat-plate boundary layer , then , sufficient information is available to at least define its order of magnitude at ground level or in the constant stress layer .

Some of the earliest assessments of the ground level shear stress were those of Taylor (1916) , from which can be derived ,

$$0.0014 \leqslant -\frac{\overline{u'v'}}{\bar{U}^2_{MAX}} \leqslant 0.0020$$

which values are applicable to open countryside having a boundary layer height of 600m.(2000 ft.) . Similarly , Scrase (1930) derived a value of approximately 0.0015 at a height of 19m. (62 ft.) above the ground ; this can be regarded also as the approximate value at ground level , since the Reynolds stress was considered to be constant (to within about 6%) up to a height of about 50 m. (165 ft.) above ground level (e.g. see Calder 1939)

Additional measurements were presented by Sheppard (1947) in the form of a drag coefficient i.e.,

$$C_D = 2\left(-\frac{\overline{u'v'}}{\bar{u}_1^2}\right)$$

where $\bar{u}_1$ = a reference velocity

The range of Reynolds stresses applicable to rural terrain for the condition of adiabatic equilibrium can be deduced from these data as :-

$$0.0016 \leq -\frac{\overline{u'v'}}{\bar{U}_{MAX.}^2} \leq 0.0043$$

Values as low as 0.0010 for short grass and sea were quoted by Pasquill (1950) and Sheppard (1952) and a value of 0.0024 by Shiotani (1950) . Hay (1954) however gave a Reynolds Stress as low as 0.0006 for flow over the sea .

A mean value for rural terrain of 0.0025 was suggested by Monin and Obukhov (1954) . The Reynolds stress of a mown grass surface was given by Rider (1954) as 0.0008 which agrees with the value for short grass given by Pasquill (1950). Ellison's (1956) review paper suggested a value of 0.0013 for open country , while Deacon's (1957) detailed analysis gives a value of 0.0022 .

The values quoted above refer mostly to various types of rural terrain . However Deland and Panofsky's (1957) paper , comparing the data from Brookhaven (y_o= 1m.) and O'Neill (y_o= 1cm) suggests that the Reynolds stress vary by a factor of about

10 for the sites , when the stresses are based on the local velocities . Lettau and Davidson (1957) quote a value of about 0.0017 for the O'Neill site based on the free-stream velocity . Finally the work of Vinogradova (1959) gives another value of the shear stress of a water surface as 0.0005 .

Neglecting the extreme cases of the above data , it is therefore suggested that typical rural stress values should lie in the range ,

$$0.0020 \leq -\frac{\overline{u'v'}}{\bar{U}_{max.}} \leq 0.0030$$

(at , or near, ground level)

The only guide to the urban stresses , or stresses due to greater roughness , comes from the work of Deland and Panofsky. Hence there is insufficient data at this stage to define the urban case .

2.4.5. The intensity of turbulence .

It has been shown that the production of turbulence , and therefore the level of its intensity , is a function of the Reynolds stresses and the mean velocity profile of the flow being considered . Therefore it is of interest to consider what the magnitude of the longitudinal (u') , lateral (w') and vertical (v') components of turbulence intensity should be in the rural and urban flows previously specified .

The general character of gustiness , i.e. turbulence , was recognised in the early literature as was the fact that it is a function of both surface roughness and height above ground level. It was additionally generally assumed that all three components of turbulence were of equal magnitude . However Scrase (1930) showed that the ratio of the three components of turbulence were as follows ,

$$\sqrt{\overline{u^2}} : \sqrt{\overline{w^2}} : \sqrt{\overline{v^2}} = 1 : 0.73 : 0.46$$

(Cf. typical flat-plate data ,

$$\sqrt{\overline{u^2}} : \sqrt{\overline{w^2}} : \sqrt{\overline{v^2}} = 1 : 0.75 : 0.54$$

from ground level up to the height of 20m. (65 ft.) considered . Eventually the magnitude of the longitudinal component was established by Best (1935) as,

$$\sqrt{\overline{u^2}}/\overline{u} \simeq 0.15 \text{ to } 0.16$$

in open countryside .

Hence , the corresponding values of the other two components could be deduced . Up to the height considered , the ratio and variations of the components were shown to agree fairly well with the pipe flow measurements of Fage and Townend (1932) . Many authors at this time also derived the ratio of the lateral to vertical turbulence intensity as being of the order 1.5 - 1.6.

A value of 0.13 was given by Shiotani and Yamamoto (1948) for $\sqrt{\overline{u'^2}}/\bar{u}$ for rural terrain . They also presented some of the first measurements of turbulence intensity made in an urban area . Their measured longitudinal turbulence intensities fall in the range 0.20 - 0.30 , whereas it can be said that rural measurements fall roughly in the range 0.10 - 0.20 near ground level .

Shiotani (1950) presented additional data on rural and urban turbulence measurements . The rural measurements fall in the range 0.10 - 0.14 and the urban measurements in the range 0.36 - 0.48 . A further value of 0.25 applicable to an area having large roughness was given by Cramer (1952) and a value for over water of 0.19 by Sheppard (1952) . Fairly extensive measurements of lateral turbulence were given by Frieman (1953) and these verify that $\sqrt{\overline{w'^2}}/\sqrt{\overline{u'^2}} \simeq 0.75$, as did the results given by Robinson (1953) . The ratio of $\sqrt{\overline{v'^2}}/\sqrt{\overline{u'^2}}$ can also be derived as of the order of 0.5 from MacCready (1953) whose turbulence measurements also fall in the ranges already quoted.

Extensive measurements made by Shiotani (1953) over snow fall in the range,

$$0.10 \leqslant \sqrt{\overline{u'^2}}/\bar{u} \leqslant 0.16$$

while the well quoted results of O'Neill , Nebraske given by Lettau and Davidson (1957) as expected range from ,

$$0.15 \leqslant \sqrt{\overline{u'^2}}/\bar{u} \leqslant 0.22$$

Neglecting measurements at heights below say 1 - 2 m. (3.3 - 6.6 ft.) the turbulence intensities of rural areas can be safely defined as falling in the range,

$$0.10 \leq \sqrt{\overline{u^2}}/\bar{u} \leq 0.20$$

up to a height of say 20 to 30 m. (65 - 100 ft.) . On the other hand urban intensities should be in the range ,

$$0.20 \leq \sqrt{\overline{u^2}}/\bar{u} \leq 0.35$$

2.4.6. The power spectral densities .

The forms of the power spectral densities of the longitudinal, lateral and vertical fluctuating velocities have now been fairly well established . However , the work involved in defining the form of the spectrum did not progress , originally , as rapidly as that on the measurement of other quantities . After the work of Scrase (1930) it was suggested by Giblett (1932) that the energy of eddies having various time periods could be represented by an"energy spectrum". Some attempts were made by Schmidt (1935) to define the high frequency end of such a spectrum.

The concept of the power spectrum was defined more scient--ifically by Taylor (1938) who suggested that it could be resolved into harmonic components and that its integrated value, $\overline{u^2}$ could be regarded as being the sum of contributions from all frequencies (n) .

He defined,

$$\int S(n)\, dn = 1$$

where S(n) , the power spectral density , represents the energy between (n) and (n + Δ n) . The high frequency end of the spectrum was defined by Kolmogoroff (1941) and shown to obey his similarity law such that ,

$$n\,S(n) \propto n^{-2/3}$$

The validity of the work of Taylor and Kolmogoroff was checked by the experimental work of Dryden (1943) who measured the power spectra of wind tunnel turbulence .

The shape of the spectrum was eventually defined by Von Karman (1948) in a form which has not been notably improved on , namely :-

$$S\left(K/K_0\right) \propto \frac{1}{\left[1 + \left(K/K_0\right)^2\right]^{5/6}}$$

where $K = \frac{2\pi n}{\bar{u}}$

It was , at this stage , generally agreed that the greater part of the turbulent energy was contained in the low frequency range i.e. in the large eddy sizes . The energy transfer processes through the complete turbulence spectrum were later defined in physical terms e.g. see Priestley and Sheppard (1952).

From measurements at Brookhaven , Panofsky and McCormick (1954) defined some of the characteristics of the longitudinal and vertical spectra . In particular they showed that the turbulence scales of the longitudinal component were much greater than those of the vertical velocity component ; both spectra were shown to be similar at high frequencies . The longitudinal spectral shapes were shown to be similar for flows over terrains of different roughness and generally it was implied that the eddy size of the vertical component increased with increase of distance from the ground .

Panofsky and Van der Hoven (1955) showed that there was a spectral gap at a period of about one hour which conveniently separated the mean and turbulent motions of atmospheric motions in the micrometeorological range . Deland and Panofsky (1957) showed that the longitudinal spectra were invariant with height and suggested that the vertical spectrum shape could be represented by ,

$$\frac{f S_v(f)}{} = \frac{cf}{(1 + 4f^{5/6})^2}$$

where $f = n y / \bar{u}$

Eventually a complete spectrum of the longitudinal velocity was presented by Van der Hoven (1957) which covered the micro and mesometeorological ranges . This is now the classical spectrum represented in most papers which refer to the atmospheric boundary layer . It showed that averaging periods of say 15 to 30 mins. should be sufficiently long for measurement of representative mean values .

It was also suggested , in the paper, that the spectral gap occured at higher frequencies in flows over rougher terrain . The important point here being that this implies a reduction in the scales of turbulence for flow over an urban area .

Most of the data confirmed that the slopes of all the spectra were approximately -5/3 at the high frequency end , in agreement with Kolmogoroff's theorem , and it was also verified by flight measurements of the spectra by e.g. Notess (1957) (1959) and Henry (1959) . Most of the relevant spectral data was summarised by Panofsky and Deland (1959) and it can be concluded that the spectral forms of the longitudinal and vertical velocity components had been established at this stage .

2.4.7. The cospectrum of the Reynolds stresses .

The relevance of the Reynolds stress cospectrum , in the context of defining the Earth's boundary layer , is that it indicates the frequency band in which these stresses are of importance .

Some of the earliest discussions on the cospectrum are included in Panofsky and McCormick (1954) and Panofsky and Van Der Hoven (1955) while Deacon (1955b) showed that the majority of the co-spectral energy was contained in the range,

$$0.01 \leq {}^{ny}/_{\bar{u}} \leq 1.0$$

a point which has been adequately verified by recent measurements. In a general discussion of the characteristics of spectra , Deland and Panofsky (1957) suggested that , in the case of the cospectra , there was an increase of energy at low frequencies and a decrease at the high frequencies with increase of height above ground level . Panofsky and Deland (1959) further showed that there was a rapid decrease in the energy content of the cospectrum in the same frequency range at which there was very little low frequency energy in the spectrum of the vertical velocity component .

It can be concluded that insufficient data is available at this stage in order to clearly define the form of the cospectrum.

2.4.8. The length scales of turbulence .

The length scales of interest are those that define the mean size of the largest eddies in the flow . It has been indicated previously that the majority of the turbulent energy is contained in these eddies ; hence it can be assumed that it is of some relevance to establish their size in relation to say the depth of the boundary layer .

The mean eddy size , in the longitudinal direction (Lu_x) seems to have been assessed initially by Taylor (1915) as being of the order of 70m.(230 ft.) at a height of 10m.(33ft.) . At a similar height , extrapolation of more recent data would

suggest a value of the order of 90m. (295 ft.) which agrees remarkably well with Taylor's original estimate . He also deduced that the mean eddy size increased with increase of height above the ground for the simple reason that "they have more room to grow " . His later work , Taylor (1920) on the concept of correlation measurements , showed how turbulence scales could be determined from the following definition ,

$$L_x = \bar{u} \int_0^{\infty} R(\tau)\, d\tau$$

It also showed how a regular eddy pattern in a flow could be distinguished from such data . Most of the later measurements of length scale supported Taylor's deduction regarding the increase of length scale with height , e.g. Giblett (1932) gives L_{ux} as about 120m. (400 ft.) at a height of 15m. (50 ft.). At this time , one of the few values of the vertical scale of turbulence (L_{uy}) was determined by Schmidt (1935) as being of the order of 15m. (50 ft.) at heights of less than 6m. (20ft.).

Taylor (1938) showed the relationship between power spectra and the correlation coefficients for isotropic turbulence as ,

$$R_x = \int_0^{\infty} S(n) \cos \frac{2\pi n x}{\bar{u}}\, dn, \quad \text{and} \quad S(n) = \frac{4}{\bar{u}} \int_0^{\infty} R(x) \cos \frac{2\pi n x}{\bar{u}}\, dx.$$

where Rx = Correlation coefficient , and S(n) = Power spectral density

Hence when x = 0, the mean largest eddy size is defined as,

$$\bar{u} \left[S(n) \right]_{n=0} = 4 \int_0^{\infty} R(x)\, dx.$$

The next significant length scale measurements were those of Shiotani and Yamamoto (1948) who determined,

$$75m \leq Lu_x(m) \leq 107$$

i.e (250 to 350 ft.)

for heights up to 50m. (165 ft.) in rural terrain . They also quoted a value of the order of 100m.(328 ft.) for urban terrain. The flate-plate boundary layer work of Laufer (1950) suggested that the length scales should increase with increase of height up to about 0.40 - 0.60 of the boundary layer height . Various other authors obtained an assortment of length scales at this stage e.g.

y(m) (ft.)	Lu_x(m) (ft.)	Source
2 (6.6)	11.5 (38)	Sheppard (1952)
2.5(8.2)	12 - 18(39 - 59)	Cramer (1952)
10 (32.8)	30 (100)	Shiotani (1953)
35 (115)	70 (230)	Webb (1955)

From collected data Webb (1955) suggested ,

$$Lu_x \propto y^{0.5}$$

more recent literature suggests $y^{0.4}$; this point will be discussed more fully later . Shiotani (1953) also suggested that the form of the eddies was such that ,

$$Lu_x > Lu_y > Lu_z$$

in the lower section of the boundary layer . A conservative

extrapolation of the measurements available up to this time suggested that Lux should be of the order of 200m(660 ft.) at a height of 100m. (328 ft.) .

Other values of the length scale Lu_x , at various heights , can be extracted from e.g. Priestley (1952) , Robinson (1953), Taylor (1955) and Hay and Pasquill (1959) . It can be concluded that the law proposed by Webb (1955) applies roughly to most data . However it is assumed that the variations in the length scales at the lower heights can be attributed to non-similarity of the suface roughness at the various sites considered . Since it has been assumed that the height of the boundary layer can be taken as 600m.(2000 ft.) , it can be seen that the mean eddy sizes are of a similar order of magnitude some distance from the ground .

2.4.9. The probability density distribution of the fluctuating velocities .

From the point of view of mathematical analysis it is of some convenience to be able to express the probability density distributions of the fluctuating velocities in terms of a normal or Gaussian distribution . Generally it was found that most measurements cover a range of about $\pm 3\sigma$ and any observations made will apply to this range . Outside this range , to date , there is insufficient evidence to define the form of the distribution.

Some of the earliest measurements of the probability density distributions were by Giblett (1932) . Later measurements were presented by Shiotani (1950) , Cramer (1952), McCready (1953) and Sutton (1953) . Although many of the distributions , measured in adiabatic conditions , had some degree of positive or negative skew there is no consistent bias one way or the other . Measurements made by Press (1957) indicated Gaussian distributions up to "moderate" values of the standard deviation , however , at extreme values the measurements varied from that predicted by the Gaussian distribution .

In conclusion , it is reasonable to assume that the distributions of the fluctuating velocities are approximately Gaussian to say $\pm 3\sigma$. Since the available data apply to rural terrain it must be assumed that urban distributions are likewise Gaussian .

2.5. Proposals for the final analysis based on the interim assessment .

All of the quantitative data from the period considered is presented in App. 1 . Some of the data has also been presented in Fig. 37 as it applies roughly to the various types of terrain specified . i.e.

1. Smooth : :- Ice, snow , concrete and mud surfaces.
2. Moderately Rough :- Rural terrain.
3. Rough :- Suburban and wooded.
4. Very Rough :- Urban .

This figure shows where the gaps occur in the existing information . Additionally , from the point of view of defining the flow structure of various types of terrain , it is seen that it is only possible , at this stage , to define the " order-of-magnitude-range " of the quantities required . Hence this data needs to be added to in order to provide the basis that is needed from which the boundary layer characteristics of any terrain likely to be considered can be defined accurately . However it is possible to propose the form that the final presentation of the data should follow .

It has been shown that some attempts have been made to define the structure of the boundary layer . Information on this point is relevant , in as much as it may influence the method of approach to the simulation of an atmospheric boundary layer , and will be noted whenever it occurs in the literature .

The wide range of indices suggested for "rural" velocity profiles suggests that this quantity may be very sensitive to changes of roughness in this particular range of roughness lengths . Therefore , it may be more practical , if possible , to present intensity of turbulence as a function of the roughness parameter in addition to the power index as a function of the same quantity (y_o) . From Lettau and Davidson (1957) is obtained ;

$$\frac{\sqrt{\overline{u^2}}}{u_*} = A \quad ; \quad \frac{\sqrt{\overline{w^2}}}{u_*} = B \quad ; \quad \frac{\sqrt{\overline{v^2}}}{u_*} = C$$

Since,

$$\frac{\bar{u}}{u_*} = \frac{1}{k} \log_e \frac{y}{y_o}$$

Then,

$$A \, \frac{\bar{u}}{\sqrt{\overline{u^2}}} = \frac{1}{k} \log_e \frac{y}{y_o}$$

$$B \, \frac{\bar{u}}{\sqrt{\overline{w^2}}} = \frac{1}{k} \log_e \frac{y}{y_o}$$

and

$$C \, \frac{\bar{u}}{\sqrt{\overline{v^2}}} = \frac{1}{k} \log_e \frac{y}{y_o}$$

Hence the turbulence intensity can be determined as a function of the roughness length for adiabatic conditions provided that the semi-empirical constants A, B and C can be determined . It can be assumed that the above expressions apply only in the lower layer of the flow i.e. say ,

$$0 \leqslant y \leqslant 50\text{m}.$$

They will clearly not apply at heights greater than 0.4 or 0.5 of the boundary layer height where flat-plate data show that the turbulence tends to become isotropic . This is also convenient since it can be seen that the majority of the turbulence measurements have been made at heights less than 50m. (165 ft.) and even more recent measurements rarely include greater heights . Therefore the proposal for the final analysis is to define both quantities as a function of the roughness length i.e.

$$\underline{1/\alpha \sim y_o}$$

and,

$$\underline{\left(\sqrt{\overline{u^2}}/\bar{u}\right)_{y=30m} \sim y_o}$$

for the range of terrains (1 to 4) specified above . The relevant anticipated range of roughness lengths should be,

$$\underline{0.001m \leq y_o \leq 10m.}$$

or neglecting the smooth surfaces , which are not of great importance ,

$$\underline{0.01m \leq y_o \leq 10m.}$$

From flat-plate data the form of the variation of turbulence intensity with height can be predicted and the ratio of the turbulence components to each other can be deduced or derived empirically from the constants A, B and C . It is assumed that the expressions containing these constants will also apply to the

rougher suburban and urban terrains . Therefore , provided that sufficient data can be aquired , the mean and fluctuating quantities of a boundary layer should be definable , on the above basis , if say , one quantity is known for any particular site .

Similarly it should be possible to present the Reynolds stresses as a function of any of the above quantities at some reference height .

It can also be deduced that the form of presentation of the power spectral densities is dependent on the derivation , from measured data , of semi-empirical constants in the case of all three fluctuating components . Perhaps the most important point to date regarding the spectra is the suggestion that the power spectral shapes are independent of roughness ; hence their variation with height need only be considered .

The remaining quantity of importance that needs to be defined more accurately is the length scale of the turbulence, as a function of both height and roughness length . The form of presentation to be adopted will beamore refined version of that given by Webb (1955) , i.e.

$$\log L/\delta \sim \log y/\delta$$

Neglecting atmospheric equilibrium effects , it is clear that some of the scatter of the results to date is due to the variations of the length scale with roughness length . Hence

the boundaries illustrating the various roughness ranges will be included in the above type of presentation , dependent on the availability of sufficient data . It is also suggested that the laws governing the variation of the length scale with height may vary for the following height ranges (assume intermittency to occur at $y \leq 0.5\delta$) ,

(a) $0 \leq y \leq 50m.$ surface layer

(b) $50m \leq y \leq 0.4\delta$ intermediate layer

(c) $0.4\delta \leq y \leq \delta$ intermittency layer

However it can be assumed that at some height the roughness effects will be reduced such that one law may be sufficient for say layer (b) i.e. the effects of roughness on length scale may be negligible in this height range .

With the above form of presentation , the more important boundary layer characteristics of a site could be defined from a knowledge of say the roughness length of that particular site .

As stated previously , since the previous text has provided an adequate backround to the foundations of boundary layer meteorology , it is intended to present the data of the 1960 to 1972 period mainly in tabular form , Appendix 2 . When relevant , comments , either on the accuracy , applicability or originality of the data , will be made in the following brief form :-

(a) Author(s)

(b) Date

(c) data

(d) Comments

This form of presentation is also clearly necessary if the relevant data from the extensive amount of literature from this period is to be considered .

2.6. Review of data from the period 1960 - 1972 .

The main data from , and developments in , this period are extensively tabulated and commented on in Appendix 2 . The following text mainly emphasises the more important points and data relevant to this period .

2.6.1. The flow structure .

The amount of data obtained from this period concerning the detailed structure of the atmospheric boundary layer flow is not very great and as a result a complete final picture does not emerge .

It was concluded in the analysis of the previous period that eddy length scales increased with increase of distance from the ground . In this context Blackadar (1962) assumed that they increased in proportion to $k \times y$ close to the ground and approached fixed values higher up in the boundary layer (i.e. for $y > 200 - 300$ m.) . Faller (1965) suggested that the large eddies in adiabatic flows resulted from shear instabilities in the main flow (Cf. Durst 1932) and that they moved relatively slowly in the mean flow , having vertical velocities of the order of $0.10\ \bar{U}_{max}$. It was also shown (Panofsky and Singer 1965) that the upper parts of the boundary layer eddies were downwind of the lower parts , due to the vertical wind shear , and had slopes of the order of one .

Again , as in the previous periods considered , some important points concerning boundary layer structure have come from work on flat-plate boundary layers . For example , Kline et al (1967) showed the presence of secondary vorticity (i.e. the large eddies proposed by Townsend 1957) in the lower part of the boundary layer . It was suggested that the action of these on the spanwise vorticity formed wall streaks . The resultant ejection of fluid from the wall region was considered to be the main mechanism for turbulent transfer between the inner and outer layers (Cf. Schmidt 1935) . They also showed that intermittency occurred in boundary layer turbulence for $y/\delta > 0.40$ (Cf. Corrsin , Kistler 1954) , in which case the turbulence scales could be expected to decrease above this height. In contrast to this the work of Tritton (1967) did not verify the existence in the boundary layer of the large eddy structure proposed by Townsend . It was suggested that the separate descriptions of large eddies for inner and outer layers may be inappropriate . Bradshaw (1968) suggested that the large eddies are in fact of the same order of magnitude as the boundary layer thickness . He agreed with Faller (1965) concerning the origin of the large eddies and that they consisted of a slow rotational drift of fluid having $\bar{U} \leq 0.1 \bar{U}_{max.}$

Panofsky (1969) pointed out that the boundary layer flow over the sea produced very large longitudinal eddies near the ground and suggested that over rough ground such eddies are likely to be broken up ; this point will be considered in more detail in SECTION 2.6.8.

It can be seen from the above that very little information was obtained on details of the boundary layer flow structure . Generally the main points that have emerged , or been verified , are that large scale motions exist in the boundary layer (i.e. the existence of large eddies) whose orientation is a function of the shear in the mean flow and whose degree of rotation is relatively slow . The extent of the effects of surface roughness on these eddies is noted and will be discussed in SECTION 2.6.8.

2.6.2. The mean velocity profile and the boundary layer height .

Assessment of the data from the period 1880 - 1959 has shown the validity and relevance of applying either the log-law or power law to describe the variation of the mean velocity with height in the atmospheric boundary layer . It has been shown that attempts to derive a power law index from mean velocity measurements below a height of say 20 - 30m. (66 - 100 ft.) clearly results in over estimates of this index ; this is also adequately illustrated in the data of APPENDIX 2 . It was decided in SECTION 2.4.2. to use the power law , in this work , in defining the mean velocity profiles of the boundary layer . Therefore the review of the relevant data from the 1960 - 1972 period has consisted mainly of classifying and re-analysing existing data in order to obtain the power indices for various types of terrain from various sources ; in particular the urban data are of most interest .

With regard to the boundary layer height , some additional data are included in APPENDIX 2 and in particular the height adopted for the constant shear stress layer is modified by more recent data .

As can be seen from APPENDIX 2 a considerable amount of data on the power indices for various types of terrain was derived from the period 1960 - 1972 . With regard to suburban and urban areas Davenport (1961b , 1964 and 1967) in particular has specified indices of the order of 0.28 and 0.40 respectively for these areas ; the most recent data suggests 0.36 for an urban area . However Shellard (1963) suggested that these high indices were neither realistic nor representative of urban areas . The most recent data (ESDU 1972) again suggested 0.35 as being representative of an urban area . In contrast , it can be seen from APPENDIX 2 that the majority of the urban data available and assessed here suggests farily conclusively that $\frac{1}{2}$ for a typical urban area should be of the order 0.28 - 0.30 . This would suggest that appropriate power indices for the various terrain types can only be determined by considering all of the available data , which has been the object of this review . An index of value 0.28 has been suggested for suburban areas , however the data presented here suggests a value of the order 0.21 - 0.23 .

With reference to the boundary layer height it was seen in SECTION 2.4.2. that for rural terrain a boundary layer height of the order of 600m.(2000 ft.) was considered to be reasonably

reliable . However Davenport (1961b) suggested that this height was a function of terrain type and proposed , e.g. a value of 274 m. (900 ft.) for rural terrain . Although no reference was quoted for the values proposed they appear to be very similar to those quoted by Pagon (1935) ; these values , being based on doubtful theoretical assumptions , are not reliable . In any case , the value of 274 m (900 ft.) suggested for a rural boundary layer is not supported by any previous meteorological data . In the same context Blackadar (1962) suggested that the boundary layer height was affected very little by changes in terrain roughness and this was further supported by Shellard (1963) who assumed a mean boundary layer height of 500m (1650 ft.) In addition , Shellard's (1967) data showed that the height of rural terrain boundary layers must,at least , be in excess of 300 - 400 m.(1000 - 1300 ft.) Hanna(1969) reviewed the many methods available of estimating the boundary layer height for various atmospheric equilibrium conditions . For adiabatic conditions he generally found the boundary layer height to be of the order 500 - 700 m. (1650 - 2300 ft.) . Theoretical estimates from the data of Smith (1970) gave heights of the order of 800m. (2600 ft.) . Finally , Pasquill (1972) suggested that the mechan--ical production of energy tended to approach zero at a height of 600m. (2000 ft.) and therefore , for adiabatic conditions , it seems reasonable to assume that his height should coincide with the top of the boundary layer .

The 1880 - 1959 data has shown that generally the constant stress layer was assumed to be of the order of 10 - 50m. (33 -165ft.) high . However , Byzova (1963) suggested a height of the order 75 m. (250 ft.) and Soma (1964) a height of at least 200m.(660ft.) for an urban area i.e. the log-law can be expected to apply over a greater height range for urban areas and hence it could be more difficult to establish a representative power law for such terrain . The above findings were further supported by Yamamoto and Shiotani (1964) and by Lappe (1965) who suggested that the log-law could be applied up to a height of about 140m.(460 ft.) and was also more applicable as the terrain roughness increased. Constant stress layer heights of the order of 100m. (330ft.) were also suggested by Deland and Binkowski (1966) , Estoque (1967) and Panofsky (1969) . By assuming the constant stress layer to apply up to heights of the order of 200m.(660 ft.) Blackadar and Chaplin (1967) produced a modified version of the log-law which effectively linearised $\log y \sim \bar{u}$ data outside the true constant shear stress layer ; the practical use of this theory is considered to be doubtful in some applications . It was also suggested by Davenport (1967) that theoretical approaches towards defining the mean velocity profile of the boundarylayer must be considered to be suspect because of the assumptions involved in their development . Finally , and more recently , Panofsky and Petersen (1972) suggested that the log layer could be assumed to have a height of the order of 100m. (330 ft.)

It can generally be concluded that sufficient data has now been tabulated in order to define the true variation of with terrain type . There is also sufficient justification for adoption of a value of 600m. 2000 ft.) as the mean value of rural and urban boundary layer heights . In addition , the height of the constant stress layer can be taken as 100m (330 ft.) and will be in excess of this for flow over urban terrain .

2.6.3. The roughness length .

The range of roughness lengths covering flat to rural types of terrain was generally established from the data of the 1880 - 1959 period . In the same period however , comparatively little data was available for suburban or urban areas and what there was , was inconclusive . In the period considered here a great deal of data was available (APPENDIX 2) on these terrain types from which they could be defined adequately .

Some of the more interesting points are noted in the following text with reference to the roughness length data in general . Panofsky et al (1960) derived some estimate of the variation of the roughness length with $1/\alpha$, which are considered in a later section , and Jensen (1961) classified the roughness length (y_o) and the displacement thickness (d) as a function of vegitation height . In the case of forests Rauner (1961) proved that y_o was a function of wind speed ; the change

of roughness can be attributed to the fact that at higher speeds the wind penetrates through the trees more . He also determined the relative roughness lengths of a forest with and without foliage . A further estimate of y_o as a function of terrain type was suggested by Davenport (1963) .

The work of Oliphant and Panofsky (1965) illustrated a point of interest when determining the roughness length of the Brookhaven site . Their data showed how two separate estimates of y_o could be made from the same site measurements . It can be assumed that one estimate was appropriate to the local flat ground and the second one to the trees just upstream ; data from both estimates were used to obtain a mean site roughness length. Barry (1966) indicated that it was possible to obtain wide variations in the value of y_o estimated for sites . The data he assessed however was taken over a very restricted height range and hence his conclusions are not taken to be completely reliable. It is also considered that large errors are possible in the estimates of y_o made by using the modified log--law proposed on a theoretical basis by Blackadar and Chaplin (1967) ; this is pointed out later when considering Harris (1972) and ESDU(1972).

When there are variations in the local terrain it is clearly essential that y_o should be defined as a function of wind direction , see e.g. Fichtl (1968a) who analysed such data for the Kennedy Space Centre . With regard to urban areas , Munn (1968) drew attention to the problem of determining realistic roughness lengths and pointed out the importance of choosing

measuring sites which were not influenced by local effects . It was also generally confirmed from data of this period that the roughness length was reasonably independent of atmospheric equilibrium e.g. Blackadar et al (1969) .

Lettau (1969) showed how the roughness length was a function of the density distribution of roughness elements and this point was treated in some detail by Wooding et al (1969) ; however the effect of fetch was not considered . Both of these quantities are considered to be of importance in the definition of suburban or urban areas . Helliwell (1970) presented further data on the variation of y_o with terrain type ; in this case the urban y_o of 0.78 seems particularly low and is considered to be more appropriate for a suburban area . The data of Harris (1972) and ESDU(1972) quote very low roughness lengths for the terrain types they define (see APPENDIX2) and this is considered to be due to the use of the modified log-law derived by Blackadar and Chaplin (1967) .

Finally , the particular points that can be made based on the extensive data of this period are that the roughness lengths for suburban and urban areas are of the order 1 m. (3.3 ft.) and 2 - 3 m. (6.6 ~ 10 ft.) respectively . Clearly , there is also now available an adequate amount of data from which to specify the roughness lengths of all the terrain types specified in FIG. 37 .

2.6.4. The Reynolds Stresses .

Assessment of the data from the 1880 - 1959 period showed very generally the probable range of Reynolds stresses for rural terrain . However , very little data was available for suburban and urban areas . There was also a considerable amount of scatter in the measurements assessed .

The same comments can be applied to the Reynolds stresses obtained from the 1960 - 1972 period with the addition that the scatter in the data apparently increases as the roughness length increases . This seems plausible since larger roughness elements would be expected to produce greater variations , locally , from a mean value of the Reynolds Stress .

The more relevant points from the data of this period are as follows . For rural terrain the Reynolds stress range can be defined more accurately as :-

$$0.0020 \leq \frac{\overline{u'v'}}{\bar{U}^2_{MAX.}} \leq 0.0025$$

and for sea as :-

$$0.0003 \leq \frac{\overline{u'v'}}{\bar{U}^2_{MAX}} \leq 0.0006$$

[$\bar{U}_{MAX}$ is assumed to occur at $y = \delta$ =600m.(2000 ft.)]

For rougher terrain , the data of Davenport (1964) normalised with respect to the free stream velocity indicated that $\overline{u'v'}/\bar{U}_{max}$ decreased with increase of rough--ness length in the range appropriate to urban terrain ; however no reason can be suggested as to why it should decrease . For roughness lengths of the order of 1m. the available data show that $\overline{u'v'}/\bar{U}_{max.}$ is still increasing . Soma (1964) showed that for an urban area the constant stress layer extends to a height of about 200 m. (660 ft.) .

Pasquill (1970) showed from accumulated data on the Reynolds stress that it increased with increase of roughness length up to at least 1m. (3.3 ft.) . He also showed that the variation of the Reynolds stress with roughness length was not very sensitive to variations in $\bar{U}_{max}$. From Pasquill (1970) , by extrapolation , and Smith (1970) the ratio of urban to rural stresses can be determined as :-

1.46 to 1.56

(for y_o 's of 2.5m.(7.5 ft.) and 0.10m. (0.33 ft.) respectively)

On the above basis it was assumed that the existing data could be extrapolated justifiably to roughness lengths representative of urban areas .

2.6.5. The intensity of turbulence .

The general range of turbulence intensities at heights of the order 20 - 30 m. (66 - 100 ft.) , for both rural and urban terrains , were generally established from the review of the 1880 - 1959 period . These data were considerably added to from the literature reviewed in the 1960 - 1972 period (APP. 2) and generally confirmed the values of the turbulence intensity , at the reference height chosen , for the various types of terrain previously defined . In addition , some points of further interest were established as follows .

It had been shown , to some extent , in the previous period that the variations of the turbulence intensities with height were comparable to those of flat-plate boundary layers ; the atmospheric data however was available only for restricted height ranges. The above was additionally verified by the work of Swanson and Cramer (1965) where both the longitudinal and lateral intensities of turbulence were shown to decrease with increase of height for all thermal stratifications . Pritchard (1966) showed that $\sqrt{\overline{v^2}}/u$ was approximately constant with increase of height up to about 370m. (1200 ft.) and assumed the turbulence to be approximately isotropic at this height and above . The turbulence was assumed to be isotropic above a height of 200m. (660 ft.) by Moore (1967) who also showed that $\sqrt{\overline{v^2}}$ decreased with increase of height up to about 300m. (1000 ft.) . The data of Harris (1972) also showed that $\sqrt{\overline{u^2}}$ was not invarient with height in the height range considered .

The use of the empirically derived expressions :-

$$\frac{\sqrt{\overline{u^2}}}{u_*} = A \quad , \quad \frac{\sqrt{\overline{w^2}}}{u_*} = B, \quad \frac{\sqrt{\overline{v^2}}}{u_*} = C$$

with the log-law for the velocity profile law , was extensive in order to obtain estimates of the turbulence intensity . Such estimates were shown to be reasonably reliable where sufficient information was available so that the estimates could be compared with measured data ; these data were mainly available for flat to rural terrain types (APP.2) . In addition Lumley and Panofsky (1964) suggested that such estimates were accurate to at least 20% . Concerning the values of the constants A, B, and C in the above expressions , Lumley and Panofsky (1964) suggested that they should be independent of height but may be dependent on terrain type . It is assumed here that the independence with height can only apply in the constant shear stress layer where it can also be assumed that $\sqrt{\overline{u^2}}$ etc. are also reasonably invariant with height . The dependence of 'A' on terrain type or roughness length , was shown to some extent by the work of Zubkovski and KravchenkO (1967) who showed a decrease of 'A' as y_o increased . Therefore at "high" roughness lengths the above expressions can be expected to over estimate the turbulence intensities . Panofsky (1969) again pointed out that 'A' and 'B' showed systematic variations from site to site which suggested that large roughness affected their behaviour . Teunisson (1970) estimated the variation of the turbulence intensities through the total boundary layer depth using these

expressions . However , as indicated above , they can only be considered to apply in the constant stress or log-layer of the boundary layer .

The values of 'A' , 'B' and 'C' have been assessed from the reviewed data to be,

$$\frac{\sqrt{\overline{u^2}}}{u_*} = 2.5 \; : \; \frac{\sqrt{\overline{w^2}}}{u_*} = 1.875 \; : \; \frac{\sqrt{\overline{v^2}}}{u_*} = 1.25$$

from which :-

$$\frac{\sqrt{\overline{w^2}}}{\sqrt{\overline{u^2}}} = 0.75 \; , \; \frac{\sqrt{\overline{v^2}}}{\sqrt{\overline{u^2}}} = 0.50$$

which values are also substantiated by the data reviewed .

2.6.6. The power spectral densities .

The basic expressions defining the power spectral density shapes of the longitudinal and vertical fluctuating velocities were established in the 1880 - 1959 period by Von Karman and Panofsky respectively . Generally , the limited amount of data available showed that the spectral shapes were not significantly altered by change of terrain roughness . There was a considerable increase in the measurements of power spectral densities and their analysis in the 1960 - 1972 period ; the more interesting points from these data (APP.2) are noted in the following text .

The work of Davenport 1961(a), (b) lead to a revised expression for the longitudinal spectrum :-

$$\frac{n S_u(n)}{} \propto \frac{\bar{x}^2}{(1+\bar{x}^2)^{4/3}} \quad , \quad \left(\bar{x} = \frac{n\ell}{\bar{u}_{10}} \quad , \quad \ell = 1200m\right)$$

from which can be derived,

$$\frac{\sqrt{\bar{u}^2}}{\bar{u}} = 2.45 \left(u_*/\bar{u}_1\right)\left(y/y_1\right)^{-1/2}$$

This form of the spectrum however under-estimates the energy in the low frequency range and therefore does not agree completely with full-scale spectral measurements . The invariance of the spectrum with height was also assumed here . The applicability of the Kolmogoroff -5/3 law in the inertial subrange was adequate--ly demonstrated by Pond (1966) from measurements over the sea ; it was shown to apply down to $n/\bar{u}$ of about 0.0025 . In general the various power spectral measurements showed that this law was applicable down to much lower frequencies than expected. Further data presented by Davenport (1967) established that the spectra measured over rural and urban terrain were basically similar . From measurements over flat terrain Elderkin (1967) determined that the -5/3 law applied down to $n/\bar{u}$ of about 0.009 . Therefore this and other data suggested that the range of frequencies over which this law applied was a function of terrain roughness . This seems plausible , since for increase of the roughness length some re-distribution of energy can be expected to occur . Singer et al (1967) established the invariance of the longitudinal spectrum with height i.e. the fact that the

peak value of $n_y/\bar{u}$ is independent of height . Spectral measurements over the sea by Busch and Panofsky (1968) showed the presence of more low frequency energy than for similar measurements over land ; this was given some support by the data of Shiotani (1968). Another form for the longitudinal spectrum was proposed by Harris (1968) :-

$$\frac{S_u(n)}{} \propto \frac{\bar{x}}{(2+\bar{x}^2)^{5/6}} \quad , \quad \left(\bar{x} = \frac{n\ell}{\bar{u}_{10}} \, , \; \ell = 1800m\right)$$

This is basically the shape proposed by Von Karman (1948) . Another form for this spectrum was given by Fichtl and McVehil (1969) as follows :-

$$\frac{n S_u(n)}{u_*^2} = \frac{2}{\pi} \cdot \frac{\bar{u}^2}{u_*^2} \cdot \frac{2\pi f L/y}{(2\pi f L/y)^2 + 1}$$

However , it was suggested by Panofsky (1969) that , due to the wide variation in spectral shapes , the application of any empirical spectral form to a particular site could only be approximate . Pasquill (1970) recommeded the use of a more simple spectrum expression which applies mainly to the inertial sub-range and for $y \leq 100m.$ (330 ft.) :-

$$\frac{n S_u(n)}{u_*^2} = 0.26\left(\frac{ny}{\bar{u}}\right)^{-2/3}$$

He suggested that at low frequencies the power spectral densities are too variable to define accurately ; a possible explanation for this variability was given by Owen (1971) . However , in

practice , the Von Karman or Harris spectrum is the form more often referred to and applied .

There are fewer data available on the power spectral densities of the lateral velocity . Elderkin (1967) showed that the -5/3 law applied to some extent in the inertial sub - range and Singer et al (1967) showed that the lateral spectrum was intermediate between those of the longitudinal and vertical velocities . The latter point was also adequately shown by the data of Fichtl and McVehil (1969) . Panofsky (1969) suggested that these spectra should be invarient with height as were the longitudinal spectra .

In the case of the power spectral density of the vertical velocity , the form proposed by Panofsky and McCormick (1960) was basically similar to that proposed by Deland and Panofsky (1957) which showed that h this spectrum is height dependent . At other stages in this period (1960 - 1972) various other spectral forms were proposed , mainly by authors concerned with the analysis of vertical gust loads on aircraft e.g. Zbrozek (1961) and Lappe (1965) . Elderkin (1967) established the peak value of n_y/σ to be of the order 0.40 (or peak n/σ in the range 0.06 - 0.13) as compared to 0.03 for longitudinal spectra . This implies that the majority of the energy , in the case of the vertical spectra , is at higher frequencies .Kaimel and Haugen (1967) established that peak n_y/σ values lie in the range 0.15 - 0.35 ; they also showed the spectra to be height

dependent i.e. the peak frequency decreased as distance from the ground increased . This implies that as the effect of the ground proximity decreases the vertical extent of the eddies can increase. Alternatively , if the data are presented as a function of $f = (ny/\bar{u})$ then f will increase with increase of height . Eventually Busch and Panofsky (1968) presented a slightly modified version of Panofsky's previous spectrum form :-

$$\frac{n S_w(n)}{u_*^2} = \frac{1.075\, f/f_m}{1 + 1.5\,(f/f_m)^{5/3}}$$

where for adiabatic conditions fm = 0.32 . This is the vertical spectrum form most commonly referred to in the literature .

Finally , the most recent spectral data for longitudinal, lateral and vertical spectra was presented by Kaimel and Haugen 1972 . From their paper it can be seen that the proposed spectral forms agree reasonably well with the full-scale data considered . These expressions having appeared only lately in the literature have not been completely assessed but are , however referred to here for completeness of the survey .

2.6.7. The cospectrum of the Reynolds stresses .

Comparatively little information was derived from the 1880 - 1959 period on the properties or form of this cospectrum. The 1960 - 1972 period however produced enough data from which it could be adequately defined , at least over a restricted height range .

The first relevant data from this period were presented by Monin (1962) who confirmed Deacon (1955) that the majority of the stress contribution lay in the range :-

$$0.10 \leq f \leq 1.0$$

and this was again further verified by Elderkin (1968) . The majority of the available data for heights less than about 50m (165 ft.) were analysed by Panofsky and Mares (1968). They derived an expression for the cospectral shape as follows:-

$$\frac{n S_{uv}(n)}{u_*^2} = \frac{f/f_m}{(1 + 0.6\, f/f_m)^{7/3}}$$

where fm (peak $ny/\bar{u}$) was taken as - 0.08 for adiabatic conditions . This quantity however is subject to a large degree of scatter and lies in the range :-

$$-0.05 \leq f_m \leq -0.12 \qquad \text{(at least)}$$

Their data also suggested that the majority of the stress contribution is in the range :-

$$0.01 \leq f \leq 1.0$$

The more recent data of Miyake et al (1970) and Sitaraman (1970) showed that the cospectral slopes at the high frequencies generally followed Kolmogoroff's - 5/3 law and the shapes were consistent with the form proposed by Panofsky and Mares . This is the cospectral form more generally used although its

applicability for heights greater than about 50m.(165 ft.) has yet to be verified .

The more recent data of Kaimel and Haugen (1972) suggested the following cospectral form :-

$$\frac{n S_{uv}(n)}{u_*^2} = \frac{14f}{(1+9.6f)^{2.4}}$$

however , as in the case of their recently proposed spectral forms , the above has yet to be verified in practice .

2.6.8. The length scales of turbulence .

The data on the length scales of turbulence from the 1880 - 1959 period were mainly very generalised data although Webb (1955) managed to derive :-

$$L_{ux} \propto y^{0.5}$$

It was also suggested that,

$$L_{ux} > L_{uy} > L_{uz}$$

The length scale data from the 1960 - 1972 period were fairly extensive (see APP.2) and the main points from these data are presented in the following text .

The majority of the data avilable were concerned with the length scale Lu_x and Pasquill (1961) showed that these could be

derived from spectral measurements since :-

$$L_{ux} = \frac{1}{2\pi}\left(\bar{u}/n\right)_{PEAK.}$$

(or see Pasquill and Butler 1964)

This form is acceptable for correlation curves having an exponential form and in practise this is found to be the case more often than not . The main difficulty can be in defining the spectral peak . However , checking estimates by use of the above expression against length scales derived from auto - or space correlation data has shown its validity . From available data Pasqill also deduced :-

$$L_{ux} \propto y^{n}$$

Blackadar (1962) assumed that L_{ux} increased with increase of height up to about 200 - 300m.(660 - 1000 ft.) and that it was of the order of 100m. (330 ft.) at greater heights . A review paper by Singer (1964) suggested that the length scale in the vertical direction was given by :-

$$L_{uy} \simeq 0.5\, L_{ux}$$

From the data of Berman (1965) it can be shown fairly conclusively that L_{ux} decreases as the roughness length increases . This fact is also shown in other data of APP.2 . Berman also showed that :-

$$L_{ux} \propto y^{0.29}$$

whereas Panofsky and Singer (1965) gave :-

$$L_{ux} \propto y^{0.66}$$

In agreement with Pasquill (1961) , Zbrozek (1965) assumed that:-

$$L_{ux} \propto y$$

and suggested that it increased with increase of height up to about 300m. (1000 ft.) . From fairly generalised data Pritchard (1966) assumed that :-

$$L_{ux}/L_{vx} = L_{wx}/L_{vx} = 1.3$$

He also assumed that these length scales were functions only of height and thermal stratification , but pointed out that other authors had assumed that greater roughness produced greater length scales . Close to the ground it can be assumed that the variation of L_{ux} with height cannot be expected to follow any of the above laws ; in this context Smith (1967) showed that it decreased very rapidly near the ground . Additional reliable data concerning the variation of L_{ux} with surface roughness can be deduced from Busch and Panofsky (1968) and yet another law concerning its variation with height was given by Fichtl (1968) as :-

$$L_{ux} \propto y^{0.2}$$

The work of Fichtl and McVehil (1969) suggested that L_{ux} decreased at heights greater than 100m. (330 ft.) and again showed the validity of estimating L_{ux} from :-

$$L_{ux} = \frac{1}{2\pi}\left(\frac{\bar{u}}{n}\right)_{PEAK.}$$

The review paper of Teunisson (1970) stated that change of roughness length had little effect on L_{ux} but that "large scale non-uniformities " of the Earth's surface tended to increase them . He concluded that for heights greater than about 300m. (1000 ft.) the length scales were independent of terrain type . No reason was given for the wide scatter of the data below this height . Again , in contrast to the above , the flat-plate data of Antonia and Luxton (1971) showed conclusively that increased roughness resulted in reduced length scales . The recent work of Colmer (1971) produced another law associating the length scale and height :-

$$L_{ux} \propto y^{0.69}$$

The semi - empirical theory of Harris (1971) predicted L_{ux} increasing as roughness increased (APP.7) and increasing in--definitely as height increased ; neither of these deductions agrees with the measured data . Harris also assumed from homogenous isotropic turbulence theory that :-

$$L_{uy} = L_{uz} = 0.5\,L_{ux}$$

However the available data (see e.g. Shiotani 1967 , Deacon '71) shows that more appropriately :-

$$L_{uy} \simeq 0.5 \sim 0.6\, L_{ux}$$

and,

$$L_{uz} \simeq 0.3 \sim 0.4\, L_{ux}$$

It can be generally conluded , with respect to the length scale L_{ux} , that it increases with height up to about 200 - 300 m. (660 - 1000 ft.) and decreases with increasing roughness length . Hence the law governing its variation with height will depend on the terrain roughness .

Some data were also available from this period concerning the variation of the length scale , L_{vx} , as a function of height . One of the first assessments of this quantity was contained in Pasquill (1961) who , from data from various sites, derived :-

$$L_{vx} \simeq 0.5y$$

Lumley and Panofsky suggested L_{vx} increased with height up to 100 - 200 m. (330 - 660 ft.) and then remained constant with further increase of height . This generally agreed with Pritchard (1966) who gave L_{vx} as increasing up to a height of about 120m. (390 ft.) and then remaining constant up to a height of about 370m. (1200 ft.) . The above again agreed with the data

of Kaimal and Haugen (1967) who suggested that L_{u_x} should either remain constant or start to decrease with increase of height above 200m. (660 ft.) . For the height range 0 - 50 m. (0 - 165 ft.) Singer et al (1967) suggested that L_{u_x} increased linearly with height and that at greater heights it increased more slowly . This result was adequately supported by the data of Panofsky (1969) . Finally a general review by Teunisson (1970) gave :-

$$L_{u_x} \simeq 0 \cdot 40 y$$

which was confirmed by the data of Warner (1972) .

The trends from the assessment of these data suggest that these scales may not be excessively affected by changes of terrain roughness and that the variation with height can be taken as :-

$$L_{u_x} \propto y$$

2.6.9. The probability density distribution of the fluctuating velocities .

The data from the previous period , 1880 - 1959 , generally indicated that probability density measurements in the range $\pm 3\sigma$ were normal in form ; outside this range there remained some doubt as to the form of the distributions .

The data from the 1960 - 1972 period did not add considerably to the above . The theoretical work of Novikov and Stewart (1964) suggested that the probability distributions may vary from the normal form , but no data were given in support of this . However the measurements of Singer (1964) confirmed that the distributions were normal , as did those of Davenport (1967) . Finally Blackadar et al (1969) proposed normal distributions for measurements in the range of $\pm 3\sigma$; for greater σ they suggested that there was a greater tendency for a higher proportion of larger gusts than indicated by the normal probability density curves .

Hence the data of this period merely confirms the conclusions made from data of the previous period (i.e. 1880 - 1959) .

3. Presentation and discussion of Adiabatic boundary layer structure .

The reviewed data has given a general backround to the Adiabatic boundary layers of the atmosphere . The completed review shows quite clearly that there is an adequate amount of information available from which the particular characteristics of these boundary layers can now be established . It will be made clear from the analysis that it was essential to consider all of the available data in order to eliminate , as much as possible , the effects of the various sources of error that necessarily occur in many of the atmospheric measurements . By this means the correct trend of the data as a function of terrain type can be established . The quantity which is representative of the terrain types is taken as the roughness length . This quantity can readily be derived from available data or easily measured on site .

It is suggested that the examination or assessment of just a limited amount of selected data can lead to large errors in the prediction of the flow structures over various types of terrain. Therefore the data presented in this analysis represents , as far as possible , all of the available measurements correlated in the following manner :-

1. $\frac{1}{\alpha} \sim y_o$
2. $(\sqrt{\bar{u}^2}/\bar{u})_{30} \sim y_o$
3. $\overline{u'v'}/\bar{U}_o^2 \sim y_o$
4. $L_{ux} \sim y_o - y$

As stated overleaf , data of this type , are subject to numerous sources of error ; the more important of these are noted as follows :-

(a) Inaccuracy due to instrument response or inertia ; this would apply mostly to say pre - 1940 data .

(b) Insufficient and / or variations in the averaging times used in obtaining the data .

(c) Thermal stratification not measured ; i.e. the possibil--ity of conditions other than adiabatic prevailing or changing during a test or varying with height .

(d) Variation of mean wind direction with time during averaging period .

(e) Measurements at low heights influenced by local effects, topographical or otherwise .

(f) Insufficient fetch for equilibrium flow to be established.

Data given in some literature can also have errors arising from :-

(g) Non - allowance for zero-plane displacements .

(h) Over-estimates of the value of $\frac{1}{2}$ from measurements in the log - layer .

(i) Roughness lengths estimated from insufficient or inaccurate data .

Many examples have been quoted in the reviewed data of errors arising from these various sources ; clearly data quoted specifically for unstable or stable conditions have not been

considered here . However it is noted , that in practise , exact Adiabatic conditions , prevailing through the full boundary layer height , may not be attained completely very often .

3.1. Analysis of the $\frac{1}{\alpha} \sim y_o$ data .

All of the known available data for these quantities are presented in Figure 63 . The roughness length scale has been divided into ranges appropriate to the terrain types defined in Figure 37 . When the actual velocity measurements were available for any particular site , they were all analysed in the same way to obtain the mean power law indices ($\frac{1}{\alpha}$) as follows .Power indices were estimated from the ratios of all the pairs of velocity measurements at their respective heights and from these a mean site power index was derived . In cases where some of the measurements were made in the log - layer this method of analysis reduced , to some extent , the amount by which the indices were over - estimated . Therefore the resultant data were assumed to be more representative of the sites . However for some of the data it can be assumed that some degree of over - estimation can--not be completely avoided .

It can be seen from Figure 63 that the degree of scatter is such that incorrect trends can easily be derived if insufficient data is considered . The amount of scatter also tends to increase with increase of the roughness length . This is to be expected since these data , in addition to being subject to errors from some over-estimates of $\frac{1}{\alpha}$, will be more subject to errors

due to insufficient fetch being available , say in urban or sub-urban areas , for equilibrium flow to be established . For these reasons a regression analysis has not been applied to the data of Figure 63 .

The proposed variation of $\frac{1}{2}\sim y_o$ shown in Figure 63 is not a mean curve through the data but has been offset downwards to some extent . The degree of off - set was based gener--ally on those data from Appendix 2 which were considered to be the most accurate and reliable . These data were taken as key points through which the proposed curve was mainly constructed . A similar form of analysis was used in deriving the curves of Figures 64 to 66 . Clearly an analysis of this form can be considered to be subjective to some extent ; however it can be assumed , that , because of the large amount of data considered here , this effect will be minimal . Hence the curve proposed in Figure 63 for the variation of $\frac{1}{2}$ as a function of y_o is considered to be the most representative of all the available data . The dotted lines which enclose this curve are suggested as possible upper and lower scatter bands for the data . Data outside these lines can generally be considered as unreliable .

Proposals , from other sources , for the variation of $\frac{1}{2}$ with y_o can now be considered and these are also shown plotted in Figure 63 . It can be seen that the proposed curve falls between the two more recent curves , i.e. those given by Helliwell (1970) and ESDU (1972) , for terrain types 1 and 2 and

some of type 3 . Generally the ESDU curve falls near the upper scatter band limit and like the remaining curves over estimates the power indices relative to the curve proposed here . For $y_o > 0.10$m. the curves generally lie outside the upper scatter band of the data .

Therefore considering the above points also , the variation of the power index with roughness length proposed here is considered to be the most representative of all the data now available.

3.2. Analysis of the $(\sqrt{\overline{u'^2}}/\bar{u})_{30m} \sim y_o$ data .

All of the available data on these measurements are presented in Figure 64 . The reference height of 30m. (100ft.) was chosen on the basis that measurements made at this height should be free from very local influences but still be representative of the local terrain . The height of 10m. (33 ft.) sometimes adopted in the literature is considered to be too low . For some extemely rough conditions a height of 30m. (100 ft.) may still be too low ; however it is assumed that most of such cases would be outside the range of interest , in which case the above height is a reasonable compromise .

The scatter of these data is considerably less than that of the mean velocity measurements ; hence measurement of this quantity at a site may prove to be the best quantity to obtain in order that the other site characteristics may be deduced .

The important point to be noted here is the similarity between the proposed curves for the variation of the mean velocity and turbulence intensity as a function of the roughness length i.e. those two quantities are directly related from the data plotted . Therefore if $1/\alpha$ is known , then the turbulence intensity at the reference height is also known .

The estimated variation of turbulence intensity as a function of roughness length is also shown in Figure 64 . This was derived from :-

$$\frac{\sqrt{\overline{u^2}}}{\bar{u}} = \frac{1}{\log_e y/y_o}$$

and it can be seen that this estimate over estimates the turbulence intensity for $y_o >$ 0.10 m. (.33 ft.) ; this point was emphasised in the review of the previous section . The above expression was derived on the basis that :-

$$\frac{\sqrt{\overline{u^2}}}{u_*} = 2.5$$

and therefore the data of Figure 64 verify the fact that this "constant" should be reduced as the roughness length is increased mainly for terrain types 3 and 4 .

If the roughness length is in this range then the correct value of this "constant" can be derived and therefore the turbulence intensity variation in the constant stress layer can be estimated . It has been previously shown that equations of this

type apply only in this layer . From the reviewed data it can also be seen that the lateral and vertical turbulence intensities can now also be estimated in this layer .

Although more data is desirable for terrain types 3 and 4 , the proposed curve of Figure 64 is presented as being the best representation of the available data .

3.3. Analysis of the $\overline{u'v'}/\bar{U}_o^2 \sim y_o$ data .

The data available on these quantities are presented in Figure 65 . Generally data of this quantity ($\overline{u'v'}/\bar{U}_o^2$) are more often than not given as a function of the Rossby Number. However as pointed out in the previous review , in most cases variations of the Rossby Number mainly reflect changes in the roughness length only . Therefore to preserve consistency with the other data given here (Figures 63 to 66) the Reynolds stresses are presented as a function of the roughness length . In all cases the free - stream velocity ($\bar{U}_o$ or $\bar{U}_{max}$) has been derived on the assumption of a boundary layer height of 600m. (2000 ft.) .

It can be seen from Figure 65 , that in the case of the Reynolds stresses the measurements are relatively few and that they are subject to some considerable scatter . The former is partly attributable to lack of reliable instrumentation until recently and the latter due to experimental problems related to

e.g. instrument alignment and positioning . It is also evident from the data that incorrect trends can be deduced by being selective in the literature considered .

It is considered that the data of Figure 65 is best represented by a straight line . However this representation is possibly open to doubt for roughness lengths greater than about 1m (3.3 ft.) where the data are scarce and probably not too reliable . As for previous cases , the reliable stress measurements have been used to determine generally the form of the proposed curve .

Other forms for the variation of the Reynolds stress with roughness length have been given by Davenport (1964) and Pasquill (1970) . These are also shown on Figure 65 and can be seen to be biased towards the lower range of the stress measurements ; on this basis they cannot be considered representative of all the data . There is also no apparent reason why the stress should decrease at high roughness lengths as suggested by Davenport (1964) .

In the case of the Reynolds stress there is an obvious need for more data for terrain types 3 and 4 . However , until more data become available , the proposed variation of Reynolds stress with roughness length as in Figure 65 is suggested as the best compromise based on the data available .

3.4. Analysis of the $L_{ux} \sim y_o$ data .

The available data on the length scale , L_{ux} , are presented in Figure 66 (a) , (b) , (c) , . Figure 66 (a) shows the variation of L_{ux} with height and roughness . Below a height of 10m. (33 ft.) it can be assumed that the data will be subjected to errors due to the effects of the local topography ; in this height range it can also be assumed that the length scale will decrease more rapidly with decrease of height due to the proximity of the ground . Therefore the data are mainly considered in the height range 10 to 600 m. (33 to 2000 ft.) as shown in Figure 66(b) . However it can be assumed that the laws describing the variation of L_{ux} with height could be taken to apply with reasonable accuracy down to a height of about 5m. (16.5ft.). In Figure 66(c) L_{ux} is plotted as a function of roughness length at a reference height of 30m. (100 ft.) for consistency with the data in Figures 63 , 64 , and 65 . This length scale is also plotted as a function of y_o at various other heights in the same figure .

The data are obviously subject to some degree of scatter, but this is considered not to be excessive . The positions of the curves of Figure 66(b) for the various values of the roughness length were again based on the data , mainly from Appendix 2 , that were considered to be accurate and reliable . It was assumed that these curves should tend to converge at some height and that above this height L_{ux} would be independent of the

roughness length . This height was assumed to be in the region where the intermittency factor began to decrease in value from one (i.e. for δ = 600m. at y = 240 m.). This height also agrees with that suggested in the reviewed data which suggested that the length scale L_{ux} should increase with increase of height up to about 200 to 300m. (660 to 1000 ft.) . This assumption also agrees reasonably well with the data presented in Figure 65(b). Above this height the variation of L_{ux} with height is mainly predictable from flat-plate data .

It was noted in the reviewed data that to date L_{ux} was regarded as being independent of terrain roughness , and this is shown here not to be justifiable . In addition , the empirical theories of Davenport and Harris predict that L_{ux} increases as the roughness increases and also increases indefinitely with increase of height ; again the reviewed and assessed data given here similarly show that these predictions cannot be accepted .

On the above basis the variations of L_{ux} with roughness length and height presented in Figure 66 (b) and (c) are considered to be the most consistent and reliable based on the data assessed here, despite the lack of agreement with previous predictions .

With regard to the length scales L_{uy} and L_{uz} it has been shown in the reviewed data that these can be derived from a knowledge of L_{ux} . The remaining length scale of importance, L_{vx} , and its variation with height have been adequately established by other authors and it can be assumed that this

length scale is reasonably independent of roughness length .

3.5. The power spectral densities in relation to the boundary layer structure .

It has been shown in the reviewed literature that expressions have been derived which adequately define the forms of the longitudinal and vertical spectra . In addition since L_{ux} can now be defined for any terrain type , the position on the frequency scale of the peak wave-length can now also be fixed ; to date this represents the degree of accuracy to which spectra can be defined . However , as stated in the reviewed literature, the detailed spectral shapes at low frequencies should not be considered as being accurately defined since the data from various sites are subject to a large degree of scatter .

It can be seen from this analysis that the major part of the boundary layer structure can now be expressed in a simple mathematical form (Section 4) . This may also provide a sound basis for a more sophisticated theoretical treatment of the structure of Adiabatic boundary layers .

4. Mathematical representation of Adiabatic boundary layers .

The mathematical representation of Adiabatic boundary layers given here is the presentation of the data analysed in the form of a series of equations from which the relevant boundary layer properties can be derived provided that one quantity is known . On the basis of the reviewed data it is assumed that the mean boundary layer height for terrain types 1 to 4 is 600m. (2000 ft.)

As a starting point it is assumed that the roughness length of the relevant terrain is known , or that using site velocity measurements it can be derived from :-

A :

$$\frac{\bar{u}}{u_*} = \frac{1}{k}\left[\log_e \frac{y-d}{y_o}\right] \qquad - 1$$

where 'd' is neglected for terrain types 1 to 2 .

B : The power index and turbulence intensity at y = 30m (100ft.) can be derived from :-

$$\frac{1}{\alpha} = \left(\frac{\sqrt{\bar{u}^2}}{\bar{u}}\right)_{30m} = 0.096 \log_{10} y_o + 0.016 (\log_{10} y_o)^2 + 0.24 \qquad - 2$$

for, $0.001 \leq y_o(m) \leq 5$

(mean accuracy of 3.0 % relative to proposed curve)

The lateral and vertical intensities of turbulence can then be derived at y = 30m.(100 ft.) from :-

$$\frac{\sqrt{\overline{w^2}}}{\sqrt{\overline{u^2}}} = 0.75 \; ; \quad \frac{\sqrt{\overline{v^2}}}{\sqrt{\overline{u^2}}} = 0.50 \qquad - 2(a)$$

The variation with height of the longitudinal turbulence intensity in the log - layer can be derived from :-

$$\frac{\sqrt{\overline{u^2}}}{\bar{u}} = 0.4A \left[\frac{1}{\log_e y/y_o} \right] \qquad - 2(b)$$

where, A = 2.5. for $0.001 \leq y_o(m) \leq 0.10$

and $2.5 \leq A \leq$ for $0.10 \leq y_o(m) \leq 5.00$

For $100 \leq y(m) \leq 600$ a linear extrapolation from the top of the constant shear stress layer is sufficient (i.e. assuming $\sqrt{\overline{u^2}}/\bar{u} \approx 0.01 \sim 0.02$ at $y = \delta = 600$m.) .

Generally this implies that,

$$\frac{\sqrt{\overline{u^2}}}{\bar{u}} \propto \frac{1}{y^x} \qquad (1.5 \leq x \leq 2)$$

C : The Reynolds stress in the constant stress layer can be derived from :-

$$\left(\frac{\overline{u'v'}}{\bar{U}_o^2} \right) = \left(\frac{u_*}{\bar{U}_o} \right)^2 = 2.75 \times 10^{-3} + 6 \times 10^{-4} \log_{10} y_o \qquad - 3$$

or from :

$$y_o = e^{\left(4000 \, \overline{u'v'}/\bar{U}_o^2 - 11\right)} \qquad -3 \text{ (a)}$$

D : The length scale of turbulence , Lu_x , at y = 30m.(100 ft.) can be derived from :-

$$Lu_x = 108\left(\frac{1}{y_o}\right)^{1/6} \qquad - 4$$

or its variation with height from :-

y_o(m)	Lu_x (m)
0.01	$146\,y^{0.125}$
0.10	$58\,y^{0.29}$
1.0	$23\,y^{0.45}$
10.0	$9.2\,y^{0.60}$

- 4(a)

for, $5 \leq y(m) \leq 240$

and

$$Lu_x = 14.3\times10^3\left(\frac{1}{y}\right)^{1/1.4} \qquad - 4(b)$$

for $240 \leq y(m) \leq 600$

E : The length scales L_{uy} and L_{uz} can be derived from :-

$$L_{uy} = 0.5 \sim 0.6\, L_{ux}$$

and

$$L_{uz} = 0.3 \sim 0.4\, L_{ux} \qquad - 5$$

for, $5 \leq y(m) \leq 240$

From homogenous isotropic turbulence theory :-

$$L_{uy} = L_{uz} = L_{ux}/2 \qquad - 5(a)$$

for $240 \leq y(m) \leq 600$

F : The length scale L_{ux} can be derived from :-

$$L_{ux} = 0.40\,y \qquad - 6$$

for $5 \leq y(m) \leq 240$

Assumed to be independent of roughness length.

G : The power spectrum and cospectrum forms are as follows :-

$$n S_u(n) = \frac{\bar{x}}{(2 + \bar{x}^2)^{5/6}} \qquad - 7(a)$$

where, $\bar{x} = n\ell / \bar{u}_{10}$, $\ell = 1800m.$

$$n S_v(n) = \frac{1.075\, f/f_m}{1 + 1.5\,(f/f_m)^{5/3}} \qquad - 7(b)$$

where, $f_m \simeq 0.32$

$$n S_{uv}(n) = u_*^2 \frac{f/f_m}{(1 + 0.6\, f/f_m)^{8/3}} \qquad - 7(c)$$

where, $f_m \simeq -0.08$

(7a , b , c from reviewed data .)

From the above equations the main quantities defining the structure of Adiabatic boundary layers can be deduced .

5. CONCLUSIONS

The following conclusions can be reached .

(a) All of the available data on adiabatic boundary layers have been adequately reviewed and analysed .

(b) The similarity of these boundary layers to flat-plate boundary layers has been generally established .

(c) From the data finally summarised the general structure of adiabatic boundary layers appropriate to a wide range of terrain types can be adequately determined .

(d) The proposed curves for the summarised data are assumed to be the most reliable and consistent available .

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	No.	Ref.	Year	Terrain Type	δ(m)	Height Range(m)	$1/\alpha$	Roughness Height(z_0)	Zero Plane Disp.(z_d)	y_0(cm)	$\sqrt{\overline{u^2}}/u$	$\sqrt{\overline{v^2}}/u$	$\sqrt{\overline{w^2}}/u$	$\overline{uv}/u^2_{max}$	Lux	Luy	Luz	$\left(\frac{\sqrt{\overline{u^2}}}{u}\right)_{y=30m}$	α_1°	$\sqrt{\overline{v^2}}/\sqrt{\overline{u^2}}$	$\sqrt{\overline{w^2}}/\sqrt{\overline{u^2}}$	$\sqrt{\overline{u^2}}/u_*$	$\sqrt{\overline{v^2}}/u_*$	$\sqrt{\overline{w^2}}/u_*$	Site Name
1880~1919	1.	Stevenson	1880	Open		0~22	0.143			0.137															
				Cereal		0~22	To	30		2.27															
				Cereal		0~22	0.166	107		4.80															
	2.	Archibald	1885	All Types	500		0.25																		
	3.	Dobson	1914	Rural	450~600		0.143												20						
	4.	Taylor	1915	Rural	600 Ass.	10									70										
	5.	Taylor	1916	Rural	600 Ass		0.143							0.0014~ 0.0020											
	6.	Taylor	1917	Rural	450~600														16~20						
	7.	Schmidt	1918	Rural	400 est.														20						
	8.	Douglas	1919	Rural	600~900 est																				
	9.	Chapman	1919	Grassland			0.166																		
1919~1939	10.	Scrase	1930	Grassland	600 Ass	1.5~13	0.13~ 0.143			1.00				0.0015~ 0.0017						0.46	0.73				Salisbury Plain
	11.	Heywood	1931	Meadows																					
				Trees Hedges			0.17			60															Leafield
	12.	Giblett	1932	Rural-Flat	450-600 est	1.5~45	0.128 0.143								120										Carrington
	13.	Sverdrup	1934	Short Grass						0.54															
				Open Land						3.29															
				Calm Sea						3.90															
	14.	Sutton	1934	Rural			0.143																		
	15.	Schmidt	1935			0~6										15									
	16.	Rossby, Montgomery	1935	Urban				3000		100~ 300									28						
	17.	Pagon	1935	Rural	325 est		0.143~ 0.166												20						
				Urban	525 est														45						
1930~1939	18.	Best.	1935	Rural		0~5 2	0.130			1.00	0.15~ 0.16														
	19.	Prescke	1937	Beat Crop		0~5	0.333		45.0	6.5															
				Cereals		0~5	0.286		130	5															
				High Grass		0~5	0.278		30	3.95															
				Low Grass		0~5	0.260		20	3.2															
				Fallow		0~5	0.250		10	2.14															
				Airport		0~5	0.233		10	1.73															
				Snow		0~5	0.200		3	0.50															
				Urban		15~150	0.358																		
	20	Reichardt	1938	Flat Plate							0.12~ 0.13	0.08		0.0020											Strasburg
	21	Calder	1939			0~30								Const.											
	22.	Frost	1946	Sea		0~15	0.143			1.0															
				Rural		0~30	0.143			2.6															Carrington
	23.	Frost	1947	Rural		8~120	0.15			1.0															Carrington

APPENDIX - 1 CONTD.

	No.	Ref.	Year	Terrain Type	δ(m)	Height Range(m)	$1/\alpha$	Roughness Height(cm)	Zero Plane Displ.(cm)	y_o(cm)	$\sqrt{\overline{u^2}}/\bar{u}$	$\sqrt{\overline{v^2}}/\bar{u}$	$\sqrt{\overline{w^2}}/\bar{u}$	$\overline{uw}/U^2_{max}$	L_{ux}	L_{uy}	L_{uz}	$\left(\sqrt{\overline{u^2}}/\bar{u}\right)_{y=30m}$	α_i°	$\sqrt{\overline{u^2}}/\sqrt{\overline{u^2}}$	$\sqrt{\overline{w^2}}/\sqrt{\overline{u^2}}$	$\sqrt{\overline{u^2}}/U_*$	$\sqrt{\overline{v^2}}/U_*$	$\sqrt{\overline{w^2}}/U_*$	Site Name
1940 ~ 1949	24	Sheppard	1947	Ice, Snow	600 ASS.	0~2				0.001														
				Cut Grass	"	0~2	0.143	1.0		0.10				0.0016											
				Downland	"	0~2	0.20	10.0		0.72														
				Thick Grass	"	0~2	0.25	10.0		2.3				To										
				Thin Grass	"	0~2		50.0		5.0														
				Thick Grass	"	0~2	0.333	50.0		8.9				0.0043										
				Root Crops	"	0~2				13.9														
	25.	Huss, Portman	1948	Open Count. Bushes, Small Trees			0.22																	Akron
	26.	Sutton	1948	Rural			0.143																	
	27.	Shiotani	1948	Rural		0~50					0.13				75~107									
				Urban		30~60	0.40	1000~2000		400	0.20~0.30				100									Tokio
	28.	Deacon	1949	Short Grass			0.152																	
				Grass				60~70		4~6														
				Downland						1~4														
				Cut Grass				1.5~3.0		0.2~0.8														
				Snow						0.1~0.4														
				Snow-Mud						0.001~0.01														
	29.	Franckenberger, Rudloff	1949	Meadows, Hedges, Trees		10~70	0.208			22.4														Quickborn
	30	Sutton	1949	Rural	500														29					
	31.	Laufer	1950	Flat Plate		y/δ <0.1					0.10~0.18				$\frac{L}{\delta}$ ≈0.3						0.60			
						=0.1									≈0.5									
						=0.4																		
	32.	Lettau	1950	Suburban	600~800	0~800	0.23			5.0									26					Leipzig
	33.	Pasquill	1950	Grass	600 ASS.			1~15	8	0.66				0.0010										
				Concrete	600 ASS.									0.00043										
	34.	Shiotani	1950	Grass and Vegetation	600 ASS.	0~16		30~40		1.5~5.5					60									
						1					0.14	0.09		0.0024							0.64			
						3					0.10	0.08									0.12			
				Urban							0.42	0.30									0.71			
											0.48	0.31									0.65			
											0.36	0.18									0.50			
1950 ~ 1959	35.	Singer, Smith	1950	Trees and Bushes			0.25																	Brookhaven
	36.	Cramer	1952	Trees, Bushes and Sand		0~12					0.12~0.33				12~18		6							
						2.5																		
	37	Gordon	1952	Sea	600 ASS.														7					
	38	Priestley	1952	Rural		2									15~20									
	39	Sheppard	1952	Water	500	2	0.122			0.10	0.19			0.0011	12									
	40.	Priestley, Sheppard	1952	Water		0~300					0.13~0.20								3.5					

APPENDIX. 1 CONT'D.

No.	Ref.	Year	Terrain Type	δ(m)	Height Range(m)	$1/\alpha$	Roughness Height(cm)	Zero Plane Displ.(cm)	y_0(cm)	$\sqrt{\overline{u^2}}/\bar{u}$	$\sqrt{\overline{v^2}}/\bar{u}$	$\sqrt{\overline{w^2}}/\bar{u}$	$\overline{u'v'}/U^2_{max}$	L_{ux}	L_{uy}	L_{uz}	$(\sqrt{\overline{u^2}}/\bar{u})_{max}$	α°	$\sqrt{\overline{v^2}}/\sqrt{\overline{u^2}}$	$\sqrt{\overline{w^2}}/\sqrt{\overline{u^2}}$	$\sqrt{\overline{u^2}}/U_\delta$	$\sqrt{\overline{v^2}}/U_\delta$	$\sqrt{\overline{w^2}}/U_\delta$	Site Name
41	Sheppard and Omar	1952	Water	450-600	0-600+								0.0004											
42.	Sherlock	1952	Rural		0-300+	0.143												17						
43.	Deacon	1953	Grass		0-10		0-4		0-3				0.0021											
44.	Friedman	1953	Rural		0-44	0.143																		
				2.7								0.233												
				5.5								0.198												
				11.0								0.185												
				22.0								0.185												
				44.0								0.149												
45.	Hellerman	1953	Urban			0.33																		
46.	McCready	1953	Rural		0.15					0.291	0.114								0.392					
					0.70					0.248	0.121								0.488					
					2.40					0.259	0.144			90					0.555					
					146.0					≈ 0.05				× 420										
47.	Panofsky	1953	Trees			0.26	1000																	
48.	Robinson	1953	Rural		1.3					0.21		0.155		12						0.74				Upton
49.	Shiotani	1953	Snow		0.4					0.124	0.04								0.338					Kew.
					0.6					0.128	0.052								0.406					
					0.9					0.089	0.043								0.484					
					1.5					0.100	0.049								0.490					
					7.5					0.156														
					11					0.120	0.061			30					0.509					
					75					0.063				90										
50.	Sutton	1953	Rural	500+		0.143																		
			Grass				1-3	0	0.50															
			Grass				60-70	30	3															
51.	Hay.	1954	Water	600ass.	2				0.10		0.035		0.0006											
52.	Marshall	1954	Land/Sea			0.167																		Stornaway
			Land/Sea			0.143																		Blackrock
			Sea			0.118																		Scilly
			Rural			0.312																		Kew.
53.	Monin, Doukhov.	1954	Rural										0.0025											
54.	Rider	1954	Rural-Flat	600ass.	2				0.82				0.00083											Carrington
55.	Collins	1955	Rural To Urban			0.10 To 0.40																		
56.	Deacon	1955	Rural			0.16-0.17			3.0-2.00															Sale.
57.	Kamei	1955	Coastal			0.20																		
			Urban		0.30	0.33																		
			Fields						33.2															
			Plain-Urban			0.33			8.0 150															Tokio

1950-1959 CONT'D

No.	Ref.	Year.	Terrain Type	δ(m)	Height Ranges	1/α	Roughness Height (cm)	Zero Plane Displ. (cm)	y_0 (cm)	$\sqrt{\overline{u^2}}/\bar{u}$	$\sqrt{\overline{v^2}}/\bar{u}$	$\sqrt{\overline{w^2}}/\bar{u}$	$\overline{u'w'}/U_{max.}$	Lu_x	Lu_y	Lu_z	$\left(\sqrt{\overline{u^2}}/\bar{u}\right)_{y=30m}$	α_1°	$\sqrt{\overline{v^2}}/\sqrt{\overline{u^2}}$	$\sqrt{\overline{w^2}}/\sqrt{\overline{u^2}}$	$\sqrt{\overline{u^2}}/U_*$	$\sqrt{\overline{v^2}}/U_*$	$\sqrt{\overline{w^2}}/U_*$	Site Name
58.	Swinbank	1955	Rural		8~30	0.143															2.3~2.2			
59.	Taylor	1955	Rural		1.5									24										
					28									40~110										
60.	Webb	1955	Rural		29									84										
61.	Ellison	1956	Rural	600 ASS.									0.0013											
62.	Deacon	1957	Rural	600 ASS.									0.0022											
63.	Deland, Panofsky	1957	Rural, Flat. Wooded			0.23~0.25	1000		0.7~1.0 100															O'Neill Brookhaven
64.	Lettau, Davidson	1957	Rural-Flat.		1.5	0.143 0.20			0.44~1.73	0.219	0.079	0.143	0.0016~0.0018						0.360	0.654	2.70	1.1	1.6	O'Neill.
					3					0.198	0.065	0.113							0.328	0.570				"
					6					0.168	0.058	0.096							0.346	0.570				"
					12					0.155	0.063	0.096							0.406	0.620				"
65.	Ely.	1958	Rural-Flat.		3				1.00	0.19-0.20														
66.	Jensen.	1958	Urban		35~80	0.36	1500		750															O'Neill.
			Very Flat		0.5~2.0	0.11			0.018															Copenhagen
			Flat			0.152			0.30															Højer
																								Fredskau
67.	DeMarrais	1959	Wooded		11~125	0.29																		B'haven
			Rural-Flat		11~49	0.20																		Tallmadge
			Mountains		15~122	0.12																		Hanford
			Airfield		9~27	0.08																		Harwell
			Desert		6~61	0.18																		Idaho.
68.	Hay, Pasquill	1959	Downland		2									20~40										
69.	Johnson	1959	Snow.			0.149~0.165																		
70.	Lettau	1959	Meadows, Suburban? Rural-Flat						5.0 5.0 0.9															Quickborn Leipzig O'Neill
71.	Panofsky, Deland	1959	Rural-Flat Wooded						0.7 100															O'Neill B'haven
72.	Singer, Smith.	1959	Wooded		11~125	0.21			100															
73.	Vinogradova	1959	Water	600 ASS.	2								0.0005											B'haven.

1950~1959 CONTD.

Addendum.

Ref.	Year	Terrain Type.	1/α	y_0 (cm)	Height Ranges (m)	Site Name
Dines	1912	Rural	0.33		80~600	
Wipperman	1921	Sea-Land	0.130	1.10	5~160	Ballybunion
Frost.	1946	Rural	0.143	1.0		Greenham Common
		Rural	0.143	2.6		
Sherlock	1953	Rural-Flat	0.093	0.3	15~76	Ann Harbor
Juul	1954	Sea-Islands	0.105	0.5	5~55	
Wax	1956	Sea-Land	0.236	13.6	17~36	
Godshalk	1957	Sea	0.081	0.2	5~50	Caspian Sea.

Ref	Year	$\sqrt{\overline{v^2}}/U_*$
Pasquill	1957	0.87

APPENDIX. 2

MAIN DEVELOPMENTS IN AND QUANTITATIVE DATA FROM THE PERIOD 1960~19

( ) INDICATES ESTIMATED QUANTITY

AUTHOR: ARIEL, N.A. ; KLIUCHNIKOVA, L.A. (COMPLETE TRANS. NOT AVAILABLE)
YEAR : 1960
DATA :

SITE	$1/\alpha$	$y(m)$	$y_o(m)$	$(\sqrt{\bar{u}'^2}/\bar{u})_{30}$
LENINGRAD	0.32	50~150	2.46	(0.40)

AUTHOR : BLACKADAR, A.K. ET AL.
YEAR : 1960
DATA :

GENERALLY SUGGESTS LITTLE DIFFERENCE IN THE LATERAL TURBULENCE OF THE O'NEILL AND BROOKHAVEN SITES, DESPITE THE LARGE DIFFERENCES IN GROUND ROUGHNESS ; DATA SUBJECT TO CONSIDERABLE SCATTER.

SITE	$y_o(m)$	$(\sqrt{\bar{u}'^2}/\bar{u})_{30}$
O'NEILL	0.0065	(0.118)

AUTHOR : DAVENPORT, A.G.
YEAR : 1960
DATA : DATA REANALYSED FOR $1/\alpha$ AND y_o AS FOLLOWS:-

SITE	$1/\alpha$	$y_o(m)$	$(\sqrt{\bar{u}'^2}/\bar{u})_{30}$
SALE	0.176	0.02~0.03	(0.141)
CARDINGTON	0.149	0.012	(0.128)
NEW YORK	0.39	3.30 (NOT RELIABLE)	
LEIPSIG	0.23	0.38	(0.230)

COMMENTS: THE VARIOUS VALUES OF $1/\alpha$ ETC, FOR SOME OF THESE SITES, SUGGESTED BY OTHER AUTHORS ARE DEPENDENT ON THE METHOD OF ANALYSIS USED. HOWEVER, AS WILL BE SHOWN LATER, THE RESULTING DEGREE OF SCATTER IS OF THE ORDER EXPECTED FOR THIS TYPE OF DATA.

AUTHOR: DURST, C.S.
YEAR : 1960
DATA :

SITE	$y(m)$	$\sqrt{\bar{u}'^2}/\bar{u}$	$y_o(m)$
CARDINGTON	15.25	0.14	0.012 EST.
	30	0.128 EST.	

AUTHOR: GRAHAM, H.E.; HUDSON, G.N.

YEAR : 1960

DATA :

SITE	$1/\alpha$	y(m)	y_o(m)	$(\sqrt{\bar{u}^2}/\bar{u})_{30}$
BROOKHAVEN	0.25		0.60	(0.256)
NEW ORLEANS	0.284	20		
WASHINGTON	0.235	30		
WATER	0.114	10	0.0055	(0.116)

AUTHOR : PANOFSKY, H.A ETAL.

YEAR : 1960

DATA :

THEORETICAL ESTIMATES OF y_o FOR HEIGHT RANGE $11 \leq y(m) \leq 46$

$1/\alpha$:	0.10	0.15	0.20	0.25	0.30
y_o(m) :	0.0010	0.025	0.15	0.30	0.75

AUTHOR : PANOFSKY, H.A.; MCCORMICK, R.A.

YEAR : 1960

DATA :

DERIVATION OF FORM OF SPECTRUM EQUATION OF VERTICAL VELOCITY.

$$\underline{n S_v(n) = \frac{\bar{v}^2 4f}{(1+4f)^2}}$$

NEED TO SUBSTITUTE FOR $\bar{v}^2$,

FOR ADIABATIC CONDITIONS :-

$$\sqrt{\bar{v}^2} = C U_*$$

WHERE $C = D k^{-1/3}$ $\quad k$ = VON KARMANS CONST.

$$\simeq 1.25$$

$$\therefore \bar{v}^2 = 1.5 U_*^2$$

HENCE

$$\underline{n S_v(n) = U_*^2 \frac{6f}{(1+4f)^2}}$$

FROM SECT. 2.5 AND $\sqrt{\bar{v}^2}/U_* = 1.25$

$$\underline{\sqrt{\bar{v}^2}/\bar{u} = 0.5 \left(\frac{1}{\log_e y/y_o} \right)}$$

(THIS EQUN. SHOWN TO APPLY IN CASE OF O'NEILL AND BROOKHAVEN DATA)

AUTHOR : DAVENPORT, A.G.

YEAR : 1961 a

DATA :

SEMI-EMPIRICAL EXPRESSION DERIVED FOR FORM OF LONGITUDINAL VELOCITY POWER SPECTRUM:-

$$\frac{n S_u(n)}{} = \frac{4 u_*^2 x^2}{(1+x^2)^{4/3}}$$

WHERE —

$x = \frac{1200 n}{\bar{u}_{10}}$, $\bar{u}_{10}$ = VEL. (m/sec) AT $y = 10m$.

THE FOLLOWING LENGTH SCALES OF TURBULENCE HAVE ALSO BEEN ESTIMATED FROM DATA GIVEN IN THIS PAPER :-

SITE	y(m)	L_{ux}(m)	$\sqrt{\bar{u}^2}/\bar{u}$
CARDINGTON.	15.3	186	
BROOKHAVEN	11	46	
	46	108	
	108	152	
	125	111	
SALE.	12.2	88	0.168
	64	70	0.124
	153	105	0.098

DERIVATION OF $\sqrt{\bar{u}^2}/\bar{u}$ AT $y = 30m$ FOR SALE:—

FROM PREVIOUS DATA, $y_o \simeq 0.025m$.

FROM ABOVE DATA,

$$0.168 = \frac{1}{\log_e y/y_o} \quad , \quad y_o = 0.030m$$

HENCE FOR $y = 30m$

$$\sqrt{\bar{u}^2}/\bar{u} = 0.145$$

INTERPOLATION (BY DRAWING) OF MEASURED DATA GIVES

$$0.147.$$

IF $y_o = 0.025$ IS ASSUMED,

THEN $\sqrt{\bar{u}^2}/\bar{u} = 0.141$

COMMENTS: APPLICATION OF EQUN. $\sqrt{\bar{u}^2}/\bar{u} = \frac{1}{\log_e y/y_o}$ GIVES REASONABLY GOOD CONSISTENCY IN RESULTS.

AUTHOR: DAVENPORT, A.G.

YEAR : 1961 b.

DATA :

GENERAL TERRAIN TYPES CLASSIFIED,

SITE	$1/\alpha$	$\delta(m)$
RURAL	0.16	274
SUBURBAN	0.28	396
URBAN	0.40	518

THE TURBULENCE INTENSITY IS RELATED TO THE POWER SPECTRUM :-

$$\sqrt{\overline{u^2}}/\bar{u} = \left[\int_0^\infty \frac{S(n)}{\bar{u}^2} \, dn \right]^{1/2}$$

FROM THE FORM OF THE SPECTRUM GIVEN BY DAVENPORT 1961a THIS INTEGRATES TO :-

$$\sqrt{\overline{u^2}}/\bar{u} = 2.45 \left(u_*/u_1\right)\left(y/y_1\right)^{-1/\alpha}$$

$$\therefore \underline{\sqrt{\overline{u^2}}/u_* = 2.45} \quad \text{(e.g c.f 2.70 LETTAU 1957)}$$

AUTHOR : IVANOV, V.N. ; KLINOV, F.Ya.

YEAR : 1961

DATA.

SITE	$y(m)$	$y_0(m)$	$1/\alpha$	$\sqrt{\overline{u^2}}/\bar{u}$	$L_{ux}(m)$	$\left(\sqrt{\overline{u^2}}/\bar{u}\right)_{30}$
MOSCOW.	25~300	3.0	0.303			
	30			0.275		(0.43)
	25				25	
	50				40	
	100				65	
	150				75	
	200				80	
	300				100	

COMMENT: PROBABLE INSTRUMENT INACCURACY?

No SITE DESCRIPTION.

AUTHOR: JENSEN, M.

YEAR : 1961

DATA :

ROUGHNESS LENGTH AND ZERO-PLANE DISPLACEMENT DATA GIVEN FOR TERRAIN VARYING FROM — "GRASS; GRASS AND CLOVER; STUBBLE, GRASS AND CLOVER; CEREALS."

VEGETATION HEIGHT

h (cm)	y_o (m)	(d/y_o)
5	0.01	5.0
10	0.031	3.2
15	0.043	3.5
20	0.055	3.6
25	0.058	4.3
30	0.070	4.3

$[\overline{(d/y_o)} \simeq 4.1]$

COMMENTS: IT CAN BE ASSUMED THAT THE DENSITY DISTRIBUTION OF THE ROUGHNESS IS HIGH, HENCE $d > y_o$. THE RESULTS APPEAR RELIABLE AND SUGGEST A TYPICAL RURAL y_o SHOULD BE AT LEAST OF THE ORDER 0.10 m.

ILLUSTRATION IS ALSO PROVIDED OF THE ERROR OCCURRING DUE TO ESTIMATING A VELOCITY PROFILE INDEX FROM MEASUREMENTS NEAR THE GROUND :-

½ FROM VELOCITY MEASUREMENTS NEAR GROUND = 0.39.

½ " " " HIGHER UP = 0.22

AUTHOR: PASQUILL, F.

YEAR : 1961

DATA :

THE STRUCTURE OF TURBULENCE AS DEFINED BY PASQUILL IS SHOWN IN FIG. 38 . FOR A CORRELATION WHICH FALLS OFF EXPONENTIALLY WITH TIME LAG :-

$$t_s = l_s/\bar{u} = \frac{1}{2\pi}\eta_m \quad \text{(AS IN FIG. 38)}$$

WHERE $l_s = Lu_x$

$$\therefore Lu_x = \tfrac{1}{2\pi} \times \text{PEAK WAVELENGTH.}$$

HENCE THE TURBULENCE LENGTH SCALE CAN BE DERIVED FROM SPECTRAL MEASUREMENST. (THIS METHOD IS USED EXTENSIVELY IN RECENT PAPERS E.G. TEUNISSEN 1970.)

FROM VARIOUS SITES THE FOLLOWING WAS DERIVED:-

$$Lu_x \simeq 0.5y$$

ALSO :-

SITE	y(m)	y_o(m)	L_{ux}(m)
VARIOUS	29	-	72
	30	-	60~130
	91	-	273

OR - $L_{ux} \simeq 3y$

TURBULENCE MEASUREMENTS :-

SITE	y(m)	y_o(m)	$\sqrt{\overline{u^2}}/\bar{u}$	$\sqrt{\overline{w^2}}/\bar{u}$	$\sqrt{\overline{v^2}}/\bar{u}$	COMMENTS
ROUND HILL	2	>0.10	-	0.22	0.09	ACCURACY?
O'NEILL	2	<0.01	-	0.12	0.07	PREV. TABULATED
BROOKHAVEN	91	1.0	-	-	0.21	
DOWNLAND	0.5~16	0.01	-	-	0.10	
CARDINGTON	600	-	0.11	-	0.09	

BROOKHAVEN: $\left(\sqrt{\overline{u^2}}/\bar{u}\right)_{30} = (0.294)$; DOWNLAND - = (0.125)

COMMENTS : ALTHOUGH THE ASSUMPTION OF AN EXPONENTIAL CORRELATION CURVE IS JUSTIFIABLE IN MANY CASES, THE DIFFICULTY IN USING THE ABOVE METHOD, FROM WHICH TO ESTIMATE LENGTH SCALES, IS CLEARLY MOSTLY DEPENDENT ON THE ACCURACY TO WHICH η_m CAN BE FIXED. HOWEVER IT WILL BE USED TO DERIVE LENGTH SCALES WHERE POSSIBLE FROM SPECTRA WHICH ARE REASONABLY WELL DEFINED.

NOT VERY MUCH CAN BE GAINED FROM THE ABOVE TURBULENCE DATA. HOWEVER, SINCE IT HAS BEEN SEEN THAT FOR RURAL TERRAIN :-

$$0.15 \leq \sqrt{\overline{u^2}}/\bar{u} \leq 0.20$$

HENCE IT CAN GENERALLY BE SEEN FROM THE ABOVE DATA :-

$$0.075 \leq \sqrt{\overline{v^2}}/\bar{u} \leq 0.10 \quad \text{i.e.} \quad \sqrt{\overline{v^2}}/\sqrt{\overline{u^2}} \simeq 0.50$$

FOR RURAL TERRAIN.

AUTHOR : RAUNER, Yu. L.

YEAR : 1961

DATA : (SEE FIG. 38.)

RATIO OF FOREST / OPEN AREA $\simeq$ 0.70~0.80 ; $h \simeq 18$m.

$\bar{u}$ (m/sec) :	2~3.5	3.5~5.0	5.0~7.0
d(m) :	8.5	6.0	4.0
y_o(m) :	2.7	3.2	5.0

THE INCREASE OF y_o AS $\bar{u}$ INCREASES IS ATTRIBUTED TO GREATER PENETRATION OF THE WIND THROUGH THE FOREST AS THE WIND SPEED INCREASES.

COMMENTS: IT IS ASSUMED THAT WHEN THERE IS FOLIAGE ON THE TREES THE BOUNDARY LAYER IS 'LIFTED OVER' THE FOREST, TO SOME EXTENT.; HENCE THE LOWER y_o THAN IN THE CASE OF THE FOREST WITHOUT FOLIAGE (FIG. 3a). THE CHANGE IN y_o WITH AND WITHOUT FOLIAGE IS ABOUT 1 m (3.2 FT.). THE MEAN d/y_o WITHOUT FOLIAGE IS ABOUT 5.0 (Cf. JENSEN 1961 – $d/y_o = 4.0$ for GRASS AND CROPS.)

AUTHOR: TAKEUCHI, K.

YEAR: 1961

DATA:

SITE	y(m)	$1/\alpha$	$\sqrt{\bar{u}^2}/U_*$	$\sqrt{\bar{w}^2}/U_*$	$\sqrt{\bar{v}^2}/U_*$	$\sqrt{\bar{w}^2}/\sqrt{\bar{u}^2}$	$\sqrt{\bar{v}^2}/\sqrt{\bar{u}^2}$
O'NEILL.	2~16	0.16~0.17	2.5	1.75	0.95	0.69	0.37

AUTHOR: ZBROZEK, J.K.

YEAR: 1961

DATA:

GENERALLY DEALS WITH VERTICAL GUST SPECTRUM; FORM ADOPTED FOR AIRCRAFT USE:-

$$\frac{G(\Omega)}{\sqrt{\bar{w}^2}} = \frac{L}{\pi} \frac{1 + 3(\Omega L)^2}{[1 + (\Omega L)^2]^2}$$

WHERE

$$\Omega = \frac{2\pi}{\lambda} = \frac{2\pi n}{U}.$$

(ASSUMES EXPONENTIAL AUTO-CORRELATION AS IN PASQUILL 1961)

DEFINES SCALE OF TURBULENCE FROM WAVELENGTH ($\lambda = V/n$) AT WHICH SPECTRUM DEPARTS FROM POWER LAW (IE. WHERE SPECTRUM DECAYS AT $-5/3$ RATE.). HENCE

$$L_{U_x} \simeq 300\text{ m (1000 ft.)} \quad \text{AT } y = ?$$

COMMENTS: VARIATION OF SCALE WITH HEIGHT NOT CONSIDERED.

AUTHOR : BLACKADAR, A.K.

YEAR : 1962

DATA :

ASSUMED THAT THE SIGNIFICANT EDDY SIZE

(a) INCREASED AS kz CLOSE TO THE GROUND

(b) APPROACHED A FIXED VALUE AT GREATER HEIGHTS

(REF: PANOFSKY AND MCCORMICK 1960). HENCE THEORETICAL DATA COMPARED WITH MEASURED DATA IN FIG. 39. ($\alpha_1^\circ = 32^\circ$ ASSUMED FOR BROOKHAVEN DATA.)

IT WAS GENERALLY SHOWN THAT LENGTH SCALES INCREASED UP TO HEIGHTS OF ABOUT 200 ~ 300m (660 ~ 1000 FT.) AND WAS LESS THAN 100m (330FT.) AT GREATER HEIGHTS; ALSO EVIDENT THAT THE BOUNDARY LAYER HEIGHT CHANGED VERY LITTLE AS y_o CHANGED. SUGGESTED THAT THE BOUNDARY LAYER HEIGHT (δ) CAN BE DERIVED FROM :

$$\log_{10}\delta = 0.008\log_{10} y_o + 0.992\log_{10}(\bar{U}_\delta/F) - 2.186$$

WHERE, F = CORIOLIS PARAMETER.

COMMENTS: LARGE SCATTER IN DATA OF FIG. 39b IS DUE TO THE EFFECTS OF HORIZONTAL TEMP. GRADIENTS (PREVIOUSLY DISCUSSED).

AUTHOR: DEACON, E.L.

YEAR : 1962

DATA : FIG. 40a.

SITE	$1/\alpha$	$\overline{u'v'}/U_o^2$	δ(m)
OPEN SEA	0.10	0.0005	600 (ASSUMED)

AUTHOR : KONDO, J.

YEAR : 1962

DATA :

SITE	y_o (m)	$\left(\sqrt{\overline{u'^2}}/\bar{u}\right)_{30}$
SENDAI (AIRFIELD).	0.0045	(0.114)
O'NEILL .	0.0065	(0.118)
CARDINGTON.	0.0033	(0.110)

AUTHOR : MONIN, A.S.

YEAR : 1962

DATA :

EMPIRICAL DATA FROM SURFACE LAYER

$\sqrt{\overline{u'^2}}/U_*$	$\sqrt{\overline{v'^2}}/U_*$	$\sqrt{\overline{v'^2}}/\sqrt{\overline{u'^2}}$
2.3	0.7	0.3

MAJORITY OF STRESS CONTRIBUTION IN RANGE $0.1 \leq f \leq 1.0$ (Cf. DEACON 1955)

AUTHOR: NAITO, T., ET AL.
YEAR : 1962
DATA :

SITE	$1/\alpha$	
TOKIO	0.33	(APPROX. ONLY.)

AUTHOR : PANOFSKY, H.A.
YEAR : 1962
DATA :

SITE	$y(m)$	$\sqrt{\bar{u}^2}/\bar{u}$	$L_{ux}(m)$	$L_{wx}(m)$
O'NEILL.	2	0.13	20	10
SEVERN BRIDGE.	30		60~130	

[STABLE AIR : SCALES SMALLER THAN NEUTRAL CASE; ALONGWIND > ACROSS WIND
UNST. AIR : SCALES LARGER THAN NEUTRAL CASE; APPROX. EQUAL IN ALL DIRECTIONS.]

AUTHOR : PASQUILL, F.
YEAR : 1962
DATA :

SITE	$y(m)$	$y_o(m)$	$\sqrt{\bar{v}^2}/\bar{u}$	$\sqrt{\bar{v}^2}/U_*$	$\left(\sqrt{\bar{u}^2}/\bar{u}\right)_{30}$
PORTON	2	0.008	0.096	1.33	0.122

AUTHOR : SHIOTANI, M.
YEAR : 1962
DATA : FIG. 40b.

SITE	$y(m)$	$y_o(m)$	$1/\alpha$	$\left(\sqrt{\bar{u}^2}/\bar{u}\right)_{30}$
TOKIO SUBURBS.	9~50	0.40	0.25	(0.232)

FIG. SHOWS CONVERGENCE OF DATA TO NEUTRAL INDEX VALUE I.E. FOR $\bar{u} > 7$ m/sec.

COMMENTS : $1/\alpha$ MAY BE OVER ESTIMATED DUE TO RESTRICTED HEIGHT RANGE.

AUTHOR : TAYLOR, R.J.
YEAR : 1962
DATA :

NOT OF DIRECT INTEREST. DISTANCE REQUIRED FOR FLOW TO BECOME ESTABLISHED TO HEIGHT y AFTER CHANGE OF SURFACE ROUGHNESS :-

$$x/y \simeq 100 \sim 150$$

RATIO OF FRICTION VELOCITIES GIVEN BY :-

$$U_{*2}/U_{*1} = \left(y_{o2}/y_{o1}\right)^{0.09}$$

AUTHOR : BURNS, A.

YEAR : 1963

DATA :

CONSIDERS MAINLY THE VERTICAL VELOCITY SPECTRA AS MEASURED BY AIRCRAFT AND BALOONS AT THREE HEIGHTS.

DATA OF INTEREST :-

y(m)	L_{w_x}(m)
61	122
300	280

WHICH VALUES OF L_{w_x} GIVE THE BEST FIT IN SPECTRUM EQUN. (REF. ZBROZEK, 1961)

COMMENT: IT IS ASSUMED HERE THAT L IN SPECTRUM EQUN $= L_{w_x}$. IT IS POINTED OUT IN LATER PAPERS THAT THE VARIOUS "L'S" OCCURRING IN DATA OF THIS TYPE ARE NOT ALWAYS CLEARLY DEFINED.

AUTHOR : BYZOVA, N.L.

YEAR : 1963

DATA : $\left(\sqrt{\overline{u^2}}/\bar{u}\right)_{30} = (0.134)$

SITE.	y(m)	y_o(m)	$1/\alpha$	$\sqrt{\overline{u^2}}/\bar{u}$	$\overline{u'v'}/U_*^2$	δ(m)
RURAL, FLAT	0~50	0.01~0.025	0.30	0.10~0.20	0.0017	600 (ASSUMED)

HEIGHT OF LOG LAYER $\simeq$ 75 m.

COMMENT : THE INDEX $1/\alpha$ IS HIGH FOR THIS TERRAIN TYPE.

AUTHOR : DAVENPORT, A.G.

YEAR : 1963

DATA :

MAINLY A REVIEW OF HIS EXISTING PUBLISHED PAPERS. SUGGESTS ADOPTION OF PANOFSKY / Mc CORMICK EXPRESSION FOR VERTICAL VELOCITY SPECTRUM :-

$$\frac{n S_w(n)}{U_*^2} \propto \frac{f}{(1+4f)^2}$$

I.E. THE SPECTRUM IS HEIGHT DEPENDENT, WHEREAS THE LONGITUDINAL VELOCITY SPECTRUM IS NOT (REF. DAVENPORT, 1961a).

THE MAIN RELEVANT DATA CAN BE SUMMARISED BY FIGS. 40c, 41.

COMMENTS : PRESENTATION OF $1/\alpha$ AS A FUNCTION OF δ AND y_o DOES NOT AGREE WITH FINDINGS OF PRESENT WORK. THE VALIDITY OF δ VARYING, AND THE $1/\alpha$ VALUES ADOPTED WILL BE DISCUSSED IN THE MAIN TEXT.

AUTHOR : JENSEN, M.

YEAR : 1963

DATA :

SUGGESTED THE FOLLOWING DATA AS BEING APPLICABLE TO AN URBAN AREA :-

A/A_T	h(m)	y_o(m)	y_o/h
0.25	21	10	0.5
0.14			0.33

COMMENTS: NO BASIS GIVEN FOR CHOICE OF ABOVE DATA.

AUTHOR : MARKEE, E.H.

YEAR : 1963

DATA :

SITE	y (m)	$\sqrt{\bar{u}^2}/\bar{u}$
'OPEN' URBAN.	0 ~ 10	0.16 ~ 0.20

COMMENTS: INSUFFICIENT INFORMATION AVAILABLE FOR PROPER ASSESSMENT OF WORK.

AUTHOR : PANOFSKY, H.A.

YEAR : 1963

DATA :

SITE	y (m)	y_o(m)	$\bar{y}_o$(m)	$(\sqrt{\bar{u}^2}/\bar{u})_{30}$
O'NEILL.	0 ~ 8	0.006 ~ 0.01	0.0086	(0.123)

AUTHOR : POOLER, F.

YEAR : 1963

DATA :

STUDY MADE IN URBAN AREA OF LOUISVILLE IN CONDITIONS VARYING FROM STABLE TO UNSTABLE. FOUND MEAN WIND DIRECTION TO BE INDEPENDENT OF HEIGHT IN RANGE,

$$0 \leq y(m) \leq 160$$

AUTHOR : SHELLARD, H.C.

YEAR : 1963

DATA :

THE MAIN IMPORTANT RELEVANT POINTS FROM THIS PAPER ARE SUMMARISED AS FOLLOWS :-

(a) THE POWER INDEX, $1/\alpha$, TAKEN AS 0.16 ~ 0.17 FOR "GENTLY ROLLING COUNTRYSIDE, WITH SCATTERED TREES OR OBSTRUCTIONS."

(b) Typically δ is assumed to be of the order of 500 m (1650 ft.) and is possibly not too dependent on the terrain roughness y_o (see Blackadar, 1962).

(c) Suggests $1/\alpha \simeq 0.23$ for urban areas such as London and regards a value of $1/\alpha = 0.40$ as being "quite inappropriate". Suggests that the high $1/\alpha$ values quoted in the literature for urban areas arise from the use of observations taken at levels which are too low to be representative of true conditions. For example, buildings can affect velocity measurements made near them up to heights of about twice the building height.

Author : Taylor, R.J.

Year : 1963.

Data :

Change of wind direction with height $\simeq 25° \pm 4°$ in Height Range $0 \sim 366$ m (1200 ft.)

Author : Davenport, A.G.

Year : 1964

Data :

Most of relevant data on spectra, $1/\alpha$ and y_o in previous papers. However the "surface drag coefficient" (K) for various terrain types are defined in more detail than previously.

	Site.	$K(\bar{u}_{10})$	$K(\bar{u}_o)$	$1/\alpha$	δ (m)
1.	Rough, open water.	0.001 ~ 0.002	: 0.0004 ~ 0.0009	0.10	600 (assumed)
2.	Open grassland.	0.003 ~ 0.005	: 0.0008 ~ 0.0014	0.16	"
3.	Woodland, suburbs.	0.015 ~ 0.030	: 0.0015 ~ 0003	0.28	"
4.	Urban centres.	0.030 ~ 0.050	: 0.0011 ~ 0.0019	0.40	"

	$K(\bar{u}_o)$	δ (m)
1.	0.0005 ~ 0.001	275
2.	0.001 ~ 0.0017	275
3.	0.0017 ~ 0.0039	400
4.	0.0012 ~ 0.0020	520

$$K = \frac{\tau}{\rho \bar{u}^2} = \frac{\overline{u'v'}}{\bar{u}^2} = \left(\frac{u_*}{\bar{u}}\right)^2$$

AUTHOR : KAWANABE, Y.

YEAR : 1964

DATA :

SITE.	y_o(m)	$1/\alpha$	$\left(\frac{\sqrt{\overline{u'^2}}}{\bar{u}}\right)_{30}$
TOKIO	2.32	0.285	(0.391)
SEA AND LAND.	0.044	0.117	(0.153)

COMMENTS. THE DATA HAVE BEEN ASSESSED OVER A LONG PERIOD AND THEREFORE SEEM FAIRLY RELIABLE. AN INDEX OF 0.34 HAS BEEN QUOTED FROM THIS REF. FOR TOKIO, HOWEVER THIS IS THE MAXIMUM VALUE OF THE RESULTS QUOTED. THE MEAN VALUE IS QUOTED AS 0.285 WHICH HAS BEEN TAKEN AS BEING MORE REPRESENTATIVE OF ALL THE SITE DATA.

AUTHOR : LUMLEY, J.L., PANOFSKY, H.A.

YEAR : 1964

DATA :

RELEVANT SECTION CONSISTS MAINLY OF QUALITATIVE DISCUSSION OF BOUNDARY LAYER STRUCTURE. THE FOLLOWING DATA HAS BEEN EXTRACTED:-

$\sqrt{\overline{u'^2}}/U_*$	$\sqrt{\overline{w'^2}}/U_*$	$\sqrt{\overline{v'^2}}/U_*$
2.5	2.0	1.25
		1.33
		0.7
		0.87

ABOVE DATA ASSUMED TO BE INDEPENDENT OF HEIGHT BUT DEPENDENT ON TERRAIN TYPE.

(a) FOR $2 \leq y(m) \leq 30$ — $0.0648 \leq \sqrt{\overline{v'^2}}/\bar{u} \leq 0.12$

IF $\sqrt{\overline{v'^2}}/U_* = 1.25$ THEN :-

$$\sqrt{\overline{v'^2}}/\bar{u} = 0.5 \; {}^{1}/_{\log_e y/y_o}$$

(b)

SITE	y(m)	y_o(m)	$\sqrt{\overline{w'^2}}/\bar{u}$	$\sqrt{\overline{v'^2}}/\bar{u}$	$\left(\frac{\sqrt{\overline{u'^2}}}{\bar{u}}\right)_{30}$	y_o(m)
ROUND HILL	11	0.10	0.208		(0.218)	(0.30)
BROOKHAVEN	23	1.00	0.195		(0.242)	(0.49)
	46		0.169			
	91		0.146	0.128		

IF $\sqrt{\overline{w'^2}}/U_* = 2.0$ THEN :-

$$\sqrt{\overline{w'^2}}/\bar{u} = 0.8 \; {}^{1}/_{\log_e y/y_o}$$

(c)

IF $\sqrt{\bar{u}^2}/U_* = 2.5$ THEN :-

$$\sqrt{\bar{u}^2}/\bar{u} = 1.0 \; {}^{1}/_{\log_e y/y_o}$$

ESTIMATES OF THE TURBULENCE INTENSITIES FROM THE ABOVE EXPRESSIONS ARE ASSUMED TO BE ACCURATE TO AT LEAST 20%.

DISCUSSION OF SPECTRA ARE MAINLY :-

(a) LONGITUDINAL :-

MOSTLY DAVENPORT'S DATA.

(b) LATERAL :-

COMMENTS MAINLY ON STABILITY EFFECTS.

(c) VERTICAL :- FIG. 42.

MOST OF THE RELEVANT COMMENTS IN PREVIOUS PANOFSKY PAPERS : e.g. Lu_x INCREASES WITH HEIGHT UP TO 100~200 m (330~660 FT.) AND THEN IS CONSTANT WITH INCREASE OF HEIGHT.

AUTHOR : MUNN, R.E.

YEAR : 1964

DATA :

SITE.	y(m)	$\sqrt{\bar{u}^2}/\bar{u}$	$\sqrt{\bar{v}^2}/\bar{u}$
DOUGLAS PT.	2 ↓ 25	REDUCES BY 50%	CONSTANT

COMMENTS. DATA MAY ONLY APPLY TO STABLE CONDITIONS – DIFFICULT TO ASSESS.

AUTHOR : NOVIKOV, E.A., STEWART, R.W.

YEAR : 1964

DATA :

MAINLY THEORETICAL. SUGGESTS THAT THE PROBABILITY DISTRIBUTION OF THE FLUCTUATING VELOCITIES MAY DIFFER FROM THE GAUSSIAN DISTRIBUTION.

AUTHOR : PASQUILL, F., BUTLER, H.E.

YEAR : 1964

DATA :

ON DERIVATION OF LENGTH SCALES FROM AUTO-CORRELATION DATA, IT IS SUGGESTED THAT THE ESTIMATION OF THE TIME T (or t_s) USUALLY DEMANDS SOME DEGREE OF EXTRAPOLATION OR ADJUSTMENT BECAUSE THE REQUIRED CONDITION OF $R(t)$ FALLING TO, AND REMAINING, ZERO IS NOT ALWAYS ACHIEVED IN PRACTISE. ALTERNATIVELY SCALES MAY BE DERIVED FROM SPECTRA :- CONSIDER FOLLOWING FORMS OF THE SPECTRA_

(a) $\frac{nS(n)}{\sigma^2} = \frac{2}{\pi(\frac{1}{N}+N)}$ - CORRESPONDS TO EXPON. AUTO-CORR.

(b) $\frac{nS(n)}{\sigma^2} = \frac{N}{(1+N)^2}$ - PANOFSKY, McCORMICK

(c) $\frac{nS(n)}{\sigma^2} = \frac{N}{(1+\frac{3}{2}N)^{5/3}}$ - FOLLOWS $5/3$ LAW.

WHERE $N = n/n_p$, n_p = FREQUENCY AT SPECTRUM PEAK.

WHEN $n=0$,

$$S(0) = 4\sigma^2 t_s$$ (SINCE SPECTRUM IS FOURIER TRANSFORM OF CORRELATION.)

HENCE :

SINCE $L = \bar{u} t_s$

$$L = \overset{(a)}{\frac{1}{2\pi}} \cdot \bar{u}/n_p \quad , \quad \overset{(b)}{\frac{1}{4}} \cdot \bar{u}/n_p \quad , \quad \overset{(c)}{\frac{1}{4}} \cdot \bar{u}/n_p$$

SITE.	y(m)	L_{ux}(m) ?
GRASSLAND	2	4

AUTHOR : SINGER, I.A.

YEAR : 1964

DATA :

MAINLY A REVIEW PAPER. $(y_0(m)) = (0.91)$

SITE.	y(m)	$1/\alpha$	$\sqrt{\bar{u}^2}/\bar{u}$	$\sqrt{\bar{w}^2}/\sqrt{\bar{u}^2}$	$\sqrt{\bar{v}^2}/\sqrt{\bar{u}^2}$	$\overline{u'v'}/D_0^2$	$\left(\sqrt{\bar{u}^2}/\bar{u}\right)_{30}$
BROOKHAVEN.	23	0.22	0.31	0.90	0.40	0.0032	(0.285)
	110		0.24				

$1/\alpha$ - TAKEN FROM PREVIOUS SITE DATA.

THE REMAINING POINTS OF INTEREST ARE :-

(a) IT WAS SUGGESTED THAT

$$L_{ux} \simeq 2 L_{uy}$$

(b) THE $^{5}/_{3}$ LAW WAS REGARDED AS BEING APPLICABLE TO LOWER FREQUENCIES FOR THE LONGITUDINAL SPECTRUM THAN THE OTHER SPECTRA IE LOCALLY ISOTROPIC FLOW DOWN TO APPROX:-

$$\bar{u}/n < 100(m)$$

(c) CONFIRMED THAT THE FLUCTUATING VELOCITIES OBEY A NORMAL OR GAUSSIAN DISTRIBUTION LAW.

COMMENTS: THE VALUE OF 0.9 FOR THE QUANTITY $\sqrt{\overline{w^2}}/\sqrt{\overline{u^2}}$ IS HIGH — IT IS POSSIBLE THAT IT MAY BE A FUNCTION OF SITE ROUGHNESS AT LOW LEVELS.

AUTHOR : SOMA, S.

YEAR : 1964

DATA : MEAN VALUES OF SEVERAL RUNS TABULATED AS FOLLOWS:-

SITE.	$1/\alpha$	$y_o(m)$	$y(m)$	$\sqrt{\overline{u^2}}/\bar{u}$	$L_{ux}(m)$	$\overline{u'v'}/U_o^2$	$(\sqrt{\overline{u^2}}/\bar{u})_{30}$
TOKIO.	0.302	2.32	26	0.222	117	0.002	0.20
			67	0.164	225		(0.39)
			107	0.135	204		
			173	0.114	230		
			253	0.088	287		

L_{ux} ESTIMATED FROM SPECTRA.

THE VARIATION OF THE REYNOLDS STRESS WITH HEIGHT IS SHOWN IN FIG. 42. . CLEARLY THIS CAN BE TAKEN AS CONSTANT UP TO A HEIGHT OF AT LEAST 200m (660 FT.) BY IGNORING THE LOWEST READING.

$$C_K = \overline{u'v'}/\bar{u}^2$$

COMMENTS: THE TURBULENCE INTENSITIES WOULD BE EXPECTED TO BE HIGHER e.g. Cf. SINGER 1964:—

for $y = 110$ m., $\sqrt{\overline{u^2}}/\bar{u} = 0.24$.

AUTHOR : THULLIER, R.H. ; LAPPE, U.O.

YEAR : 1964.

DATA :

SITE.	$y(m)$	$y_o(m)$	$1/\alpha$	$\overline{u'v'}/U_o^2$	$(\sqrt{\overline{u^2}}/\bar{u})_{30}$
CEDAR HILL (OPEN FIELDS, SMALL ORCHARDS)	10-137	0.03	0.143	0.00145	(0.145)

AUTHOR : YAMAMOTO, G.; SHIMANUKI, A.

YEAR : 1964

DATA :

SITE	y_o(m)	$(\sqrt{\overline{u'^2}}/U)_{30}$
TOKIO	1.45 ~ 1.85	(0.345)

OTHER RELEVANT POINTS :-

THKKNESS OF THE CONSTANT SHEAR STRESS LAYER FOUND TO BE GREATER OVER ROUGH THAN SMOOTH TERRAIN i.e. CONSTANT SHEAR STRESS LAYER EXTENDS TO A HEIGHT OF ABOUT 200 m. MOSTLY THEORETICAL PAPER.

AUTHOR: BERMAN, S.

YEAR : 1965

DATA :

ANALYSED THE SPECTRA OF THE LONGITUDINAL VELOCITY FROM VARIOUS SITES ; FROM THE DATA FOR ALL THESITES COLLECTIVELY THE FOLLOWING IS DEDUCED :-

y(m)	2 ,	4 ,	12 ,	15 ,	16 ,	23 ,	30 ,	46,	64 ,
L_{ux}(m)	28·6 ,	31·1 ,	53·4 ,	72·4 ,	49·6,	55·5 ,	88 ,	96 ,	66 ,
	91 ,	153.							
	134 ,	74.							

IN ORDER TO ASSESS HOW L_{ux} VARIES AS A FUNCTION OF y_o DATA FROM SOME PARTICULAR SITES HAVE BEEN ANALYSED TO GIVE THE FOLLOWING :-

SITE	y(m)	y_o(m)	L_{ux}(m)	$\frac{\overline{u'v'}}{U_o}$
BROOKHAVEN.	16	1.00	36·6	
ROUND HILL.	16	0.1 ~ 0.04	55	0.0028
CARDINGTON.	15	0.01	82	
BROOKHAVEN	64	1.00	66	
SALE	46	0.025	96	

$\therefore$ L_{ux} INCREASES AS y_o DECREASES.

AUTHOR SUGGESTS, $L_{ux} \propto y^{0.29}$ (Cf. WEBB '55, $L_{ux} \propto y^{0.5}$)

COMMENTS: SOME DEGREE OF ERROR IS POSSIBLE IN THE ABOVE DATA DUE TO THE FACT THAT THE NEUTRAL CASES, FOR SOME SITES, WERE DERIVED BY INTERPOLATION ; HOWEVER IT IS CONSIDERED THAT THIS ERROR SHOULD NOT BE EXCESSIVE.

ANALYSIS OF THE DATA INDICATES FAIRLY CONCLUSIVELY THAT THE TURBULENT LENGTH SCALE INCREASES AS y_o REDUCES. THIS POINT IS WORTH NOTING SINCE MORE UP-TO-DATE LITERATURE SUGGESTS EITHER THE OPPOSITE OR THAT THE LENGTH SCALE IS INDEPENDENT OF y_o, WITHOUT, HOWEVER, HAVING ANALYSED ALL OF THE AVAILABLE DATA.

AUTHOR : BLACKADAR, A.L. ET AL.

YEAR : 1965

DATA :

MUCH OF THE RELEVANT DATA HAS PREVIOUSLY BEEN EXTRACTED FROM BLACKADAR (1962).

ADDITIONAL DATA INCLUDE :-

SITE	y_o (m)	$\overline{u'v'}/U_o^2$
BROOKHAVEN.	1.00	0.0025
HANFORD.	0.05	0.0012
O'NEILL.	0.006	

SUGGESTS THAT VELOCITY PROFILES DEVIATE FROM THE LOG-LAW FOR $y > 10$ TO 100m.

AUTHOR: BYZOVA, N.L., MASHKOVA, G.B.

YEAR : 1965

DATA :

AUTHOR : DAVENPORT, A.G.

YEAR : 1965

DATA :

SITE	y (m)	y_o (m)	$1/\alpha$	$\overline{u'v'}/U_o^2$
LONDON (ONT.)	25-41	2.42	0.36	0.0016

AUTHOR : FALLER, A.J.

YEAR : 1965

DATA :

THE LARGE EDDIES IN ADIABATIC SHEAR FLOWS ARE ATTRIBUTED TO SHEAR INSTABILITY OF MEAN FLOW. SUGGESTS THAT THE VERTICAL VELOCITIES INDUCED BY SUCH EDDIES COULD BE OF THE ORDER $0.1\,\bar{U}_0$ AND THAT SUCH EDDIES MOVE SLOWLY IN THE MEAN FLOW.

AUTHOR : LAPPE, O.S.

YEAR : 1965

DATA :

MAINLY CONCERNED WITH VERTICAL GUSTS RE-EFFECTS ON AIR CRAPT.

POINTS OF INTEREST :-

(a) SPECTRAL FORM OF VERTICAL GUSTS REPRESENTED BY:-

$$\phi(k) = \frac{2\pi L}{(1+2\pi kL)^2}$$

WHERE $k = n/\bar{u}$, L = SCALE PARAMETER, FUNCTION OF y AND y_0.

(b) $\sqrt{\overline{w^2}}$ ASSUMED CONSTANT UP TO $y \simeq 300$m.

(c) LOG-LAW FOUND TO BE APPLICABLE UP TO $y \simeq 140$m. AND TO FOLLOW THIS LAW MORE CLOSELY AS y_0 INCREASES.

AUTHOR : MONIN, A.S.

YEAR : 1965

DATA :

MAINLY THEORETICAL PAPER

$\sqrt{\overline{u^2}}/U_*$	$\sqrt{\overline{w^2}}/U_*$	$\sqrt{\overline{v^2}}/U_*$
2.4	1.7	0.8

SUGGESTS TURBULENCE INTENSITIES ARE DEPENDENT ON THE VARIATION OF THE WIND DIRECTION WITH HEIGHT i.e.

$$\frac{\sqrt{\overline{w^2}}/\sqrt{\overline{u^2}}}{} \simeq \frac{1+\sin^2\beta}{1+\cos^2\beta}$$

β = CHANGE OF WIND DIRECTION = α'

AUTHOR : OLIPHANT, J.E., PANOFSKY, H.A.

YEAR : 1965

DATA :

DISCUSSION OF y_0 VARIATION AT BROOKHAVEN AS FUNCTION OF FETCH. i.e. THERE ARE TWO 'LAYERS' FROM WHICH y_0 MAY BE DEDUCED (SEE LATER - FRIZZOLA 1967), MEAN VALUE IS 1.0m (d = 5.5m) FOR $\bar{h}$ = 8.2m.

AUTHOR: PANOFSKY, H.A, SINGER, I.A.

YEAR : 1965

DATA :

GENERAL POINTS OF INTEREST SUGGESTED:-

(a) UPPER SECTIONS OF BOUNDARY LAYER EDDIES ARE DOWNWIND OF LOWER PARTS, HAVING SLOPES OF APPROXIMATELY 1, DUE TO WIND SHEAR.

(b) L_{u_x} INCREASES WITH HEIGHT AT SLOWER RATE THAN y. SUGGESTS,

$$L_{u_x} \propto y^{0.66}$$

COMMENTS:

THE REASONS FOR THE DISCREPANCIES IN DETERMINING L_{u_x} AS $f(y)$ WILL BE DISCUSSED LATER.

AUTHOR : 1ST. CAN. CONF. ON MICROMET.

YEAR : 1965

DATA :

PARTICULAR DATA : SITE : O'NEILL , y_o(m) = 0.0067

GENERAL DATA : $\sqrt{\bar{w}^2}/U_* = 2.0$, $\sqrt{\bar{v}^2}/U_* = 1.0$ } FIGS. 43, 44

IN FIGS. $B = \frac{g}{T} \frac{y^2}{\bar{u}^2} \frac{\partial \theta}{\partial y}$

θ = POTENTIAL TEMP.

SCATTER CAN PARTLY ATTRIBUTED TO SITE DEPENDANCE OF ABOVE 'CONSTANTS'.

AUTHOR : SWANSON, R.N., CRAMER, H.E.

YEAR : 1965

DATA :

SITE	h (m)	p (m)	y (m)	$\sqrt{\bar{w}^2}/\sqrt{\bar{u}^2}$
WHITE SANDS (BRUSH TOPPED SAND DUNES)	2.5	8	1	0.60 (fn. of y)

ϕ = DUNE PITCH.

(a) LONG. AND LAT. TURBULENCE ARE SHOWN TO DECREASE WITH INCREASE OF y FOR ALL THERMAL STRATIFICATIONS – FIG. 45.

(b) SUGGESTS

$$\sqrt{\bar{u}^2}/\bar{u} = C y^p$$

WHERE C = fn. OF y_o

(c) FIG. SUGGESTS $\sqrt{\bar{u}^2}/\bar{u} = f(\bar{u})$ AND GIVES

$$\left(\sqrt{\bar{u}^2}/\bar{u}\right) \simeq 0.20 \quad \text{FOR } y = 30\text{m}.$$

AUTHOR : ZBROZEK, J.K

YEAR : 1965

DATA :

MAINLY CONCERNED WITH METHODS OF ESTIMATING AIRCRAFT GUST LOADS. MAIN POINTS OF INTEREST :-

(a) $\sqrt{\overline{u^2}}/\overline{u}_{10} \approx 0.20$ (TERRAIN ?)

(b) SCALE OF TURBULENCE INCREASES WITH HEIGHT AT LEAST UPTO $y = 300m$.

(c) SUGGESTS SOME CONFUSION EXISTS DUE TO DIFFERENT DEFINITIONS OF "LENGTH SCALES" OF TURBULENCE.

(d) ASSUMES

$L_{u_x} \propto y$.

AUTHOR: BARRY, P.J.

YEAR : 1966.

DATA :

MAINLY A CRITICAL REVIEW OF METHODS OF ESTIMATING U_*, WHICH GENERALLY INVOLVES A KNOWLEDGE OF y_o. THE RIDER (1954) DATA IS CONSIDERED IN SOME DETAIL RE- y_o ESTIMATES. ALTHOUGH RIDER QUOTES A VALUE OF $\bar{y}_o = 0.32$cm FROM HIS DATA, THE AUTHOR SHOWS THAT IT IS POSSIBLE TO ESTIMATE A VERY WIDE RANGE OF VALUES FROM THE MEASUREMENTS.

COMMENTS:

THE MAIN POINT HERE, WHICH IS ONLY CONSIDERED BRIEFLY IN THE REPORT, IS THE FACT THAT THE DATA ONLY COVER A RANGE OF HEIGHT OF 0~2m. HENCE THE MEAN VELOCITY MEASUREMENTS MUST BE EXTREMELY SENSITIVE TO SMALL CHANGES IN SURFACE VEGETATION AND PROBABLY TO WIND DIRECTION; THIS MAY LEAD TO WIDE VARIATIONS IN THE DETERMINATION OF y_o RATHER THAN THE ANALYSIS TECHNIQUES USED. THEREFORE THE y_o VALUE QUOTED BY RIDER IS TAKEN TO BE RELIABLE.

AUTHOR: DELAND, R.J., BINKOWSKI, F.S.

YEAR : 1966

DATA :

SITES.	y (m)	y_o(m)	$\overline{1/\alpha}$
MINNEAPOLIS- ST. PAUL.	150m +	(2m +)	0.31
LOUISVILLE	~	(2m +)	0.26

DEPTH OF LOG-LAYER SUGGESTED TO BE ≈ 100m.

AUTHOR: ELDERKIN, C.E.

YEAR : 1966

DATA :

SITE	y_o(m)	y(m)	$\sqrt{\overline{u'^2}}/\bar{u}$	$\sqrt{\overline{w'^2}}/\bar{u}$	$\sqrt{\overline{v'^2}}/\bar{u}$	$\overline{u'v'}/\bar{U}_o^2$	$\overline{u'w'}/\bar{U}_o^2$
HANFORD	0.025	3	0.23	0.16	0.11	0.0018	0.00038
		6.1	0.18	0.12	0.09	0.0015	0.00012

$\sqrt{\overline{u'^2}}/U_*$	$\sqrt{\overline{w'^2}}/U_*$	$\sqrt{\overline{v'^2}}/U_*$	$\sqrt{\overline{w'^2}}/\sqrt{\overline{u'^2}}$	$\sqrt{\overline{v'^2}}/\sqrt{\overline{u'^2}}$	L_{ux}(m)
2.92	2.04	1.32	0.70	0.48	12.2
2.61	1.71	1.37	0.67	0.50	24.0

$\overline{1/\alpha} = 0.12$ (DE MARRAIS 1959)

ESTIMATES GIVE : $y_o = (0.023\text{m})$; $\left(\sqrt{\overline{u'^2}}/\bar{u}\right)_{30} = (0.141)$

AUTHOR : MAC CREADY, P.B.

YEAR : 1966.

DATA :

DEALS WITH MEASUREMENTS OF MEAN VELOCITY PROFILES AND ERRORS INVOLVED DUE TO DEVIATION OF WIND DIRECTION, E.G. STANDARD DEVIATION OF WIND DIRECTION IN VERTICAL PLANE (IN EFFECT VERTICAL TURBULENCE) IS GIVEN AS:-

$$\sigma_\theta = 0.42 \left(\log_e y/y_o\right)^{-1}$$

(Cf. PANOFSKY, McCORMICK 1960 :-

$$\sqrt{\overline{v^2}}/\bar{u} \simeq 0.5 \left(\frac{1}{\log_e y/y_o}\right) \quad)$$

AUTHOR: MORDUKOVICH, H.I., TSUANG, L.R.

YEAR : 1966.

DATA :

SITE.	y (m)	$\sqrt{\overline{u^2}}/U_*$	$\sqrt{\overline{v^2}}/U_*$
OPEN COUNTRY	1	2.8	1.2
	4	2.3	1.2

$\sqrt{\overline{u^2}}/U_*$ AGREES WITH SWINBANK 1955 AND ZUBKOUSKI 1962.

$\sqrt{\overline{v^2}}/U_*$ AGREES WITH E.G. PANOFSKY, McCORMICK 1960, PASQUILL 1962,
BUT GURVICH 1962 GIVES - 0.70.

AUTHOR: KRAUS, E.B.

YEAR : 1966

DATA :

ASSUMED $^1/_\alpha = 0.11$, $\delta = 600m$ FOR ESTIMATE OF STRESS

SITE	y (m)	y_o (m)	$\overline{u'v'}/\bar{U}_o^2$
SEA	0~10	0.0001	0.00036

AUTHOR: POND, S. ET AL.

YEAR : 1966

DATA.

SITE.	y (m)	$\sqrt{\overline{u^2}}/\bar{u}$
SEA	1~5	0.10 (ORIGIN ?)

RE-SPECTRA: $-5/3$ LAW APPLIES DOWN TO $n/\bar{u} \simeq 0.0025$,
BELOW THIS LAW OF -1 FITS DATA BETTER.

AUTHOR: PRITCHARD, F.E.

YEAR : 1966

DATA :

GENERALISED DATA OF STRUCTURE OF TURBULENCE FOR USE IN AIRCRAFT DESIGN CALCULATIONS.

MAIN RELEVANT POINTS ARE AS FOLLOWS:-

(i) L_{ux} INCREASES (NEUTRAL DATA) WITH INCREASE OF HEIGHT UP TO ABOUT 120m. AND IS THEN CONSTANT UP TO A HEIGHT OF $y \simeq 370m$ (FIG. 46.)

(ii) FOR $y \geq 150m$ ALL TURBULENT LENGTH SCALES ARE ASSUMED TO BE EQUAL.
FOR $y \leq 150m$

$$\frac{L_{ux}}{L_{vx}} = \frac{L_{wx}}{L_{vx}} = 1.3 \quad \text{(VERY APPROX.)}$$

(iii) FIG. 46 INDICATES THAT THE LENGTH SCALES DEPEND ONLY ON y AND THE TEMP. GRADIENT, BUT OTHER WORK (E.G. TAYLOR 1965) HAS ASSUMED THAT GREATER ROUGHNESS GIVES GREATER LENGTH SCALES.

(iv) FIG. 47 SHOWS $\sqrt{\overline{u'^2}}/\bar{u}$ TO BE APPROX. CONSTANT AS y INCREASES UP TO ABOUT 370m.

(v) TURBULENCE ASSUMED TO BE ISOTROPIC FOR $y > 300m$.

(vi) FOR $y < 30m$:-

$$\frac{\sqrt{\overline{w^2}}}{\sqrt{\overline{u^2}}} = 0.66 \quad , \quad \frac{\sqrt{\overline{v^2}}}{\sqrt{\overline{u^2}}} = 0.33 \quad \text{(APPROX. VALUES.)}$$

(vii) ONE OF THE FIRST ATTEMPTS TO DEFINE THE TURBULENCE INTENSITY AS A FUNCTION OF TERRAIN TYPE; THE VARIATIONS SUGGESTED ARE VERY APPROXIMATE. BUT GIVE THE CORRECT TREND.

AUTHOR : BLACKADAR, A.K., CHAPLIN, A.S.

YEAR : 1967

DATA :

PAPER IS MAINLY THEORETICAL. VELOCITY PROFILES ARE ANALYSED UP TO A HEIGHT OF 200m BASED ON THE ASSUMPTIONS THAT α' IS CONSTANT NEAR THE GROUND, THEN VARIES SLOWLY WITH HEIGHT AND FINALLY VARIES MORE RAPIDLY.

THEY ASSUME α' IS CONSTANT FOR $0 \leq y(m) \leq 200$ AND HENCE DERIVE:-

$$\bar{u}_y / u_* = \frac{1}{k} \log_e \left(\frac{y + y_o}{y_o} \right) + cFy$$

WHERE

$F = 2\omega \sin\phi$ - CORIOLIS PARAMETER.

$C = \text{CONST} = f(u_*, \alpha', R_o)$ - A RELATIONSHIP FOR WHICH WAS DERIVED BY BLACKADAR.

THIS EFFECTIVELY PRODUCES A LINER PLOT OF $\log u \sim y$ UP TO THE HEIGHT TO WHICH ANALYSIS IS CARRIED OUT. THEREFORE y_o VALUES CAN BE DERIVED FROM VELOCITY MEASUREMENTS MADE OUTSIDE THE TRUE LOG-LAYER.

COMMENTS.

ABOVE ANALYSIS MAY BE JUSTIFIABLE ON THEORETIC BASIS BUT CAN LEAD TO LARGE ERRORS IN DETERMINATION OF y_o. THIS WILL BE ILLUSTRATED LATER.

AUTHOR: DAVENPORT, A.G.

YEAR : 1967

DATA :

MOST OF THE RELEVANT DATA ALREADY CONSIDERED PREVIOUSLY IN THIS WORK.

SITE.	y_o(m)	y(m)	$1/\alpha$	L_{ux}(m)
ST. LOUIS.	1.7	37~152	0.28	
MONTREAL.	1.0	12~300	0.28	
		76		110

MAIN POINTS FROM PAPER :-

(a) BEST AVERAGING TIME FOR DETERMINATION OF $\bar{u} \approx$ 20 MINS.

(b) FOR BUILT-UP AREAS $1/\alpha \simeq 0.36$ (Cf. DAVENPORT '63, $1/\alpha \simeq 0.40$)

(c) URBAN AND RURAL SPECTRA SHOWN TO BE SIMILAR, FIG. 48

(d) RECENT DATA CONFIRMS NORMALITY OF PROBABILITY DISTRIBUTION OF FLUCTUATING VELOCITIES.

(e) SUGGESTS THAT THE THEORETICAL INVESTIGATIONS OF THE VELOCITY PROFILE (E.G. THOSE OF BLACKADAR, LETTAU ETC.) CANNOT BE VERY RELIABLE SINCE THEY ARE BASED ON THE AVAILABILITY OF KNOWLEDGE ON THE EDDY VISCOSITY; THIS RESULTS IN SOME DEGREE OF EMPIRICISM. HENCE DEFINING THE TERRAIN USING $1/\alpha$, y_o ETC DATA IS CONSIDERED TO BE MORE RELIABLE AND PRACTICAL. N.B.

AUTHOR : DAVENPORT, A.G., ISYUMOV, N.

YEAR : 1967(a)

DATA :

SITE.	y_o(m)	y(m)	$\sqrt{\overline{u^2}}/\bar{u}$	$(\sqrt{\overline{u^2}}/\bar{u})_{30}$	$(y_o$(m)$)$
BROOKHAVEN	1.0	23.8	0.32	0.29	1.0
		25	0.275	0.27 (INTERP.)	
		46	0.23~.24		
		92	0.214		

THE DAVENPORT FORM OF THE LONG. SPECTRUM IS RE-QUOTED IN TERMS OF $\sqrt{\overline{u^2}}$:-

$$\frac{n S(n)}{\overline{u^2}} = \frac{2}{3} \frac{\left(\frac{L n}{\bar{u}_{10}}\right)^2}{\left[1 + \left(\frac{L n}{\bar{u}_{10}}\right)^2\right]^{4/3}}$$

WHERE :- $L = 1200$ m , $\left[\sqrt{\overline{u^2}}/U_* \simeq 2.45 \text{ - DAVENPORT 1961b}\right]$

AUTHOR. ELDERKIN, C.E.
YEAR. 1967
DATA.

SITE	y_o(m)	y(m)	L_{ux}(m)
HANFORD.	0.03	3	16
		6.1	32
LIBERAL.	0.01	3	16
		6.1	32

GENERAL POINTS:-

(a) VERTICAL SPECTRA.
SIMILAR FOR BOTH SITES; SLIGHT SHIFT OF PEAK $ny/\bar{u}$ VALUE FOR STABLE CASES AND MORE LOW FREQUENCY ENERGY FOR UNSTABLE CASES. PEAK $ny/\bar{u}$ OCCURS AT ABOUT 0·40 (Cf. PANOFSKY, McCORMICK. 1960. $0.2 \leq ny/\bar{u} \leq 0.6$)

(b) LONGITUDINAL SPECTRA.
SIMILAR FOR BOTH SITES; PEAK $ny/\bar{u}$ AT 0·03 (APPROX.).
$-5/3$ LAW APPLIES DOWN TO ABOUT $ny/\bar{u}$ OF 0·40.

(c) LATERAL SPECTRA.
VARIATION WITH TERRAIN TYPE NOT AS CONSISTENT AS FOR OTHER SPECTRA; $-5/3$ LAW ALSO DOES NOT APPLY AS WELL.

AUTHOR. ESTOQUE, M.A.
YEAR. 1967.
DATA.

MAINLY THEORETICAL; ESTIMATES BOUNDARY LAYER PROFILE ASSUMING CORIOLIS EFFECT IS SMALL. SHOWS LOG LAYER IS SUITABLE UP TO $y \approx 100$m AT ROUND HILL SITE (SEE THULLIER AND LAPPE 1964.)

AUTHOR: FRIZZOLA, J. A. ET AL.
YEAR. 1967
DATA

DERIVED DATA –

SITE.	y_o(m)	y(m)	$1/\alpha$	$\overline{u'v'}/\bar{U}_o^2$	$\sqrt{\overline{u'^2}}/U_*$	L_{ux}(m)
BROOKHAVEN.	1.0	23	0.33	0.0025	1.22	73
		46			1.18	146
		92			1.26	292

N.B. LOWER LAYER OF FLOW GIVES y_o OF ORDER 10'S OF CMS. – HIGHER LAYER GIVES y_o OF ORDER SEVERAL M'S – HENCE $\bar{y}_o \approx 1$m.

OTHER GENERAL POINTS:-

(a) LONGITUDINAL SPECTRA.
NO EFFECTS DUE TO CHANGE OF STABILITY CONDITIONS.

(b) VERTICAL SPECTRA.
SPECTRAL PEAKS SHIFT TO HIGHER FREQUENCIES AS y INCREASES.

(c) LATERAL SPECTRA.
SPECTRAL PEAKS SHIFT TO HIGHER FREQUENCIES AS y INCREASES, ALSO INCREASE OF LOW FREQUENCY ENERGY AS STABILITY DECREASES.

AUTHOR: JONES, P.M., WILSON, C.B.
YEAR : 1967
DATA :
FOR URBAN AREA, z_0 = 0.33 MODELLED IN TUNNEL BUT SUGGESTED 0.50 MORE APPROPRIATE (SOURCE ?)

AUTHOR : KAIMAL, J.C., HAUGEN, D.A.
YEAR : 1967
DATA :
VERTICAL VELOCITIES ONLY CONSIDERED.

SITE.	y(m)
CEDAR HILL. (FLAT TERRAIN)	46, 137, 229, 320.

MAIN POINTS:-

(a) FIG. 49(a) SHOWS TYPICAL VARIATION OF NEUTRAL SPECTRA WITH INCREASE OF HEIGHT. AGREES WITH PANOFSKY, McCORMICK (1960) DATA. IF n_p DECREASES AS y INCREASES, ALSO $f_p (= n_y/\bar{u})$ LIES BETWEEN 0.15 AND 0.35 (Cf. 0.25 - 1960 DATA.)

(b) SHOWS INCREASE OF SCALE OF TURBULENCE UP TO y OF ABOUT 200m, THEN REMAINS CONSTANT OR STARTS TO DECREASE SLIGHTLY WITH INCREASE OF y - THIS AGREES WITH KOPROV ('65) AND MOORE ('67). THE FORMER INDICATED A MAXIMUM AT $y \simeq 200$m., FOLLOWED BY A GRADUAL DECREASE TO ABOUT 1000m., AND THEN AN ABRUPT DECREASE TO VERY LOW VALUES.

(c) SHOWS, $(\sqrt{\bar{u}^2})^3 \propto \varepsilon / n_p$ WHERE ε = DISSIPATION.
(ALSO SUGGESTED BY PASQUILL 1967.)
OR DISSIPATION CAN BE DERIVED FROM SPECTRA SINCE,
$S(n/\bar{u}) \propto \varepsilon^{2/3} (n/\bar{u})^{-5/3}$

AUTHOR: KLINE, S.J. ET AL.
YEAR : 1967.
DATA :

MAINLY CONCERNING THE BOUNDARY LAYER STRUCTURE FROM FLAT PLATE BOUNDARY LAYER MEASUREMENTS. SHOWED THE EXISTENCE OF SECONDARY VORTICITY (LARGE SCALE EDDIES OF TOWNSEND 1957) IN THE INNER REGION OF THE BOUNDARY LAYER. IT IS SUGGESTED THAT THE ACTION OF THESE SECONDARY VORTICES ON THE SPANWISE VORTICITY GIVES RISE TO THE FORMATION OF WALL STREAKS. THE FLUID SUBSEQUENTLY EJECTED AWAY FROM THE WALL IS CONSIDERED TO BE THE MAIN MECHANISM FOR THE TRANSFER OF TURBULENT ENERGY BETWEEN INNER AND OUTER LAYERS.

QUANTITATIVE DATA INCLUDE INTERMITTENCY MEASUREMENTS (FIG. 49b.) (SEE ALSO CORRSIN, KISTLER 1954)

AUTHOR : LILLY, D.K., PANOFSKY, H.A.
YEAR : 1967.
DATA :

GENERAL REVIEW PAPER.

THE RATIO OF: $\frac{S(n)\ \text{LONG.}}{S(n)\ \text{LAT.}} \simeq 4/3$ (IN INERTIAL SUB-RANGE)

IS GENERALLY, BUT NOT ALWAYS, AGREED ON ; IT HAS BEEN CONFIRMED THAT ITS ACCURACY DEPENDS ON THE ACCURACY OF THE $2/3$ POWER OF THE DISSIPATION TERM ε (SEE e.g. KAIMAL, HAUGEN OR PASQUILL 1967.)

AUTHOR: MOORE, D.J.
YEAR : 1967.
DATA :

POINTS OF INTEREST :-

(a) TURBULENCE GENERALLY ISOTROPIC AT $y \simeq 200$m (i.e. $y/\delta \simeq 0.33$)

(b) $\left(\sqrt{\overline{u'^2}}/\sqrt{\overline{w'^2}}\right) \simeq 0.75$, WHICH AGREES WITH FLAT-PLATE DATA ETC.

(c) FOR $\bar{u} > 10$m/sec, $\sqrt{\overline{u'^2}}$ DECREASES WITH INCREASE OF y UP TO 300m, ABOVE THIS HEIGHT THE RATE OF DECREASE SLOWS DOWN.

e.g. $\left(\sqrt{\overline{u'^2}}\right)_{300\text{m.}} / \left(\sqrt{\overline{u'^2}}\right)_{38\text{m.}} \simeq 0.40$

AND $\left(\sqrt{\overline{u'^2}}\right)_{1200\text{m}} / \left(\sqrt{\overline{u'^2}}\right)_{300\text{m}} \simeq 0.78.$

AUTHOR : PASQUILL, F.

YEAR : 1967

DATA :

SITE	y(m)
CARDINGTON.	300 ~ 1200.

SHOWS RELATIONSHIP BETWEEN $\sqrt{\overline{u'^2}}$ AND DISSIPATION :-

DISSIPATION $\varepsilon = u_*^3 / ky$

AND $\sqrt{\overline{u'^2}} = a u_*$

ALSO $n_p \simeq \bar{u} / b y$ (n_p = SPEC. PEAK FREQUENCY)

$$\therefore \left(\sqrt{\overline{u'^2}}\right)^3 = \frac{a^3 k}{b} \cdot \frac{\bar{u} \varepsilon}{n_p}$$

WHERE $a \simeq 1.2$, $b \simeq 8$ AND $k = 0.4$.

NOTE ALSO DISSIPATION TERM IN EXPRESSION FOR SPECTRUM INERTIAL RANGE ;

$$S(n) = C \bar{u}^{2/3} \varepsilon^{2/3} n^{-5/3} \qquad [C = \text{CONST.}]$$

AUTHOR : PAULSON, C.A.

YEAR : 1967.

DATA

SITE	$\bar{y}_o$(m)	$\overline{u'v'}/U_o^2$	$1/\alpha$ (ASS).
SEA	0.0004	0.0006	0.11

$$\left(\frac{\overline{u'v'}}{\bar{u}_{10}^2}\right) = C_D = \left(1 + 0.07\, \bar{u}_{10}\right) \times 10^{-3} \quad , \quad \bar{u}_{10} = \text{VEL. AT } y = 10\text{m.}$$

DATA FOR VARIOUS CONDITIONS OF TEMP. STRATIFICATION SHOWN IN FIG. 50 (ADIAB DATA □).

COMMENTS:

DATA AGREES VERY WELL WITH OTHER SEA MEASUREMENTS.

AUTHOR: SHELLARD, H.C.

YEAR : 1967.

DATA :

SITE	y(m)	y_o(m)	$\overline{1/\alpha}$	$\overline{\sqrt{u'^2}/\bar{u}}$	$\overline{h}$(m)
LONDON.	42.6		0.29	0.228	25 ?
	61			0.201	
	189			0.125	
MENDLESHAM.	18.3	0.13	0.17	—	
	91.5			0.099	
	300			0.064	

THE DEGREE OF SCATTER IN THE LONDON TURBULENCE DATA IS:-

y(m)	$\sqrt{\bar{u}^2}/\bar{u}$
42.6	0.15~0.32
61	0.14~0.27
189	0.07~0.18

THE VARIATION OF THE GUSTS WITH HEIGHT ($\propto \sqrt{\bar{u}^2} \sim y$) IS SHOWN TO FOLLOW A POWER LAW HAVING A POWER INDEX OF 0.09.

COMMENT.

THE HIGH TURBULENCE MEASURED AT 300m. IMPLIES THAT δ FOR RURAL TERRAIN IS > 300m. AS SUGGESTED IN DAVENPORT (1963).

AUTHOR: SHIOTANI, M., ARAI, H.

YEAR: 1967.

DATA:

SITE	y_o(m)	y(m)	$\sqrt{\bar{u}^2}/\bar{u}$	L_{ux}(m)	L_{uw}(m)	$\left(\sqrt{\bar{u}^2}/\bar{u}\right)_{30}$ / (0.104)
SHIKOKU ISLAND (ON SHORE WIND)	(0.002)	40	0.10	190	60	

ASSESSMENT OF AUTO-CORRELATION CURVES SUGGESTS

$$150 \leq L_{ux}(m) \leq 200$$

- AN ESTIMATE BASED ON $(\bar{u}/n)_p$ GIVES 190m.

AUTHOR: SINGER, I.A. ETAL.

YEAR: 1967.

DATA:

SITE	y(m)	$\sqrt{\bar{u}^2}/u_*$	L_{ux}
BROOKHAVEN.	23	1.27	87
	46	1.18	198
	92	1.26	366 ($\simeq$)

GENERAL POINTS:-

(a) LONG. SPECTRA. SIMILAR AT $y = 23, 92$m AND FOLLOW $-5/3$ LAW.

(b) VERTICAL SPECTRA. SUGGESTS FORM OF SPECTRA:-

$$\frac{n\,S(n)}{u_*^2} \propto \frac{x}{(1+1.5x)^{5/3}}, \quad x = f/f_m, \quad f = \bar{u}y/n$$

SPECTRA SHIFT TO RIGHT AS y INCREASES (PLOTTED AGAINST f.)

— AS $f \to \infty$:-

$$\frac{n\,S(n)}{u_*^2} \propto \frac{1}{1.5^{5/3}} \cdot x^{-2/3}$$

(AS PER KOLMOGOROFF)

(c) Lu_x INCREASES LINEARLY WITH y UP TO ABOUT 50m — AT GREATER HEIGHTS INCREASES MORE SLOWLY.

SUGGESTS $Lu_x \simeq 140m$ AT $y = 200m$

EXAMPLES OF SPECTRA GIVEN IN FIG 51.

(d) THE LATERAL SPECTRA AND SCALES ARE INTERMEDIATE BETWEEN LONG. AND VERT. SPECTRA.

AUTHOR : SMITH, S.D.

YEAR : 1967

DATA :

SITE	y (m)	$\frac{\overline{u'v'}}{U_0^2}$	Lu_x (m)	$\frac{\sqrt{\overline{u'^2}}}{u_*}$
SEA	5	0.00035	18	2.5 (INDEP. OF $\bar{u}$)

ADDITIONAL DATA GIVEN IN FIG. 52 a. WHERE

$C_D = \frac{\overline{u'v'}}{\bar{u}_5^2}$, $\bar{u}_5$ = VEL. AT $y = 5m$.

INDICATES RANGE OF DATA AVAILABLE FROM MEASUREMENTS OVER SEA.

GENERALLY THE DATA ALSO SHOW THAT Lu_x DECREASES VERY RAPIDLY AS THE SURFACE IS APPROACHED.

AUTHOR : TRITTON, D.

YEAR : 1967

DATA :

DETAILED MEASUREMENTS MADE IN FLAT PLATE BOUNDARY LAYER IN ATTEMPT TO DETERMINE BOUNDARY LAYER STRUCTURE. THE MAIN POINTS FROM THIS PAPER ARE CONCERNED WITH THE LARGE SCALE EDDY STRUCTURE OF THE BOUNDARY LAYER.

THE DATA DID NOT AGREE WITH THE LARGE EDDY STRUCTURE PICTURE PROPOSED BY TOWNSEND (1957) AND SUGGEST THAT THE SEPARATE DESCRIPTIONS OF LARGE EDDIES FOR INNER AND OUTER BOUNDARY LAYER REGIONS MAY BE INAPPROPRIATE.

AUTHOR : WEILER, H.S., BURLING, R.W.

YEAR : 1967

DATA :

SITE.	$\frac{\overline{u'v'}}{U_0^2}$
SEA	0.00052

GENERALLY CONFIRMS SMITH (1967) DATA.

AUTHOR : VOLKOVITSKAYA, Z.I., IVANOV, V.N.

YEAR : 1967.

DATA :

SITE.	y(m)	$\bar{y}_o$ (m)	$1/\alpha$	Lux(m)
(MET. TOWER-INST.	17	0.70	0.35	200
GEOPH. U.S.S.R.)	40			300
	85			400

AUTHOR : ZUBKOVSKI, S.L., KRAVCHENKO, T.K.

YEAR : 1967.

DATA :

SITE	y(m)	$\frac{\overline{u'v'}}{\sqrt{\overline{u'^2}}\sqrt{\overline{v'^2}}}$	$\sqrt{\overline{v'^2}}/\sqrt{\overline{u'^2}}$	$\sqrt{\overline{u'^2}}/U_*$
SEA	2	0.31	0.50	(SEE FIG. 52c)

SHOWS y_o CAN BE DERIVED FROM C_D :-

$$C_D = \tau/\rho \; 1/\bar{u}^2$$

ALSO

$$\bar{u} = U_*/k \log_e y/y_o \quad , \; U_* = \sqrt{\tau/\rho}$$

$$\therefore \quad \frac{k}{\log_e y/y_o} = \sqrt{\tau/\rho} \cdot \frac{1}{\bar{u}}$$

OR

$$\frac{k^2}{(\log_e y/y_o)^2} = \tau/\rho \cdot 1/\bar{u}^2 = C_D$$

FIG. 52 b SHOWS C_D IS FUNCTION OF $\bar{u}$ IE. DOES NOT AGREE WITH DATA OF SMITH 1967 (FIG. 52 a)

FIG. 52 c SHOWS, AS EXPECTED FROM PREVIOUS DATA, THAT $\sqrt{\overline{u'^2}}/U_*$ IS A FUNCTION OF y_o

IE. SOME REDUCTION FROM THE ACCEPTED VALUE OF 2.5 CAN BE EXPECTED AS TERRAIN ROUGHNESS INCREASES — OTHERWISE TURBULENCE ESTIMATES FROM,

$$\sqrt{\overline{u'^2}}/\bar{u} = 1 \times \frac{1}{\log_e y/y_o}$$

FOR HIGH y_o VALUES CAN BE EXPECTED TO BE EXCESSIVE - N.B.

COMMENT :

SUFFICIENT INFORMATION IS NOT AVAILABLE FROM WHICH TO OBTAIN A TRUE ESTIMATE OF HOW $\sqrt{\overline{u'^2}}/U_*$ SHOULD VARY WITH y_o — HOWEVER THIS WILL BE DISCUSSED AGAIN IN A LATER SECTION.

AUTHOR: — OTTAWA CONF.

YEAR : 1967

DATA :

PAPER 5.

TERRAIN TYPE SPECIFICATIONS:-

SITE	$1/\alpha$.	δ(m)
URBAN.	0.33	396
SUBURBAN.	0.22	336
RURAL.	0.14	274

PAPER 12.

SPECIFIES THAT FOR MODEL AND FULL SCALE SIMILARITY THAT THERE SHOULD BE EQUALITY OF:—

h/δ AND k/δ N.B

WHERE h = ROUGHNESS HEIGHT

k = LENGTH SCALE ASSOCIATED WITH ROUGHNESS SIZE IE OF y_o.

AUTHOR: BRADLEY, E.F.

YEAR : 1968.

DATA :

SITE	y_o (m)	$(u_*/\bar{u})^2_{y=2m}$
TARMAC.	0.00002	0.00147
MESH_VERT. SPIKES.	0.0025	0.00441
GRASS.	0.005	

AUTHOR: BRADSHAW, P.

YEAR : 1968

DATA :

MAINLY REFERRED TO FOR DATA ON BOUNDARY LAYER STRUCTURE AS FOLLOWS:-

(a) LENGTH SCALE OF LARGE EDDIES IS OF THE SAME ORDER OF MAGNITUDE AS THE BOUNDARY LAYER THICKNESS δ.

(b) LARGE EDDIES SEEM TO ARISE FROM INSTABILITIES IN THE TURBULENT SHEAR LAYER.

(c) LARGE EDDIES CONSIST OF A SLOW DRIFT OF ROTATIONAL FLUID WHERE $\bar{v}/\bar{U}$ IS NO GREATER THAN 0.10.

AUTHOR: BUSCH, N.E., PANOFSKY, H.A.

YEAR : 1968

DATA :

SITE	y(m)	L_{ux}(m)		$\sqrt{\overline{v^2}}/u_*$
ROUND HILL		A	B	
	15		60	
	16	102		
	40	159		
	46		120	
CEDAR HILL	46			1.35
HANFORD	4.5	14		
SEA	2(≈)	27		
	3(≈)	48		

FOR ROUND HILL DATA:- A – SMOOTH GRASS.
B – SCATTERED WOODS.

THE OTHER MAIN POINTS ARE AS FOLLOWS :-

(a) THE RATIO OF $\frac{S_w(n)}{S_u(n)} = \frac{S_v(n)}{S_u(n)} = \frac{4}{3}$ SHOWN TO BE VALID DESPITE A LOT OF SCATTER.

(b) SUGGESTED FORM FOR VERTICAL SPECTRUM:

$$\frac{n S_v(n)}{u_*^2} = \frac{1.075^{f/f_m}}{1 + 1.5(f/f_m)^{5/3}}$$

$f_m = 0.32$ FOR ADIAB. CONDITIONS = PEAK VALUE OF $ny/\bar{u}$.
(TENDS TO UNDERESTIMATE ENERGY AT LOW FREQUENCIES)

(c) SPECTRA AT VARIOUS HEIGHTS SHOW SHIFT OF PEAK f TO RIGHT WITH INCREASE OF y. (FIG. 53a)

(d) SPECTRA OVER SEA SHOW MUCH MORE ENERGY AT LOW FREQUENCIES (FIG. 53b.)

COMMENTS. DATA FROM ROUND HILL PROVIDE ADDITIONAL PROOF OF DECREASE OF L_{ux} AS SITE ROUGHNESS INCREASES.

AUTHOR: CHANDLER, T.J.

YEAR : 1968

DATA :

GENERAL REVIEW PAPER ; RELEVANT POINTS ARE AS FOLLOWS:-

(a) LATERAL SPREAD OF POLLUTANT UNAFFECTED BY DEGREE OF BACKGROUND TURBULENCE IN FLOW OVER CITIES. COULD IMPLY THAT LARGE ROUGHNESS ELEMENTS OF CITIES DO NOT PRODUCE LARGE SPANWISE GRADIENTS IN FLOW AS EXPECTED, WHICH WOULD PRODUCE LARGE LATERAL DIFFUSION.

(b) STUDIES OF AIRFLOW IN CITIES TEND TO BE CONCERNED WITH INDIVIDUAL BUILDINGS RATHER THAN WITH GROUPS OF BUILDINGS.

COMMENTS. RE-POINT (b) THIS OBVIOUSLY CAN AND DOES LEAD TO MISLEADING GENERAL ASSUMPTIONS RE-URBAN SITES, SINCE SUCH DATA IS MORE OFTEN THAN NOT ILLUSTRATING JUST A VERY LOCAL CHARACTERISTIC. N.B.

AUTHOR : ELDERKIN, C.E.

YEAR : 1968

DATA :

RELEVANT DATA INCLUDED IN ELDERKIN 1967.

SITE	y_o(m)
HANFORD	0.03

THE COSPECTRAL MEASUREMENTS OF $u'v'$ INDICATE, AS DO PREVIOUS DATA, THAT THE MAXIMUM ENERGY CONTENT IS IN THE RANGE,

$$0.1 \leq {}^{ny}/_{\bar{u}} \leq 1.0$$

AUTHOR: FICHTL, G.H.

YEAR : 1968 a

DATA :

VARIATION OF y_o WITH WIND DIRECTION FOR KENNEDY SPACE CENTRE (N.A.S.A. 150m. TOWER) :-

WIND DIRECTION	y_o(m)
0° ~ 150°	0.23
150° ~ 180°	0.51
180° ~ 240°	0.23
240° ~ 300°	0.65
300° ~ 360°	0.23

AUTHOR: FICHTL, G.H.

YEAR : 1968 b

DATA :

UNSTABLE DATA PRESENTED BUT OF INTEREST. ROUGHNESS LENGTH FOUND TO BE INDEPENDENT OF ATMOSPHERIC EQUILIBRIUM AND WIND SPEED :-

SITE	$\bar{y}_o$(m)
KENNEDY S.C.	0.23

FIG. 53 SHOWS DATA ON VARIATION OF SPECTRAL PEAK $f\ (= ny/\bar{u})$ AS A FUNCTION OF HEIGHT.

GIVES, $f_m \propto y^{4/5}$

AND SINCE, $L_{u_x} \propto y/f_m$

$\therefore \underline{L_{u_x} \propto y^{1/5}}$

OTHER DATA SUGGESTS :-

$$\underline{L_{u_x} \propto y^{3/5}} \quad \text{for } y < 60\text{m}.$$

COMMENTS: HOW f_m VARIES AS A FUNCTION OF y MUST DEPEND ON ATMOSPHERIC EQUILIBRIUM CONDITIONS, WHICH COULD ACCOUNT FOR SOME OF THE ABOVE DISAGREEMENT; IN ADDITION THE DISAGREEMENT COULD BE DUE TO THE FACT THAT f_m WILL ALSO BE A FUNCTION OF SURFACE ROUGHNESS.

AUTHOR: GRAHAM, I.R.

YEAR : 1968

DATA :

SITE		y(m)	$\sqrt{\bar{u}^2}/\bar{u}$	$\sqrt{\bar{w}^2}/\bar{u}$	$(y_o(m))$	$\left(\sqrt{\bar{u}^2}/\bar{u}\right)_{30}$
FORT WAYNE (URBAN)	A	30.5	0.178	0.120		
	A	91	0.117	0.089		
	B	22.9	0.382	0.339	1.31	0.32 (INT.)
	B	47.2	0.212	0.201		

A – WINDWARD EDGE OF CITY.

B – CITY CENTRE.

FOR $y = 9$m VARIOUS URBAN MEASUREMENTS GIVE

$$\underline{0.21 \leq \sqrt{\bar{u}^2}/\bar{u} \leq 0.33}$$

COMMENTS : RELATIVE MAGNITUDES OF $\sqrt{\bar{u}^2}/\bar{u}$ AND $\sqrt{\bar{w}^2}/\bar{u}$ DO NOT AGREE WITH OTHER DATA.

AUTHOR: HARRIS, R.I.

YEAR : 1968

DATA :

SITE	$1/\alpha$	y_o(m)	y(m)	L_{u_y}(m)	L_{w_y}(m)	$(y_o(m))$	$\left(N\sqrt{\bar{u}^2}/\bar{u}\right)_{30}$
RUGBY TOWER	0.176	0.07~0.08	17.7	56	16.2	0.03	0.169
			100	50	29		0.145 (INTER)
			182	100	34		

$\sqrt{\bar{u}^2}/\bar{u}$ AT $y = 30$m :- 0.145 FROM FIG. 54

FIG. 54 GIVES $\sqrt{\overline{u^2}}/\bar{u} \sim y(m)$ UP TO 180m. AND THE FORM OF THE CORRELATIONS FROM WHICH L_{uy} IS OBTAINED BY INTEGRATION.

ADDITIONAL DATA INCLUDES:-

(a) CHANGE OF WIND DIRECTION WITH HEIGHT BETWEEN 17.7 AND 182m IS APPROXIMATELY 10°, I.E. ABOUT 50% LESS THAN THAT PREDICTED BY THEORY.

(b) SUGGESTS FORM FOR SPECTRUM OF LONGITUDINAL VELOCITY—

$$\frac{S(n)}{} = \frac{0.6\,\bar{x}}{(2+\bar{x}^2)^{5/6}}, \quad \bar{x} = {}^{nL}/_{\bar{u}_{10}}$$

SUGGESTS L SHOULD BE OF ORDER 1800m.

(ABOVE FORM IS SIMILAR TO THAT DERIVED BY VON KARMEN 1948)

COMMENTS: ONE OF THE FEW RELIABLE SETS OF DATA FOR HEIGHTS > 100m.

AUTHOR: JONES, P.M. ET AL.

YEAR: 1968

DATA:

SITE	$y(m)$	$y_o(m)$	$1/\alpha$
LIVERPOOL	0~300	1.23	0.21

MORE DETAIL IN LATER PAPER.

AUTHOR: MERONEY, R.N.

YEAR: 1968

DATA:

GENERAL COMMENTS RE. TURBULENCE INTENSITY ETC. IN WAKE OF LARGE SCALE ROUGHNESS IE TREES (MODEL TESTS):-

(a) MAXIMUM TURBULENCE INTENSITIES, MEASURED AT ABOUT TREE TOP LEVEL, ARE OF THE ORDER 0.30 (BASED ON LOCAL VEL.) – GENERALLY FALL IN RANGE 0.20~0.30.

(b) MAX. INTENSITY STAYS RELATIVELY CONSTANT FOR ABOUT 50 TREE HEIGHTS DOWNSTREAM, ALTHOUGH FORM OF THE VERTICAL DISTRIBUTION OF INTENSITY CHANGES AS DOWNSTREAM DISTANCE INCREASES.

(c) AVERAGE INTENSITY FROM FULL-SCALE TESTS (TOURIN AND SHEN '66) IS 0.33

AUTHOR : MUNN, R.E.

YEAR : 1968

DATA :

SITE	$\overline{1/d}$	α'	
NEW YORK	0.32 (≃)	59°	(ADIAB. ?)

REVIEW PAPER, MAINLY SUMMARISES PROBLEMS TO BE SOLVED IN ORDER TO OBTAIN PROPER DEFINITION OF URBAN SITES. E.G.

(a) PROBLEM OF DEFINING REPRESENTATIVE URBAN SITES IN ORDER TO BE FREE OF LOCAL EFFECTS.

(b) PROBLEM OF DEFINING TRUE y_o AND d FOR URBAN SITES.

AUTHOR: PANOFSKY, H.A.

YEAR : 1968

DATA :

REVIEW PAPER – MOST OF DATA ALREADY CLASSIFIED.

SITE	$\sqrt{\overline{u'^2}}/\bar{u}$	$\sqrt{\overline{w'^2}}/\bar{u}$	$\sqrt{\overline{v'^2}}/\bar{u}$
GENERAL	2.5	2.0	1.25

AUTHOR: PANOFSKY, H.A., MARES, E.

YEAR : 1968

DATA

ASSESSMENT OF AVAILABLE CO-SPECTRAL ($u'v'$) DATA – MOSTLY FOR $y < 50m$.

SUGGEST FORM FOR COSPECTRUM SHAPE :-

$$\frac{n\,S_{uv}(n)}{u_*^2} = \frac{f/f_m}{(1+0.6\,f/f_m)^{8/3}}$$

$f = ny/\bar{u}$, $f_m \simeq 0.08$ FOR ADIABATIC CASE ; SUBJECT TO LARGE DEGREE OF SCATTER :-

$$0.05 \leq f_m \leq 0.12 \quad \text{(AT LEAST)}$$

MOST OF ENERGY CONTAINED IN RANGE –

$$0.01 \leq f \leq 1.0$$ – FIG. 55

COMMENTS :

ONE OF FIRST ATTEMPTS TO EMPIRICISE CO-SPECTRAL DATA.

AUTHOR: SHIOTANI, M.

YEAR : 1968

DATA :

AUTHOR : WILSON, C.B.

YEAR : 1968

DATA :

VERY GENERALISED REPORT OF WORK AT EDINBURGH UNIV.

SUGGESTS:-

SITE	$1/\alpha$
RURAL	0.143
URBAN	0.50 (VERY APPROX.)

AUTHOR : BLACKADAR, A.K., PANOFSKY, H.A.

YEAR : 1969

DATA :

SITE	$y(m)$	$\overline{y_0}(m)$
WHITE SANDS	0~25	0.06~0.08

AUTHOR : BLACKADAR, A.K. ET AL.

YEAR : 1969.

DATA :

MOST OF RELEVANT DATA INCLUDED IN FICHTL 1968 (IE. RE-y_o OF KENNEDY SPACE CENTRE). FOLLOWING POINTS OF GENERAL INTEREST:-

(a) MEAN SITE ROUGHNESS LENGTH FOUND TO BE INDEPENDENT OF ATMOSPHERIC STABILITY CONDITION AND WIND SPEED.

(b) THE PROBABILITY DENSITY DISTRIBUTIONS OF THE LONGITUDINAL FLUCTUATING VELOCITY SHOW THAT FOR STANDARD DEVIATIONS GREATER THAN ABOUT ±3 THERE IS A GREATER TENDENCY FOR A HIGHER PROBABILITY OF LARGER GUSTS THAN INDICATED BY THE NORMAL DISTRIBUTION CURVE.

AUTHOR : CERMAK, J.E., ARYA, S.P.S.

YEAR : 1969

DATA :

VERY GENERAL REVIEW PAPER, MOSTLY CONCERNED WITH MODEL TESTS. POINTS OF INTEREST :-

(a) FOR LARGE ROUGHNESS LOG REPRESENTATION OF VELOCITY PROFILE SHOULD BE - $\bar{u}/U_* = \frac{1}{k} \log_e \left(\frac{y-d}{y_o}\right)$

(b) FOR ADIABATIC CASE - $\sqrt{\bar{u}^2}/U_* \simeq 1.25.$

AUTHOR : FICHTL, G.H., McVEHIL G.E.

YEAR : 1969

DATA :

SITE	$\bar{y}_o$ (m)	y (m)	Lu_x (m)
KENNEDY SPACE CENTRE.	0.23	18	64
		30	108
		60	100
		90	143
		120	120
		150	100

THERE IS SOME DOUBT RE-CORRECT y_o VALUE FOR THIS SITE.

LENGTH SCALE Lu_x TENDS TO DECREASE FOR $y > 100$m.

- ESTIMATED AS BY PASQUILL AND OTHERS :-

I.E. IF THE MEASURED CORRELATIONS ARE OF EXPONENTIAL FORM - $R(x) = e^{-x/L}$

THEN THE ASSOCIATED SPECTRUM HAS THE FORM:-

$$\frac{nS(n)}{U_*^2} = \frac{2}{\pi} \cdot \frac{\bar{u}'^2}{U_*^2} \cdot \frac{2\pi f L_y}{(2\pi f L_y)^2 + 1}$$

WHICH HAS A MAXIMUM AT

$$\frac{L f_m}{y} = \frac{1}{2\pi} \quad \text{OR} \quad L = \tfrac{1}{2\pi} \left(\bar{u}/n\right)_{\text{PEAK.}}$$

(f_m = PEAK VALUE OF $ny/\bar{u}$)

AUTHOR: GIBSON, C.H., WILLIAMS, R.B.

YEAR : 1969

DATA :

SITE	$\overline{u'v'}/U_{10}^2$	$\overline{u'v'}/U_*^2$
SEA	0.00074	0.0003

[ASSUME $1/\alpha = 0.11$, $\delta = 600m$]

COMMENT: DATA MAY APPLY TO CONDITIONS SLIGHTLY STABLE, HENCE LOW STRESS VALUE.

AUTHOR: GUNTER D.E., ET AL.

YEAR : 1969

DATA :

SITE.	y(m)	L_{max}(m)
	79	115
	230	130

AUTHOR : HANNA, S.R.

YEAR : 1969

DATA :

CONCERNED WITH DIFFERENT METHODS OF ESTIMATING THE BOUNDARY LAYER HEIGHT. THE FORMULAE FOR USE IN ADIABATIC EQUILIBRIUM HAVE BEEN SHOWN TO BE RELIABLE AND ARE :-

$$\delta = 0.2\,(U_*/f) \quad \text{AND} \quad \delta = 0.006\,(\bar{U}_0/f)$$

WHERE f = CORIOLIS PARAMETER.

e.g. for $\bar{U}_0 = 10$ m/sec $\quad \delta = 0.006\left(\frac{10}{0.0001}\right) = 600$m.

FROM ABOVE FORMULAE O'NEILL DATA GIVE GENERALLY $500 \leq \delta(m) \leq 800$.

REMAINDER OF DATA SHOW δ TO BE OF ORDER 500~700 m.

AUTHOR : HASSE, L., ET AL.

YEAR : 1969.

DATA :

SITE	y(m)	$\overline{u'v'}/\bar{U}_0^2$
SEA	3.5	0.00048

[ASSUME $\frac{1}{\alpha} = 0.11$, $\delta = 600$m]

AUTHOR : KAIMEL, J.C., HAUGEN, D.A.

YEAR : 1969.

DATA :

PAPER GENERALLY CONCERNED WITH ERRORS INVOLVED IN STRESS MEASUREMENTS. SITE DATA OF INTEREST IS AS FOLLOWS:-

SITE	y(m)	$\sqrt{\overline{u^2}}/\bar{u}$	$\sqrt{\overline{w^2}}/\bar{u}$	$\sqrt{\overline{v^2}}/\bar{u}$	$\overline{u'v'}/\bar{U}_0^2$	$(y_0$ m)	$\left(\sqrt{\overline{u^2}}/\bar{u}\right)_{30}$
RURAL	5.6	0.24	0.26	0.10	0.0009	0.085	0.17

DATA REPRESENT MEAN OF SITE 1 MEASUREMENTS.

COMMENTS : SIMILARITY OF LONGITUDINAL AND LATERAL COMPONENTS OF TURBULENCE MAY BE DUE TO CLOSENESS TO GROUND OF MEASURING POINT (?)

AUTHOR : LETTAU, H.

YEAR : 1969

DATA : GIVES ESTIMATES OF y_0 FOR VARIOUS SITE TYPES :-

SITE	h(m)	y_0(m)	h/y_0
TREES - HOUSES.	10	2.14	5
FIELD CROPS ETC.	1	0.14	7
SAND FLATS.	0.001	0.000036	27

SUGGESTS USE OF FORMULA :- $y_0 = 0.5h^{S/S}$ ($S/S = 7$ OF FIG. 57)

COMMENTS : FORMULA DOES NOT APPLY AS $S/S \to 1$ AND DOES NOT PREDICT EFFECT OF FETCH.

AUTHOR : PANOFSKY, H.A.

YEAR : 1969

DATA :

VERY DETAILED REVIEW PAPER FROM WHICH THE FOLLOWING MAIN POINTS ARE NOTED :-

(a) SURFACE LAYER EXTENDS TO $y \simeq 100m$.

(b) ANALYSIS OF MANY RESULTS GIVE —

$$\sqrt{\overline{u^2}}/U_* = 2.5 \; ; \; \sqrt{\overline{v^2}}/U_* = 2.0 \; ; \; \sqrt{\overline{w^2}}/U_* = 1.25$$

(c) THE VALUES OF $\sqrt{\overline{u^2}}/U_*$ AND $\sqrt{\overline{w^2}}/U_*$ SHOW SYSTEMATIC VARIATIONS FROM PLACE TO PLACE WHICH GENERALLY SUGGEST THAT TERRAIN FEATURES OF LARGE SCALE AFFECT THEIR BEHAVIOUR. (N.B.) (SEE ALSO ZUBKOVSKI, KRAVCHENKO 1967.)

(d) INERTIAL SUBRANGE OF SPECTRA WELL DEFINED BY —

$$S(k) = b\,\varepsilon^{2/3} k^{-5/3}$$

WHEN k = WAVE NO. RADS/UNIT LENGTH, b = 0.50 FOR LONG. SPEC.
= 0.66 FOR LAT. SPEC.

(e) AS INDICATED IN BUSCH AND PANOFSKY 1968, SPECTRA MEASURED OVER THE SEA INDICATE MORE ENERGY AT LOW FREQUENCIES THAN, SAY, RURAL SPECTRA. THIS IS ATTRIBUTED TO THE PRESENCE OF LARGE LONGITUDINAL EDDIES NEAR THE GROUND — OVER ROUGH GROUND SUCH EDDIES ARE LIKELY TO BE BROKEN UP (ie. L_{u_x} DECREASES AS y_0 INCREASES.)

(f) VERTICAL SPECTRA.

FOR $y \leq 50m$. — k_y (max) IS CONSTANT — IMPLIES LINEAR INCREASE OF L_{u_x} WITH HEIGHT.

$y > 50m$. — k_y(max) INCREASES WITH y — IMPLIES L_{u_x} INCREASES LESS RAPIDLY WITH HEIGHT AND EVENTUALLY BECOMES CONSTANT. (FIG.56a)

LONG. SPECTRA. (FIG.56b)

DO NOT FOLLOW SIMILARITY THEORY PREDICTIONS — I.E. PLOT OF $k S_u(k) \sim k$ SHOWS LITTLE SHIFT OF PEAK VALUE AS y INCREASES. IF SIMILARITY THEORY APPLIED PEAK VALUE WOULD BE HEIGHT DEPENDENT. DUE TO WIDE VARIATION OF SPECTRAL SHAPES, THE APPLICATION OF AN EMPIRICAL SPECTRUM FORM TO ANY PARTICULAR SITE CAN ONLY BE VERY APPROXIMATE.

LATERAL SPECTRA. (FIG.56c)

BEHAVE SIMILARLY TO LONG. SPEC. WITH REGARD TO THEORY.

COMMENTS: THIS AUTHORS PAPERS GENERALLY OF VALUE DUE TO PRACTICAL APPROACH TO DEFINING THE BOUNDARY LAYER STRUCTURE FROM EXISTING DATA.

AUTHOR : PASQUILL, F.

YEAR : 1969

DATA :

SITE	y_o (m)
RURAL	0.03
URBAN	1 ~ 3

DERIVED FROM DAVENPORT AND MARSH (1969).

MARSH DATA IS FROM MEASUREMENTS AT READING e.g. AT $y = 14m$. $\sqrt{\overline{u'^2}}/\bar{u} = 0.17$

HENCE USING $\sqrt{\overline{u'^2}}/U_* = 1.25$ AND $k\,\bar{u}/U_* = \log_e y/y_o$

$$y_o \simeq 0.70m.$$

COMMENTS. READING DATA IS CONSIDERED TO BE MORE APPLICABLE TO A SUBURBAN SITE.

AUTHOR : SLADE, D.H.

YEAR : 1969

DATA :

SITE.	y (m)	$\bar{y}_o$ (m)	$\overline{1/\alpha}$	$\overline{\alpha^{1.0}}$	$\bar{h}$ (m)	$\sqrt{\overline{w'^2}}/U_*$
PHILADELPHIA.	12~270	2.6	0.28	16	8~12	1.97

COMMENTS. RELIABLE DATA THAT SHOULD BE REPRESENTATIVE OF URBAN TERRAIN; RESULTS AVERAGED OVER LONG PERIODS.

AUTHOR : WOOLDING, R.E. ET AL.

YEAR : 1969

DATA :

CORRELATION OF EXTENSIVE DATA RE-DRAG OF VARIOUS TYPES OF ROUGHNESS ELEMENTS. DATA APPLICABLE TO EQUILIBRIUM D

DATA OF INTEREST SHOWN IN FIG. 57

WHERE k_s = EQUIV. SAND-GRAIN ROUGHNESS

k = ROUGHNESS HEIGHT, m = FACTOR ALLOWING FOR DIFFERENT SHAPES OF ELEMENTS (KOLOSEUS AND DAVIDIAN 1966).

$\therefore$ VERTICAL SCALE IS $\propto y_o$. VARIATION OF y_o AS A FUNCTION OF FETCH NOT CONSIDERED.

COMMENTS: THESE DATA ARE OF IMPORTANCE WHEN ASSESSING THE CHARACTERISTICS OF URBAN OR SUBURBAN SITES — INDICATE IMPORTANCE OF DEFINING IN SOME DETAIL THE TOPOGRAPHY OF SITES BEING INVESTIGATED.

THE FOLLOWING DATA HAS BEEN EXTRACTED FROM SOME OF THE MORE IMPORTANT PAPERS FROM THE PERIOD 1970~1972.

AUTHOR : HELLIWELL, N.C.

YEAR : 1970

DATA :

SOME OF DATA ALREADY INCLUDED IN SHELLARD (1967). ADDITIONAL DATA ARE MEANS FROM VARIOUS SITES:-

SITE.	y_o(m)	$1/\alpha$
RURAL.	0.08	0.100
SUBURBS, WOODS.	0.43	0.19
URBAN	0.78	0.23

URBAN SITE MEASUREMENTS OF $\sqrt{\overline{u'^2}}/\bar{u}$ SHOWN TO BE INDEPENDENT OF MEAN WIND SPEED.

AUTHOR : MIYAKE, M. ETAL.

YEAR : 1970

DATA :

SITE.	y(m)	$(y_o$(m))	$\sqrt{\overline{u'^2}}/\bar{u}$	$\sqrt{\overline{w'^2}}/\bar{u}$	$\sqrt{\overline{v'^2}}/\bar{u}$	$\sqrt{\overline{w'^2}}/\sqrt{\overline{u'^2}}$	$\sqrt{\overline{v'^2}}/\sqrt{\overline{u'^2}}$	$\overline{u'v'}/U_o^2$
SEA	1.5	0.00006	0.098	0.071	0.05	0.73	0.51	0.00036

$\sqrt{\overline{u'^2}}/u_*$	$\sqrt{\overline{w'^2}}/u_*$	$\sqrt{\overline{v'^2}}/u_*$
2.66	1.95	1.36

CO-SPECTRA HAVE SLOPES OF $-5/3$ AT HIGH FREQUENCY END AND GENERALLY AGREE WITH SPECTRAL FORM PROPOSED BY PANOFSKY AND MARES (1968).

AUTHOR : PASQUILL, F.

YEAR : 1970

DATA :

THE MAIN POINTS FROM THIS PAPER ARE AS FOLLOWS:-

(a) DEPTH OF CONSTANT STRESS LAYER $\simeq$ 30m. (i.e. WHERE STRESS CHANGES BY LESS THAN 10%)

(b) LOG-LAW APPLIES ONLY IN CONSTANT STRES LAYER (REF. MONIN-OBUKHOV 1954.)

(c) FIG. 58(a) SHOWS STRESS TO BE MORE SENSITIVE TO CHANGES IN TERRAIN AT LOW y – DUE MERELY TO REDUCTION IN $\bar{u}$ AS y_o INCREASES. (ESTIMATE FROM $k\,\bar{u}/u_* = \log_e(y/y_o)$ – IT IS NOT VERY SENSITIVE TO VARIATIONS IN $\bar{U}_o$.

(d) FIG. 58(b) SHOWS COLLECTED DATA FROM VARIOUS SOURCES AS FUNCTION OF ROSSBY NO. – MOST OF VARIATIONS ARE DUE TO y_o CHANGES.

(e) SPECTRA UP TO $y = 100$m. CAN BE DEFINED BY PEAK SPECTRAL VALUES OF WAVELENGTH (OF ORDER 300~600m) AND FROM :-

$$\frac{n S_u(n)}{u_*^2} = 0.26 \left(ny/\bar{U}\right)^{-2/3}$$

[DERIVED FROM

$$S_u(n) = C u_*^{-2/3} \varepsilon^{2/3} n^{-5/3}, \quad C = 0.14$$

AND DISSIPATION, $\varepsilon = u_*^3/ky$ FOR ADIAB. CONDNS. AND k = VON KARMANS CONST.]

AT LOWER FREQUENCIES THE SPECTRAL DENSITIES ARE VERY VARIABLE.

(f) SUGGESTS URBAN SPECTRA ARE NO DIFFERENT FROM RURAL SPECTRA.

AUTHOR : SITARAMAN, V.

YEAR : 1970.

DATA :

SITE CONSIDERED WAS FLAT GRAZING LAND AT $y = 4$m. ALL THE MEASURED SPECTRA OBEY KOLMOGOROFFS LAW AT HIGH FREQUENCIES. THE CO-SPECTRA GENERALLY AGREE WITH PREVIOUS DATA I.E. RE-FREQUENCY RANGE WHICH CONTAINS MOST ENERGY, OBEYING KOLMOGOROFFS LAW AND FOLLOWING THE FORM PREDICTED BY PANOFSKY AND MARES (1968.)

AUTHOR : TEUNISSON, H.W.

YEAR : 1970.

DATA :

GENERAL REVIEW PAPER FROM WHICH MOST OF DATA HAS ALREADY BEEN CONSIDERED. MAIN RELEVANT POINTS :-

(a) FIG. 59 SHOWS L_{ux} AS FUNCTION OF y. - DEDUCES :-

$$L_{ux} \simeq 0.40y$$

WHICH IS GENERALLY WIDELY AGREED ON.

(b) DATA ON L_{ux} ANALYSED (SOME DERIVED FROM $\frac{1}{2}\pi \left(\bar{u}/n\right)_{PEAK}$)
IT IS DEDUCED THAT FOR $y > 300$m, L_{ux} IS INDEPENDENT OF TERRAIN TYPE. STATES - "ROUGHNESS LENGTH HAS LITTLE EFFECT ON SCALES, WHILE INCREASING LARGE SCALE NON-UNIFORMITIES OF THE SURFACE TENDS TO INCREASE THEM."

(c) CALCULATES TURBULENCE INTENSITIES AS FUNCTION OF HEIGHT FROM $\sqrt{\overline{u^2}}/u_* = f\left(\log_e y/y_0\right)$

COMMENT : THE PREVIOUSLY TABULATED DATA SHOWS CLEARLY THAT L_{ux} INCREASES AS y_0 DECREASES. THIS POINT IS DISCUSSED FURTHER IN THE TEXT. THE ESTIMATES OF TURBULENCE INTENSITY THROUGH THE BOUNDARY LAYER

HEIGHT ARE NOT CONSIDERED TO BE VERY REPRESENTATIVE SINCE THE EXPRESSIONS USED ARE VALID ONLY IN THE LOG LAYER; IN ADDITION IT IS ASSUMED IN THEIR USE THAT $\sqrt{\overline{u^2}}$ ETC ARE INVARIANT WITH HEIGHT, WHICH THEY ARE NOT. (SEE HARRIS 1972)

AUTHOR : SMITH, F.B.

YEAR : 1970

DATA :

THEORETICAL PAPER FROM WHICH MAIN POINTS, AS FOLLOWS, ARE TAKEN :-

(a) SUGGESTS THAT THE VARIATION OF THE WIND DIRECTION WITH HEIGHT (α') IS A LINEAR FUNCTION.

(b) DERIVES AN EXPRESSION FOR ESTIMATION OF THE BOUNDARY LAYER HEIGHT :-

$$\delta = 80 \times \bar{U}_o \quad (m)$$

$\bar{U}_o$ = GRADIENT WIND.

e.g. FOR $\bar{U}_o = 10$ m/sec.

$$\delta = 800 m$$

(Cf. HANNA 1969)

(c) THEORETICAL ESTIMATE OF VARIATION OF SHEAR STRESS WITH HEIGHT :-

(y/δ) :	0	0.2	0.4	0.6	0.8	1.0
$\overline{u'v'}/(\overline{u'v'})_{y=0}$:	1	0.64	0.36	0.16	0.04	0

(d) THE RATIO OF RURAL TO URBAN STRESSES (BASED ON $\bar{U}_o$) CAN BE DERIVED :-

FOR RURAL $y_o = 0.10$ m, URBAN $y_o = 2.5$ m

THEN $\dfrac{\text{URBAN } \overline{u'v'}}{\text{RURAL } \overline{u'v'}} \simeq 1.46$ (Cf. 1.56 from PASQUILL 1970)

AUTHOR : ANTONIA, R.A., LUXTON, R.E.

YEAR : 1971

DATA :

PAPER MAINLY REFERRED TO FOR DATA ON VARIATION OF L_{ux} AS FUNCTION OF ROUGHNESS FROM FLAT PLATE BOUNDARY LAYER MEASUREMENTS. DATA HAVE BEEN SCALED UP ASSUMING FULL SCALE BOUNDARY LAYER HEIGHT OF 600m (FIG. 60 a)

	L_{ux} (m)	
y(m)	ROUGH	SMOOTH
10	33	165
30	100	186
50	138	201
100	204	224
200	242	242
300	234	234
360	220	220
480	185	185
600	130	130

IT CAN BE SEEN THAT THE ROUGHER SURFACE DECREASES L_{ux} AND THAT FOR $y/\delta > 0.40$, L_{ux} DECREASES AS y INCREASES; ABOVE THIS HEIGHT THE ONSET OF INTERMITTENCY IN THE TURBULENCE BEGINS.

COMMENTS: IT IS ASSUMED THAT THE SMOOTH FLOW DATA ARE IN EQUILIBRIUM, WHEREAS THE ROUGH SURFACE DATA ARE NOT.

AUTHOR: COLMER, M.J.

YEAR : 1971.

DATA :

SITE	y_o(m)	y(m)	$1/\alpha$	$\sqrt{\bar{u}^2}/\bar{u}$	L_{ux}(m)	$(y_o$(m)$)$
R.A.E BEDFORD.	0.010~	3.05	0.16	0.22	40	0.05
	0.037	9.15		0.19	80	
		18.3		0.18	150	
		30.5		0.17	220	

DERIVES:- $L_{ux} \simeq 21.1\, y^{0.69}$

(USING $L_{ux} = \frac{1}{5}(\bar{u}/n)_{PEAK}$)

COMMENT: $1/\alpha$ MAY BE OVERESTIMATED DUE TO RESTRICTED HEIGHT RANGE OF MEASUREMENTS; IN ADDITION THIS SITE HAS MANY OBSTRUCTIONS NEAR MEASURING MAST.

AUTHOR : DUTTON, J.A. ETAL.

YEAR : 1971.

DATA :

SITE	$\overline{1/\alpha}$	y_o(m) AS FUNCTION OF WIND DIRECTION.
KENNEDY SPACE CENTRE	0.25	(a) 0.159 – DENSE WOODS – 180° ~ 300°
		(b) 0.039 – LOW SCRUB, SAND – 300° ~ 90°
		(c) 0.121 – LOW TREES, HUMMOCKS – 90° ~ 180°

AUTHOR : HARRIS, R.I.

YEAR : 1971

DATA :

SITE	$(y_o$(m)$)$	y(m)	$1/\alpha$	$\alpha'°$	L_{ux}(m)	L_{uy}(m) UP	L_{uy}(m) DOWN
RUGBY	0.08	0~182	0.172	NO CHANGE			
		18			168	57	9
		100			226	68	50
		182			252	74	71

VARIATION OF TURBULENCE INTENSITY WITH y IN FIG. 60b.

OTHER MAIN POINTS :-

(a) SHOWS $\sqrt{\overline{u^2}}$ BASED ON $\bar{U}_o$ TO BE RELATIVELY INDEPENDENT OF TERRAIN TYPE :- AT $y = 10m$

$$\frac{\sqrt{\overline{u^2}}}{\bar{U}_o} \simeq 0.106 \quad \text{- RURAL}$$

$$\simeq 0.115 \quad \text{- URBAN.}$$

(b) ESTIMATES OF L_{ux} AS $f(y, y_o)$ SHOWN IN FIG 61(a) AND (b) (α VARIES IN ESTIMATES - SEE HARRIS 1967). HOWEVER L_{ux} INCREASING AS y_o INCREASES DOES NOT AGREE WITH FULL SCALE MEASUREMENTS.

(c) ASSUMES FROM HOMOGENEOUS ISOTROPIC TURBULENCE THEORY THAT -

$$L_{uy} = L_{uz} = \tfrac{1}{2} L_{ux}$$

FULL SCALE MEASUREMENTS SHOW, AS BEING MORE TRUE -

$$L_{uy} \simeq 0.5 \sim 0.6\, L_{ux}$$

$$L_{uz} \simeq 0.3 \sim 0.4\, L_{ux}$$

(SEE e.g. SHIOTANI 1967, DEACON 1971.)

(d) ESTIMATION OF u_* FROM TURBULENCE DATA :-

$$\frac{\sqrt{\overline{u^2}}}{u_*} = \text{CONS.}$$

$$\therefore \quad \frac{\sqrt{\overline{u^2}}}{\bar{u}} = \text{CONS.} \; \frac{u_*}{\bar{u}}$$

$$\text{OR} \quad \sqrt{\overline{u^2}} = \text{CONS}\,(\sqrt{K})\,\bar{u} \qquad \left[K = \left(\frac{u_*}{\bar{u}}\right)^2 - \text{DAVENPORT 1963}\right]$$

AUTHOR : HAUGEN, D.A. ET AL.

YEAR : 1971.

DATA :

SITE.	$y(m)$	$\overline{u'v'}$	$\sqrt{\overline{u^2}}/u_*$
RURAL (STUBBLE)	5.66 ~ 22.6	NO CHANGE.	1.3 ~ 1.85

AUTHOR : OLIVER, H.R.

YEAR : 1971

DATA :

SITE	$y_o(m)$	$h(m)$	$d(m)$
WOODS (1 TREE/10m²)	0.91	15.5	11.8

(Cf WITH DUTTON 1971 FOR DENSE WOODS.)

FOLLOWING DERIVED :-

$$y_o = (0.91 + 3.2 Ri)\, m, \quad \text{(FIG. 61c)}$$

Ri = RICHARDSON No. AT $y = 20.5m$. (-VE, UNSTABLE : +VE, STABLE)

MAJORITY OF PREVIOUS DATA HAS SHOWN y_o INDEPENDENT OF Ri (COULD BE SCALE EFFECT?)

COMMENT: THIS VALUE OF y_o FOR WOODED AREA SEEMS REALISTIC. (Cf. BROOKHAVEN DATA.)

AUTHOR: OWEN, P.R.

YEAR : 1971.

DATA :

RE-ERRATIC BEHAVIOUR OF u-SPECTRA AT LOW FREQUENCIES:- ASSUMING THE BOUNDARY LAYER CAN BE DIVIDED INTO INNER AND OUTER LAYERS IT HAS BEEN SHOWN THAT THE LARGE EDDIES IN THE OUTER LAYER OBTRUDE INTO THE INNER LAYER BUT DO NOT CONTRIBUTE TO MOMENTUM TRANSFER OF SHEAR STRESS IN THIS LAYER. THE STRESS BEARING EDDIES OF THE INNER REGION HAVE A UNIVERSAL STRUCTURE IN RELATION TO WHICH THE LARGE OUTER EDDIES PRODUCE MOTIONS ON A LARGER SCALE WHICH ARE RANDOM I.E. WITHOUT DEFINITE PATTERNS ; HENCE THE RESULTANT SCATTER IN LOW FREQUENCY SPECTRAL DATA.

AUTHOR: HARRIS, R.I.

YEAR : 1972

DATA :

SITE	y(m)	h(m)	y_o(m)	$\overline{1/d}$	$\sqrt{\bar{u}^2}/\bar{u}$	L_{ux}(m)	L_{uz}(m)
CRANFIELD.	0~20	0.02~0.1	0.003	0.11~0.14			
	10				0.137	125	35
	20				0.126	147	
	30				0.121	—	
SEUREN BR.	50						52
NORTHUMBERLAND PARK - SUBURBS.				0.25			
RUGBY.	25	0.1~0.2	0.08~0.14	0.16~0.18		127	
	50					182	
	100					250	
	175					250	

AS y INCREASES $\sqrt{\bar{u}^2}$ AND $\sqrt{\bar{w}^2}$ START TO DECREASE.

COMMENT. IN THIS PAPER HARRIS QUOTES y_o VALUES FOR GRASS COVER MOSTLY IN RANGE 0.02 ~ 0.03 m. BY APPLYING EQUATION OF BLACKADAR AND CHAPLIN 1967 y_o FOR RUGBY SITE IS FOUND TO LIE IN SAME RANGE (IE 0.02 ~ 0.03 m). HOWEVER DATA QUOTED HAS MOSTLY BEEN OBTAINED FROM MEASUREMENTS IN RESTRICTED HEIGHT RANGE IE EQUIVALENT TO CONSIDERING A LARGE UPSTREAM FETCH OF JUST GRASS, FOR THIS CONDITION $0.02 < y_o < 0.03$ IS REASONABLE. THEREFORE FOR THE RUGBY SITE, CONSIDERING ITS TOPOGRAPHY AND u RANGE OF DATA A y_o OF 0.08 m SEEMS MORE REASONABLE

AUTHOR : KAIMAL, J. C. ET AL.

YEAR : 1972

DATA :

MOST UP-TO DATA AND SYSTEMATIC DATA ON POWER SPECTRA MEASUREMENTS. AUTHORS HAVE DERIVED FORMS OF SPECTRA FROM EXTENSIVE FULL SCALE MEASUREMENTS. DERIVED EXPRESSIONS FOR SPECTRA ARE SHOWN TO AGREE GENERALLY WITH SPECTRAL DATA FROM OTHER SOURCES. THE FORMS OF THE SPECTRA ARE SHOWN IN FIG. 62 AND THE EXPRESSIONS DESCRIBING THEM FOR NEUTRAL CONDITIONS (ie. $\phi_\varepsilon = G = 1$ WHERE $\phi_\varepsilon = ky\varepsilon / u_*^3$) ARE AS FOLLOWS:-

$$\frac{n S_u(n)}{u_*^2} = \frac{105 f}{(1+33f)^{5/3}}$$

$$\frac{n S_w(n)}{u_*^2} = \frac{17 f}{(1+9.5f)^{5/3}}$$

$$\frac{n S_v(n)}{u_*^2} = \frac{2f}{[1+5.3(f)^{5/3}]}$$

$$\frac{n S_{uw}(n)}{u_*^2} = \frac{14f}{(1+9.6f)^{2.4}}$$

AUTHOR : PASQUILL, F.

YEAR : 1972

DATA. :

REVIEW PAPER MOSTLY CONCERNED WITH VERTICAL COMPONENT OF TURBULENCE, ALSO DISCUSSES SOME NEW APPROACHES TO BOUNDARY LAYER DESCRIPTION. MAIN RELEVANT POINTS ARE AS FOLLOWS:-

(a) MECHANICAL PRODUCTION OF ENERGY TENDS TO ZERO AT APPROXIMATELY 600m. (I.E. AT WHAT HAS BEEN TAKEN AS THE AVERAGE BOUNDARY LAYER HEIGHT FOR NEUTRAL CONDITIONS.)

(b) FOR $y \leq 100m$, $\sqrt{\overline{u'^2}}/u_*$ IS IN RANGE 1.2 ~ 1.4 AND, $\sqrt{\overline{u'^2}}/\bar{u}$ IS IN RANGE 0.1 ~ 0.2 NEAR GROUND LEVEL.

AUTHOR : PANOFSKY, H.A., PETERSEN, E.L.

YEAR : 1972

DATA :

SUGGESTS LOG LAYER IS VALID FOR y UP TO 100m. [SUPPORTED BY THUILLIER AND LAPPE 1964 AND DATA FROM CAPE KENNEDY.]

AUTHOR : WARNER, J.

YEAR : 1972.

DATA : – NEAR NEUTRAL DATA SHOWN HERE.

SITE	$y(m)$	$\sqrt{\overline{u'^2}}/\bar{u}$	$\sqrt{\overline{v'^2}}/\bar{u}$	$\left(\sqrt{\overline{w'^2}}/\bar{u}\right)$
SEA	30	0.04~0.05	0.08	0.11~0.12

THE VARIATION OF Lu_x WITH y HAS ALSO BEEN DERIVED AND GENERALLY AGREES WITH THE DATA OF TEUNISSEN 1970.

AUTHOR : E.S.D.U. DATA SHEET No. 72026

YEAR : 1973.

DATA :

SITE.	$y_o(m)$	$1/\alpha$
SEA, COASTAL AREAS, DESERT.	0.001	0.13
FLAT OPEN COUNTRY, GRASS PLAINS, FEW OBSTRUCS.	0.01	0.15
TERRAIN WITH NUMEROUS SMALL OBSTRUCTIONS I.E. HEDGES, TREES ETC.	0.10	0.19
SUBURBS.	0.50	0.26
CENTRES OF LARGE TOWNS.	1.50	0.35

APPENDIX. 3

DATA PLOTTED IN FIG. 63.

SYMBOL	SOURCE	SITE	$1/\alpha$	y_o (m)
a	STEVENSON, 1880	OPEN TERRAIN CEREAL	0.143 0.166	0.0014 0.048
b	DINES, 1912-'13	FARNBOROUGH	0.33	
c	WING, 1921	BALLYBUNION	0.130	0.011
d	SCRASE, 1930	SALISBURY PLAIN	0.13 ~ 0.143	0.01
e	HEYWOOD, 1931	LEAFIELD	0.17	0.60
f	GIBLETT, 1932	CARDINGTON	0.128 ~ 0.143	
g	BEST, 1935	~	0.130	0.01
h	FROST, 1946	~	0.143 0.143	0.01 0.026
i	FROST, 1947	CARDINGTON	0.15	0.01
j	HUSS, PORTMAN, 1948	AKRON	0.22	
k	SHIOTANI, 1948	TOKIO	0.40	4.00
l	FRANCKENBERGER, 1949	QUICKBORN	0.208	0.224
m	LETTAU, 1950	LEIPZIG	0.23	0.05
n	SHEPPARD, 1952 HAY, 1955	SEA	0.122	0.001
o	SHERLOCK, 1953	ANN ARBOR	0.093	0.003
p	JUUL, 1954	SEA + ISLANDS	0.105	0.005
q	RIDER, 1954	CARDINGTON		0.0032
r	DEACON, 1955	SALE	0.16 ~ 0.17	0.02 ~ 0.03

Symbol	Source	Site	$1/\alpha$	y_0(m)
s	Kamei , 1955	Tokio	0.33	1.50
t	Wax , 1956	Sea + Land	0.236	0.136
u	Goptarev , 1957	Caspian Sea	0.081	0.002
v	Lettau , 1957	O'Neill	0.17	0.01
w	Panofsky , 1957	O'Neill Brookhaven	 0.23~0.25	0.007~0.01 1.00
x	Jensen , 1958	Copenhagen Hojer Freerslau	0.36 0.11 0.152	7.50 0.00018 0.003
y	De Marrais , 1959	Hanford Harwell Idaho	0.12 0.08 0.18	
z	Singer , 1959	Brookhaven	0.21	1.00
a'	Ariel, et al. , 1960	Leningrad	0.32	2.46
b'	Blackadar, et al., 1960 Takeuchi , 1961	O'Neill	0.16~0.17	0.0065
c'	Durst , 1960	Cardington		0.012
d'	Davenport , 1960	Sale Cardington New York Leipzig	0.176 0.149 0.39 0.23	0.02~0.03 0.012 3.30 0.38
e'	Graham, Hudson, 1960	Brookhaven New Orleans Washington Water	0.25 0.284 0.235 0.114	0.60 0.0055
f'	Ivanov , 1961	Moscow	0.303	3.00

Symbol	Source	Site	1/α	y_0 (m.)
g'	Pasquill, 1961	Round Hill, Downland.	– –	> 0.10 0.01
h'	Takeuchi, 1961	O'Neill.	0.16 ~ 0.17	0.0065 (b')
i'	Deacon, 1962	Open sea.	0.10	0.0028 (n, u, e')
j'	Kondo, 1962	Sendai Airfield. Cardington.	–	0.0045 0.0033 (?)
k'	Naito et al., 1962	Tokio.	0.33	4.0 (k)
l'	Pasquill, 1962.	Porton.	–	0.008.
m'	Shiotani, 1962	Tokio suburbs.	0.25	0.40
n'	Byzova, 1963	Rural, Flat.	0.30 (?)	0.0175
o'	Panofsky, 1963.	O'Neill.	0.16 ~ 0.17 (h')	0.008
p'	Kawanabe, 1964.	Tokio. Coast.	0.285 0.117	2.32 0.044
q'	Lumley, Panofsky, 1964.	Round Hill.	–	0.10
r'	Singer, 1964	Brookhaven.	0.22	1.0
s'	Soma, 1964.	Tokio.	0.302	2.32
t'	Thullier, Lappe, 1964	Cedar Hill.	0.143	0.03
u'	Yamomoto, Shimanuki, 1964	Tokio.	0.302 (s')	1.45 ~ 1.85
v'	Berman, 1965	Round Hill. Cardington. Sale.	– 0.149 (d') 0.176 (d')	0.10 ~ 0.04 0.01 0.025
w'	Blackadar, 1965	Hanford.	0.12 (y)	0.05

Symbol	Source	Site	$1/\alpha$	y_o(m)
x'	Davenport, 1965.	London (Ont.)	0.36	2.42
y'	Deland, Binkowski, 1966.	Minneapolis. Louisville	0.31 0.26	2.0 + 2.0 +
z'	Elderkin, 1966.	Hanford.	0.12 (y)	0.025
A	Kraus, 1966.	Sea	0.10 (i')	0.0001
B	Davenport, 1967.	St. Louis. Montreal.	0.28 0.28	1.7 1.0
C	Elderkin, 1967.	Hanford. Liberal.	0.12 (y) –	0.03 0.01
D	Frizzola, 1967	Brookhaven.	0.33	1.0
E	Paulson, 1967.	Sea.	0.11 (Mean.)	0.0006
F	Shellard, 1967.	Mendlesham.	0.17	0.13
G	Shiotani, 1967.	Sea.	0.11 (Mean)	0.002
H	Volkov, Ivanov, 1967.	–	0.35	0.70
I	Harris, 1968	Rugby.	0.176	0.07 ~ 0.08
J	Jones et al., 1968	Liverpool.	0.21	1.23
K	Munn, 1968	New York.	0.32 ($\simeq$)	3.3 (α')
L	Blackadar et al., 1969.	White Sands.	–	0.07
M	Fichtl, McVehil, 1969.	Kennedy S.C.	–	0.23
N	Pasquill, 1969.	Urban.	–	1.0 ~ 3.0
O	Slade, 1969	Philadelphia.	0.28	2.6

Symbol	Source	Site	$1/\alpha$	y_o(m.)
P	Colmer, 1971	R.A.E. (Bedford)	0.16	0.02
Q	Dutton, 1971.	Kennedy S.C.	0.25	0.23 (M)
R	Harris, 1971.	Rugby.	0.17	0.08
S	Harris, 1972	Cranfield. Rugby. Suburbs.	0.125 0.17 0.25(Mean.)	0.003 0.11 1.23 (J)

APPENDIX 4.

WHERE SUFFICIENT DATA IS NOT AVAILABLE FROM WHICH TO INTERPOLATE THE VALUE OF THE TURBULENCE INTENSITY AT A HEIGHT OF 30m., THE FOLLOWING METHOD OF ESTIMATION IS USED. THE DATA OF SHOTANI (1953) IS USED AS AN EXAMPLE SINCE SUFFICIENT INFORMATION IS GIVEN FROM WHICH A VALUE OF TURBULENCE INTENSITY CAN BE INTERPOLATED GRAPHICALLY, AND HENCE THE ESTIMATED VALUES CHECKED.

SITE :- SNOW COVERED

y (m)	$\sqrt{\overline{u^2}}/\bar{u}$
7·5	0.156
11	0.120
75	0.063

(a) $y = 11m$.

$$\sqrt{\overline{u^2}}/\bar{u} = \frac{1}{\log_e y/y_o}$$

$$\therefore \log_e y/y_o = 8.34$$

GIVING $y_o \simeq 0.0026\,m.$

$\therefore$ AT $y = 30m$

$$\sqrt{\overline{u^2}}/\bar{u} = \frac{1}{\log_e 30/.0026}$$

$$\therefore \left(\sqrt{\overline{u^2}}/\bar{u}\right)_{30m} \simeq 0.107$$

(b) $y = 7.5m$.

$$\log_e y/y_o = 6.40$$

$$\therefore y_o \simeq 0.0012\,m.$$

AT $y = 30m$

$$\sqrt{\overline{u'^2}}/\bar{u} = \frac{1}{\log_e 30/.0012}$$

$$\therefore \underline{\left(\sqrt{\overline{u'^2}}/\bar{u}\right)_{30m} \simeq 0.099}$$

MEAN VALUES FROM (a) AND (b) ARE :-

$$\underline{\underline{\left(\sqrt{\overline{u'^2}}/\bar{u}\right)_{30m} = 0.103}} \qquad \underline{\underline{y_o = 0.0019m.}}$$

(c) GRAPHICAL INTERPOLATION OF TURBULENCE INTENSITY AT $y = 30m$. GIVES —

$$\underline{\underline{\left(\sqrt{\overline{u'^2}}/\bar{u}\right)_{30m} \simeq 0.100 \sim 0.105.}}$$

NOTE :

IN THE FOLLOWING TABULATED DATA (E) EITHER INDICATES :-

$\underline{y_o}$ ESTIMATED FROM GIVEN TURBULENCE DATA

OR $\left(\sqrt{\overline{u'^2}}/\bar{u}\right)_{30m}$ ESTIMATED FROM A GIVEN ROUGHNESS LENGTH.

THE RANGE OF ROUGHNESS LENGTHS OVER WHICH SUCH ESTIMATES ARE CONSIDERED TO APPLY IS DISCUSSED IN THE MAIN TEXT. THE OTHER VALUES OF TURBULENCE INTENSITY AT $y = 30m$. HAVE BEEN OBTAINED BY EITHER INTERPOLATION OR A MODERATE DEGREE OF EXTRAPOLATION OF AVAILABLE MEASUREMENTS.

———— · ————

APPENDIX. 4. CONTD.

DATA PLOTTED IN FIG. 64.

SYMBOL	SOURCE	SITE.	$(\sqrt{\overline{u^2}}/\bar{u})_{30m.}$	$y_o(m)$
a	BEST, 1935	RURAL.	0.109	0.01
b	SHIOTANI, 1948	SNOW (?)	0.097	0.001 (E)
c	CRAMER, 1952	SHRUBS ETC.	0.142 (MEAN) 0.182 (MAX.)	0.026 (E) 0.120 (E)
d	SHEPPARD, 1952	WATER.	0.122	0.001
e	Mc CREADY, 1953	TREES ETC.	0.156	0.05 (E)
f	SHIOTANI, 1953	SNOW.	0.103	0.0019 (E)
g	LETTAU, DAVIDSON, 1957	RURAL, FLAT.	0.134	0.0075
h	DURST, 1960	RURAL, FLAT.	0.128	0.0065
i	DAVENPORT, 1961	RURAL, FLAT.	0.145	0.025
j	IVANOV, KLINOV, 1961	URBAN.	0.275	3.00
k.	PASQUILL, 1961	DOWNLAND.	0.125 (E)	0.01
l	KONDO, 1962	AIRFIELD. RURAL FLAT. RURAL FLAT.	0.114 (E) 0.118 (E) 0.110 (E)	0.0045 0.0065 0.0033
m	PASQUILL, 1962	RURAL, FLAT.	0.122 (E)	0.008
n	SHIOTANI, 1962	SUBURBS.	0.232 (E)	0.40
o	BYZOVA, 1963	RURAL, FLAT.	0.14	0.0175
p	KAWANABE, 1964	URBAN. COAST.	0.391 (E) 0.153 (E)	2.32 0.044
q	LUMLEY, PANOFSKY, 1964	WOODS.	0.240	1.00

Symbol	Source.	Site.	$(\sqrt{\overline{u^2}}/\bar{u})_{30m}$.	y_o (m)
r	Singer, 1964	Woods.	0.285	1.00
s	Soma, 1964	Urban.	0.20 (0.39E)	2.32
t	Yamamoto, 1964 Shimanuki,	Urban.	0.345 (E)	1.65
u	Swanson, Cramer, 1965	Brush, sand-dunes.	0.20	0.07
v	Elderkin, 1966	Rural, Flat.	0.12	0.025
w	Davenport, 1967 Isyumov,	Woods.	0.27	1.00
x	Shellard, 1967	Rural.		0.13
y	Shiotani, Arai, 1967	Coast.	0.115	0.002
z	Graham, 1968	Urban.	0.32	1.31 (E.)
a'	Harris, 1968	Rural.	0.145	0.075
b'	Kaimel, Haugen, 1969	Rural.	0.17 (E)	0.085 (E.)
c'	Slade, 1969	Urban.	0.30	2.60
d'	Colmer, 1971	Rural.	0.17	0.02
e'	Harris, 1971	Rural.	0.175	0.08
f'	Harris, 1972	Rural, Flat.	0.121	0.003

APPENDIX 5

DATA PLOTTED IN FIG. 65.

SYMBOL	SOURCE	SITE	$\overline{u'v'}/U_0^2$	y_0 (m)
a	TAYLOR, 1916	RURAL, FLAT.	0·0014 ~ 0·0020	0·01 (ASSUMED)
b	SCRASE, 1930	GRASSLAND.	0.0015 ~ 0.0017	0.01
c	SHEPPARD, 1947	RURAL.	0.0030 (MEAN)	0.05 (MEAN)
d	PASQUILL, 1950	GRASS.	0.0010	0.0066
e	SHIOTANI, 1950	GRASS, VEGETATION.	0.0024	0·035
f	SHEPPARD, 1952	SEA.	0.0011	0.001
g	SHEPPARD, OMAR, 1952	WATER.	0.0004	0.001 (ASS.)
h	DEACON, 1953	GRASS.	0.0021	0.015
i	HAY, 1954	WATER.	0.0006	0.0010
j	MONIN, OBUKHOV, 1954	RURAL.	0.0025	—
k	RIDER, 1954	RURAL, FLAT.	0.00083	0.0032
l	ELLISON, 1956	RURAL.	0.0013	—
m	DEACON, 1957	RURAL.	0.0022	—
n	LETTAU, DAVIDSON, 1957	RURAL, FLAT.	0.0017	0.011
o	VINOGRADOVA, 1959	SEA.	0.0005	—
p	DEACON, 1962	SEA.	0.0005	—
q	BYZOVA, 1963	RURAL, FLAT.	0.0017	0.017
r	SINGER, 1964	WOODS.	0.0032	1.00
s	SOMA, 1964	URBAN.	0.002	2.32

Symbol	Source	Site	$\overline{w'v'}/\overline{U}_0^2$	y_0(m)
t	Thullier, Lappe, 1964	Rural.	0.00145	0·03
u	Berman, 1965	Rural.	0.0028	0.07
v	Blackadar et al, 1965	Woods. Rural.	0.0025 0.0012	1.00 0.05
w	Davenport, 1965	Urban.	0.0016	2.42
x	Elderkin, 1966	Rural.	0.00165	0.025
y	Kraus, 1966	Sea.	0.00036	0·0001
z	Frizzola et al., 1967	Woods.	0.0025	1.0
a'	Paulson, 1967	Sea.	0.0006	0.0006
b'	Smith, 1967	Sea.	0.00035	—
c'	Weiler, Burling, 1967	Sea.	0.00052	—
d'	Gibson, Williams, 1969	Sea.	0.0003	—
e'	Hasse et al., 1969	Sea.	0.00048	—

APPENDIX. 6.

DATA PLOTTED IN FIG. 66.

SYMBOL	SOURCE	SITE	y(m)	Lux(m.)
a	TAYLOR, 1915	RURAL.	10	70
b	GIBLETT, 1932	RURAL, FLAT.	15~45	120
c	SHIOTANI, 1948	RURAL. URBAN.	0~50 30~60	75~107 100
d	SHIOTANI, 1950	GRASS, VEGETATION	0~16	60
e	CRAMER, 1952	TREES, BUSHES.	2.5	12~18
f	PRIESTLEY, 1952	RURAL.	2	15~20
g	SHEPPARD, 1952	WATER.	2	12
h	MC CREADY, 1953	RURAL.	2.4 146	90 420
i	ROBINSON, 1953	RURAL.	1.3	12
j	SHIOTANI, 1953	SNOW	11 75	30 90
k	TAYLOR, 1955	RURAL.	1.5 28	24 40~110
l	WEBB, 1955	RURAL.	29	84
m	HAY, PASQUILL, 1959.	DOWNLAND.	2	20~40
n	DAVENPORT, 1961a	RURAL, FLAT. WOODS. RURAL	15.3 11 46 108 125 12.2 64 153	186 46 108 152 111 88 70 105

Symbol	Source	Site	y(m)	Lux(m)
o	Ivanov, Klinov, 1961	Urban.	25	25
			50	40
			100	65
			150	75
			200	80
			300	100
p	Pasquill, 1961.	Rural.	29	72
			30	60~130
			91	273
q	Panofsky, 1962	Rural.	2	20
			30	60~130
r	Soma, 1964	Urban	26	117
			67	225
			107	204
			173	230
			253	287
s	Berman, 1965	Various sites.	2	28·6
			4	31·1
			12	53·4
			15	72·4
			16	49·6
			23	55·5
			30	88
			46	96
			64	66
			91	134
			153	74
		Woods.	16	36·6
			64	66
		Rural, flat.	15	82
		Rural.	16	55
			46	96
t	Elderkin, 1966	Rural.	3	12.2
			6.1	24.0

Symbol	Source	Site	y(m)	Lux(m)
u	Davenport, 1967	Urban.	76	110
v	Elderkin, 1967	Rural.	3	16
			6.1	32
			3	16
			6.1	32
w	Frizzola et al, 1967	Woods.	23	73
			46	146
			92	292
x	Shiotani, 1967	Coast.	40	190
y	Singer et al, 1967	Woods.	23	87
			46	198
			92	366
z	Smith, 1967	Sea.	5	18
a'	Volkovitskaye, Ivanov, 1967	Rural (?)	17	200
			40	300
			85	400
b'	Busch, Panofsky, 1968	Grass.	16	102
			40	159
		Woods.	15	60
			46	120
		Rural.	4.5	14
		Sea.	2	27
			3	48
c'	Harris, 1968.	Rural.	17.7	56
			100	50
			182	100
d'	Fichtl, McVehil, 1969	Shrubs, trees.	18	64
			30	108
			60	100
			90	143
			120	120

Symbol	Source	Site	y (m)	L_{u_x} (m)
d'	"	"	150	100
e'	Gunter, 1969	?	79	115
			230	130
f'	Antonia, Luxton, 1971	W.T. Tests.	10	Rough 33 / Smooth 165
			30	100 / 186
			50	138 / 201
			100	204 / 224
			200	242 / 242
			300	234 / 234
			360	220 / 220
			480	185 / 185
			600	130 / 130
g'	Colmer, 1971	Rural.	3	40
			9.15	80
			18	150
			30.5	220
h'	Harris, 1971	Rural.	18	168
			100	226
			182	252
i'	Harris, 1972	Rural, flat.	10	125
			20	147
			30	-
		Rural.	25	127
			50	182
			100	250
			175	250

APPENDIX. 7.

THEORETICAL ESTIMATES OF THE LENGTH SCALE L_{ux}.

HARRIS'S EXPRESSION FOR THE LONG. SPECTRUM IS :-

$$\underline{n\,S(n) = 4u_*^2 \left[\frac{x}{(2+x^2)^{5/6}}\right]}, \quad \left(x = \frac{n\ell}{\bar{u}_{10}}\right)$$

$$\therefore \quad S(n)\,dn = 4u_*^2 \frac{x}{(2+x^2)^{5/6}} \cdot \frac{1}{n} \cdot dn \qquad \text{—— 1}$$

$$n = \frac{x\bar{u}_{10}}{\ell}, \quad dn = \frac{\bar{u}_{10}}{\ell}\,dx$$

Subst. in 1 for n and dn,

$$S(n)\,dn = 4u_*^2 \frac{x}{(2+x^2)^{5/6}} \cdot \frac{\ell}{x\,\bar{u}_{10}} \cdot \frac{\bar{u}_{10}}{\ell}\,dx$$

$$\therefore \quad \underline{\int_0^\infty S(n)\,dn = 4u_*^2 \int_0^\infty \frac{dx}{(2+x^2)^{5/6}}}$$

or $$\sqrt{\overline{u^2}}/\bar{u}_y = \frac{1}{\bar{u}_y}\left[\int_0^\infty S(n)\,dn\right]^{1/2} = \frac{1}{\bar{u}_y}\left[4u_*^2 \int_0^\infty \frac{dx}{(2+x^2)^{5/6}}\right]^{1/2}$$

which reduces to:-

$$\sqrt{\overline{u^2}}/\bar{u}_y = 2.58\,u_* \cdot \frac{1}{\bar{u}_y}$$

but $$K_{10} = \left(u_*/\bar{u}_{10}\right)^2$$

$$\therefore \quad \sqrt{\overline{u^2}}/\bar{u}_{10} = 2.58\,K_{10}^{1/2}\,\frac{\bar{u}_{10}}{\bar{u}_y}$$

FROM THE POWER LAW:

$$\bar{u}_y/\bar{u}_{10} = \left(y/10\right)^{1/\alpha}$$

$$\therefore \quad \underline{\sqrt{\overline{u^2}}/\bar{u}_y = 2.58\,K^{1/2}\left(y/10\right)^{-1/\alpha}}$$

$\therefore$ KNOWING $1/\alpha$ AND K_{10} THE VARIATION OF THE TURBULENCE INTENSITY WITH HEIGHT CAN BE ESTIMATED.

FROM TAYLORS HYPOTHESIS :-

$$\underline{L_{ux} = \bar{u}_y \cdot T}$$

but $$T = \frac{1}{\bar{u}^2} \int_0^\infty R(\tau)\, d\tau$$

$$\therefore \quad L_{ux} = \bar{u}_y \cdot \frac{1}{\bar{u}^2} \int_0^\infty R(\tau)\, d\tau$$

IT HAS BEEN SHOWN IN THE REVIEWED LITERATURE THAT THE POWER SPECTRUM AND AUTOCORRELATION FUNCTION ARE FOURIER TRANSFORMS OF EACH OTHER , HENCE:-

$$S(n) = 4 \int_0^\infty R(\tau) \cos 2\pi n \tau \, d\tau.$$

AND AT ZERO FREQUENCY,

$$S(0) = 4 \int_0^\infty R(\tau)\, d\tau$$

$$\therefore \quad \underline{L_{ux} = \frac{1}{4} \frac{\bar{u}_y}{\bar{u}^2} \cdot S(0)} \qquad \text{— 2.}$$

SINCE: $$S(n)\,dn = 4K \bar{u}_{10}^2 \cdot \frac{1200}{\bar{u}_{10}} \cdot \frac{dn}{(2+x^2)^{5/6}}, \quad (l = 1200\,m)$$

$$\therefore \quad S(0) = 4K \bar{u}_{10} \cdot 673$$

Subst. in 2.

$$L_{ux} = 673\, K \cdot \frac{\bar{u}_y}{\bar{u}^2} \cdot \bar{u}_{10}$$

$$\therefore \quad \underline{L_{ux} = 673\, K \left(\frac{\bar{u}_y}{\sqrt{\bar{u}^2}}\right)^2 \cdot \frac{\bar{u}_{10}}{\bar{u}_y}}$$

Subst. for, $$\left(\frac{\bar{u}_y}{\sqrt{\bar{u}^2}}\right)^2 = \frac{1}{6.65\, K \left(\frac{y}{10}\right)^{-2/\alpha}}$$

$$\therefore \quad \underline{\underline{L_{ux} = 101 \left(\frac{y}{10}\right)^{1/\alpha}}} \qquad \text{— 3.}$$

HENCE $L_{ux}(m)$ CAN BE ESTIMATED AS A FUNCTION OF $1/\alpha$ AND y :-

$1/\alpha$ \ y(m)	30	50	100	200	300	500
0.143	118	127	140	155	164	177
0.21	127	142	163	190	206	230
0.28	136	157	192	234	261	300

CLEARLY THE THEORETICAL ESTIMATES PREDICT THAT THE LENGTH SCALE INCREASES AS THE TERRAIN ROUGHNESS (OR $1/\alpha$) INCREASES WHICH IS AT VARIANCE WITH THE RESULTS OF THIS REVIEW AND ANALYSIS.

THIS IS ATTRIBUTED TO THE CHOICE OF A CONSTANT VALUE FOR L, INDEPENDENT OF TERRAIN TYPE, WHICH OCCURS IN THE EXPRESSION FOR THE SPECTRUM, C.f. TO AS SHOWN IN SECT. 4 (EQUNS. 4a)

$$L_{ux} = \text{CONST.}\,(y)^n$$

WHERE THE CONSTANT IS A FUNCTION OF THE TERRAIN ROUGHNESS.

ALSO, MORE CORRECTLY FROM EQUS. 4a

$$L_{ux} \propto (y)^{2/\alpha}$$

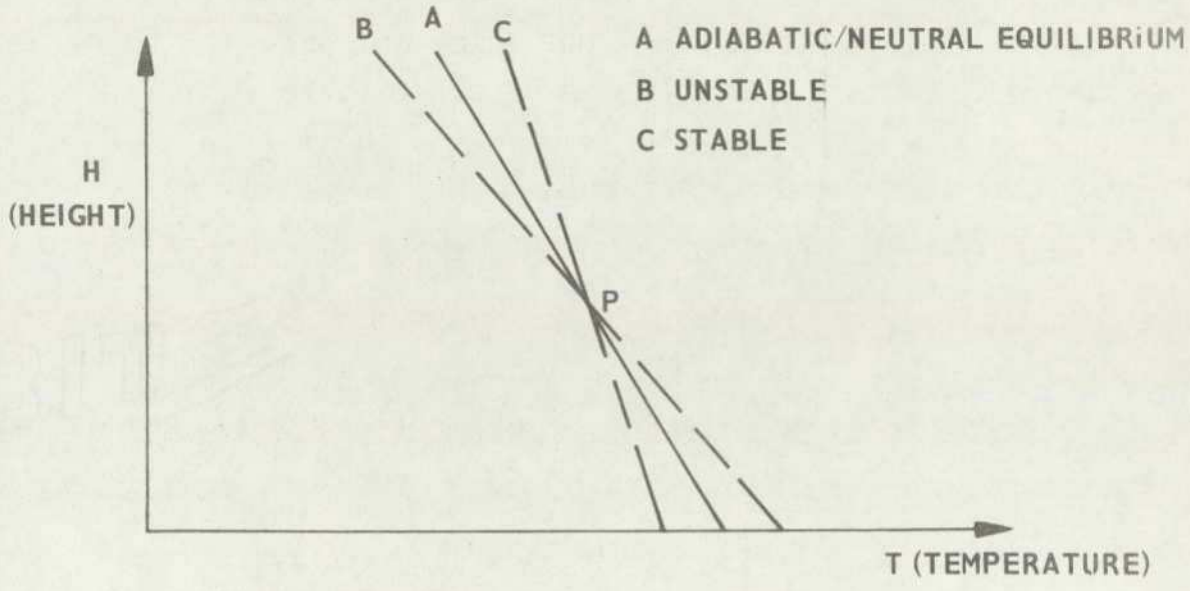
WHEREAS 3 ABOVE GIVES:-

$$L_{ux} \propto (y)^{1/\alpha}$$

ATMOSPHERIC BOUNDARY LAYER SIMULATION

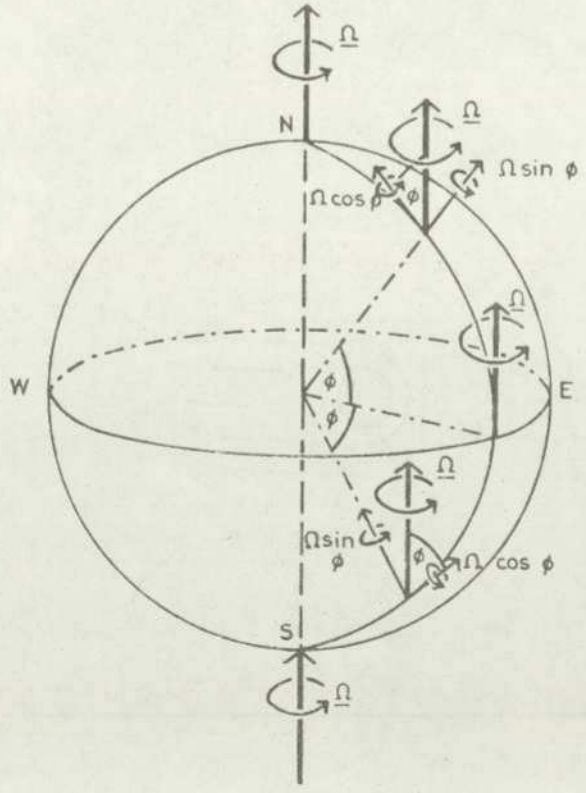
SURVEY OF METEOROLOGICAL DATA

Fig. 1a



STABILITY CONDITIONS OF THE ATMOSPHERE

Fig. 1b.



VERTICAL AND HORIZONTAL COMPONENTS OF THE EARTHS ANGULAR VELOCITY

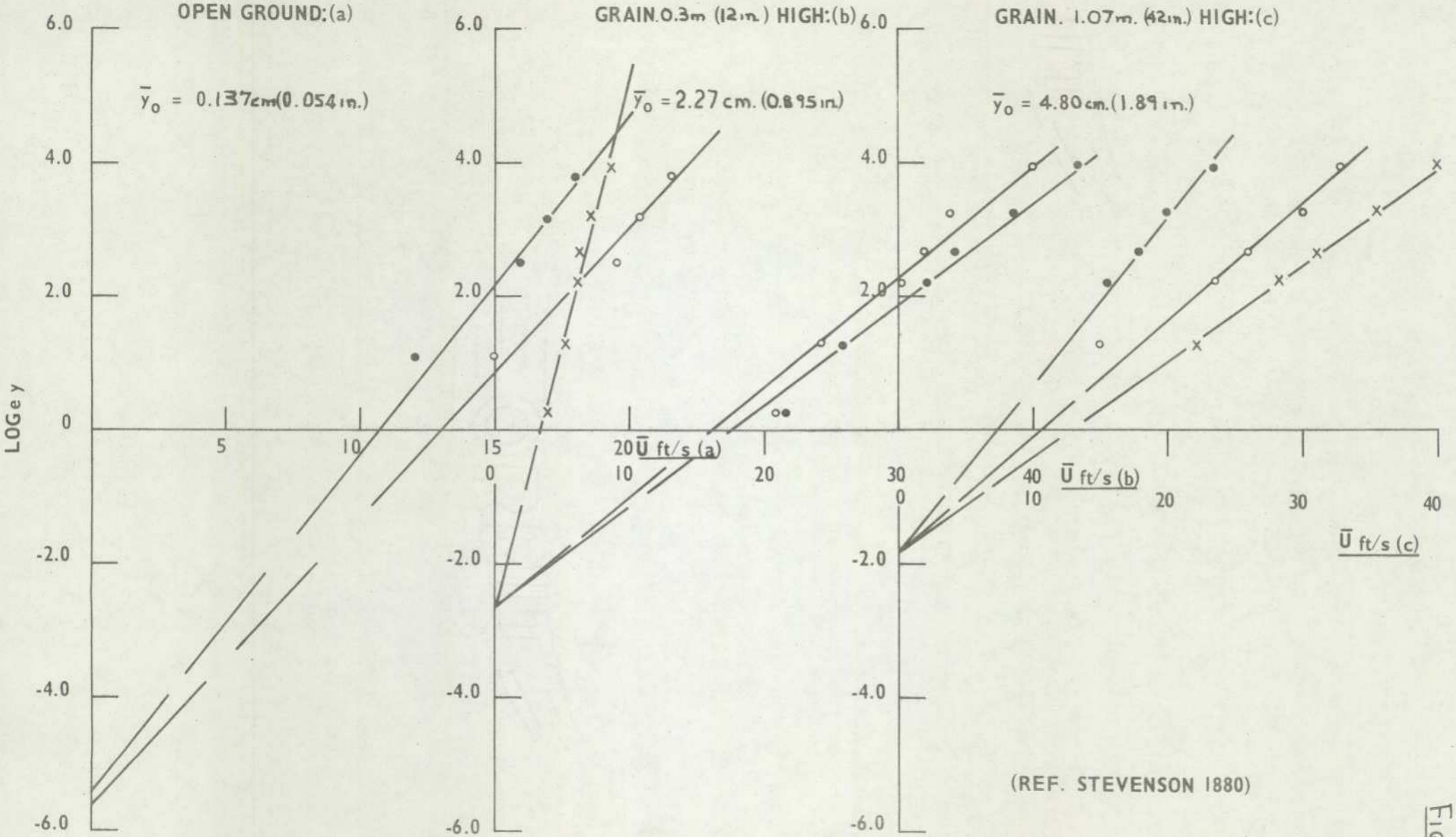
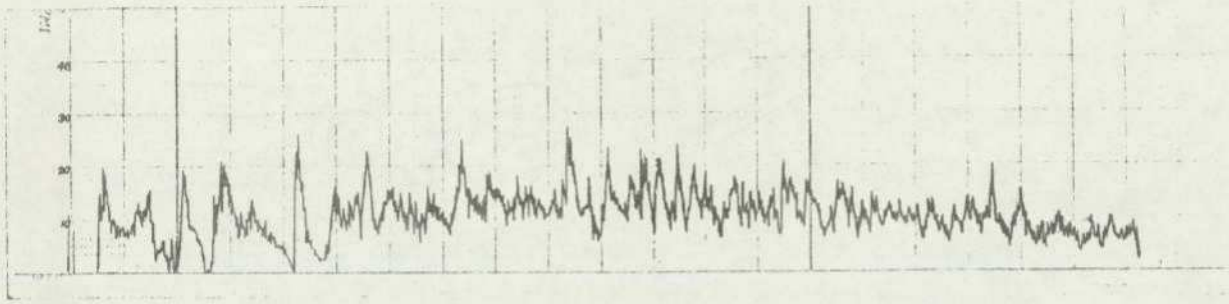


FIG. 2 ATMOSPHERIC BOUNDARY LAYER SIMULATION SURVEY OF METEOROLOGICAL DATA

Fig. 2.

ATMOSPHERIC BOUNDARY LAYER SIMULATION

SURVEY OF METEOROLOGICAL DATA



Recurring squalls at Aberdeen. An anemogram obtained at Aberdeen on January 1, 1908, showing a succession of twenty-seven "squalls" in a light wind between 10.30 a.m. December 31 and 6 a.m. January 1. The intensity of the squalls is not great, as the highest velocity is less than 30 miles per hour, but the squally fluctuations as distinct from the gustiness of short period are well marked.

WIND CURRENTS BEHIND STABLE BUILDINGS AT PYRTON HILL.

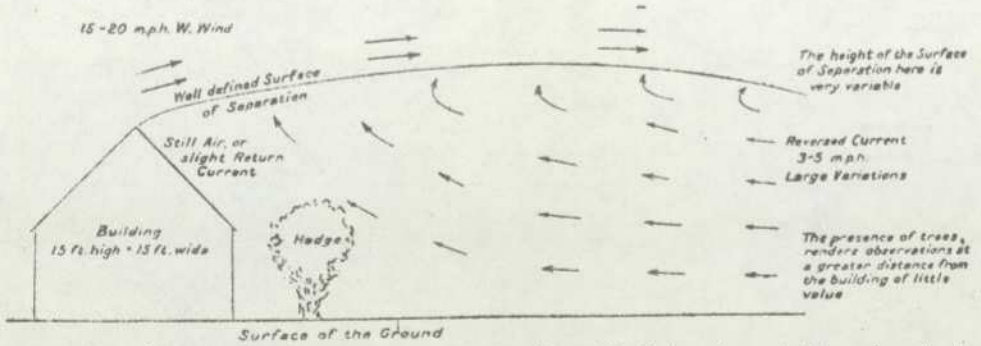
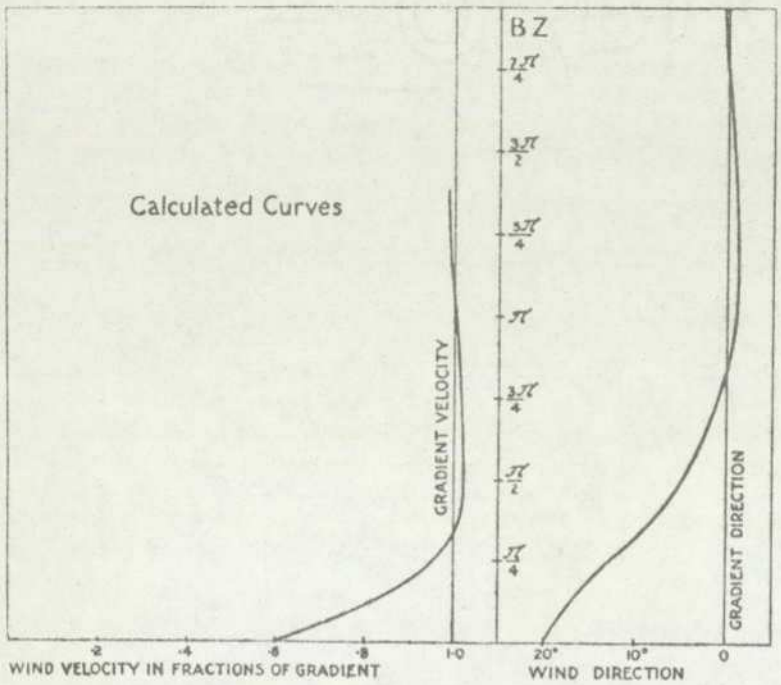


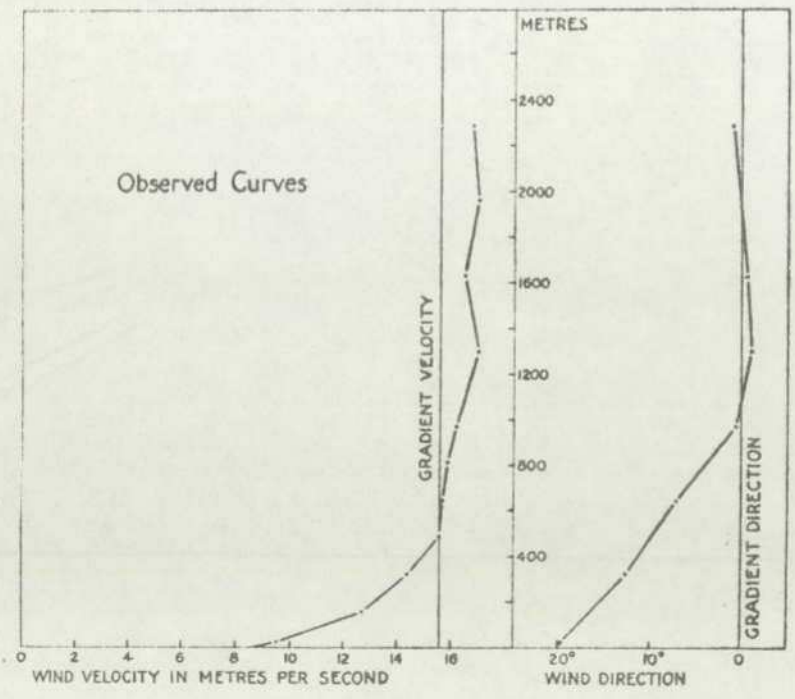
Diagram showing the "cliff eddy" in the neighbourhood of a stable at Pyrton Hill, due to a 15-20 mile wind blowing on the side of the building.

(REF. SHAW 1914)

ATMOSPHERIC BOUNDARY LAYER SIMULATION

SURVEY OF METEOROLOGICAL DATA.



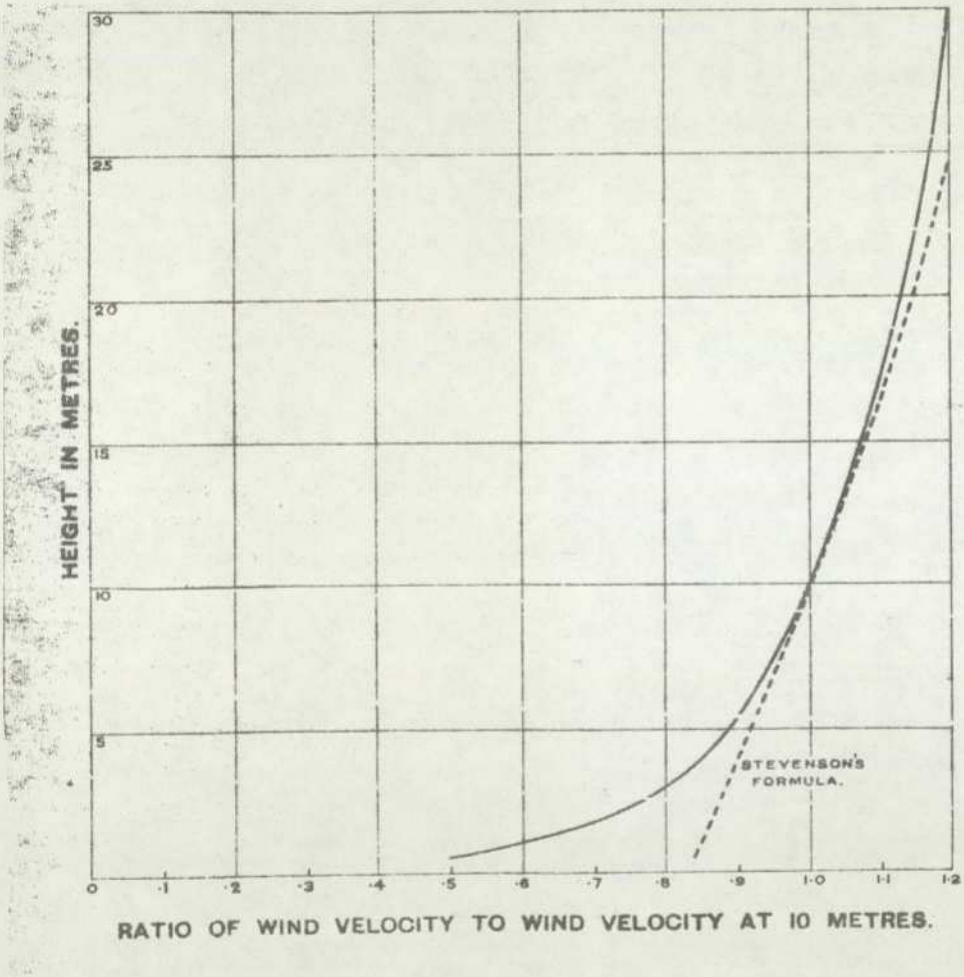


(REF. TAYLOR 1915)

FIG. 5.

ATMOSPHERIC BOUNDARY LAYER SIMULATION

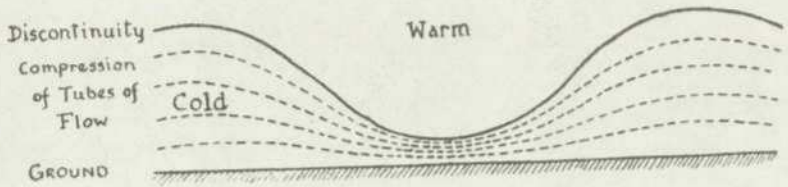
SURVEY OF METEOROLOGICAL DATA.

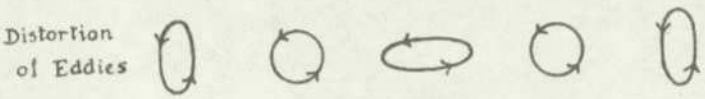


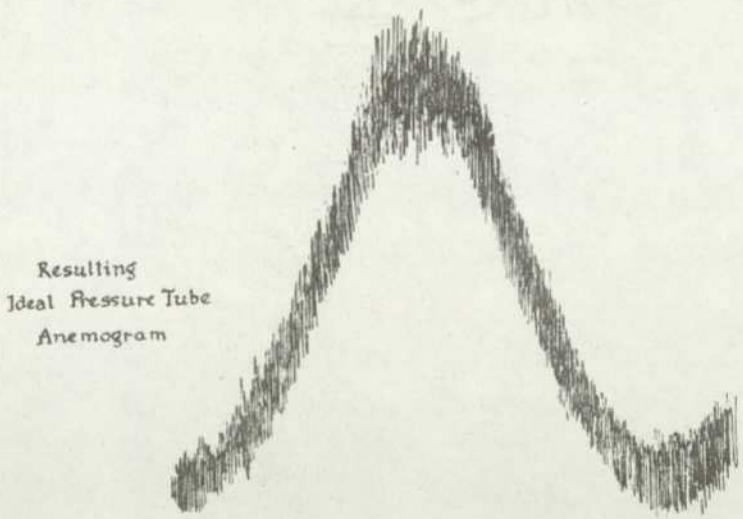
(REF. CHAPMAN 1919.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA



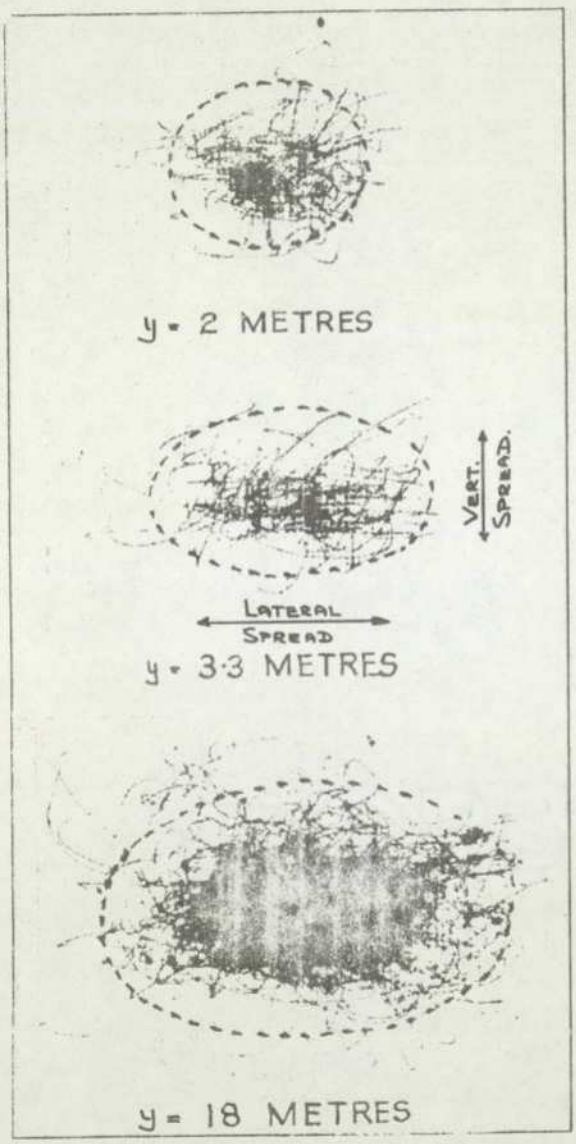




(REF. GOLDIE 1925)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



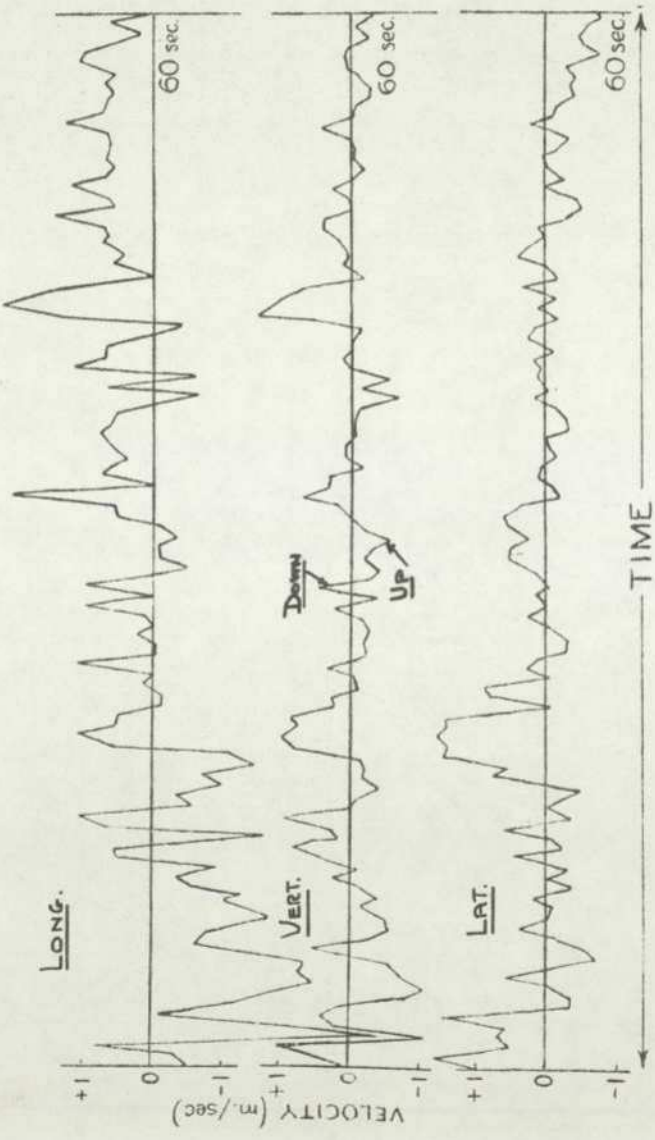
TYPICAL DIAGRAMS OBTAINED WITH A SMALL BI-DIRECTIONAL VANE AT DIFFERENT HEIGHTS ABOVE THE GROUND.

(REF. SCRASE 1930)

FIG. 8.

ATMOSPHERIC BOUNDARY LAYER SIMULATION

SURVEY OF METEOROLOGICAL DATA.

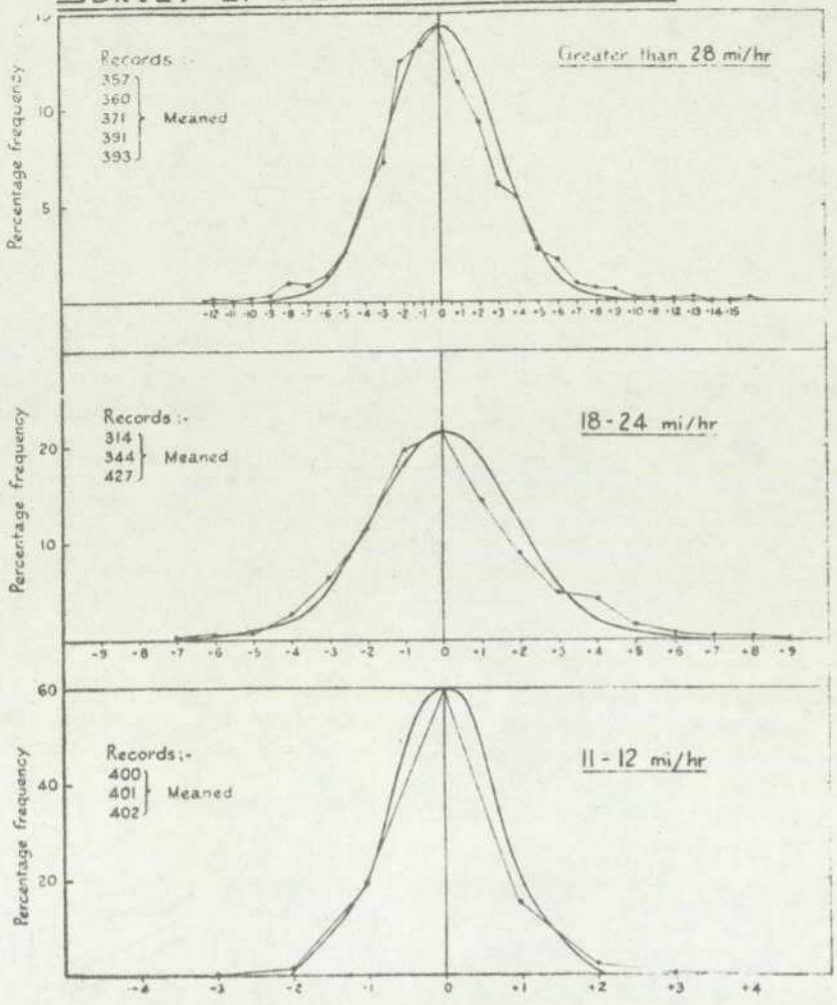


—SIMULTANEOUS RECORDS OF THE THREE COMPONENTS OF EDDY VELOCITY AT 10 METRES ABOVE THE GROUND (MEAN WIND VELOCITY 30 M./SEC.)

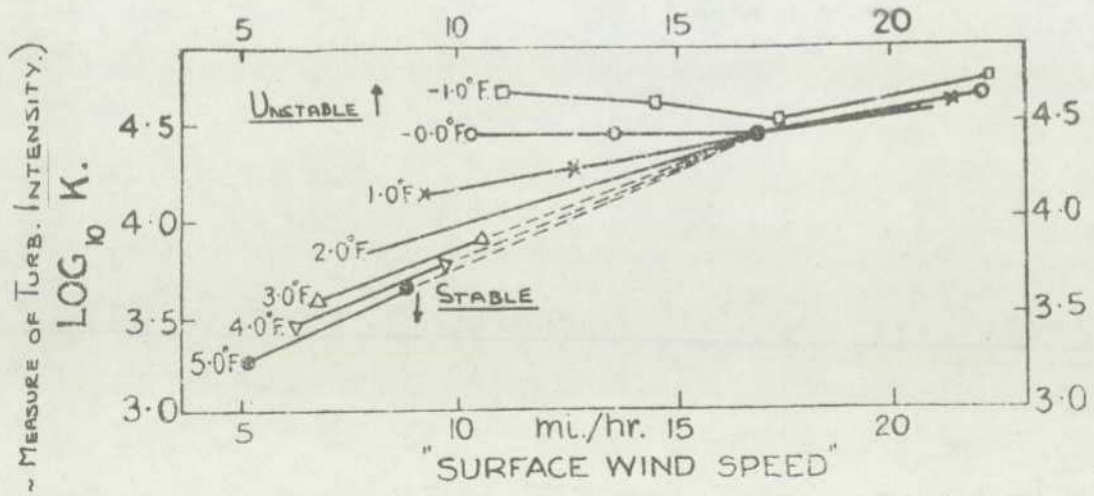
(REF. SCRASE 1930.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



THIS DIAGRAM SHOWS THE FREQUENCIES OF ACCELERATION OF WIND OVER INTERVALS OF 5 SECONDS, THE DATA USED BEING THE SAME AS THOSE SHOWN IN FIG. 41, BUT COMBINATIONS WERE MADE OF THE CASES TO GIVE THE MEAN WIND OF THE RECORD WAS OVER 28 MI/HR., 18 TO 24 MI/HR., AND 11 TO 12 MI/HR. FOR COMPARISON FREQUENCY CURVES ARE ALSO DRAWN TO PASS THROUGH THE PEAK OF THE CURVE OBTAINED FROM THE DATA. THE ORDINATES ARE GIVEN IN PERCENTAGE FREQUENCY, THE ABSCISSÆ IN THE UNIT MILES PER HOUR PER 5 SECONDS.

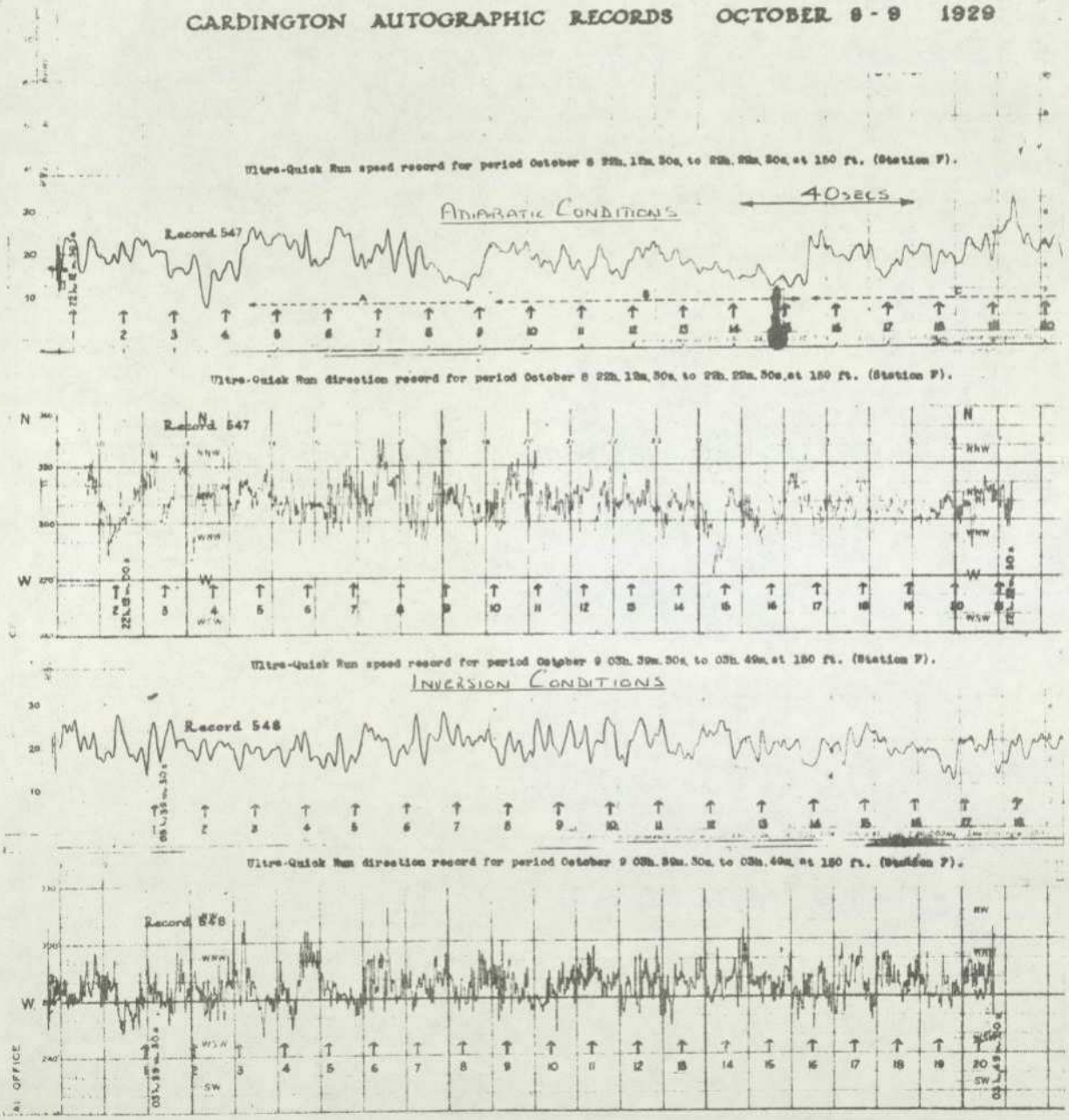


RELATION OF THE COEFFICIENT OF TURBULENCE TO THE MEAN WIND SPEED FOR DIFFERENT VALUES OF THE VERTICAL TEMPERATURE GRADIENT.

(REF. GIBLETT 1932.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.

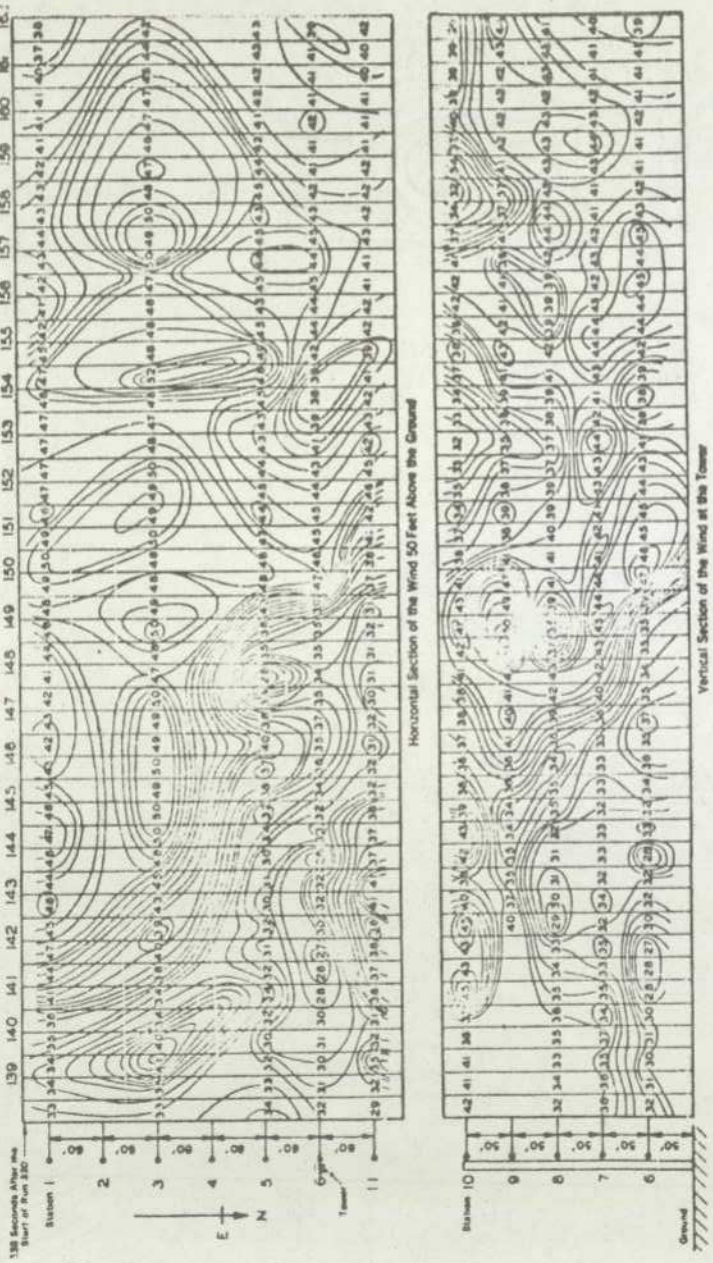


(REF. GIBLETT 1932.)

FIG. 11

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.

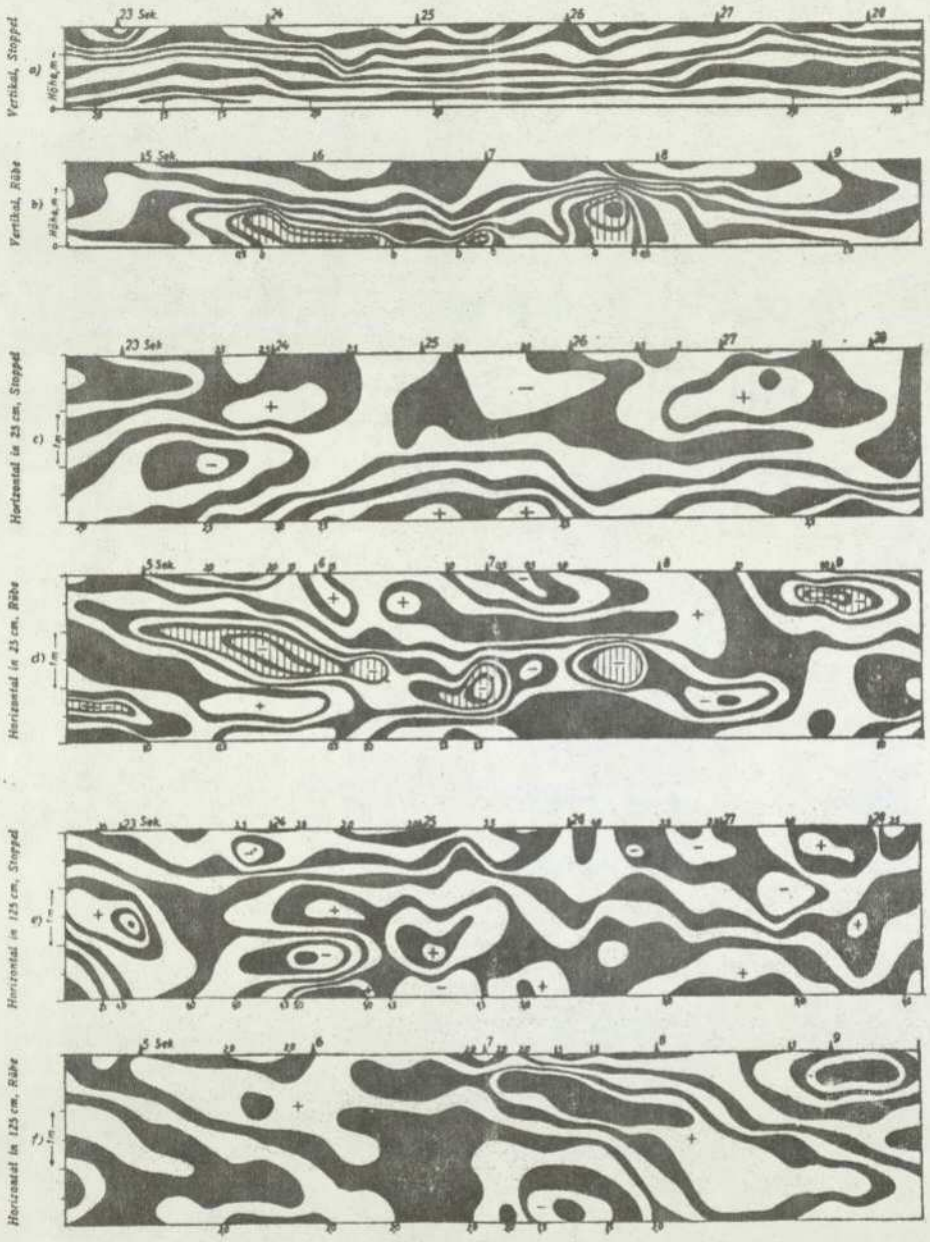


ISO-VELOCITY LINES IN PART OF A WIND GUST

(REF. SHERLOCK AND STOUT. 1932.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



Wind records from Hommelsheim, October, 1928. Changes in velocity with time at different sections. Scale on the left metres, large figures on top time in seconds, small figures on top and below velocities in metres per second; dashed areas: negative velocities (motion against the wind).

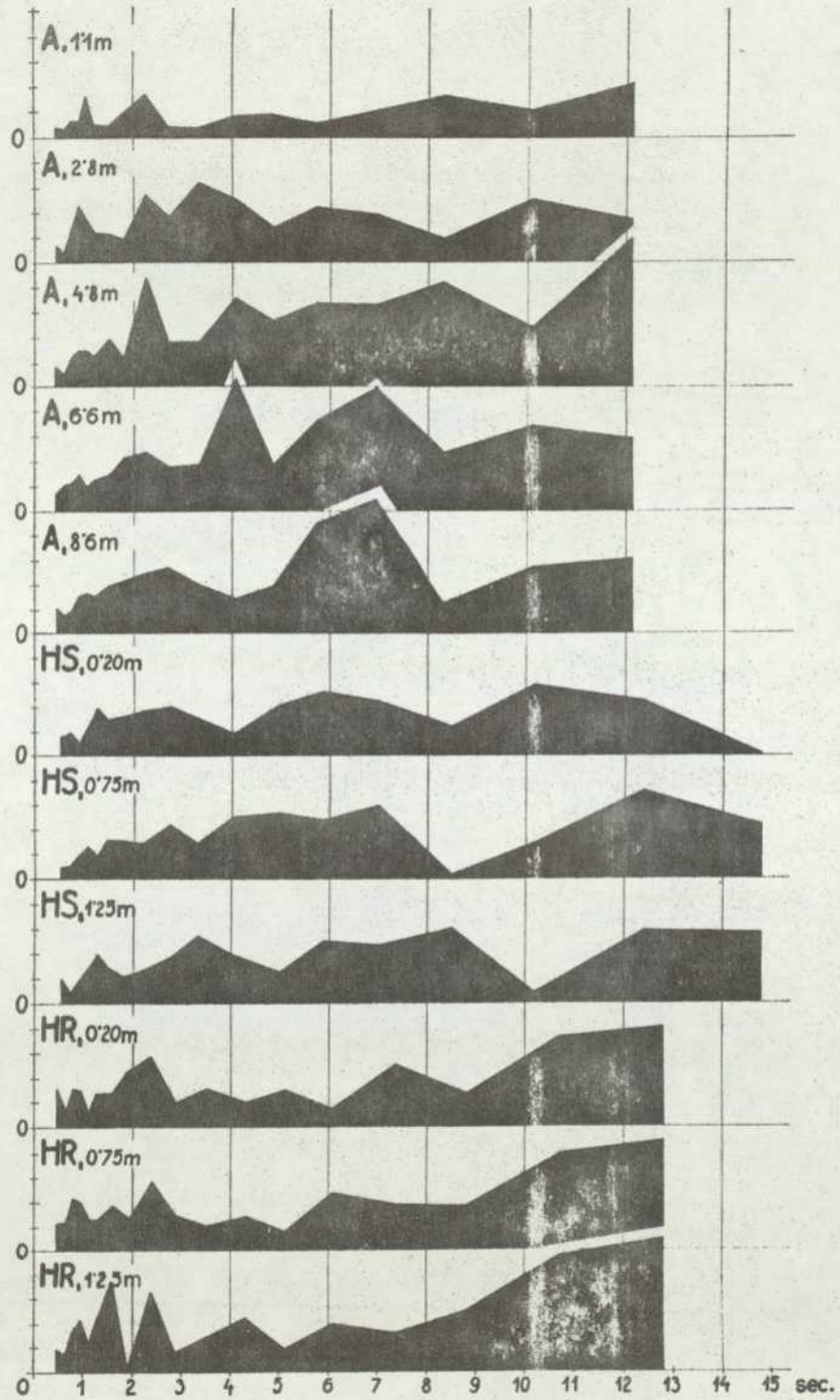
(a) and (b) vertical sections, (c) and (d) horizontal at a height of 25 cm., (e) and (f) the same at 125 cm., (a), (c) and (e) taken over stubble field, (b), (d) and (f) over a field of turnips.

(REF. SCHMIDT 1935.)

FIG. 13.

ATMOSPHERIC BOUNDARY LAYER SIMULATION

SURVEY OF METEOROLOGICAL DATA.

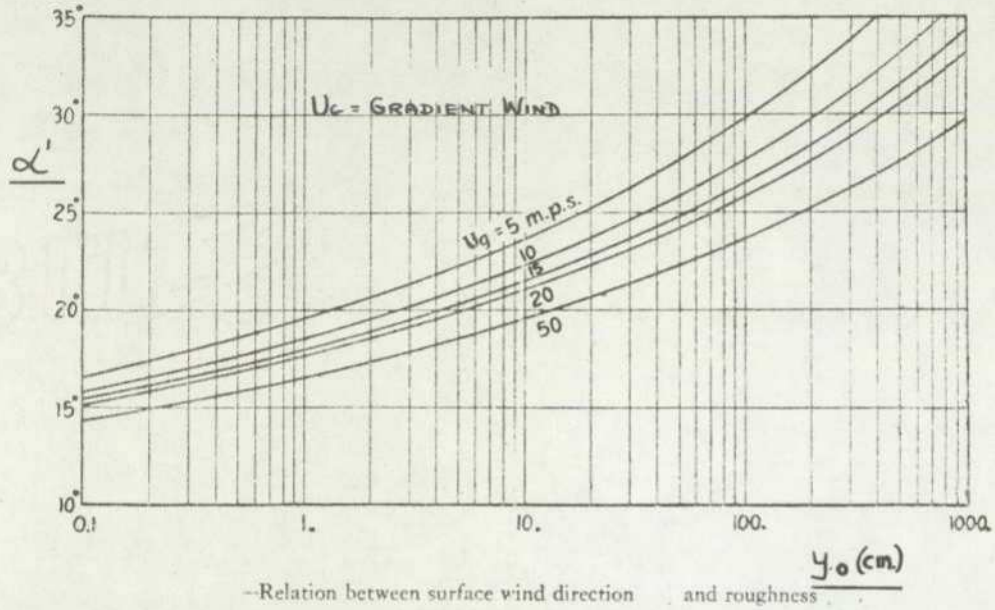


"Gust spectra," amplitudes of wind oscillations of different periods. A = observations taken at Aspern (aerodrome, flat grass land), HS = Hommelsheim (over stubble field), HR = Hommelsheim (over turnip field). The figures near these indications give the height above ground.

(REF. SCHMIDT 1935.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION

SURVEY OF METEOROLOGICAL DATA.



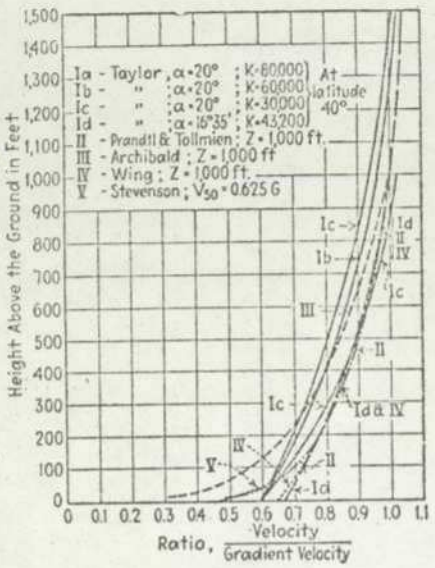
--Relation between surface wind direction and roughness.

(REF. ROSSBY AND MONTGOMERY 1935.)

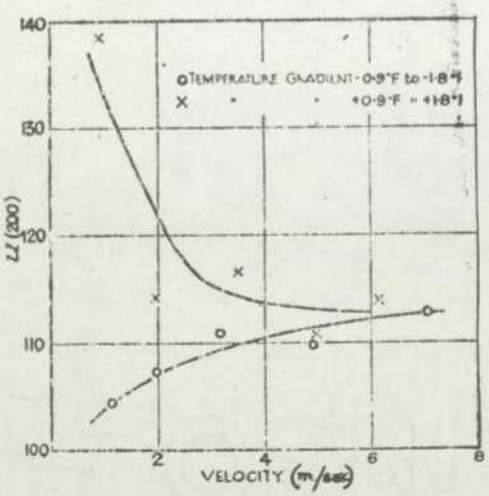
ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.

CHANGE of wind velocity with height above ground as found by different investigators.



(REF. PAGON. 1935)

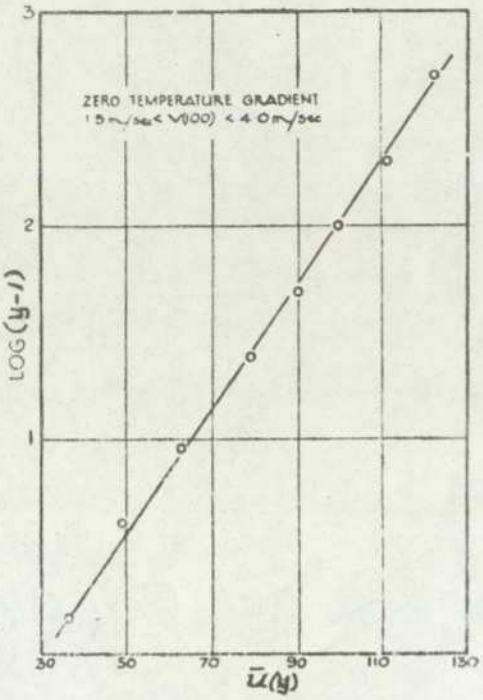


.—EFFECT OF VELOCITY UPON VELOCITY GRADIENT.

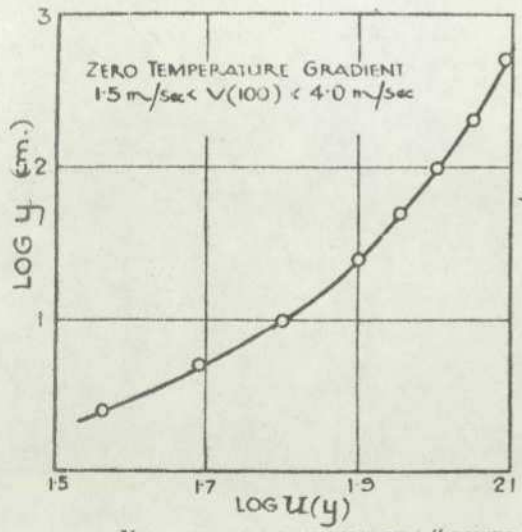
(REF. BEST 1935.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

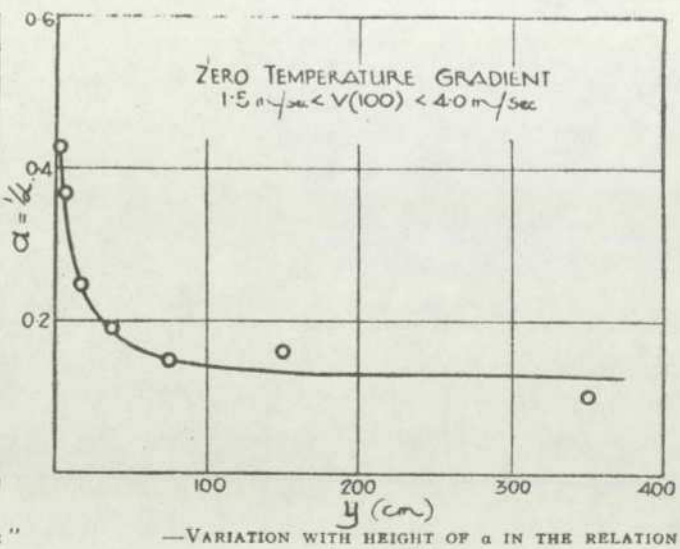
SURVEY OF METEOROLOGICAL DATA.



—VELOCITY AS A FUNCTION OF LOG (y−1).



—VELOCITY AS A FUNCTION OF A " POWER " OF THE HEIGHT.

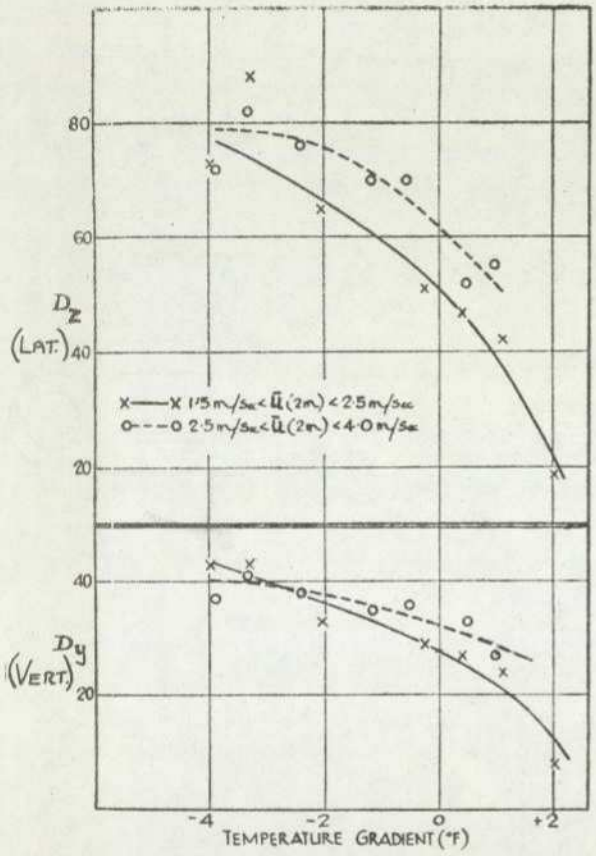


—VARIATION WITH HEIGHT OF α IN THE RELATION $U(z) = Ay^{\alpha}$.

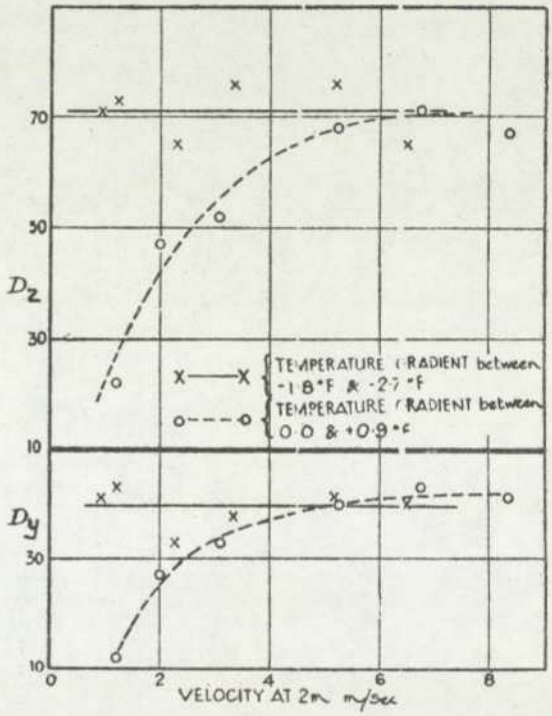
(REF. BEST 1935.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



—VARIATION OF GUSTINESS WITH TEMPERATURE GRADIENT.

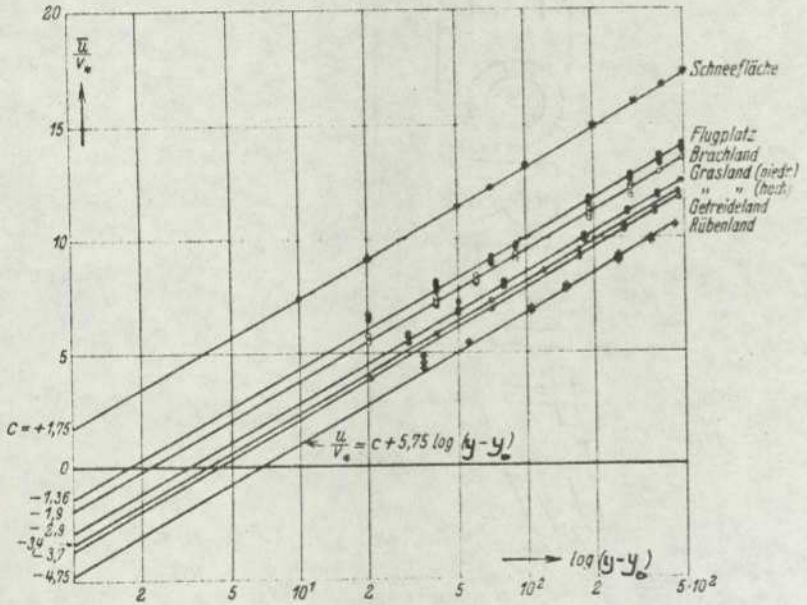


—VARIATION OF GUSTINESS WITH VELOCITY.

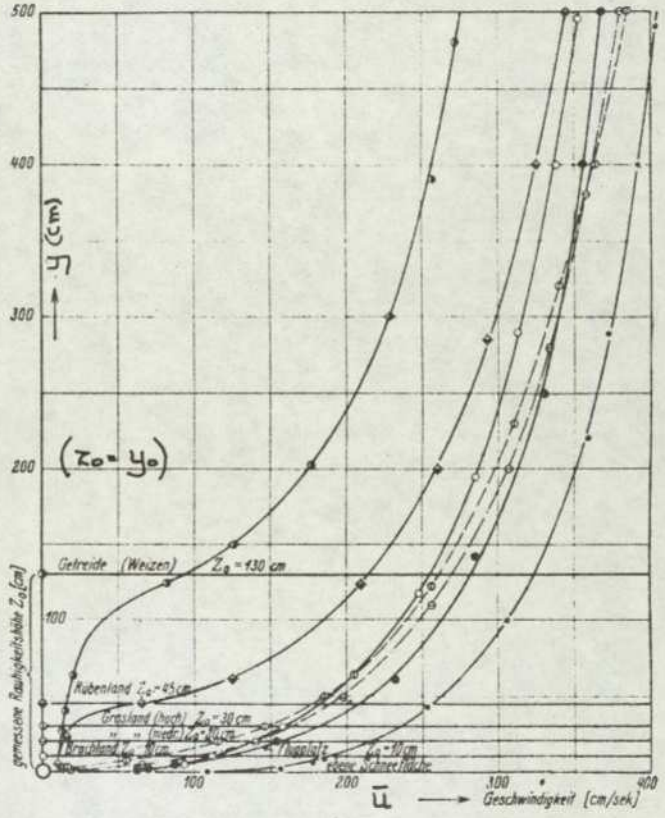
(REF. BEST 1935.)

Atmospheric Boundary Layer Simulation.

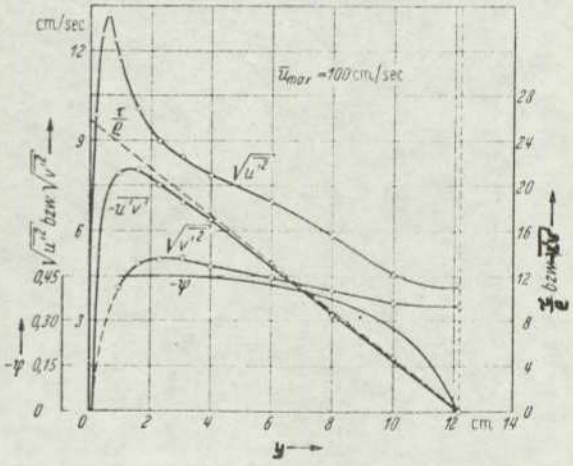
Survey of Meteorological Data.



(a)



(b)



(c)

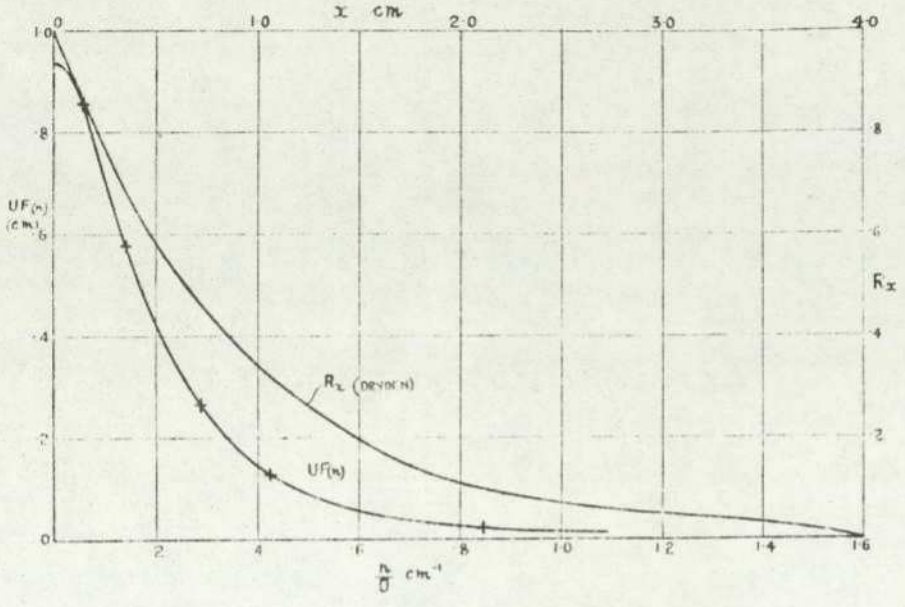
(Ref. Paeschke - 1937.)

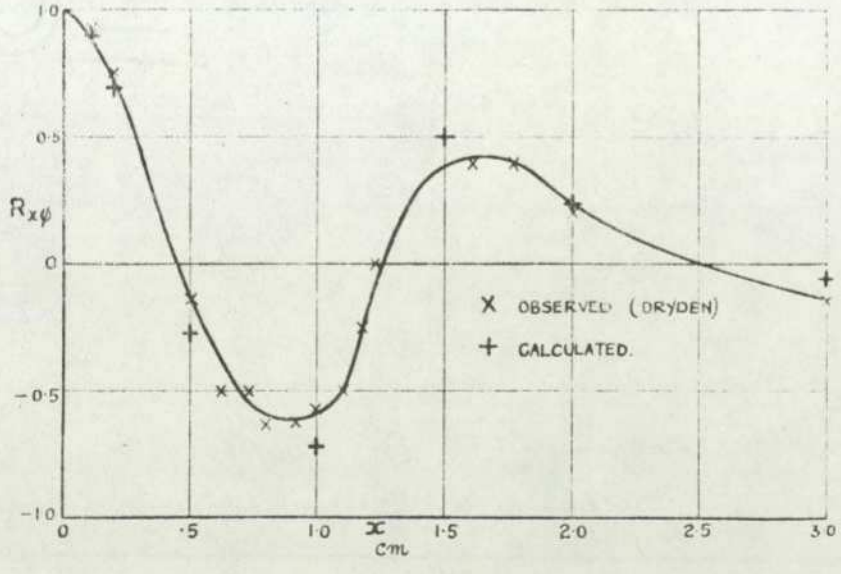
(Ref. Reichardt - 1938.)

Fig. 18

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



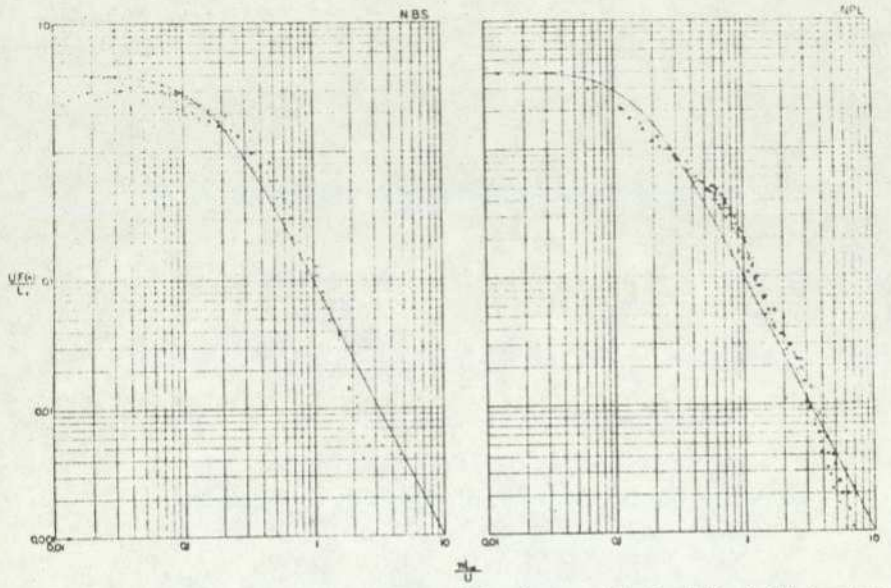


(REF. TAYLOR 1938.)

FIG. 20.

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



Comparison of National Bureau of Standards and National Physical Laboratory measurements of the spectrum of turbulence, plotted non-dimensionally.

At left, NBS values 40(·) and 160(+) inches behind 1-inch mesh screen at 40 ft/sec.

At right, NPL values of ($F(n)$ from Table II of reference 21, L_x from reference 20) 82 inches behind 3-inch mesh screen at 15(·), 20(×), 25(+), 30(△), and 35(□) ft/sec.

The reference curve in each case is the curve

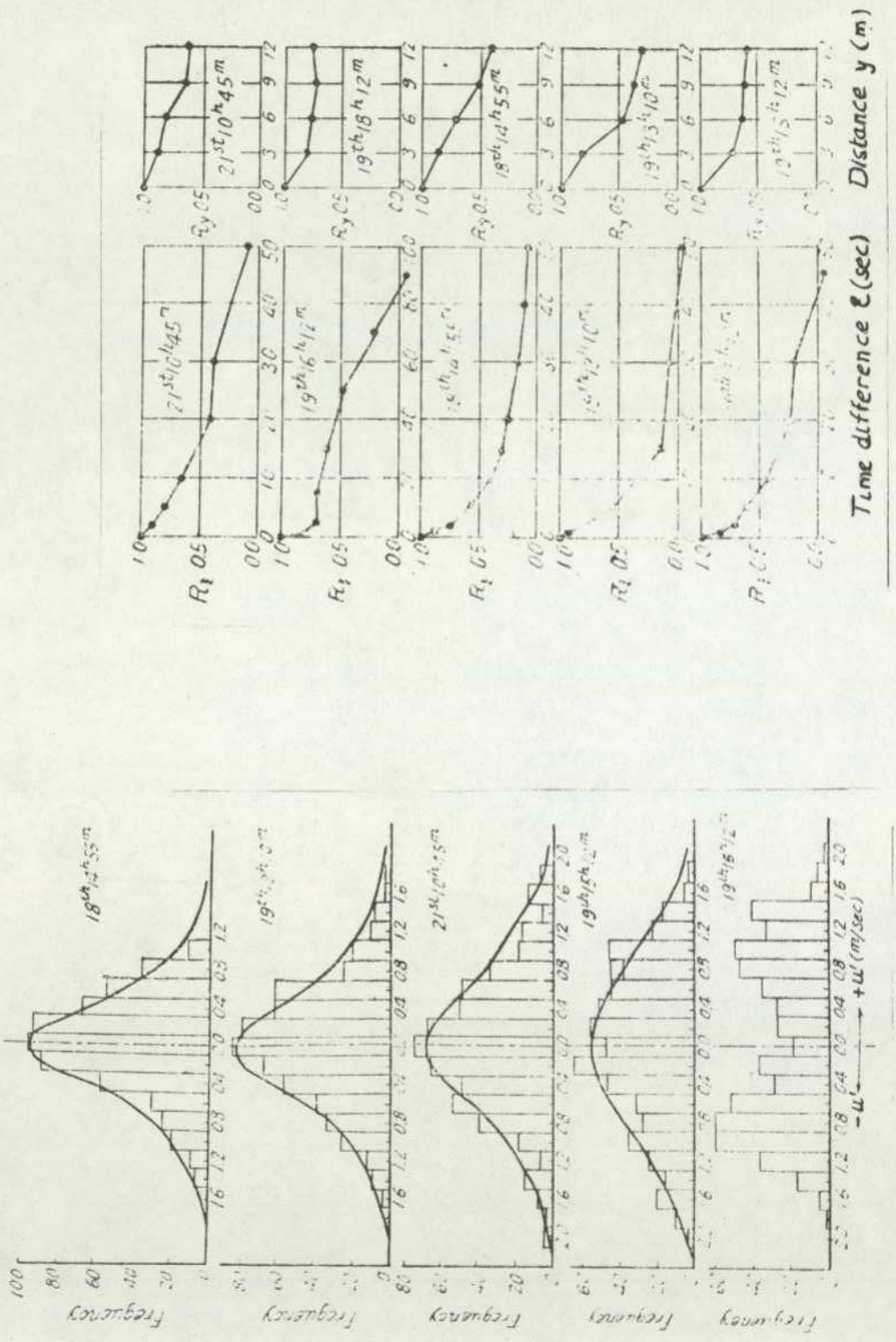
$$\frac{UF(n)}{L_x} = \frac{4}{1 + \frac{4\pi^2 n^2 L_x^2}{U^2}}$$

where U is the mean speed, L_x is the integral $\int_0^\infty R_x dx$, R_x is the correlation between the fluctuations at two points separated by the distance x in the direction of flow, n is the frequency, and $F(n)$ is the fraction of the total energy of the turbulence arising from frequencies between n and $n + dn$.

(REF. DRYDEN 1943.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

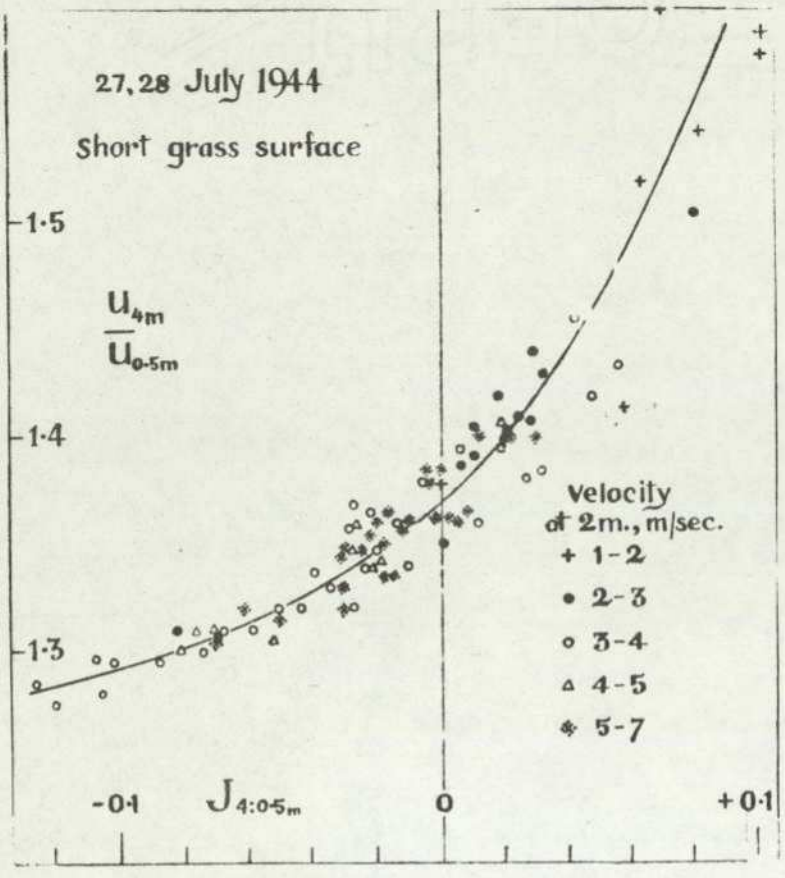
SURVEY OF METEOROLOGICAL DATA.



(REF. YAMAMOTO AND SHIOTANI. 1948.)

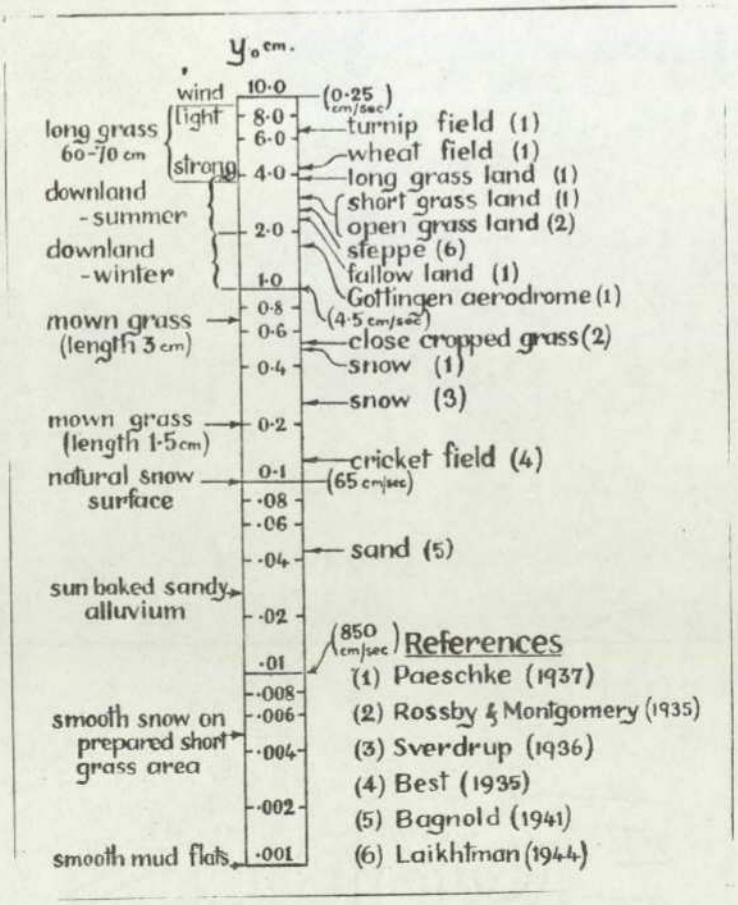
ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



(a)

(J = FORM OF RICHARDSON NO. FOR $0.5 < y_m < 4$)



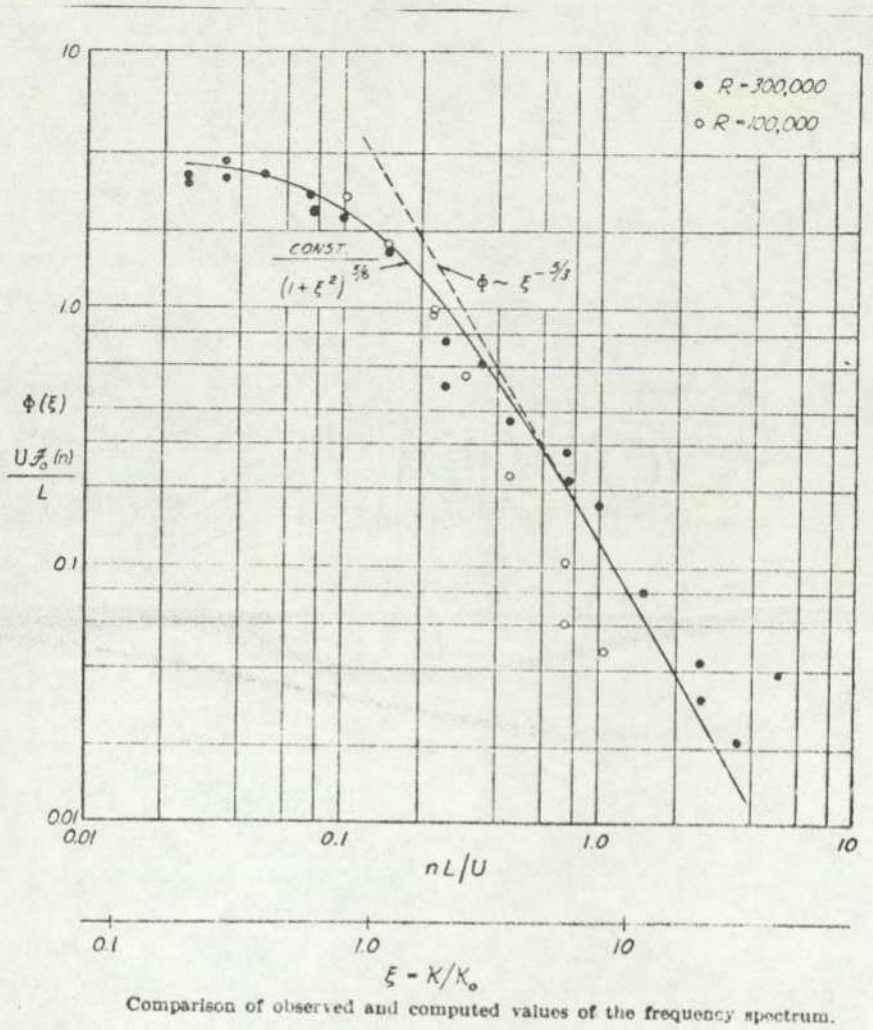
(b)

(REF. DEACON 1948.)

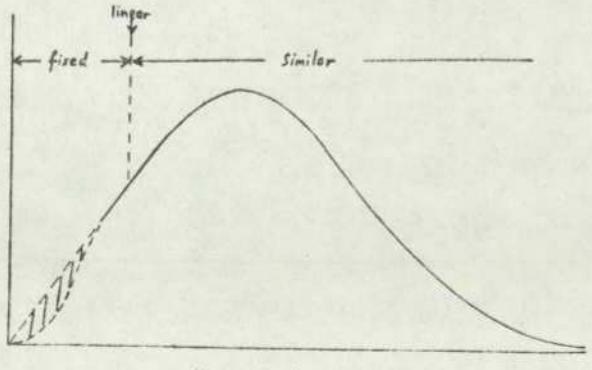
FIG. 23.

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



Comparison of observed and computed values of the frequency spectrum.



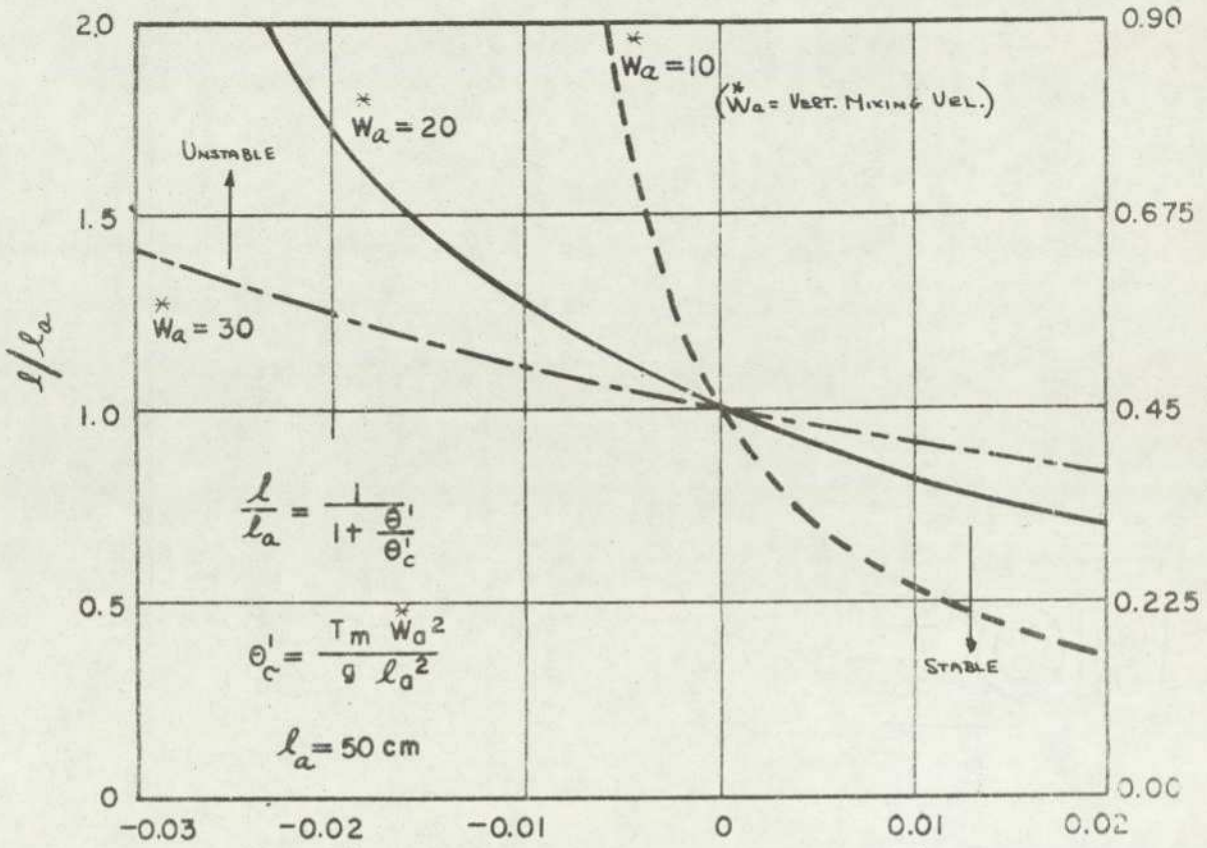
Spectrum during early period.

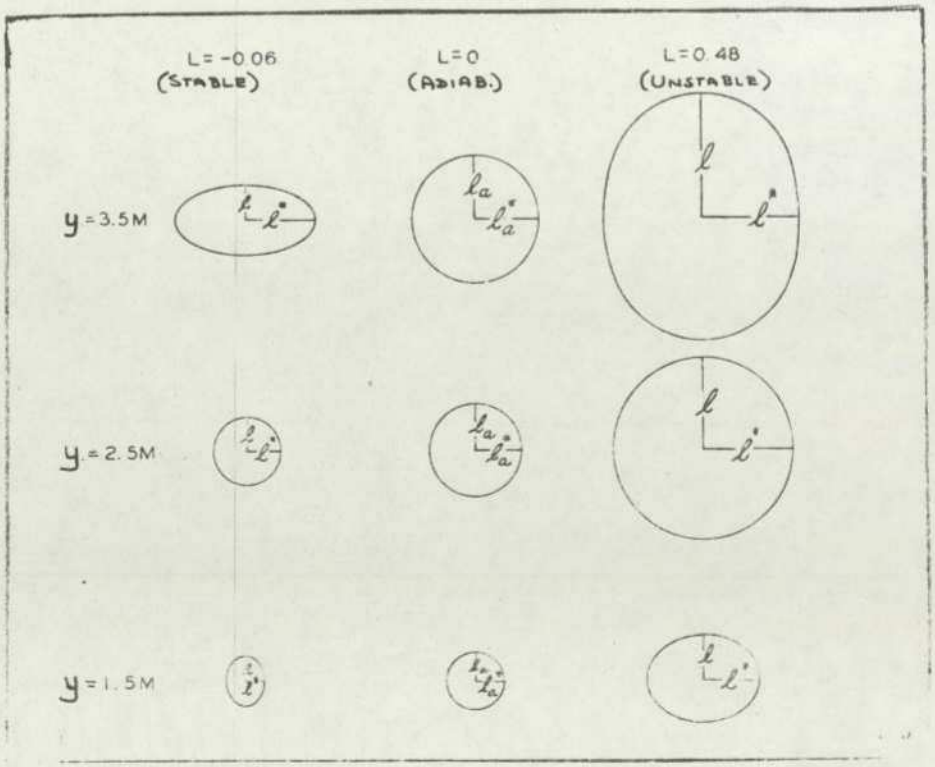
(REF. VON KARMEN 1948.)

FIG. 24.

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.

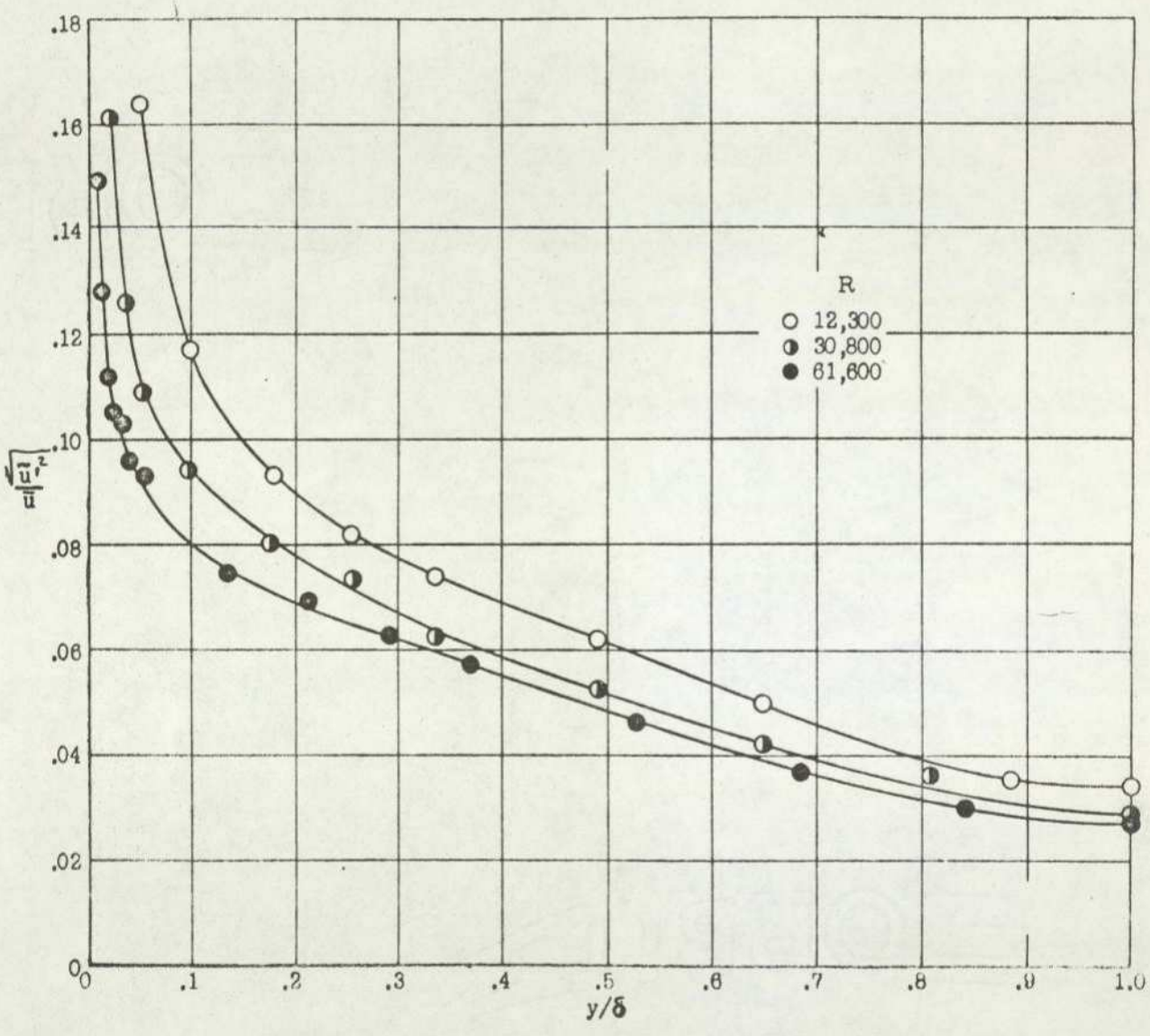




(REF. LETTAU 1949.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.

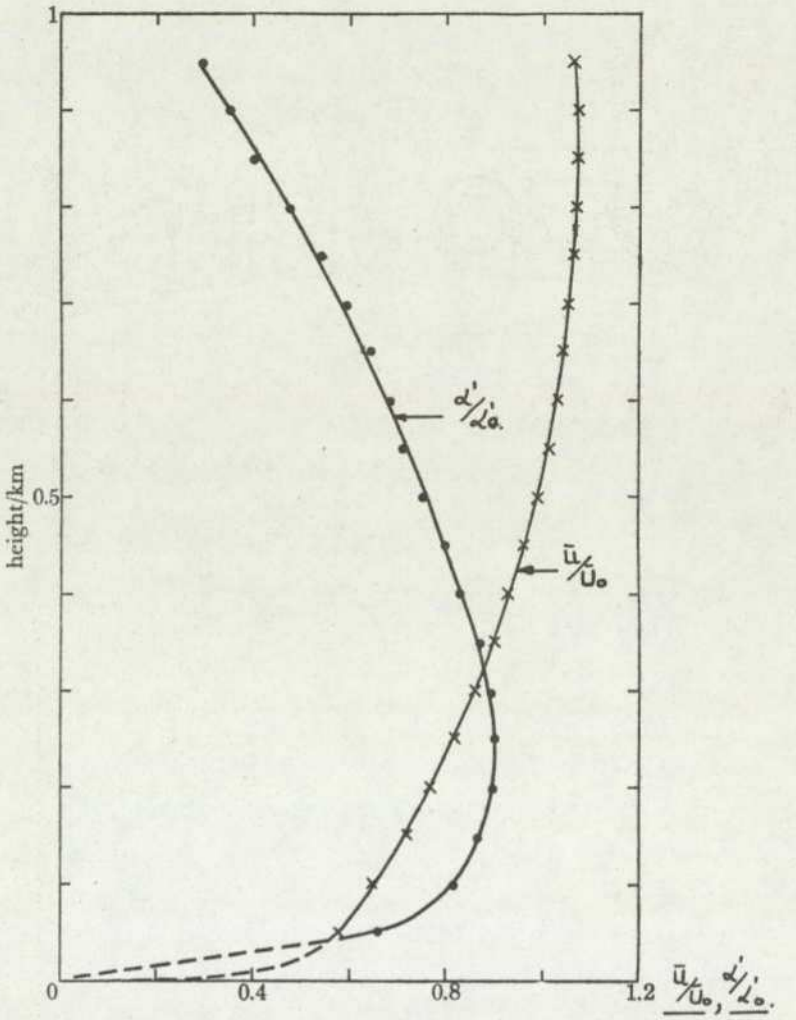


Velocity fluctuations u' relative to local speeds.

(REF. LAUFER 1950.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

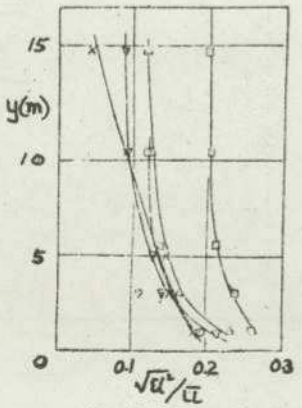
SURVEY OF METEOROLOGICAL DATA.



. General nature of wind profile in near-neutral conditions (from re-analysis by Lettau (1950)

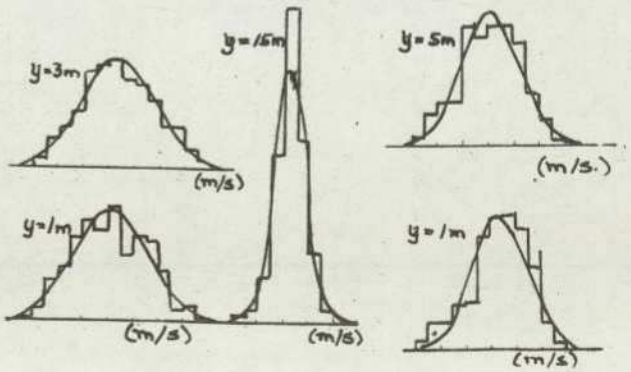
(a)

(REF. LETTAU 1950.)



Vertical Distribution of $\sqrt{\overline{u'^2}}/\bar{u}$

(b)

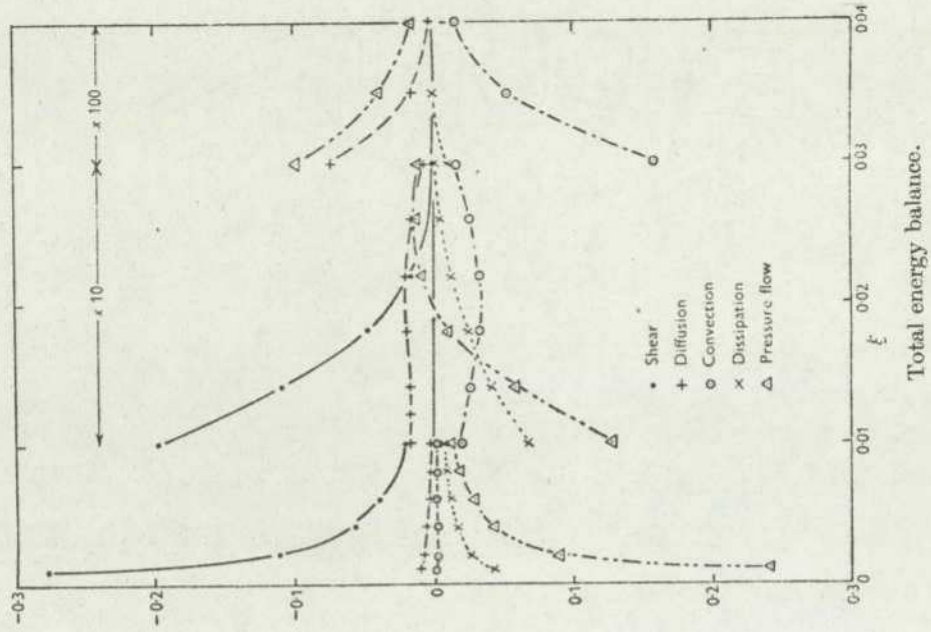


(c)

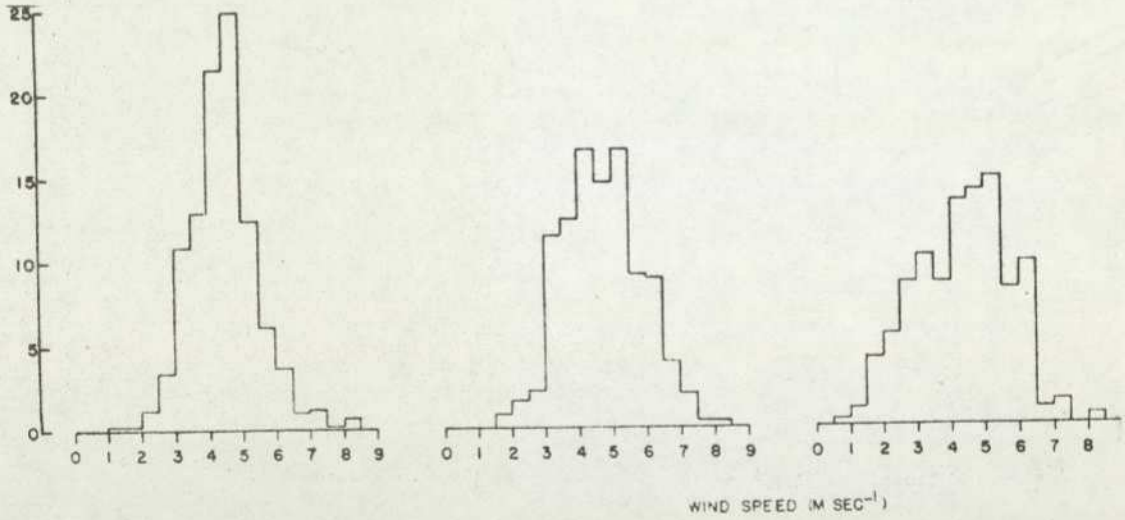
(REF. SHIOTANI 1950.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

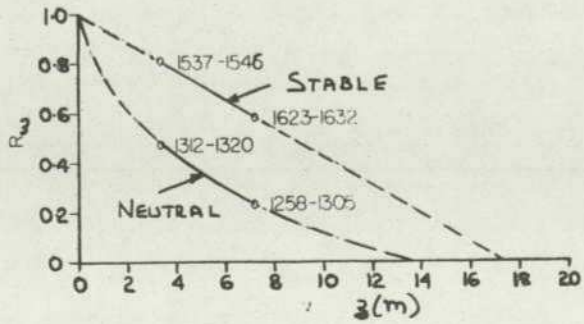
SURVEY OF METEOROLOGICAL DATA.



(a) (REF. TOWNSEND 1951.)



(b)



Scale of transverse turbulence

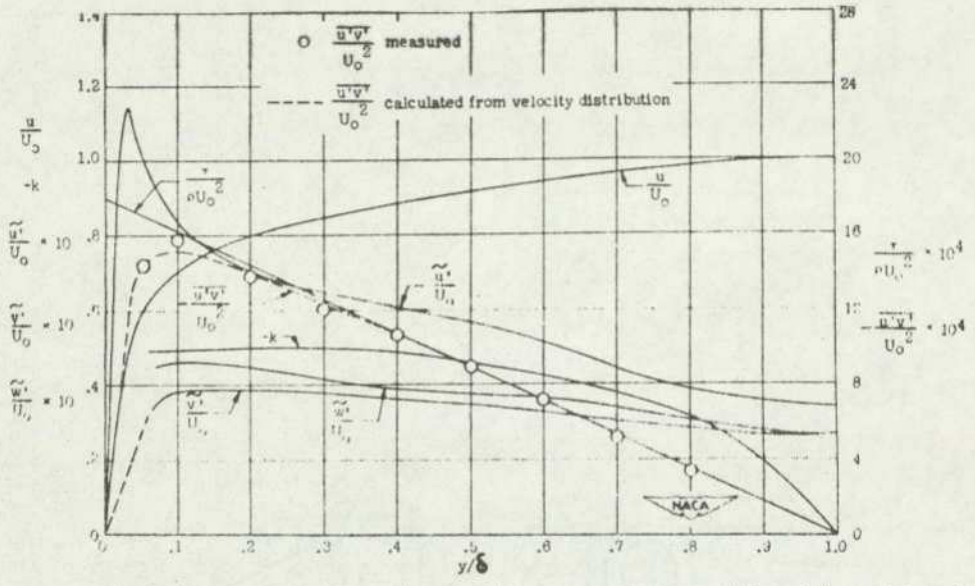
(c)

(REF. CRAMER 1952.)

FIG. 28.

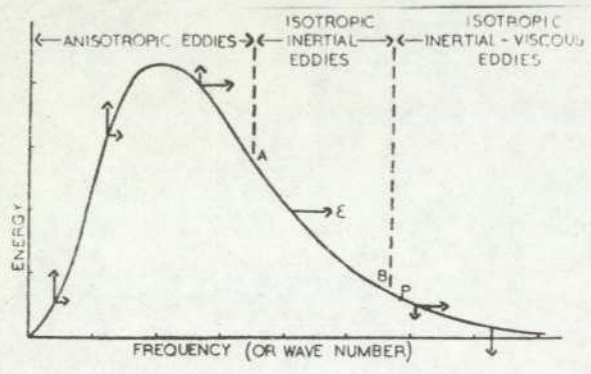
ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



(a)

Distribution of mean and fluctuating quantities in a two-dimensional channel, $R = 12{,}300$ (aft.

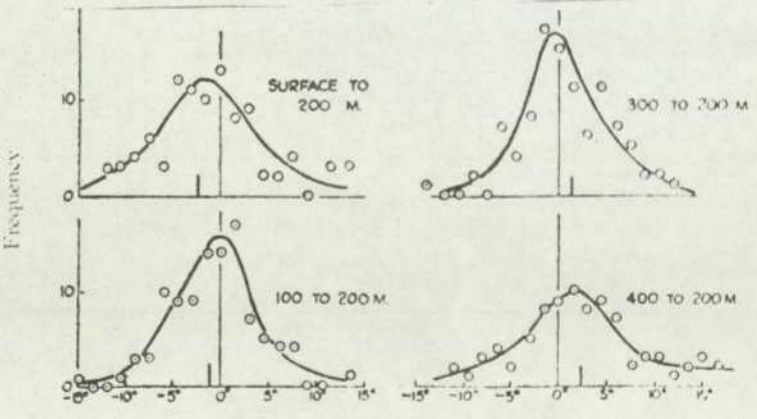


(b)

Diagrammatic representation of energy transfer processes in a steady turbulence spectrum in which similarity in eddy structure is assumed to exist among eddies smaller than those represented by the point A and viscous dissipation is appreciable only in eddies smaller than B.

↑ = energy input from mean motion (total = ϵ)
→ = energy transfer from larger to smaller eddies
↓ = energy dissipated by viscosity (total = ϵ)

(REF. PRIESTLEY AND SHEPPARD 1952.)



(c)

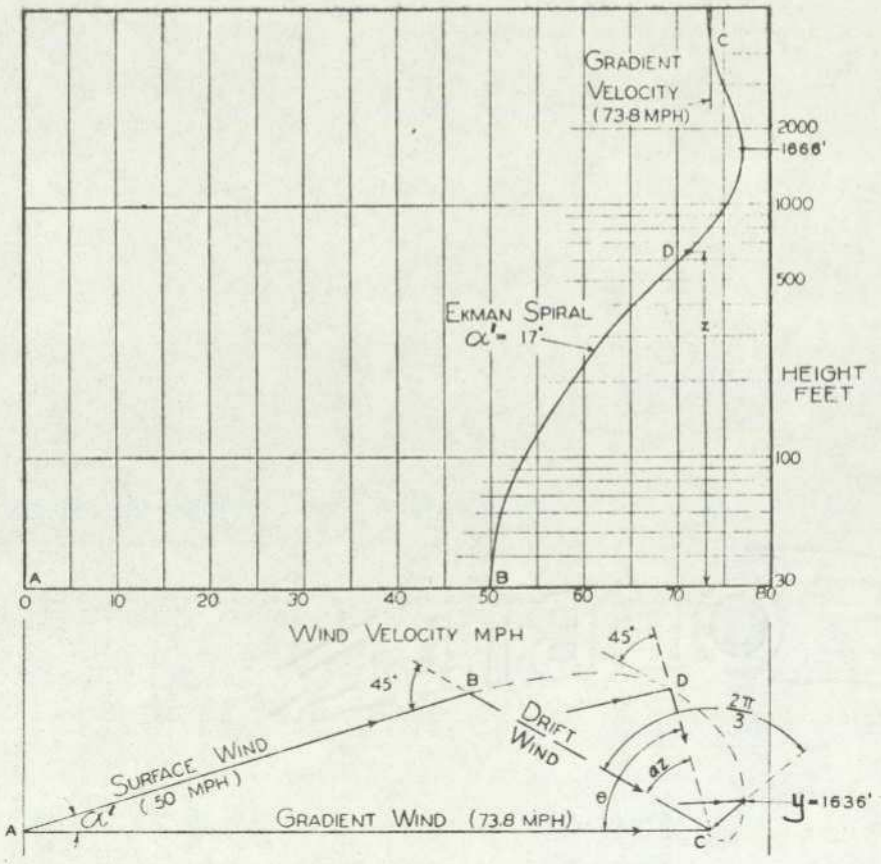
Wind direction relative to 200 m wind

Frequency distribution of variation of wind direction with height using the 200 m wind direction as reference. Positive direction implies veer relative to 200-m direction. Mean values of direction at each level relative to 200-m direction shown by short vertical lines on abscissae.

(REF. SHEPPARD, CHARNOCK AND FRANCIS 1952.)

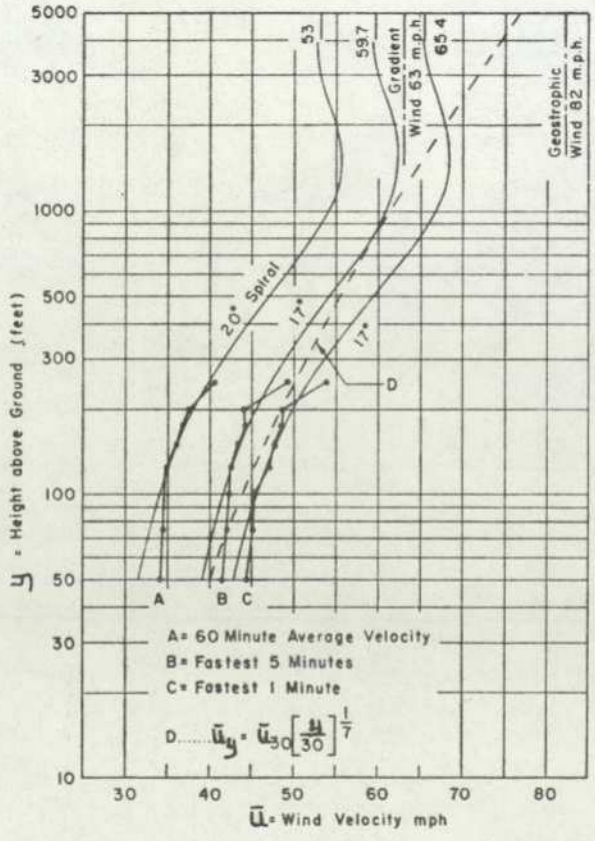
ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



(a)

—THEORETICAL VARIATION OF WIND VELOCITY WITH HEIGHT ACCORDING TO THE EKMAN SPIRAL



(b)

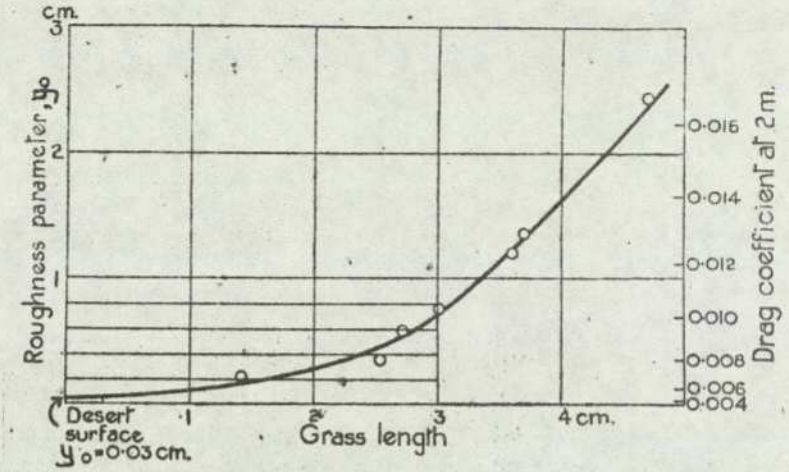
—EKMAN SPIRALS FITTED TO OBSERVED WIND VELOCITIES AND COMPARED WITH COMPUTED GRADIENT WIND

(REF. SHERLOCK 1952.)

FIG. 30.

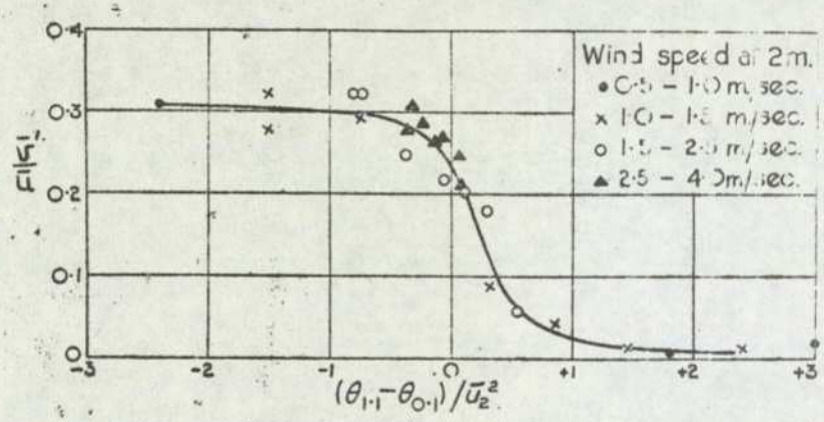
ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



(a)

—ROUGHNESS PARAMETER RELATED TO GRASS LENGTH



(b)

—RELATION BETWEEN BEST'S GUSTINESS VALUES AND STABILITY

ROUGHNESS PARAMETERS OF VARIOUS SURFACES

$C_D = 2\left(\frac{u_*}{\bar{u}}\right)^2$

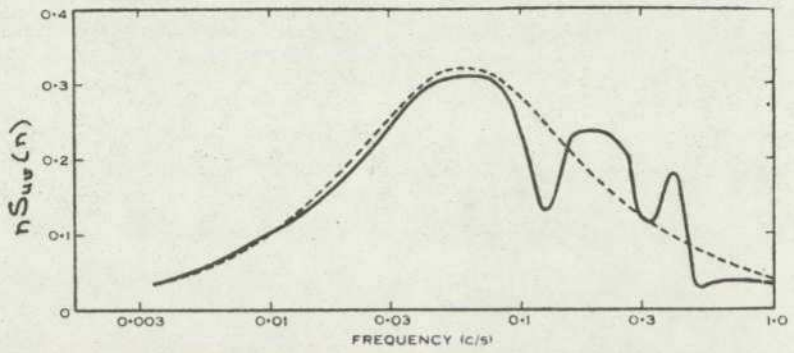
Type of surface	R_2	y_0	Drag coefficient at 2 m.
		cm.	
Smooth mud flats	1·06	0·001	0·0021
Smooth snow on short grass	1·07	0·005	0·0024
Sea*	..	0·02	0·0038
Desert near Karachi†	1·085	0·03	0·0041
Snow surface, Canada‡	1·10	0·10	0·0055
Mown grass surface			
grass length 1·5 cm.	1·11	0·2	0·0067
grass length 3·0 cm.	1·14	0·7	0·010
grass length 4·5 cm. $\bar{u}_2$ = 2 m./sec.	1·185	2·4	0·017
grass length 4·5 cm. $\bar{u}_2$ = 6–8 m./sec.	1·15	1·7	0·014
Long grass, 60–70 cm. high $\bar{u}_2$ = 1·5 m./sec.	1·275	9·0	0·033
Long grass, 60–70 cm. high $\bar{u}_2$ = 3·5 m./sec.	1·25	6·1	0·026
Long grass, 60–70 cm. high $\bar{u}_2$ = 6·2 m./sec.	1·21	3·7	0·021

(c)

(REF. DEACON 1953.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

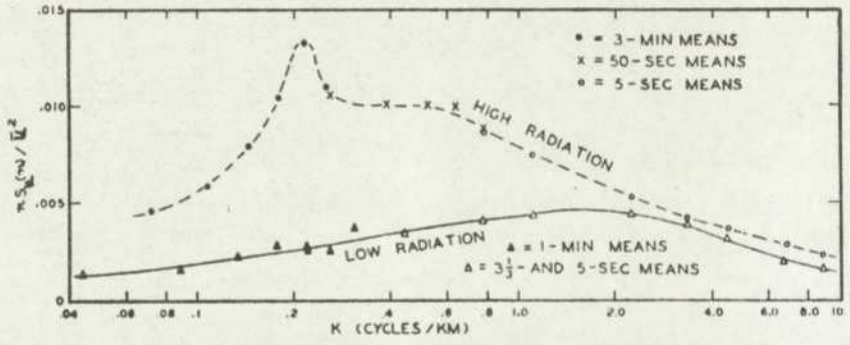
SURVEY OF METEOROLOGICAL DATA.



(a)

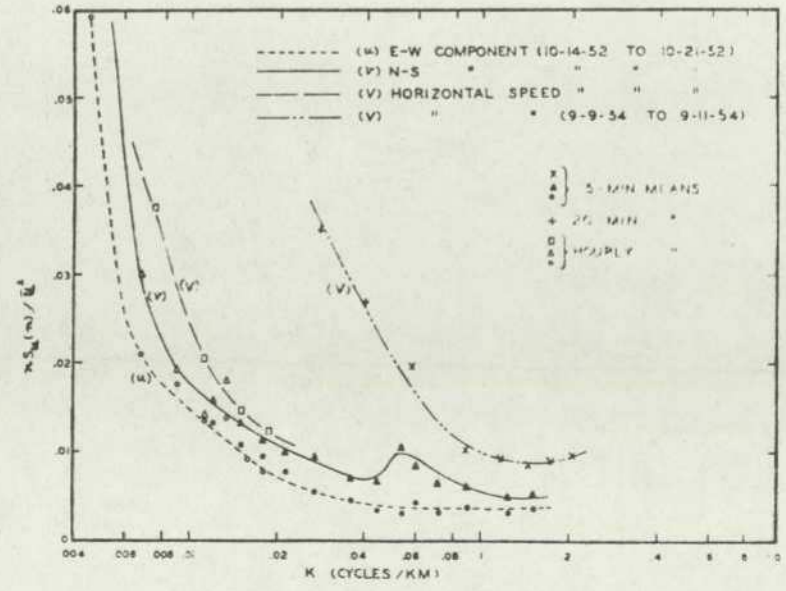
—Spectrum of stress at 7 m height. Run No. 1 of January 16, 1952; $Ri_{1\text{-}5} = -0{\cdot}08$; $\bar{u} = 3{\cdot}34$ m/sec.

(REF. DEACON 1955 b.)



(b)

Behaviour of the spectra of horizontal wind components under high and low radiation conditions in the micrometeorological frequency range.



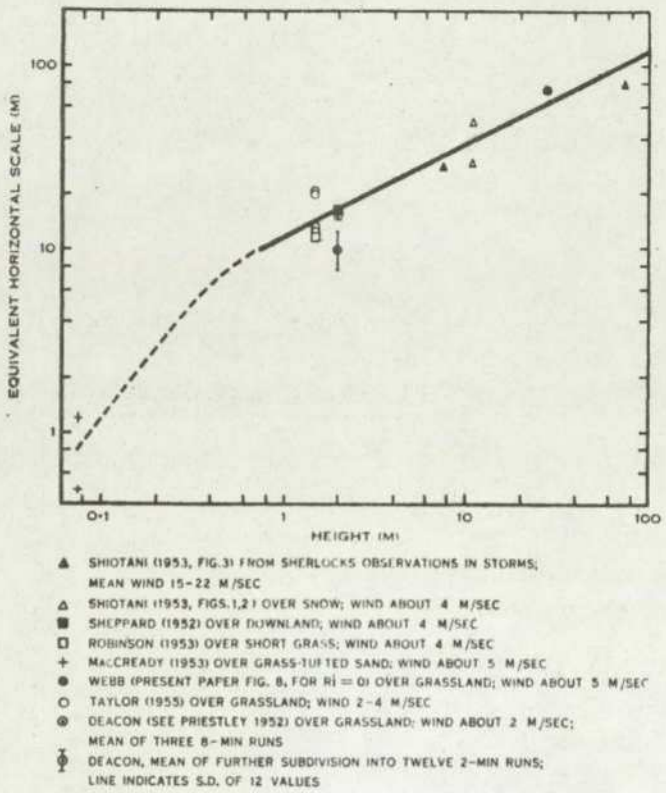
(c)

Behaviour of the spectra of horizontal wind components in the mesometeorological frequency range.

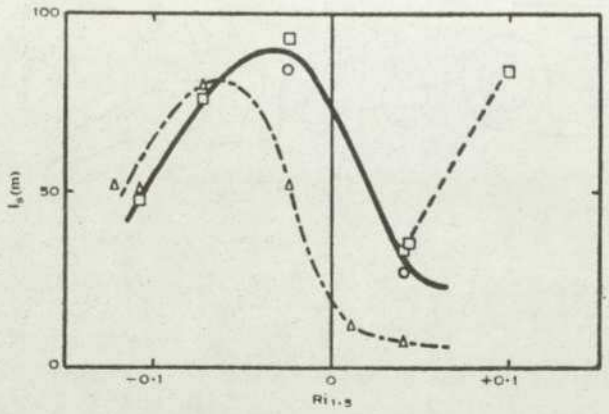
(REF. PANOFSKY AND VAN DER HOVEN 1955)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



–Scale of u plotted against height. From autocorrelations in near-neutral or moderately unstable conditions.

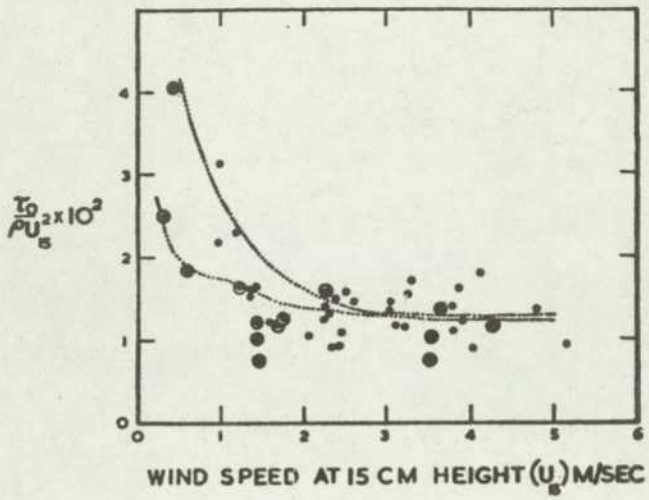


–Horizontal scale l_s from 29 m autocorrelation plotted against $Ri_{1\cdot5}$. The point for w with l_s = 6·9 m at $Ri_{1\cdot5}$ = +0·10 (see Table 3) was obtained while the paper was in press and therefore does not appear on the figure. — □ — u; – – △ – – v; ○, T.

(REF. WEBB 1955.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

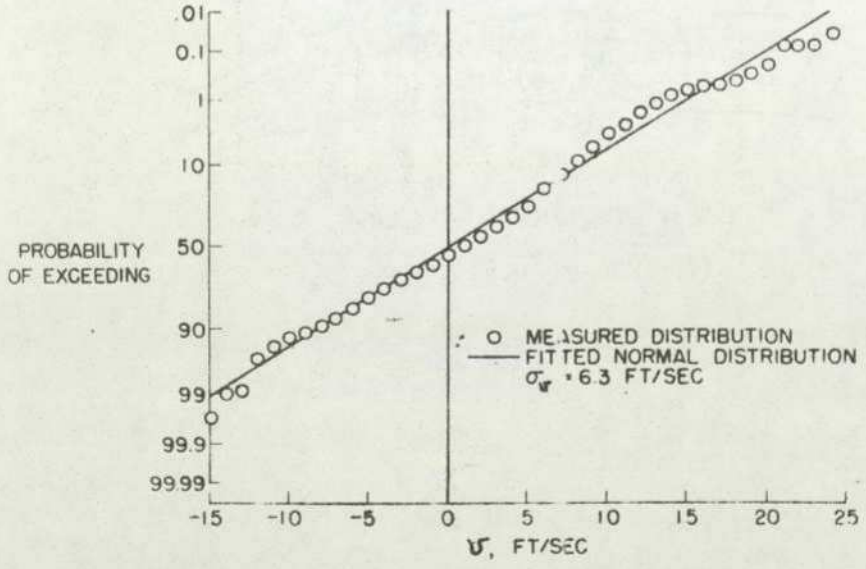
SURVEY OF METEOROLOGICAL DATA.



The variation of the drag coefficient of a grass surface with wind speed (Rider's

(a)

(REF. DEACON 1957.)



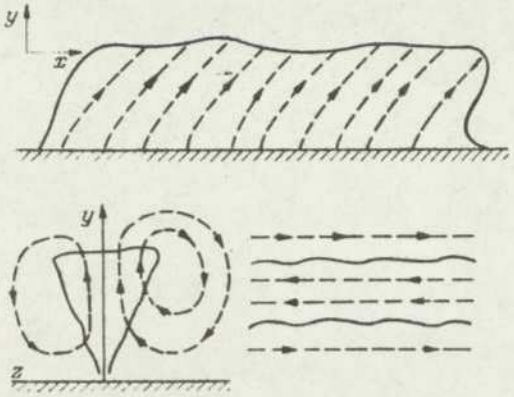
Probability of equalling or exceeding given values of v_g

(b)

(REF. PRESS 1957.)

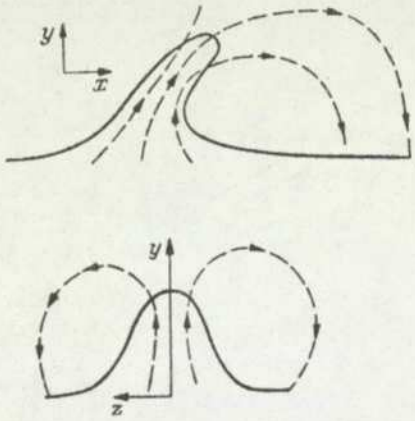
ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURUEY OF METEOROLOGICAL DATA.



(a)

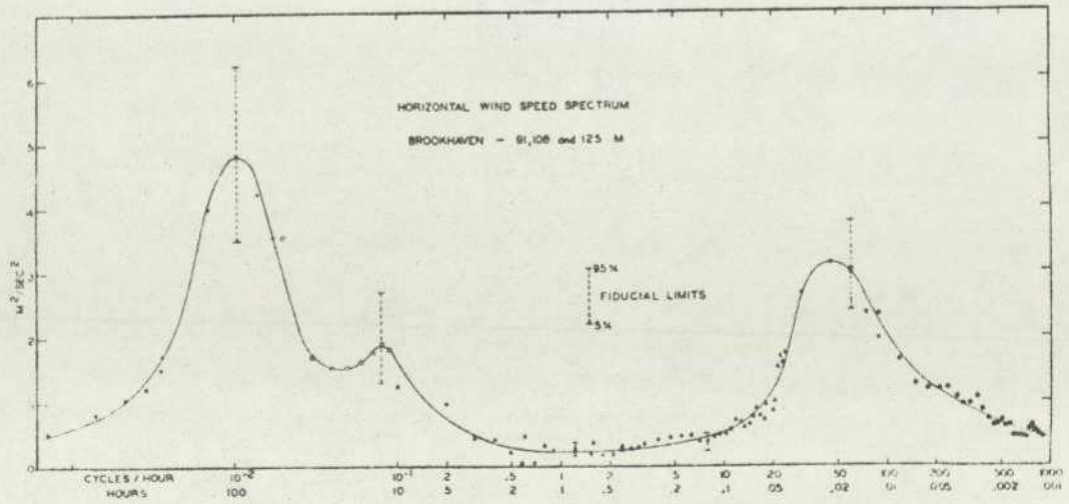
Structure of the "two-dimensional" jets in the constant-stress layer. (The full line represents the edge of the jet. The dashed lines are streamlines relative to the mean velocity at the base of the jet.)



(b)

. Structure of a mixing jet in the outer part of a boundary layer. (The full line represents the edge of the jet and is nearly the boundary of the turbulent fluid. The dashed lines are streamlines relative to the mean velocity at the base of the jet.)

(REF. TOWNSEND 1957.)



. Horizontal wind-speed spectrum at Brookhaven National Laboratory at about 100-m height.

(REF. VAN DER HOVEN 1957.)

FIG. 35.

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.

Values of k determined at various locations
* Investigation made by author in 1957.)
(a)

Site	Super-adiabatic	Neutral	Stable	Inversion	Height Range	Terrain
Quickborn, Germany [3]	0.25	0.27		0.61	10–70 m	meadows
Tallmadge, Ohio [8]	0.16	0.20	0.25	0.36	11–49 m	flat field
Hanford, Washington [9]	0.09	0.12	0.14	0.25	15–122 m	mountainous
Cardington, England [4]	0.145	0.17	0.27	0.32 to 0.77	8–120 m	grass field
Harwell, England [14]	0.09	0.08	0.18		9–27 m	airfield
Idaho Falls, Idaho*	0.15	0.18	0.22		6–61 m	desert
Brookhaven	0.19	0.29	0.35	0.46 to 0.59	11–124 m	nearby wooded area

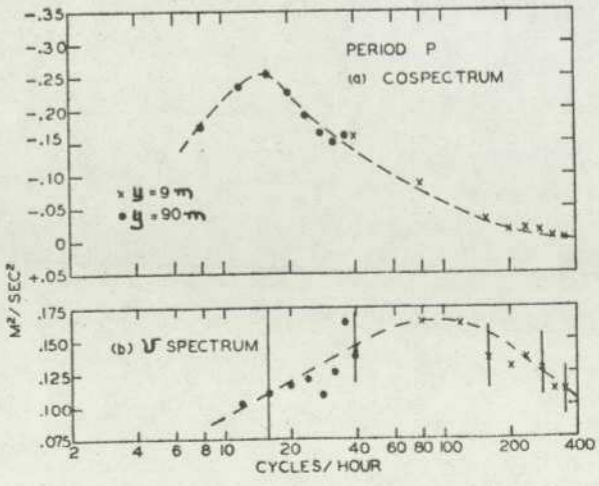
(a)

Variation of k with height of layer.

Type of Observation	Height of Layer 32–258 m	123–258 m	32–123 m
Nauen			
Summer noon	0.06	0.04	0.11
Summer midnight	0.36	0.28	0.60
Winter noon	0.12	0.27	0.06
Winter midnight	0.29	0.43	0.31
Quickborn			
Lapse Rate	Height of Layer 10–70 m	30–70 m	10–30 m
Unstable	0.25	0.22	0.28
Neutral	0.27	0.21	0.33
Inversion	0.61	0.57	0.63
Cardington			
Lapse Rate	Height of Layer 9–107 m	46–107 m	9–46 m
Unstable	0.14	0.12	0.15
Neutral	0.17	0.18	0.17

(b)

(REF. DE MARRAIS 1959.)

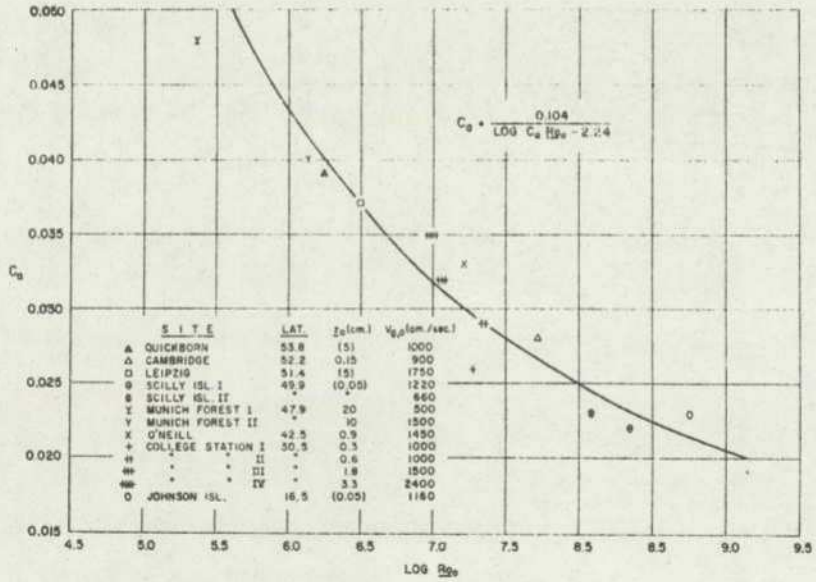


(c)

(REF. PANOFSKY AND DELAND 1959.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.

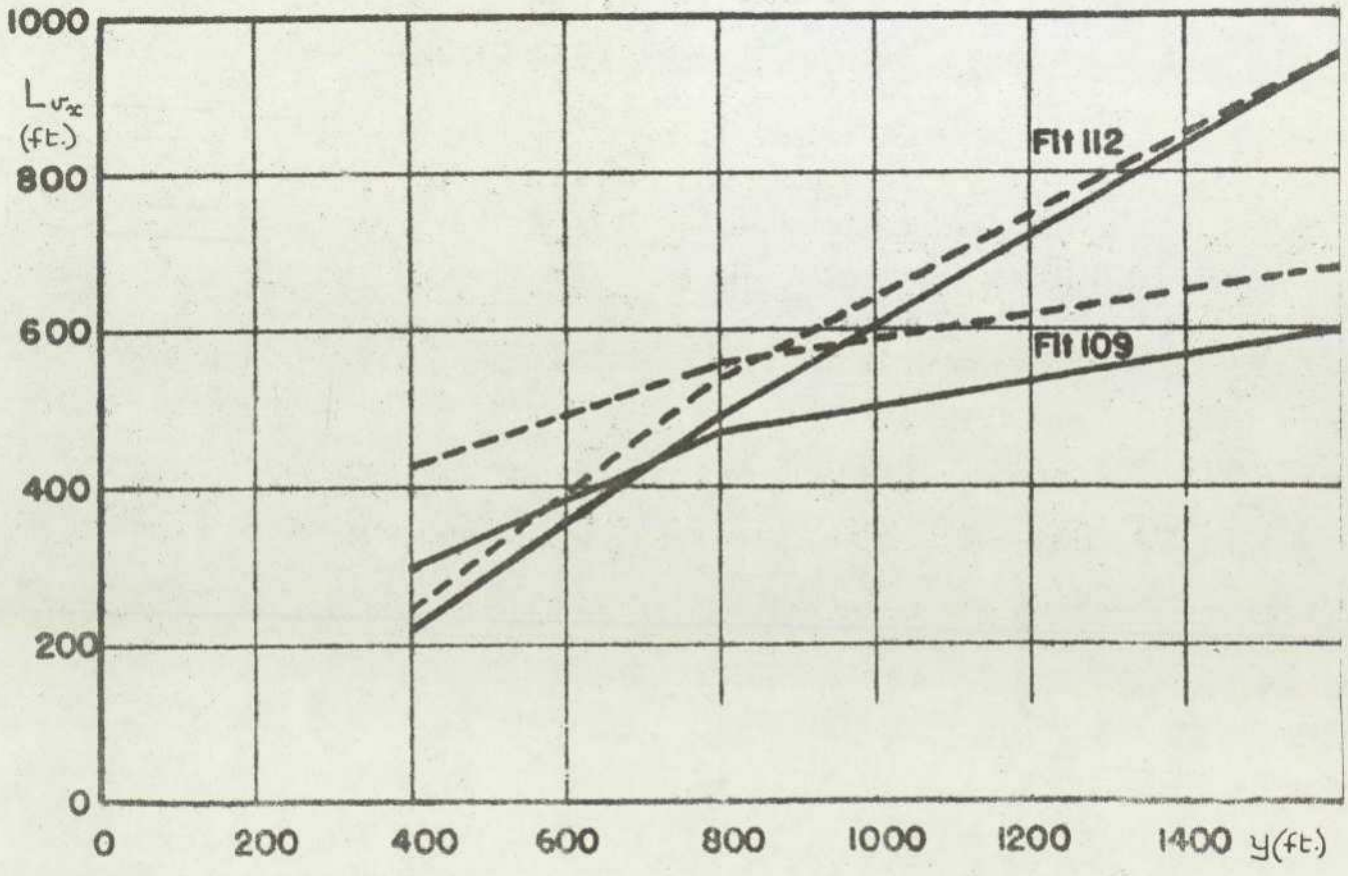


Geostrophic drag coefficient versus Surface Rossby number.

(a)

(REF. LETTAU 1959.)

VARIATION OF SCALE OF VERTICAL GUSTS
BROOKHAVEN, L.I. FLIGHTS 109 AND 112



(b)

(REF. LAPPE ET AL. 1959.)

Atmospheric Boundary Layer Simulation.

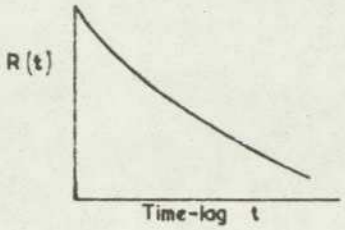
Survey of Meteorological Data. (1880~1959.)

Terrain Type. / Quantity	1. Smooth Ice _ Mud _ Snow _ Sea	2. Moderately Rough Short Grass _ Grass + Crops _ Rural	3. Rough Rural + Woods _ Woods _ Suburbs	4. Very Rough. Urban
y_o (cm.)	0.001 _ 0.04 _ 0.1 _ 2.0	0.1 _ 3~7 _ 20	100 ___ ___ 150	100 _ 300 _ 400
$\overline{u'v'} / \bar{U}_o^2$	0.0004 _ 0.006 _ 0.001	0.0014 _ 0.0020 _ 0.0040	___	___
$1/\alpha$	0.08 _ 0.11 _ 0.12	0.13 _ 0.143 _ 0.16	0.20 ___ 0.23	0.25 _ 0.40
$\left(\sqrt{\bar{u}^2} / \bar{u}\right)_{0 \le y(m) \le 30}$	0.10 ___ 0.12	0.13 ___ 0.20	___ 0.20 ___	0.30 _ 0.48

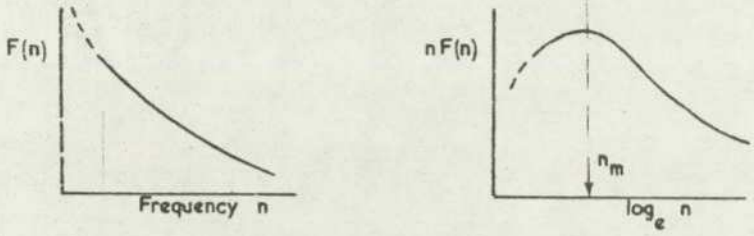
Fig. 37

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

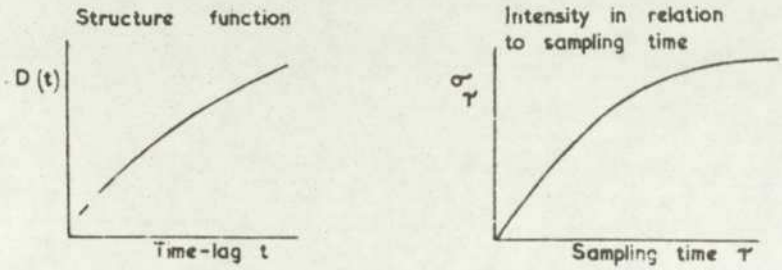
SURVEY OF METEOROLOGICAL DATA.



Frequency spectrum



(REF. PASQUILL 1961.)



$$F(n) = 4\int_0^\infty R(t)\,\cos 2\pi n t\,dt$$

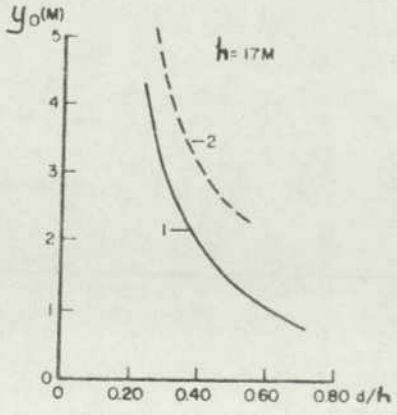
$$D(t) = \sigma^2\left[1 - R(t)\right]$$

$$\int_0^\infty R(t)\,dt = t_s = l_s/\bar{u}$$

If $F(n) \propto n^{-p}$, $\left[1 - R(t)\right]$ and $D(t) \propto t^{p-1}$

For $R(t) = \exp\left[-t/t_s\right]$ $\begin{cases} l_s = \bar{u}/2\pi n_m \\ \sigma_{t_s}/\sigma_\infty = \sqrt{(1-2^{-1})} \end{cases}$

Representation of atmospheric turbulence.

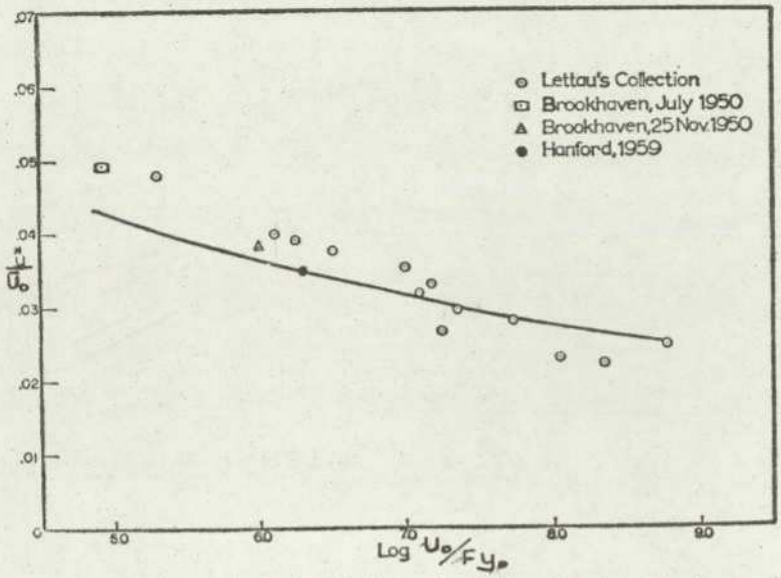


Variation of roughness parameter y_o, within a deciduous forest
1 - during a foliage, 2 - without a foliage.

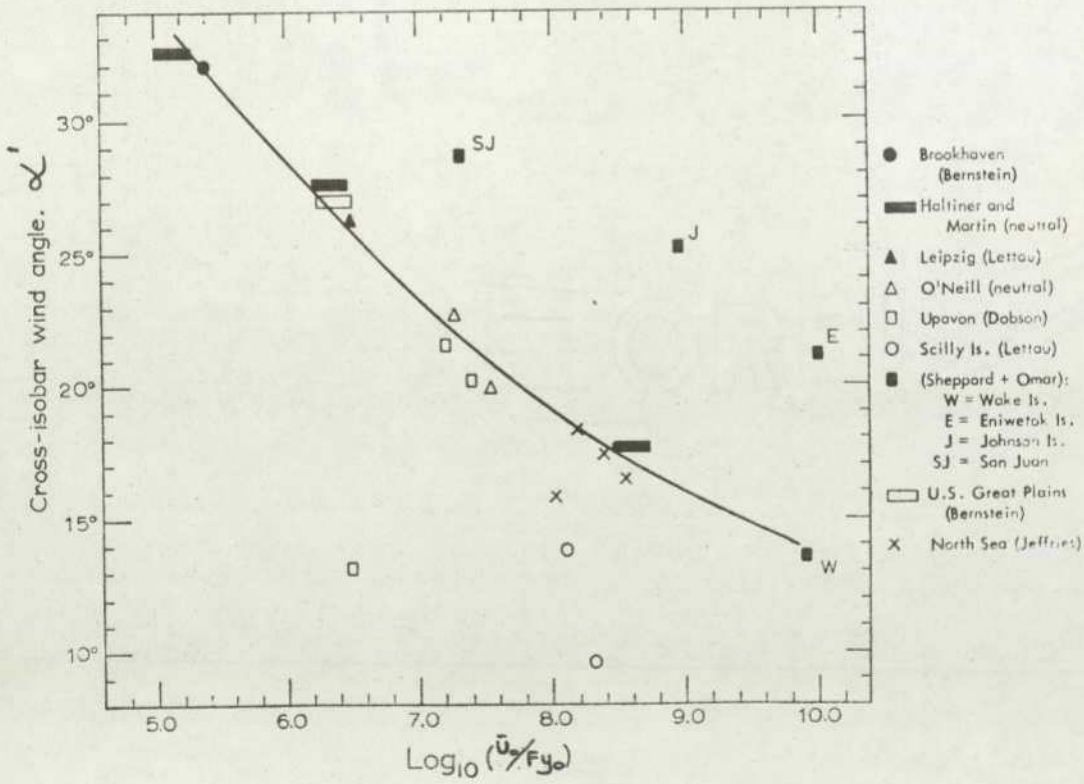
(REF. RAUNER 1961.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



Predicted and observed relationship between $u^*/\bar{U}_o$ and surface Rossby number $\bar{U}_o/Fy_o$

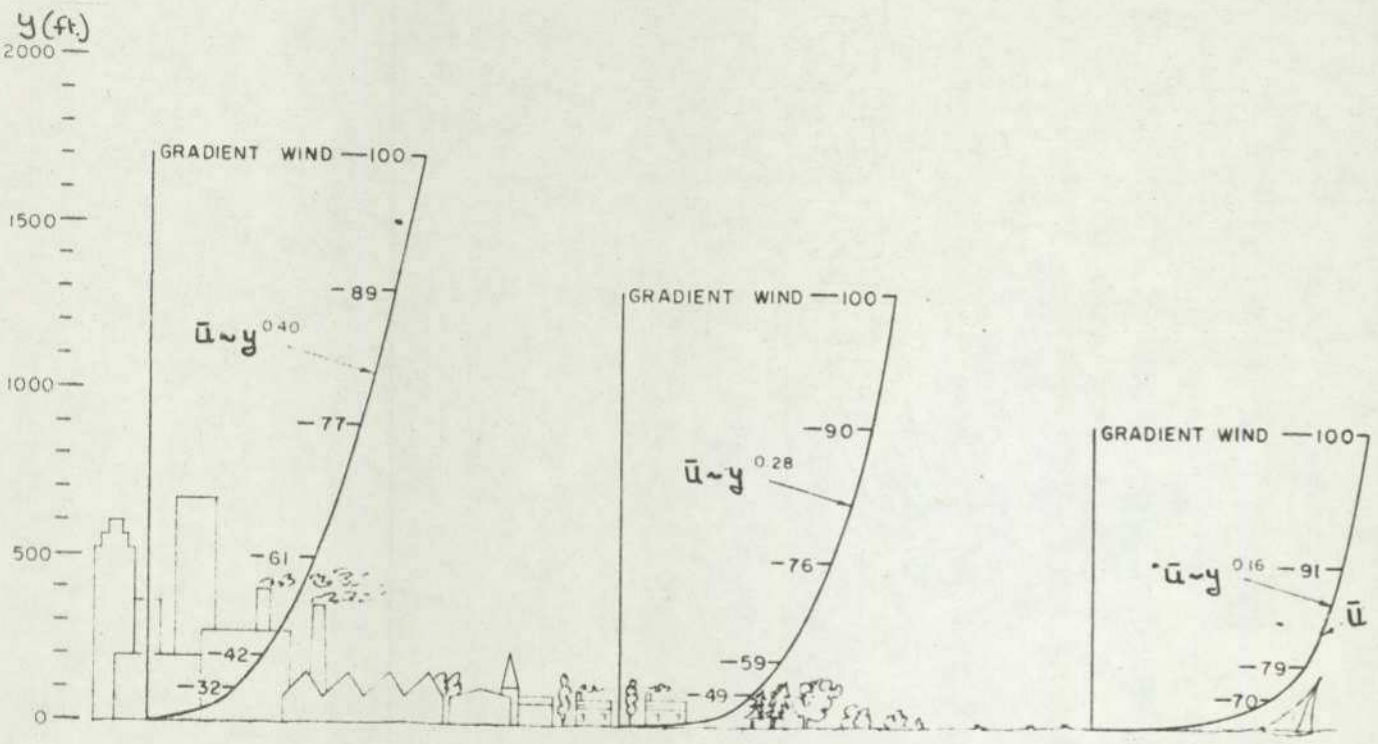


Predicted and observed angle between the surface wind direction and surface isobars.

(REF. BLACKADAR 1962.)

Atmospheric Boundary Layer Simulation.

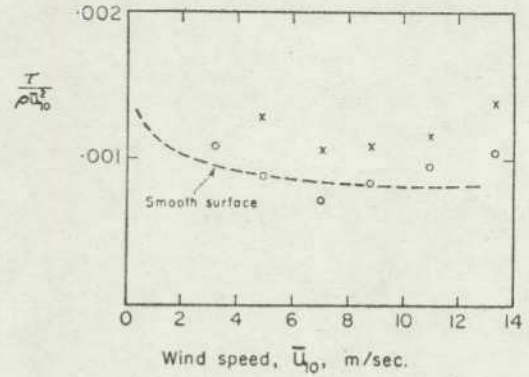
Survey of Meteorological Data.



Profiles of mean wind velocity over level terrains of differing roughness.

(c)

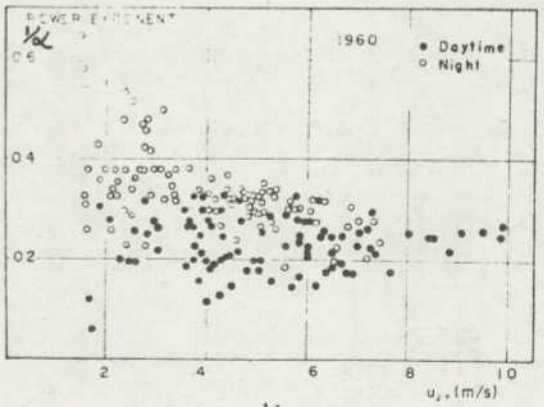
(Ref. Davenport 1963.)



Drag coefficient for neutral stability. Circles, Port Phillip; crosses, open sea.

(a)

(Ref. Deacon 1962.)



Variation of $\frac{1}{2}$ with wind velocity.

(b)

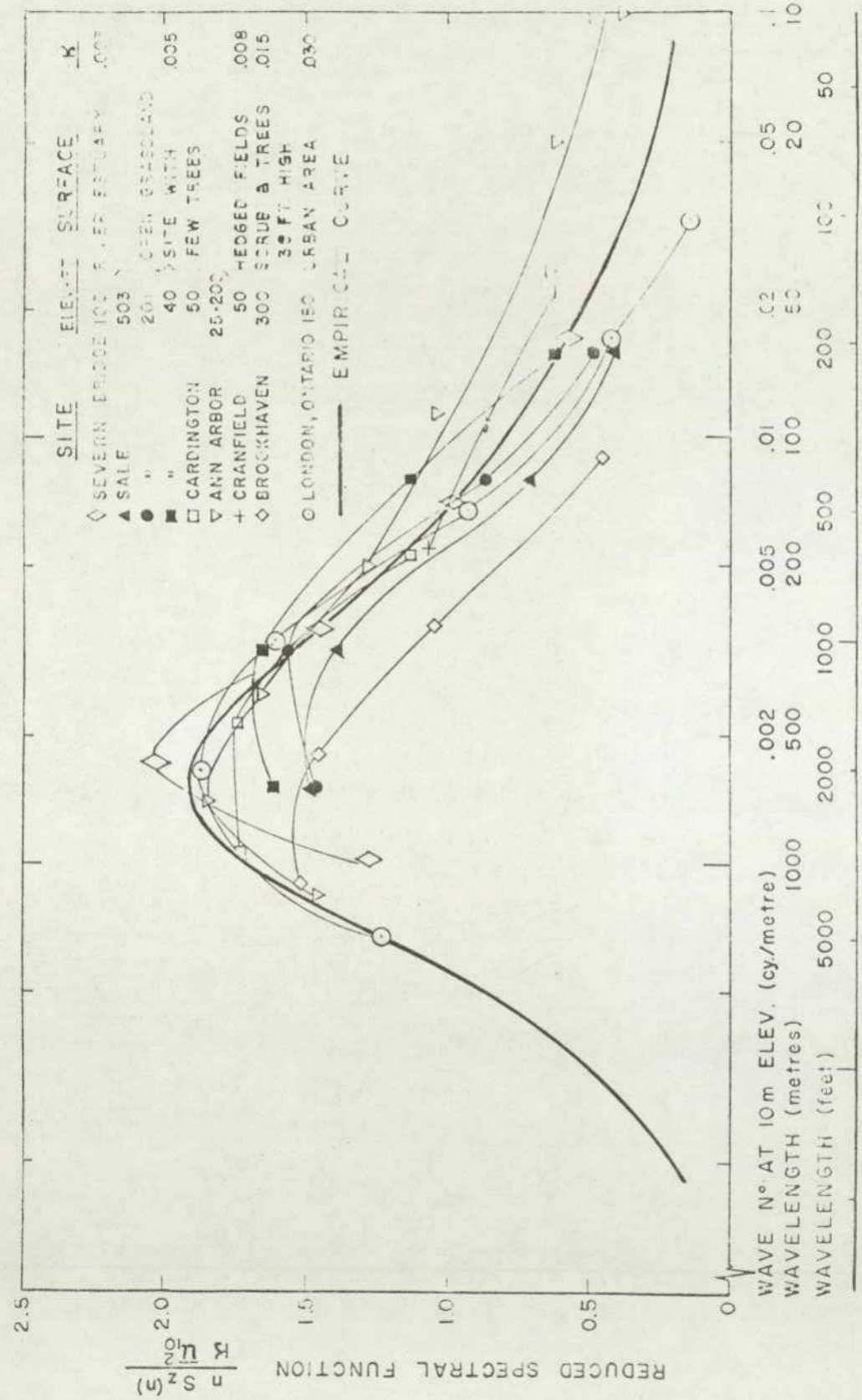
(Ref. Shiotani 1962.)

Fig. 40.

FIG. 41.

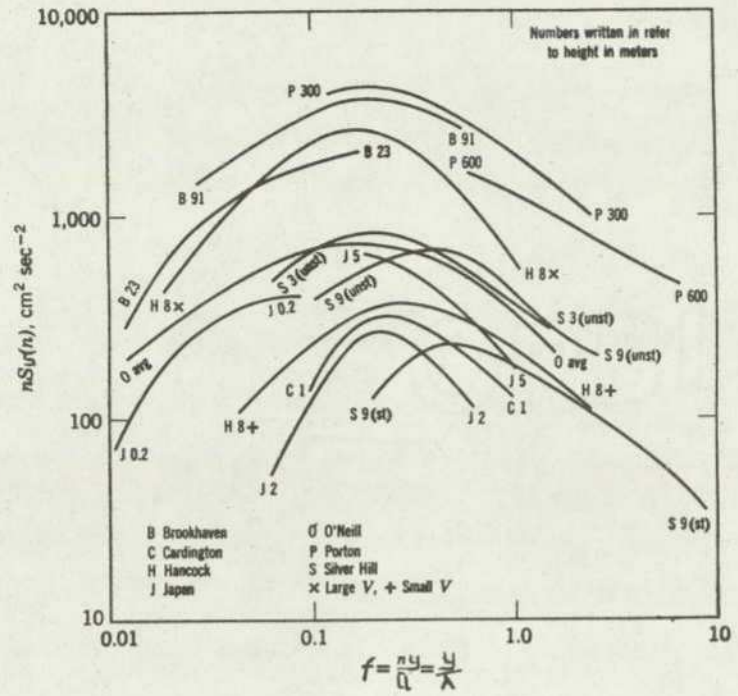
ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.

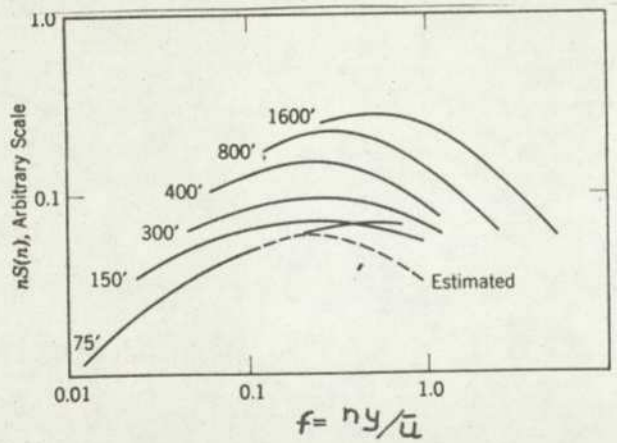


(REF. DAVENPORT 1963.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.
SURVEY OF METEOROLOGICAL DATA.

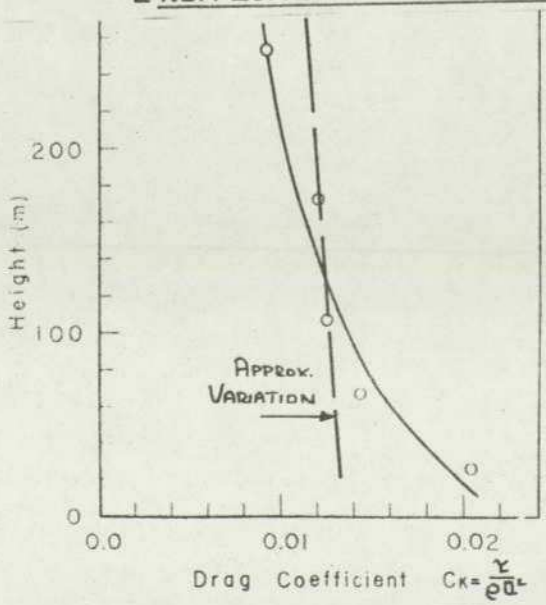


Spectra of vertical velocity at numerous locations as function of nondimensional frequency $nY/\bar{u}$ (According to Panofsky and McCormick, 1960.)



Spectra of vertical velocity observed by Lappe et al. as function of nondimensional frequency. (According to Panofsky and McCormick, 1960.)

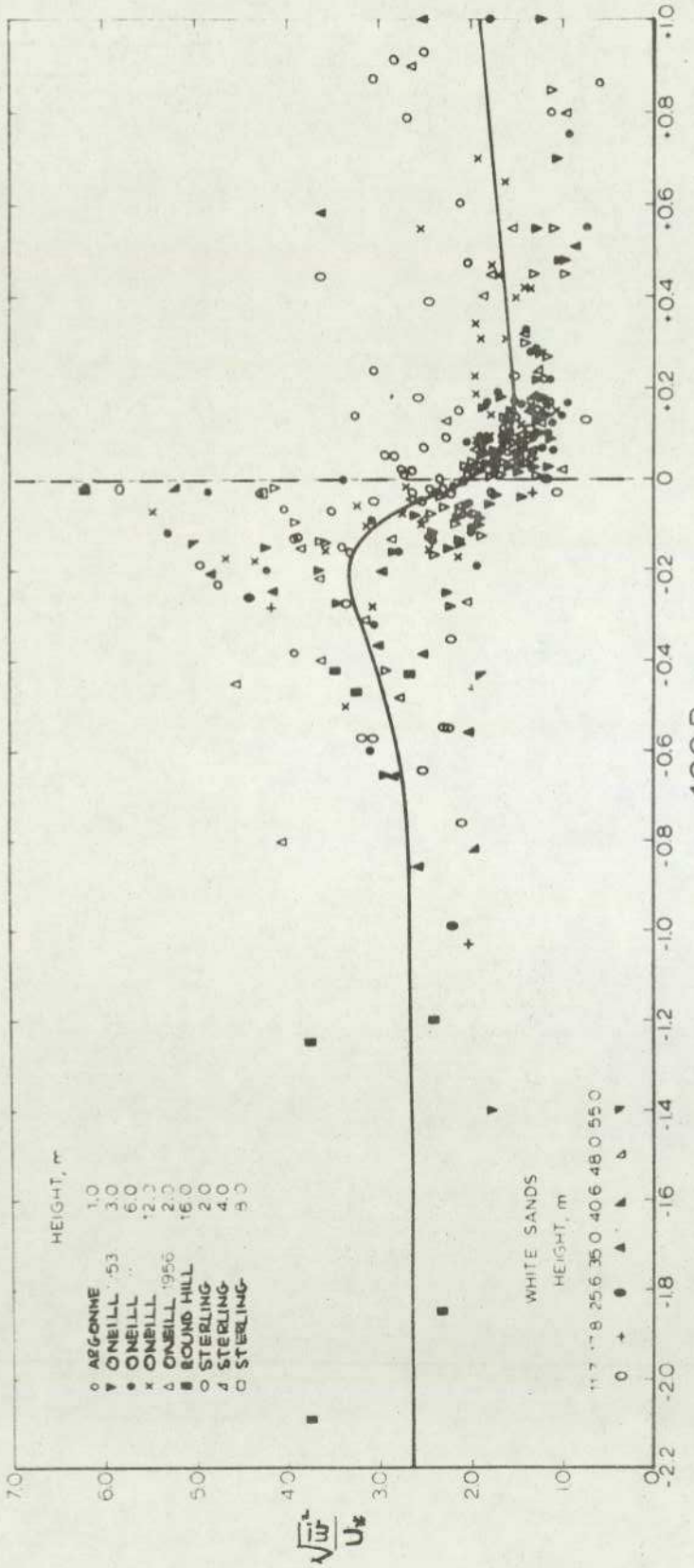
(REF. LUMLEY AND PANOFSKY. 1964)



(REF. SOMA 1964)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.

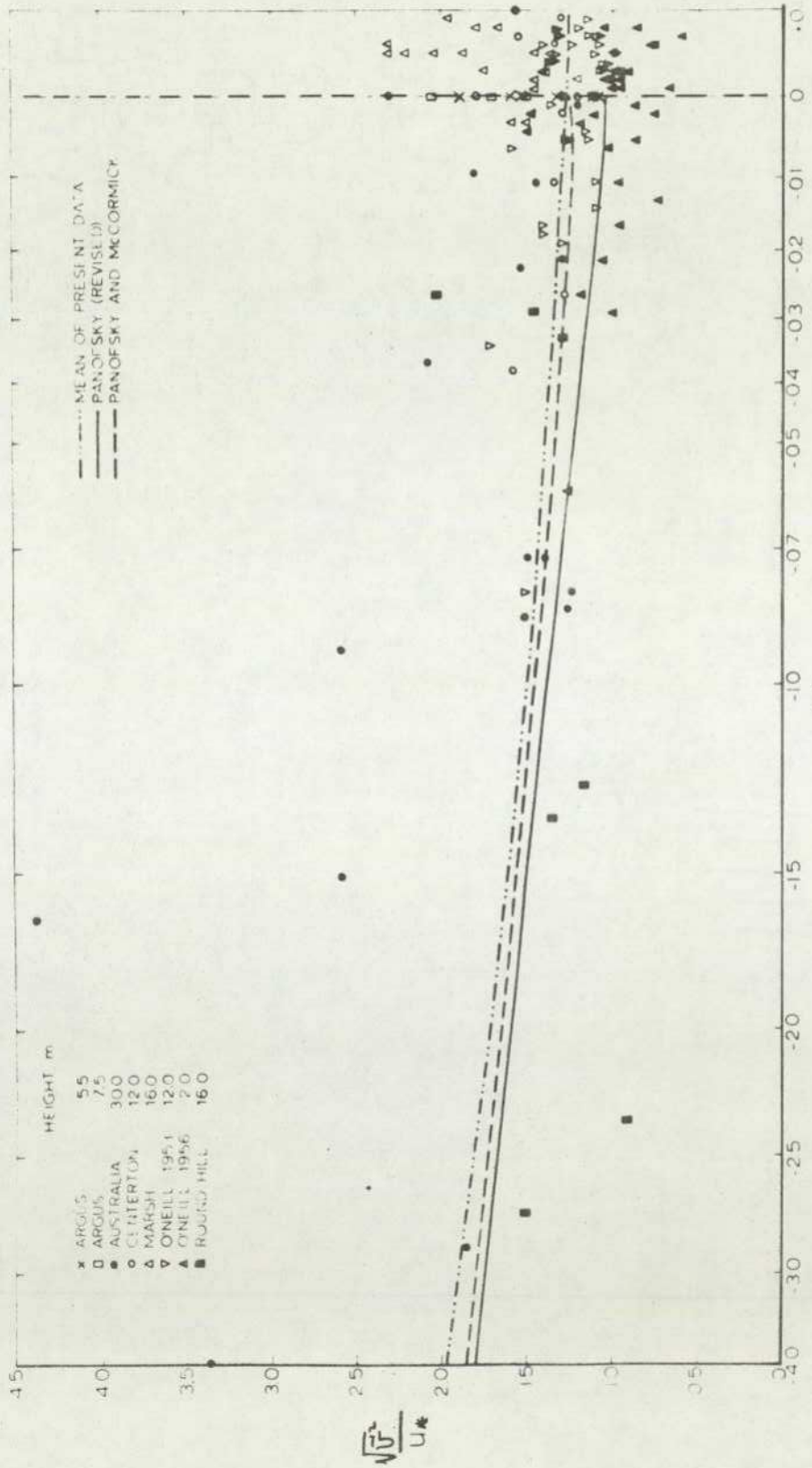


The ratio $\sqrt{\overline{u'^2}}/u_*$ as function of B.

(REF. 1ST. CANAD. CONF._MICROMET._ 1965.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.

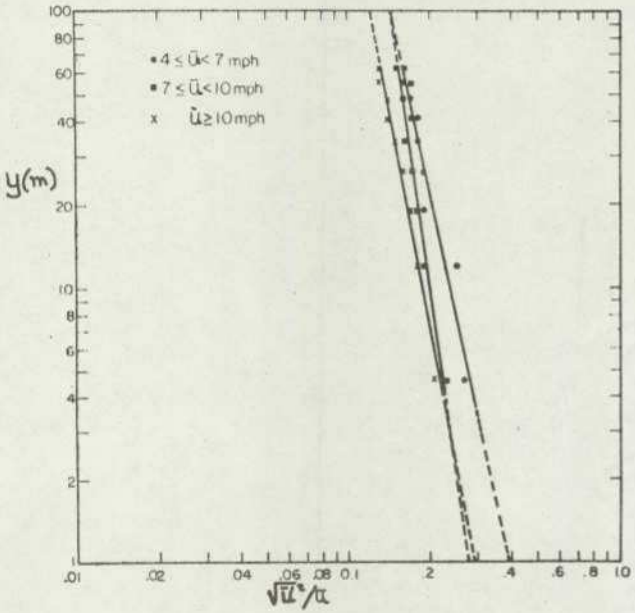


The ratio $\frac{\sqrt{u'^2}}{u_*}$ as function of Richardson number.

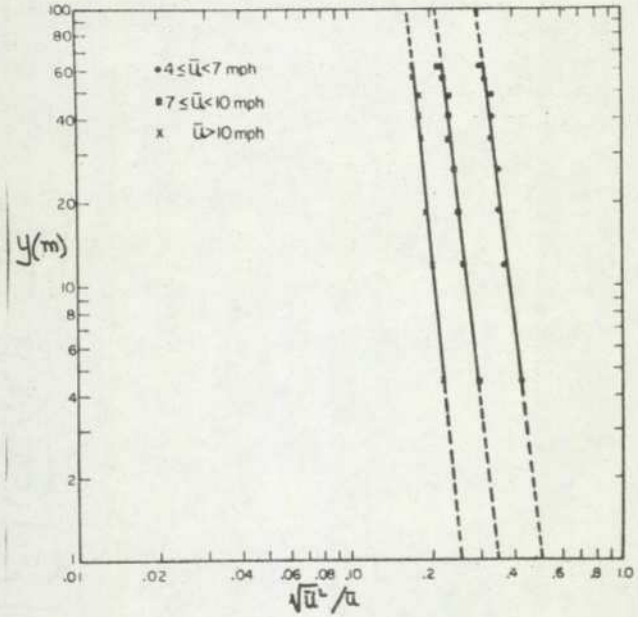
(REF. 1ST CANAD. CONF. MICROMET. 1965.)

Atmospheric Boundary Layer Simulation.

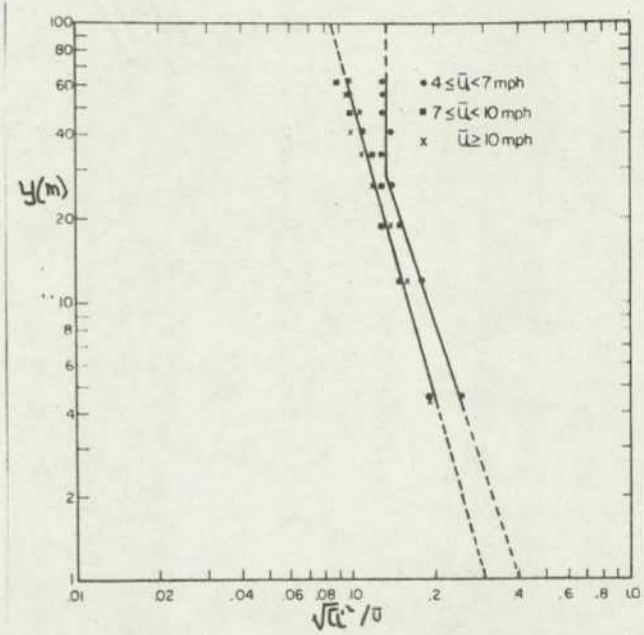
Survey of Meteorological Data.



Height dependence of the longitudinal intensity of turbulence during neutral stratification.



Height dependence of the longitudinal intensity of turbulence during unstable stratification.



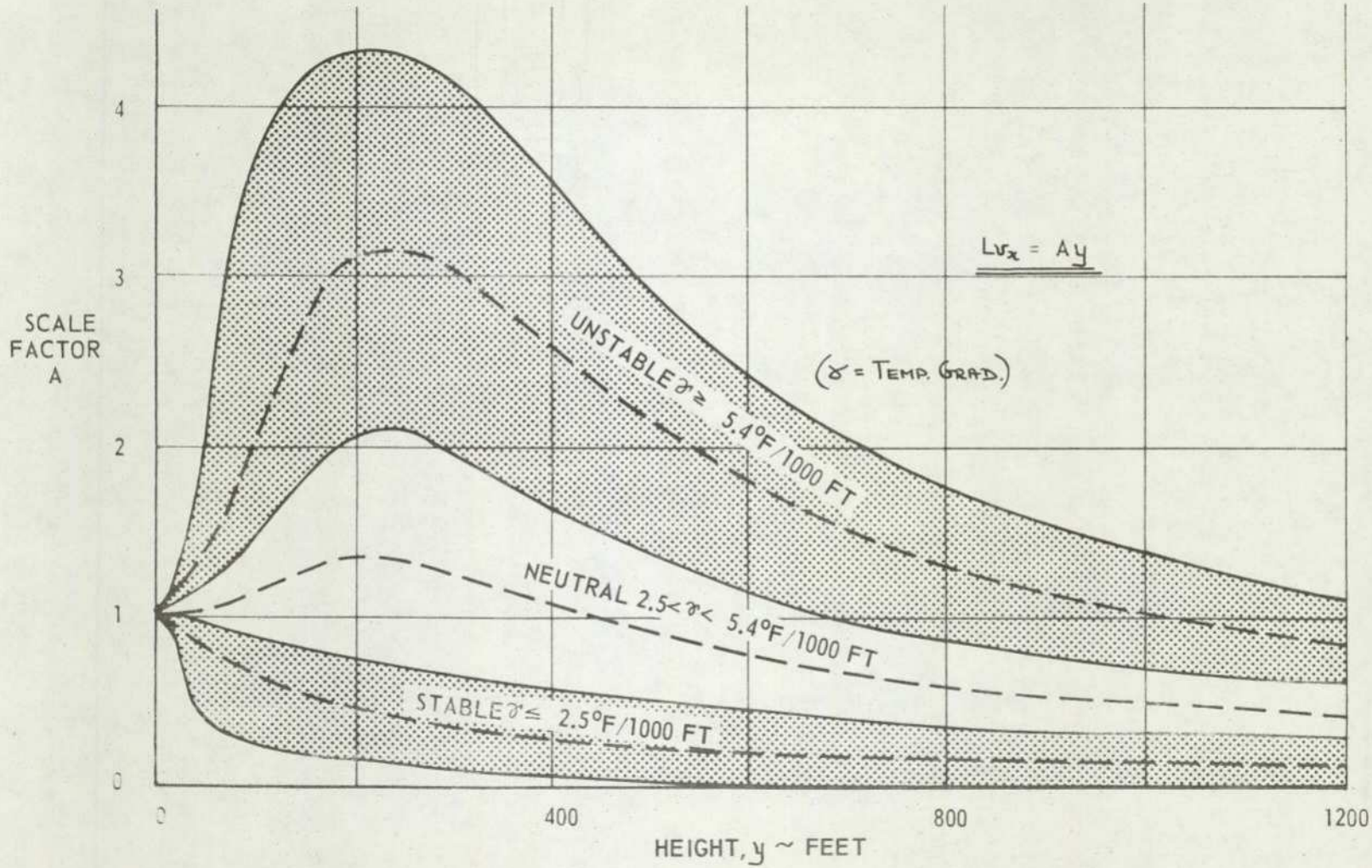
Height dependence of the longitudinal intensity of turbulence during stable stratification.

(Ref. Swanson, Cramer - 1965.)

Fig. 45.

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



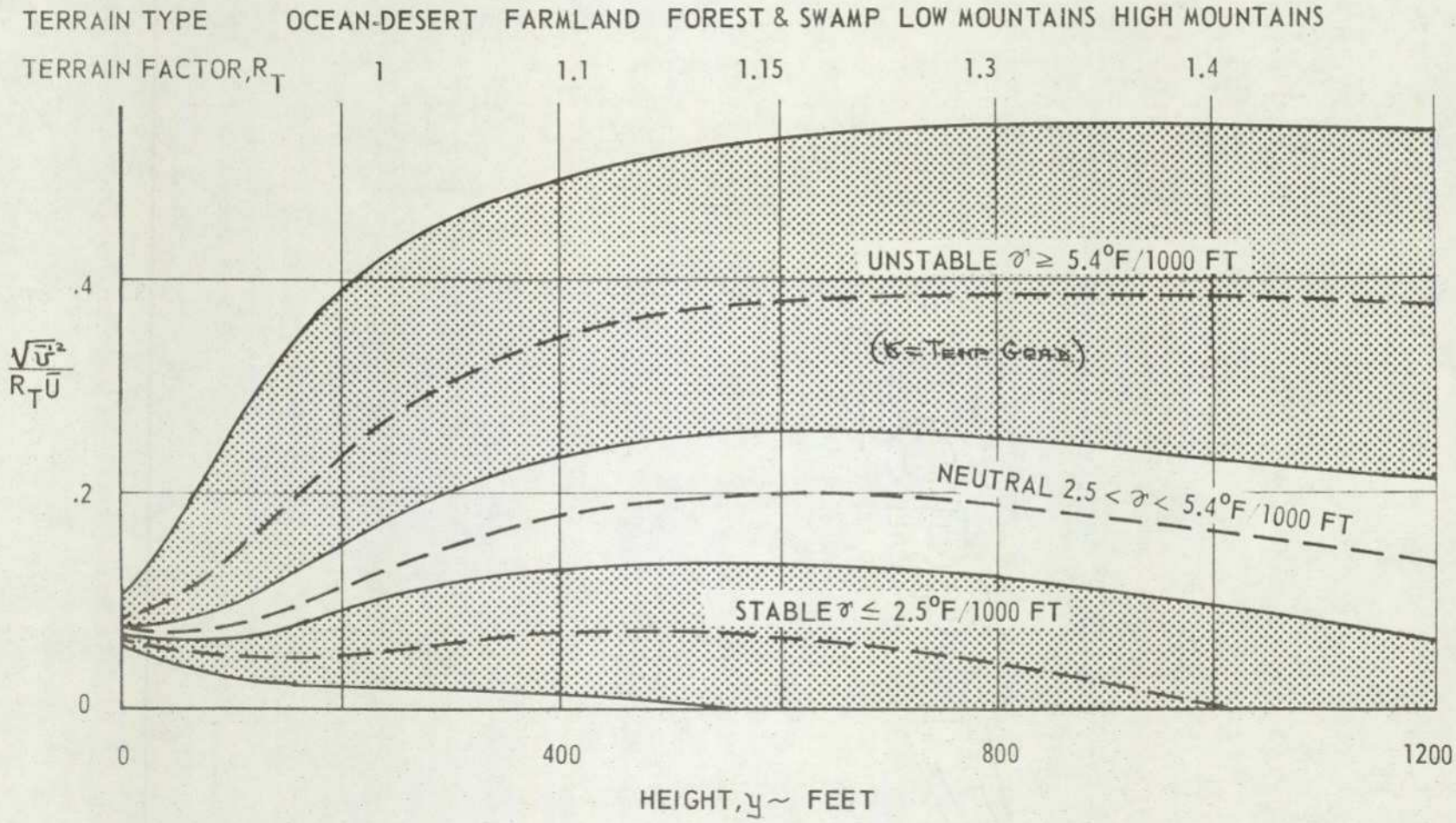
Vertical turbulence spectrum. Estimation of scale

(REF. PRITCHARD. 1966)

FIG. 46.

Atmospheric Boundary Layer Simulation.

Survey of Metedrological Data.



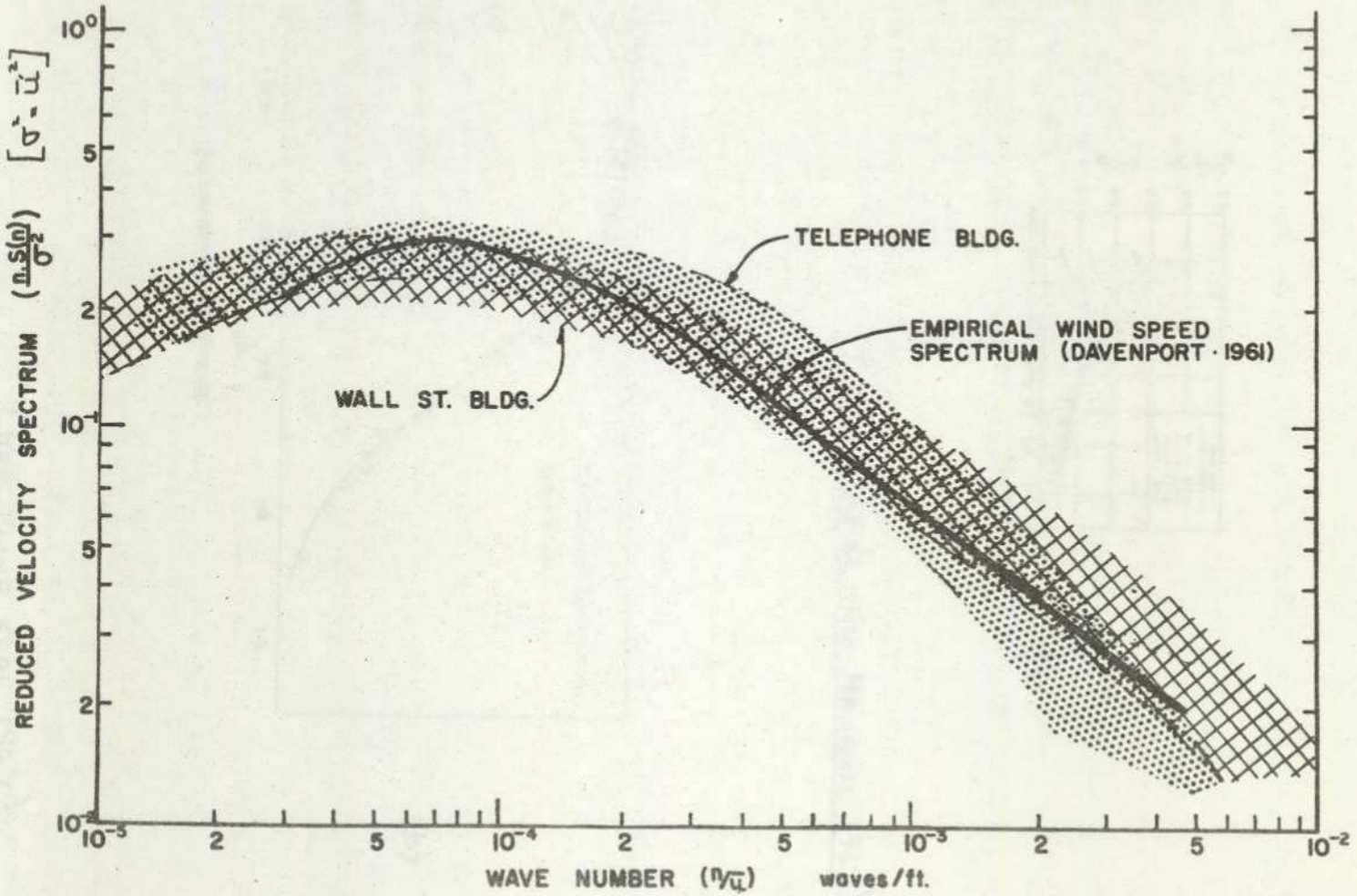
Vertical turbulence spectrum. Estimation of intensity

(Ref. Pritchard. 1966.)

Fig. 47.

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



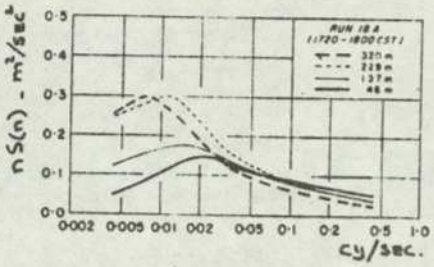
COMPARISON OF MEASURED WIND SPEED SPECTRA AT N.Y. TELEPHONE BLDG AND 40 WALL ST. BLDG WITH EMPIRICAL SPECTRUM

(REF. DAVENPORT 1967.)

FIG. 48

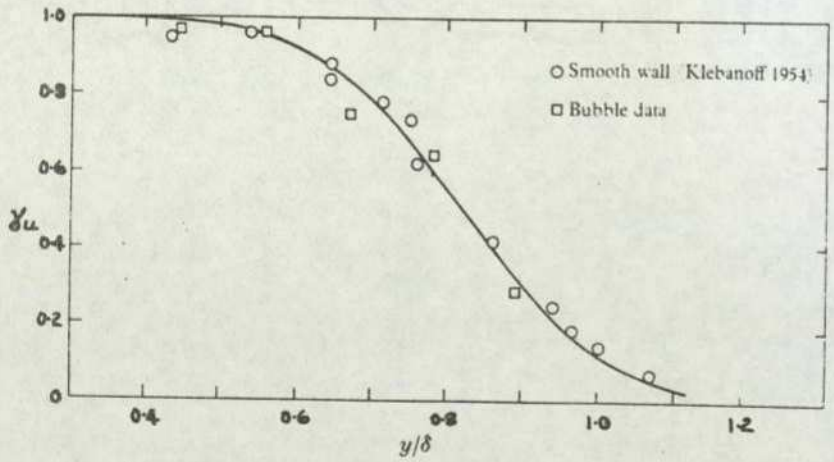
ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



(a)

(REF. KAIMAL AND HAUGEN. 1967)



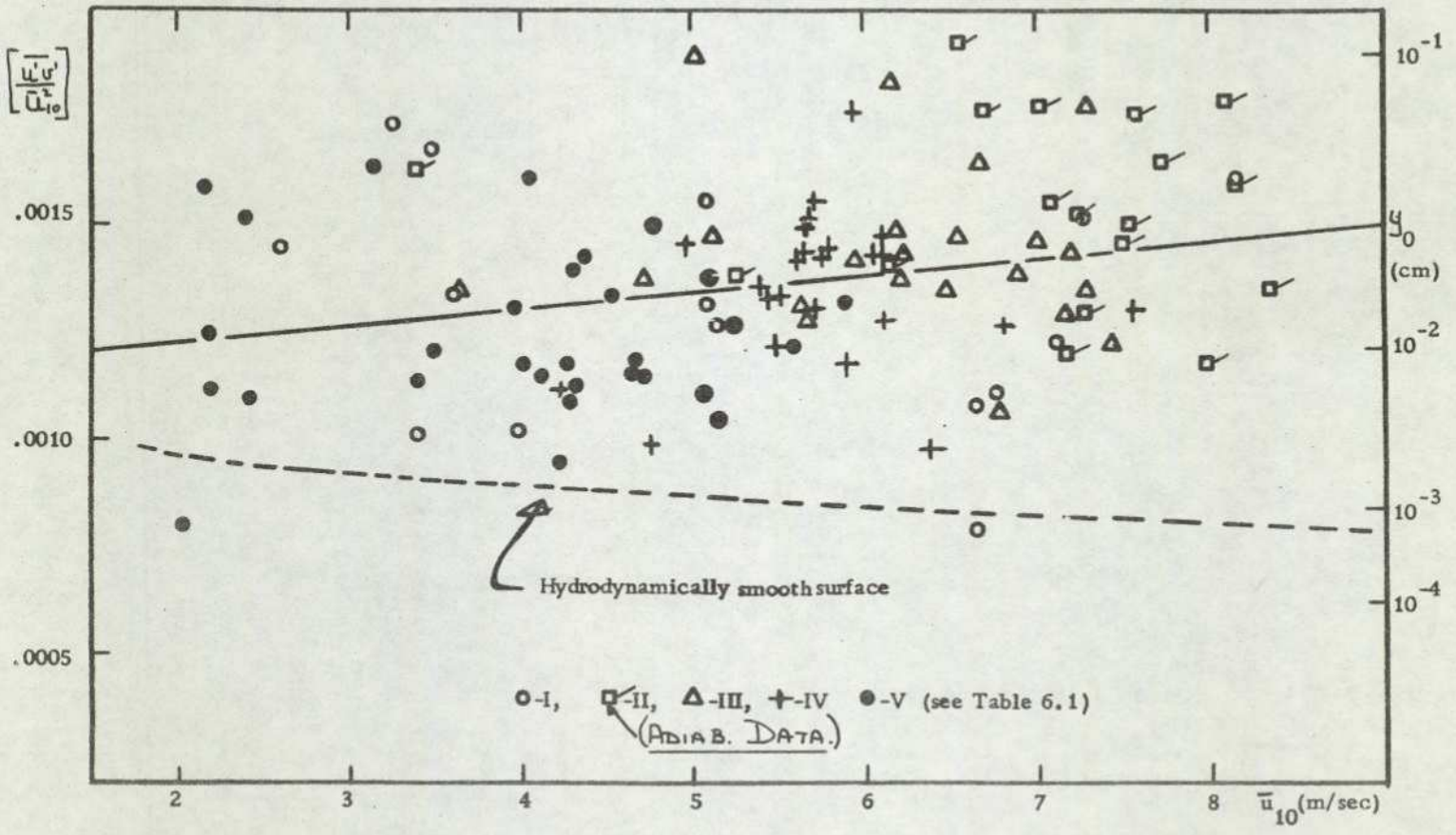
(b)

Intermittency distribution

(REF. KLINE ET AL. 1967.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



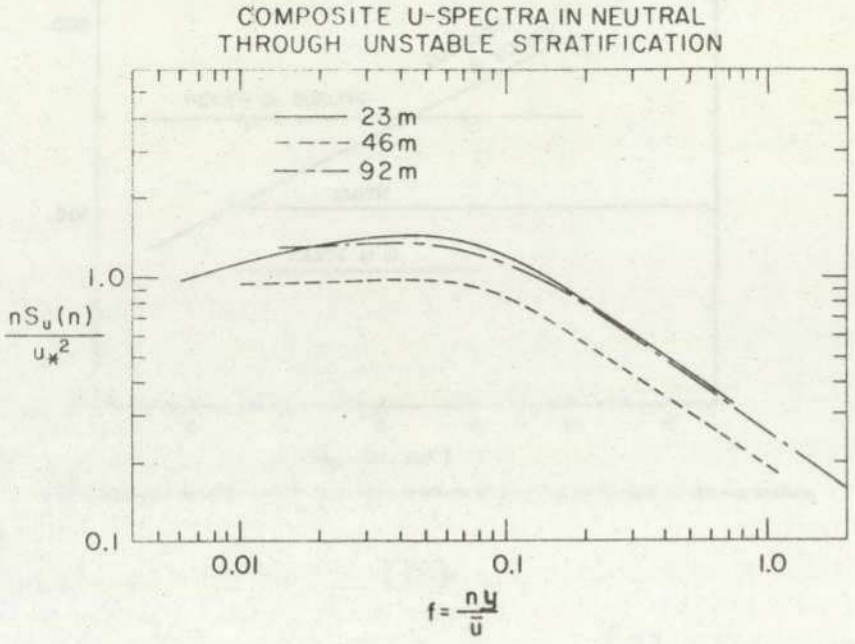
THE VARIATION OF DRAG COEFFICIENT WITH WIND SPEED COMPUTED FROM THE INDIAN OCEAN

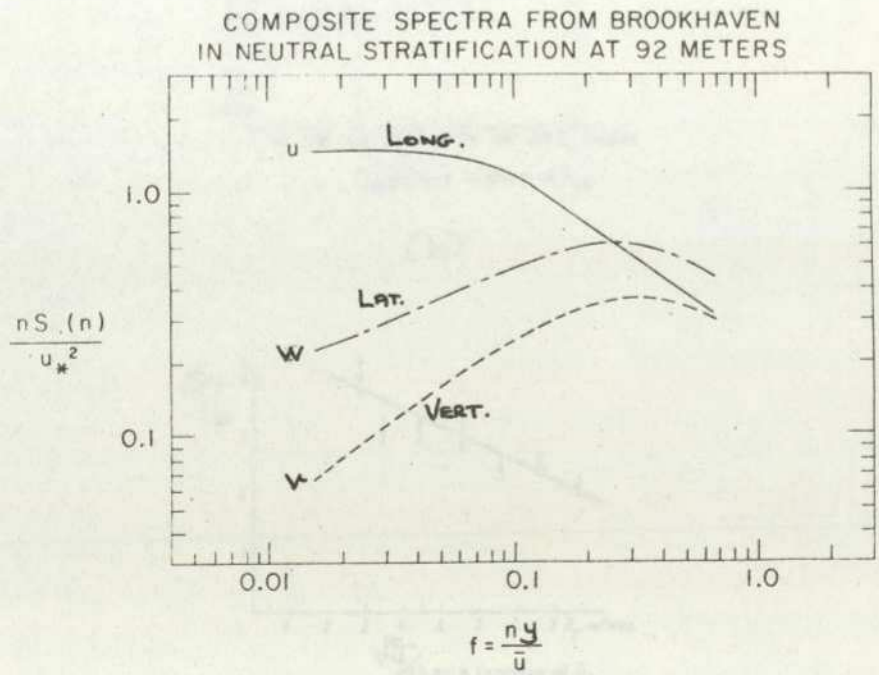
(REF. PAULSON 1967)

FIG. 50

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.

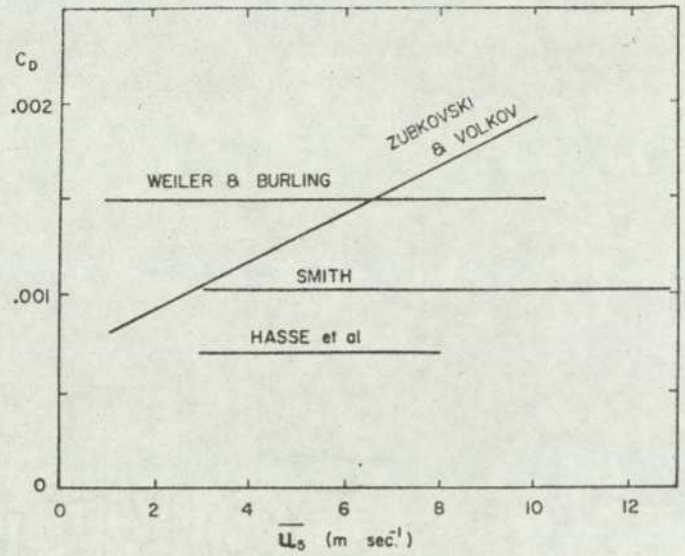




(REF. SINGER ET AL. 1967.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

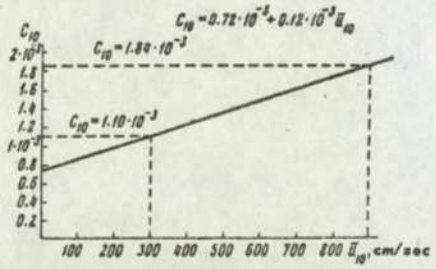
SURVEY OF METEOROLOGICAL DATA.



Recent direct determinations by various workers of the drag coefficient of the sea surface.

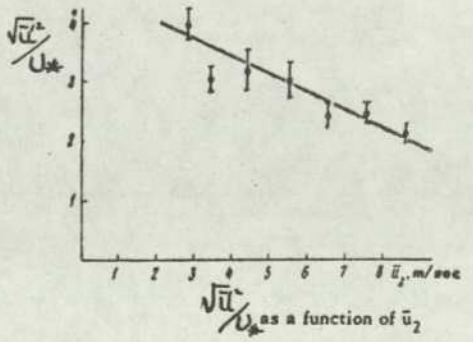
(a)

(REF. SMITH 1967.)



$C_u(10)$ as a function of $\bar{u}_{10}$

(b)



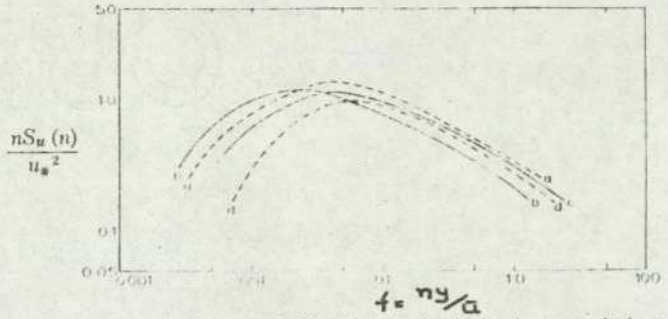
$\sqrt{\overline{u'^2}}/u_*$ as a function of $\bar{u}_z$

(c)

(REF. ZUBKOVSKI AND KRAVCHENKO 1967.)

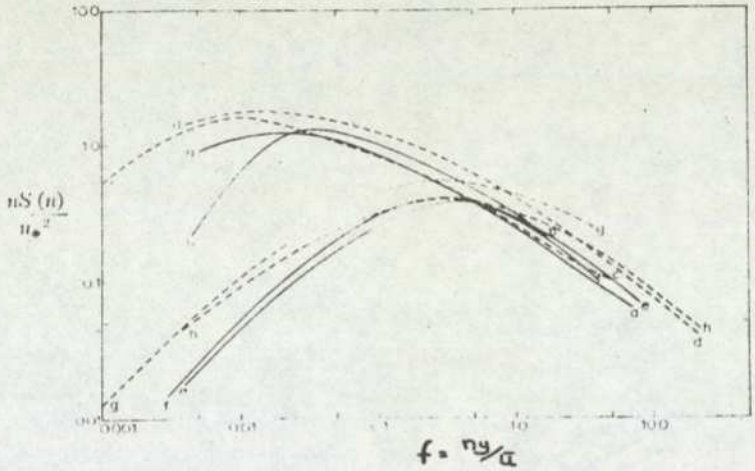
ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



(a)

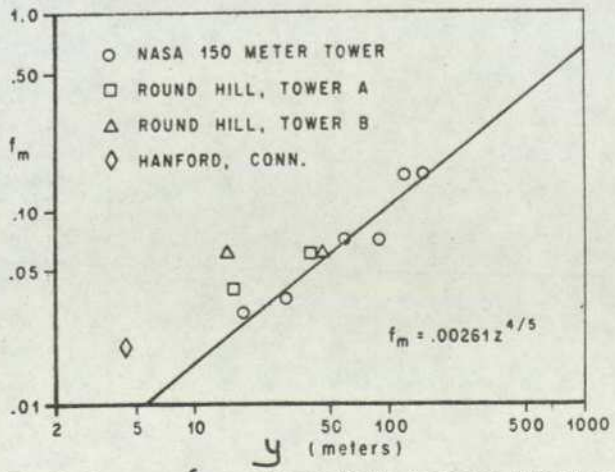
Smoothed and averaged spectra of longitudinal velocity in neutral air at Round Hill. a. 15 m, tower B; b. 16 m, tower A; c. 40 m, tower A; d. 46 m, tower B.



(b)

Comparison of spectra over land and sea. Longitudinal velocity, a. Hanford; b. Round Hill; c. over sea near Vancouver (Smith); d. over sea near Vancouver (Weiler and Burling). Vertical velocity; e. Hanford; f. Round Hill; g. over sea near Vancouver (Smith); h. over sea near Vancouver (Weiler and Burling).

(REF. BUSCH AND PANOFSKY 1968.)



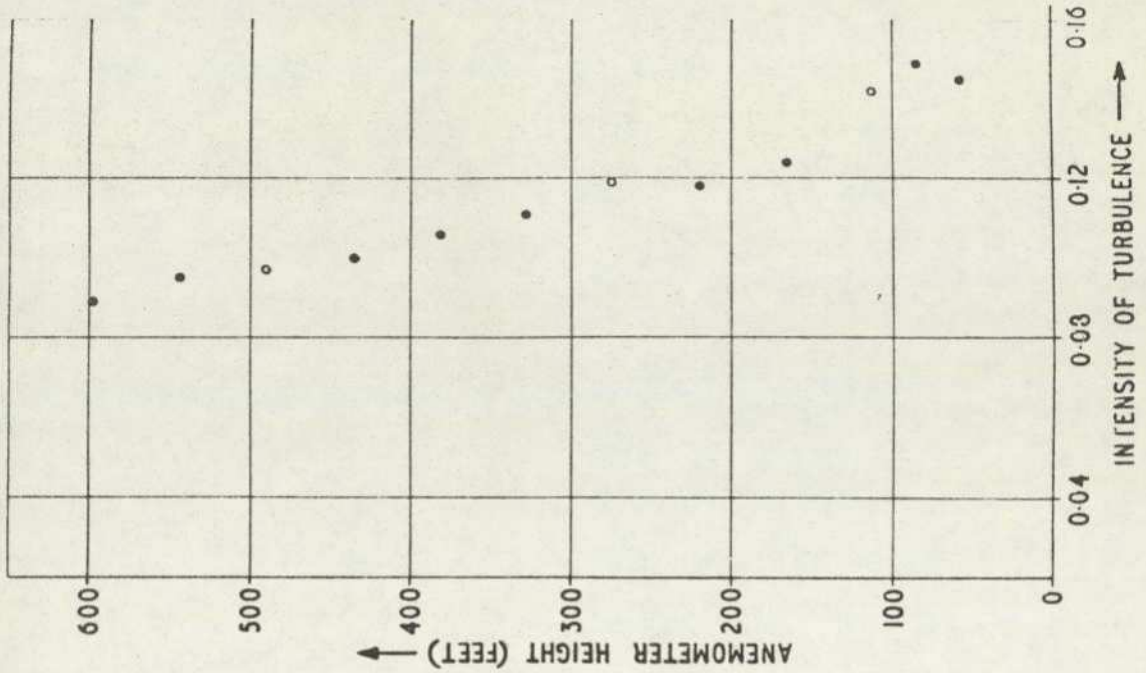
(c)

FIG. 9. Frequency f_m associated with the maximum of the logarithmic spectrum at KSC as a function of y

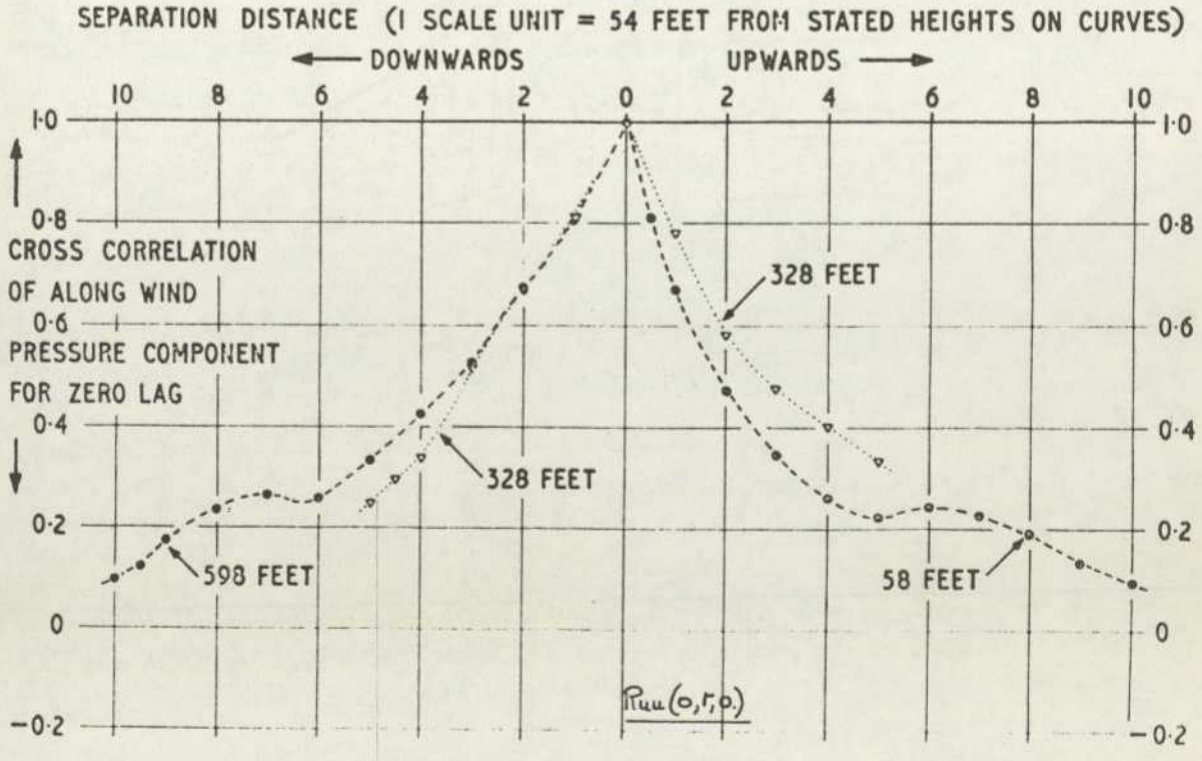
(REF. FICHTL 1968b)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



(a)

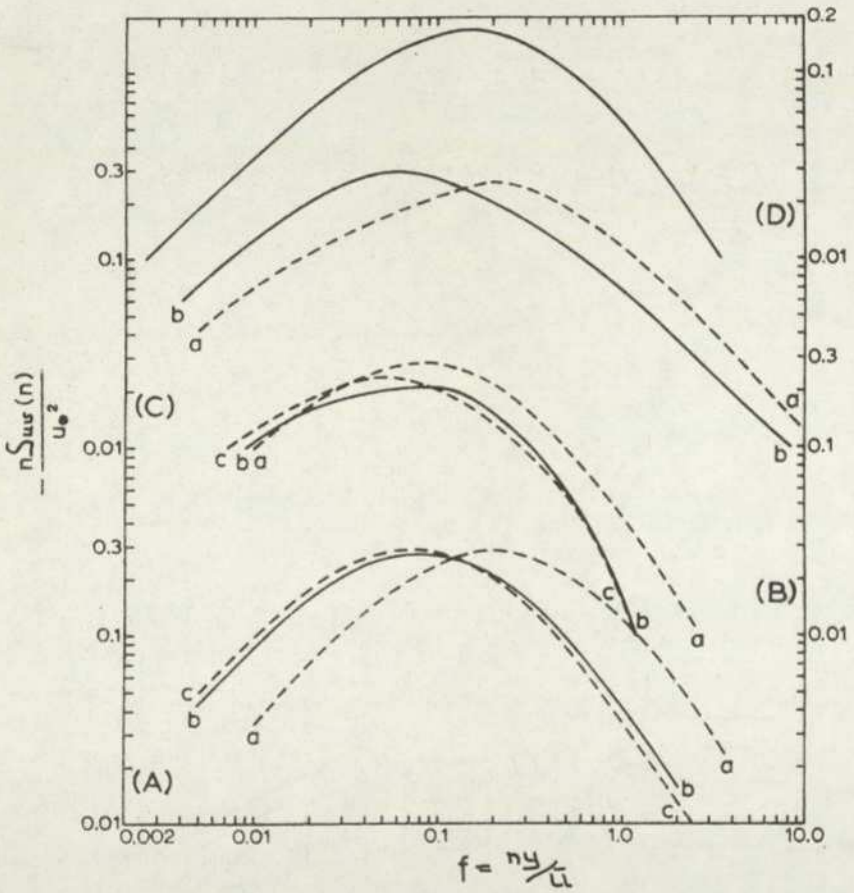


(b)

(REF. HARRIS. 1968.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.



Averaged, normalized, logarithmic $\overline{uv}$-cospectra.

(A) South Dartmouth at 15 to 91 m. a: stable ($+ 0{\cdot}420 \geq z/L \geq + 0{\cdot}051$); b: neutral ($+ 0{\cdot}050 \geq z/L \geq - 0{\cdot}050$); c: unstable ($- 0{\cdot}051 \geq z/L \geq - 1{\cdot}119$).

(B) Hanford at 3 and 6·1 m. a: stable ($+ 0{\cdot}18 \geq Ri \geq + 0{\cdot}01$); b: neutral ($0 \geq Ri \geq - 0{\cdot}03$); c: unstable ($- 0{\cdot}04 \geq Ri \geq - 0{\cdot}16$).

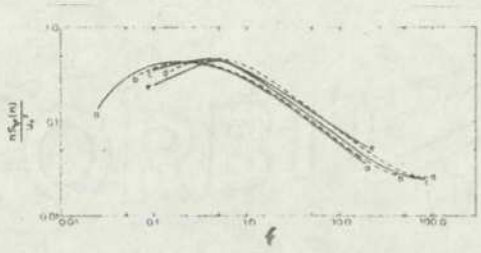
(C) Over sea near Vancouver according to Weiler and Burling (1967). a: stable; b: unstable.

(D) Empirical formula, arbitrary f_m.

(REF. PANOFSKY AND MARES. 1968.)

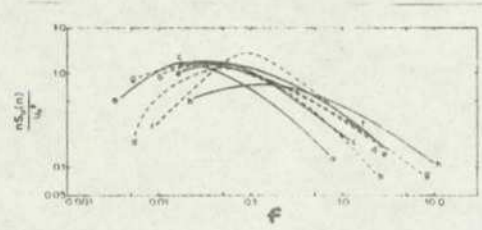
Atmospheric Boundary Layer Simulation.

Survey of Meteorological Data.



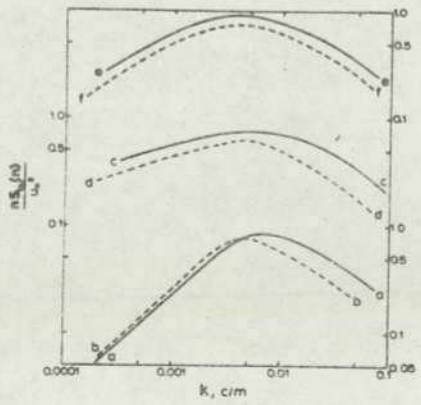
Variation of vertical-velocity spectra with height in neutral to slightly unstable air. Dallas: a. 46 m; b. 137 m; c. 229 m; d. 320 m. LO-LOCAT: e. 229 m.

(a)



Assorted longitudinal-velocity spectra in neutral air at various locations. a. St. Louis, 76 m. b. New York City, Telephone Bldg., SW winds, 177 m. c. Brookhaven, 91 m. d. South Dartmouth, 15 to 46 m (neutral and unstable). e. New York City, Wall St. Tower, NW winds, 280 m. f. Montreal, 76 m. g. Hanford, 3 and 6.1 m. h. Cape Kennedy, 90 and 120 m.

(b.)



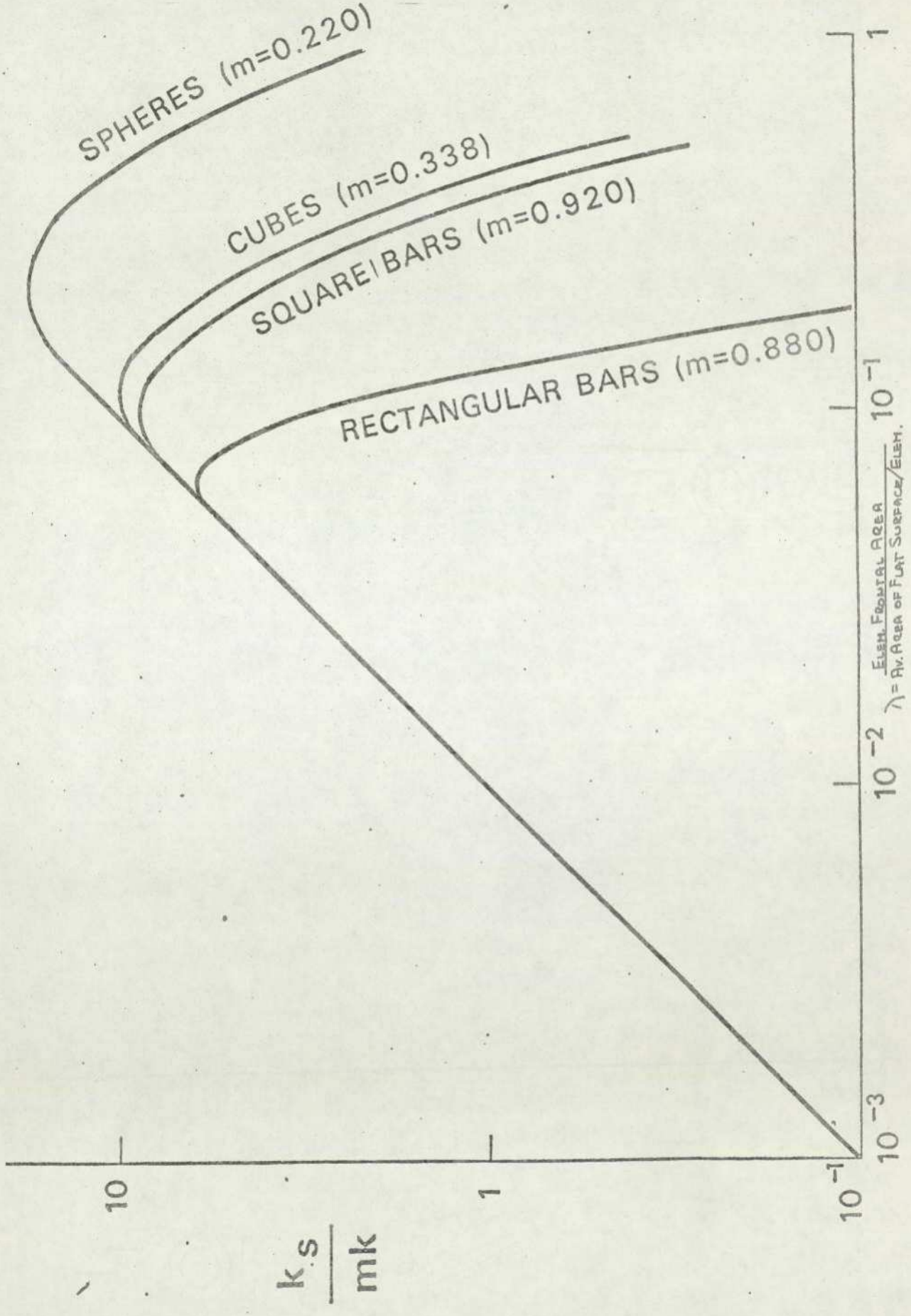
Spectra of lateral velocity at South Dartmouth, Mass. Stable: a. height 46 m; b. height 91 m. Unstable: c. heights 15 and 16 m; d. heights 40 and 46 m. Neutral: e. heights 15 and 16 m; f. heights 40 and 46 m.

(c)

(Ref.- Panofsky 1969.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

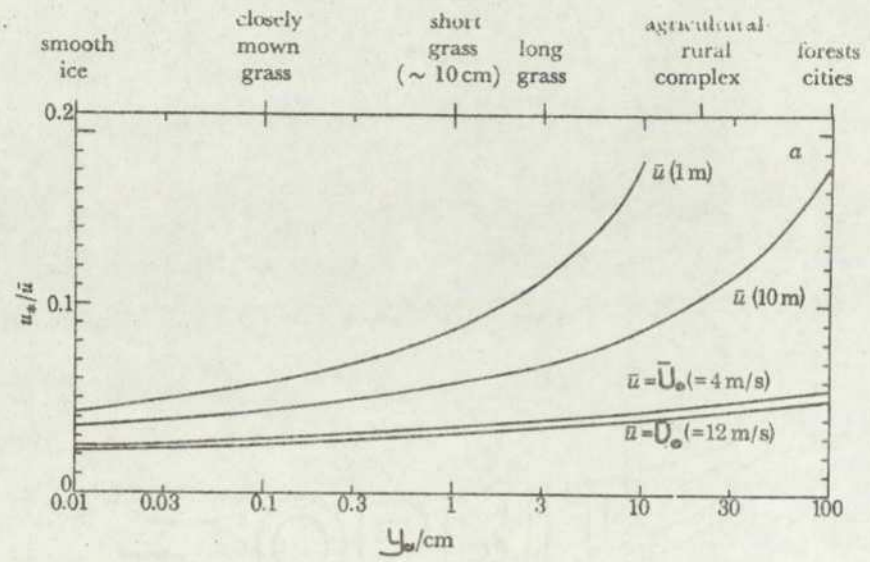
SURVEY OF METEOROLOGICAL DATA.



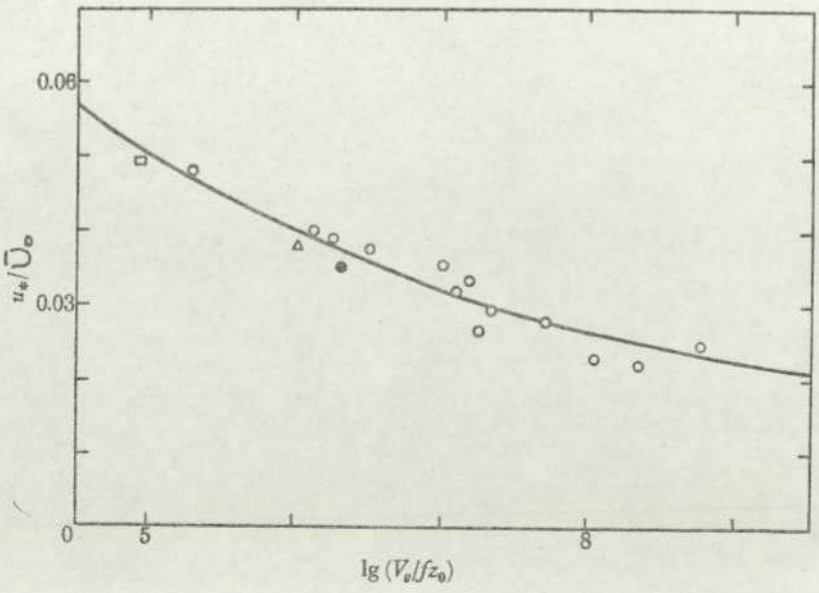
(REF. - WOODING ETAL. 1969)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEORDLOGICAL DATA.



(a)

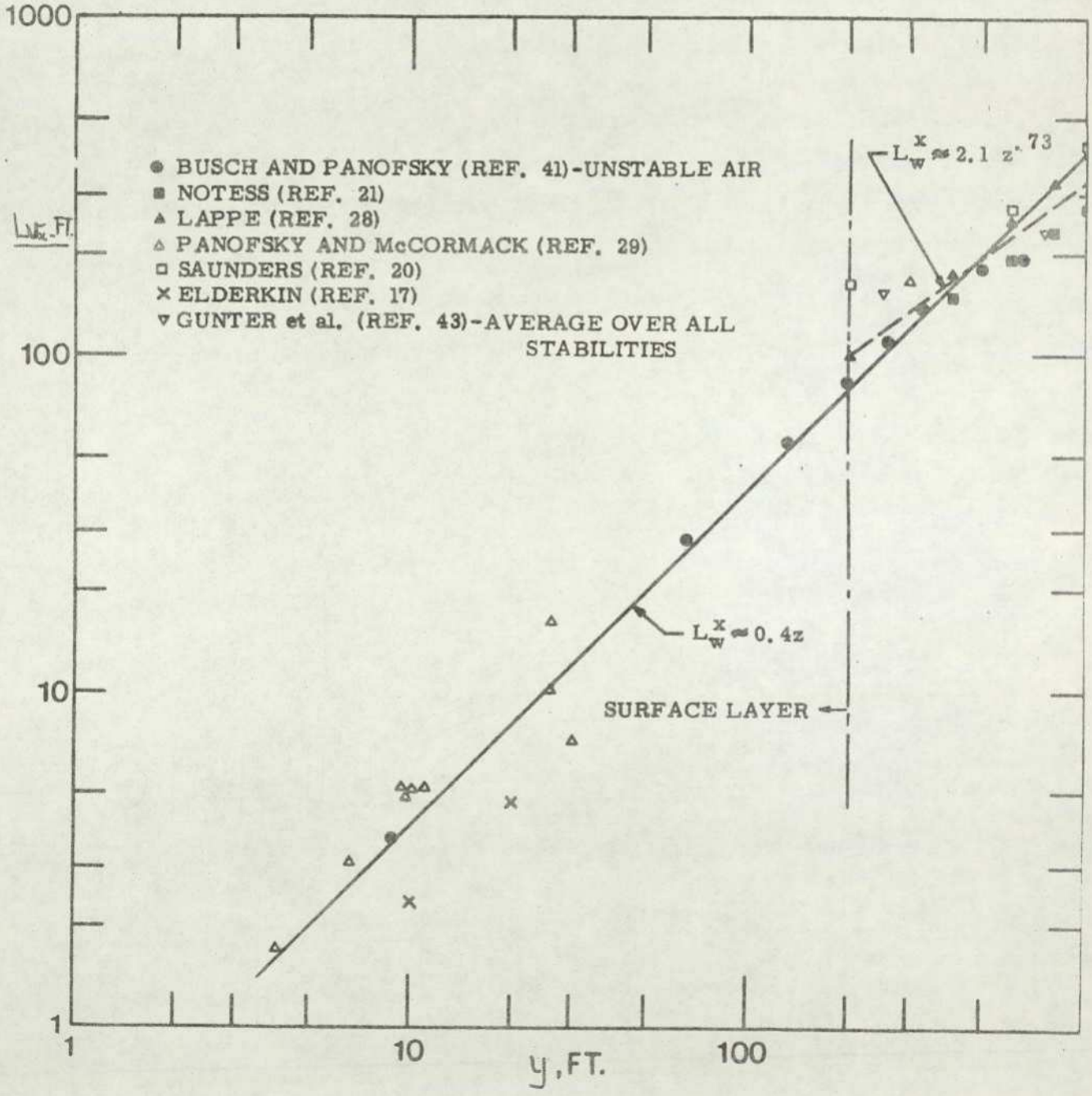


(b)

(REF. - PASQUILL 1970.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA.

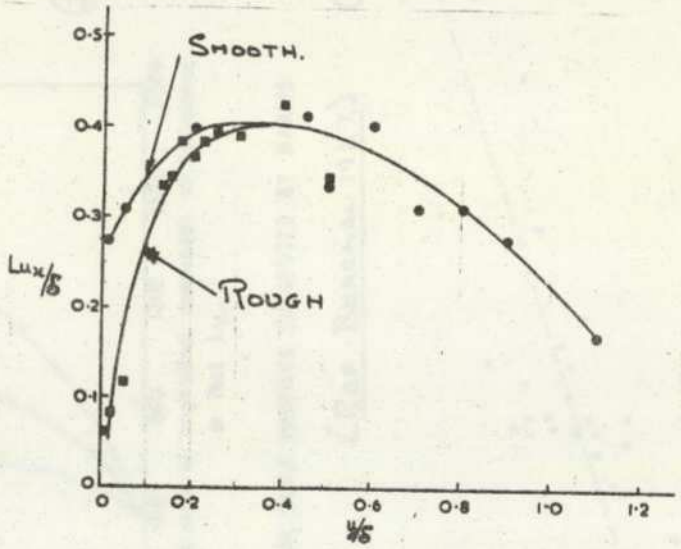


VERTICAL COMPONENT SCALE VARIATION WITH HEIGHT IN NEUTRAL STABILITY OVER FLAT TERRAIN

(REF. TEUNISSEN 1970.)

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

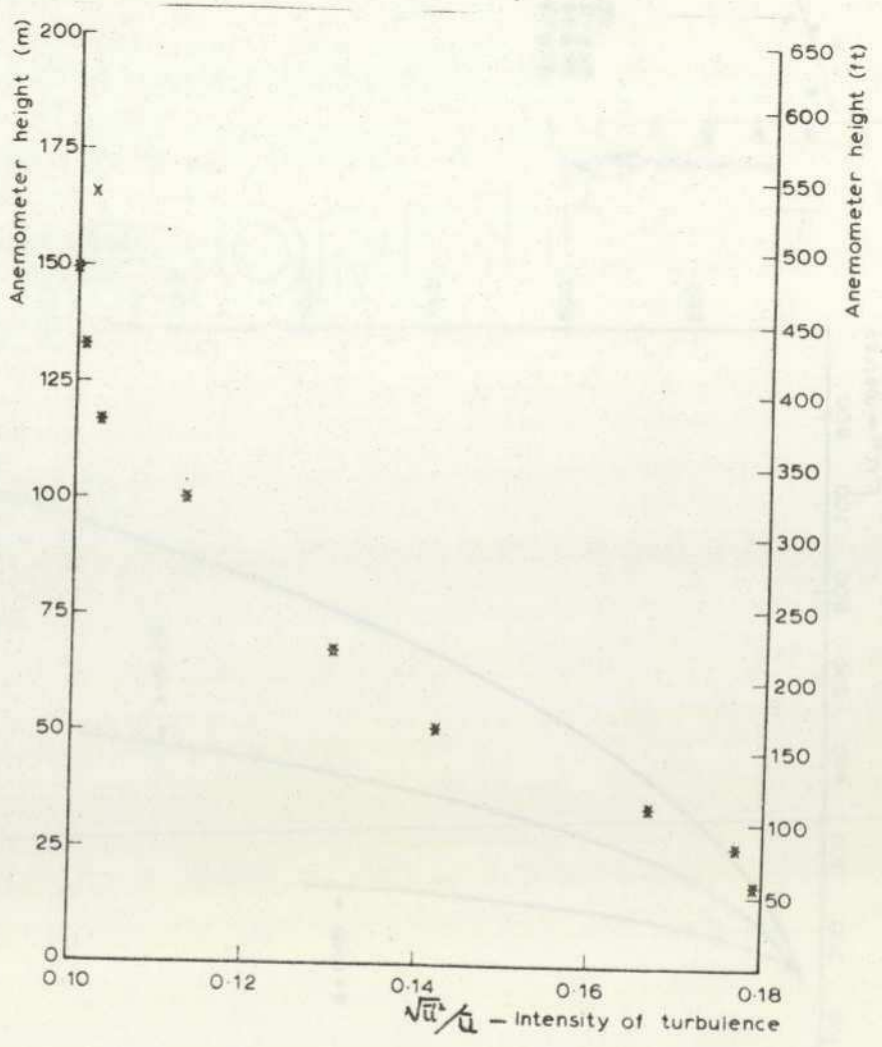
SURVEY OF METEOROLOGICAL DATA.



Distribution of length scales over smooth and rough walls

(a)

(REF.- ANTONIA AND LUXTON 1971.)

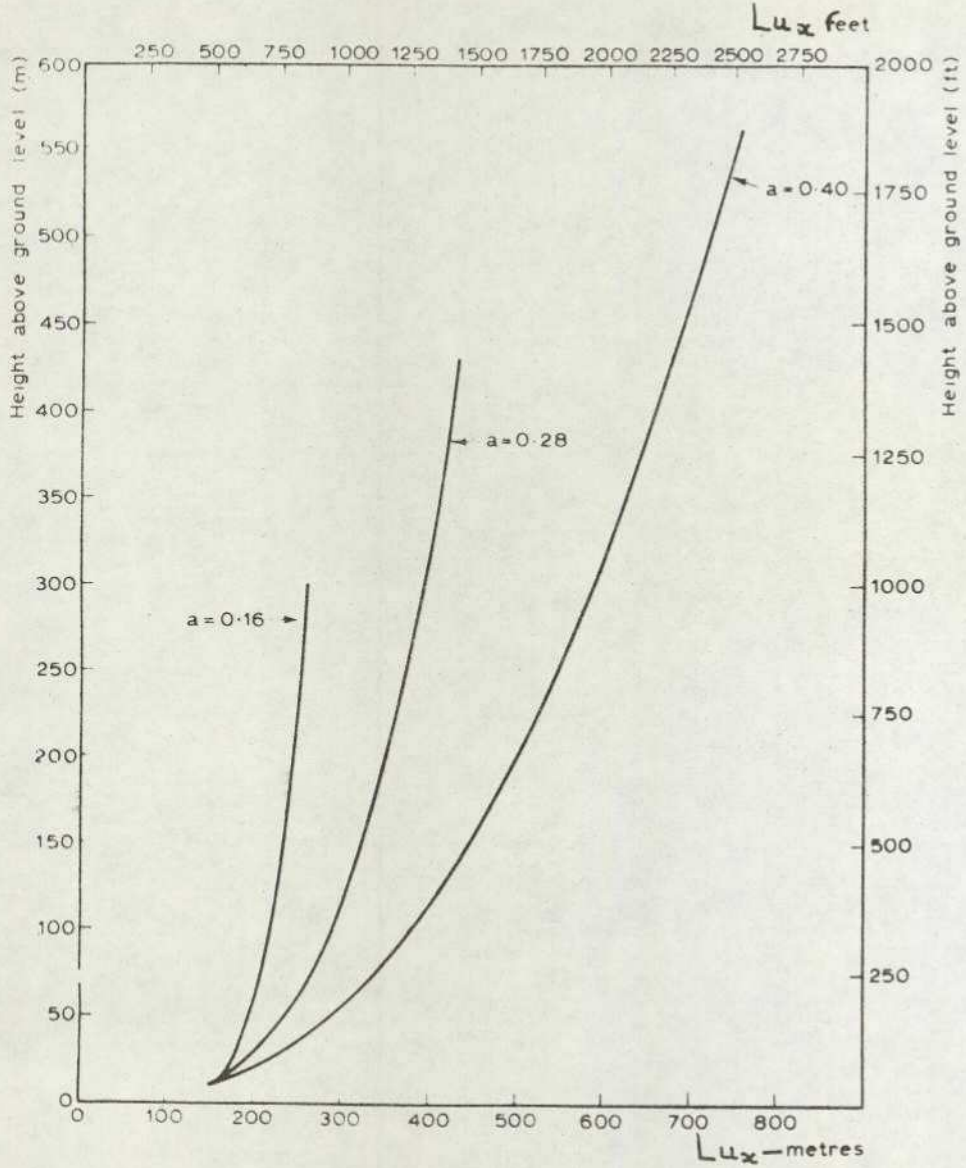


Intensity of turbulence measured at Rugby

(b)

(REF.- HARRIS 1971.)

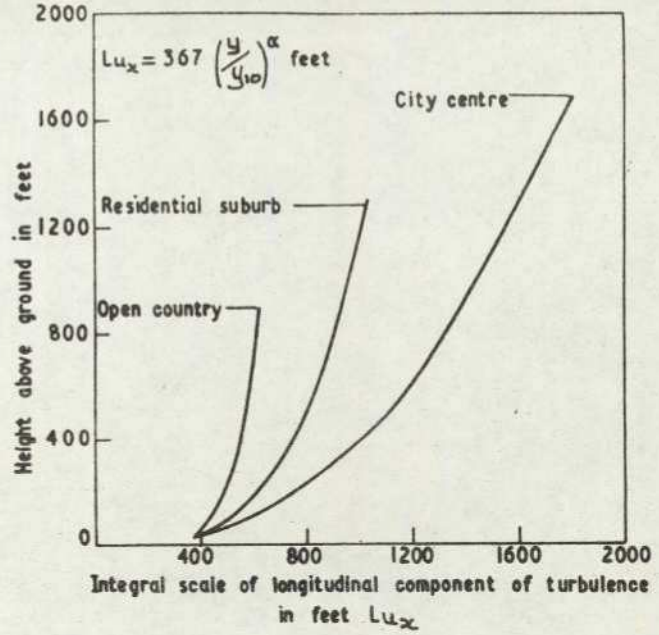
Atmospheric Boundary Layer Simulation. Survey of Meteorological Data.



Length scale of longitudinal components over level terrains of differing roughness

(a)

(Ref. Harris 1971)

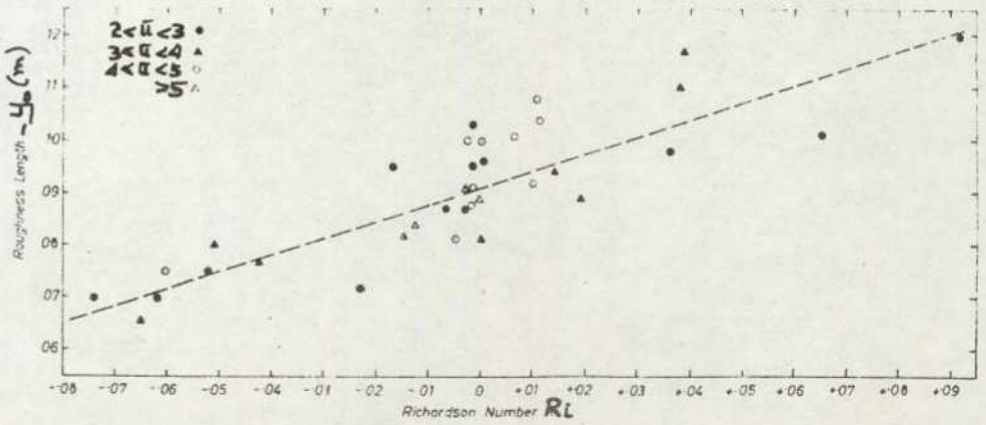


(b)

INTEGRAL SCALE PROFILES SUGGESTED BY HARRIS

(Ref. Bearman 1967.)

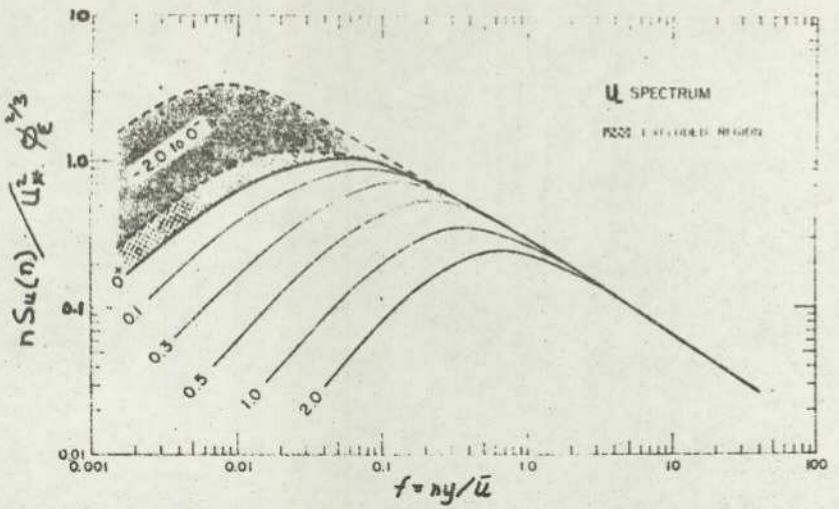
(c)



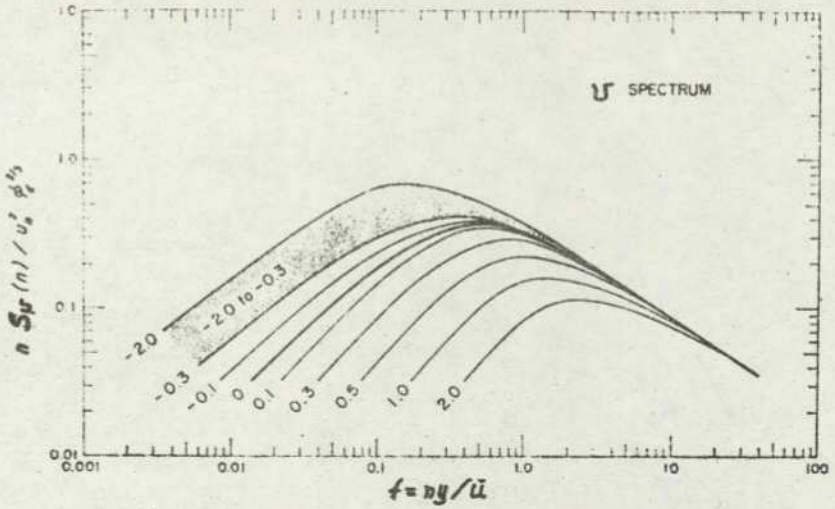
Variation of roughness length with Richardson Number.

(Ref. Oliver 1971.)

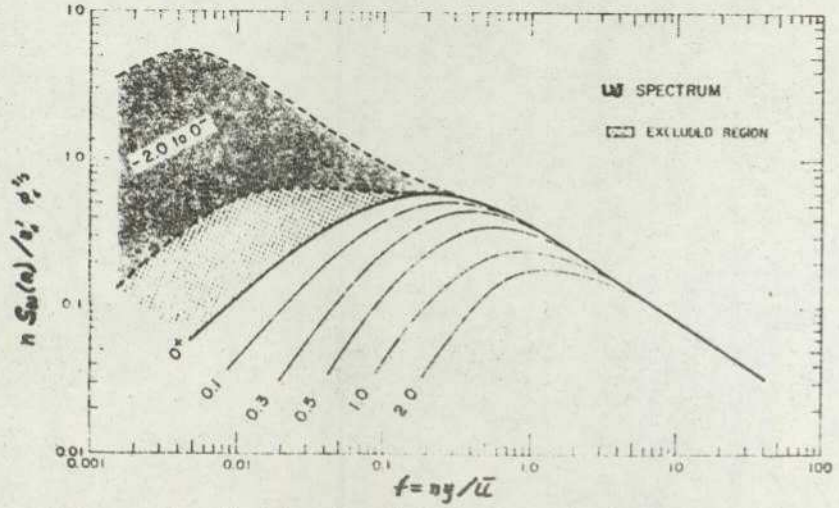
Fig. 61



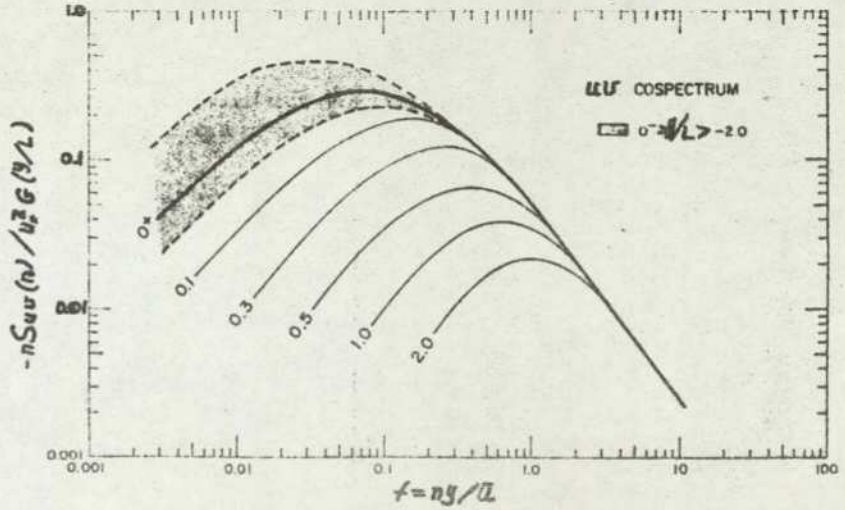
Generalized u spectrum for z/L values ranging from $+2{\cdot}0$ to $-2{\cdot}0$. 0^+ and 0^- denote $z/L=0$ approached from positive and negative sides respectively.



Generalized v spectrum for y/L values ranging from $+2{\cdot}0$ to $-2{\cdot}0$. Stippling indicates absence of any well defined trend with y/L.



Generalized w spectrum for y/L values ranging from $+2{\cdot}0$ to $-2{\cdot}0$.



Generalized uv cospectrum for y/L values ranging from $+2{\cdot}0$ to $-2{\cdot}0$.

FIG. 62.

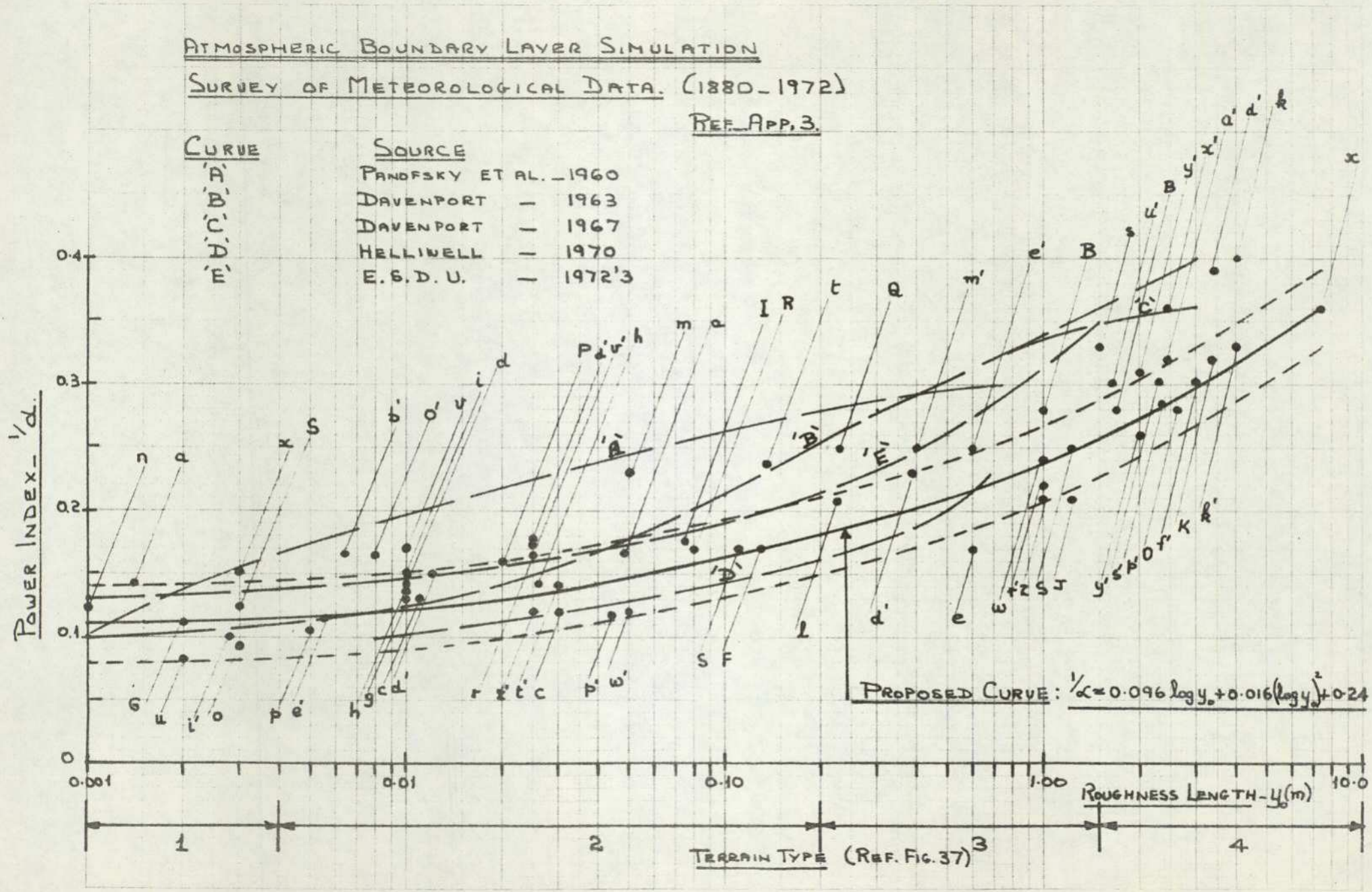

ATMOSPHERIC BOUNDARY LAYER SIMULATION
SURVEY OF METEOROLOGICAL DATA. (1880-1972)
REF. APP. 3.
CURVE
SOURCE
'A' PANOFSKY ET AL. - 1960
'B' DAVENPORT - 1963
'C' DAVENPORT - 1967
'D' HELLIWELL - 1970
'E' E.S.D.U. - 1972'3
POWER INDEX - 1/α
0·4
0·3
0·2
0·1
0
0·001
0·01
0·10
1·00
10·0
ROUGHNESS LENGTH - y₀(m)
PROPOSED CURVE: 1/α = 0·096 log y₀ + 0·016 (log y₀)² + 0·24
1
2
3
4
TERRAIN TYPE (REF. FIG. 37)

FIG. 63

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA. (1880–1972.)
REF. APP. 4.

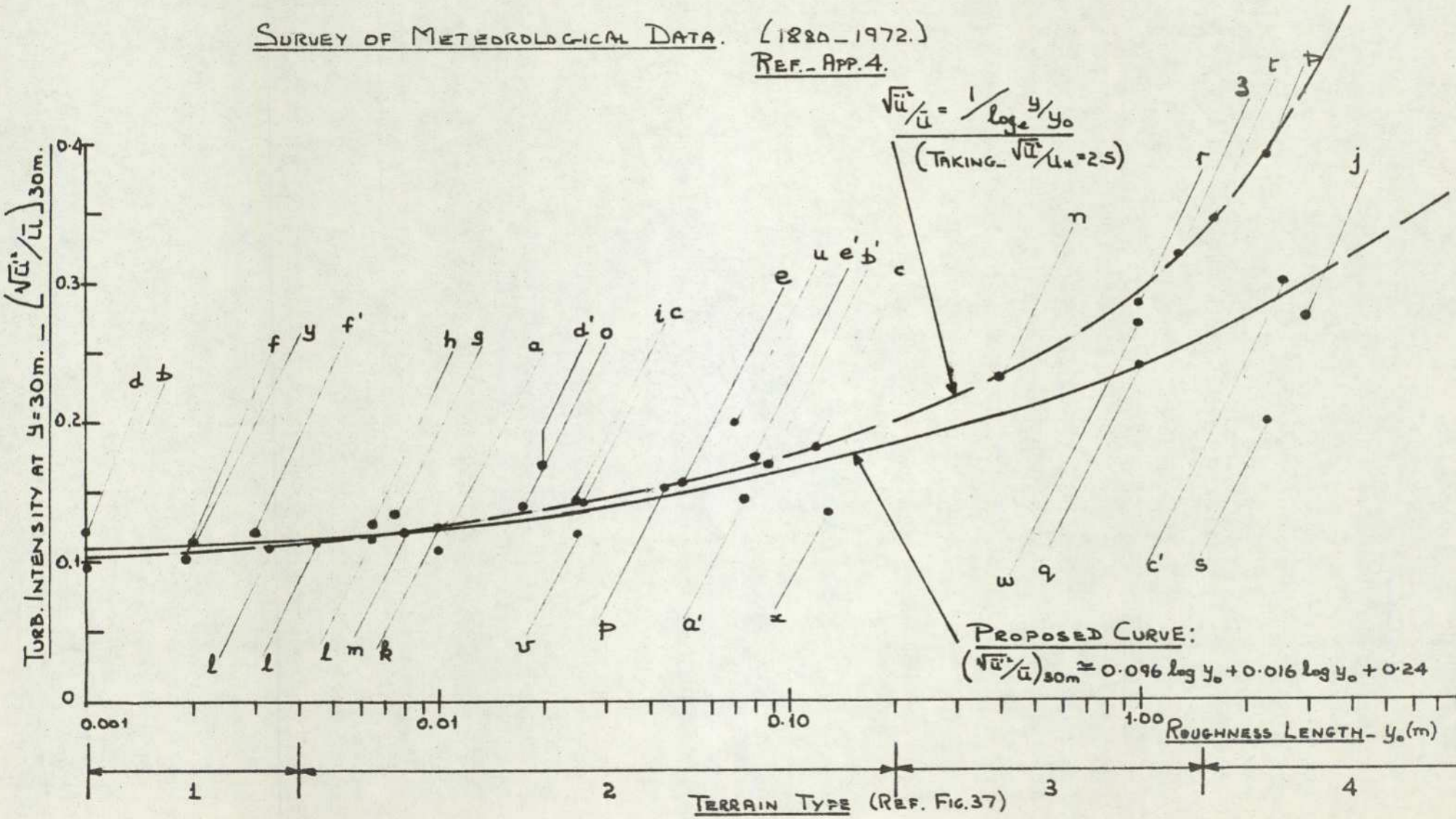


FIG. 64.

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA. (1880 - 1972)

REF. APP 5

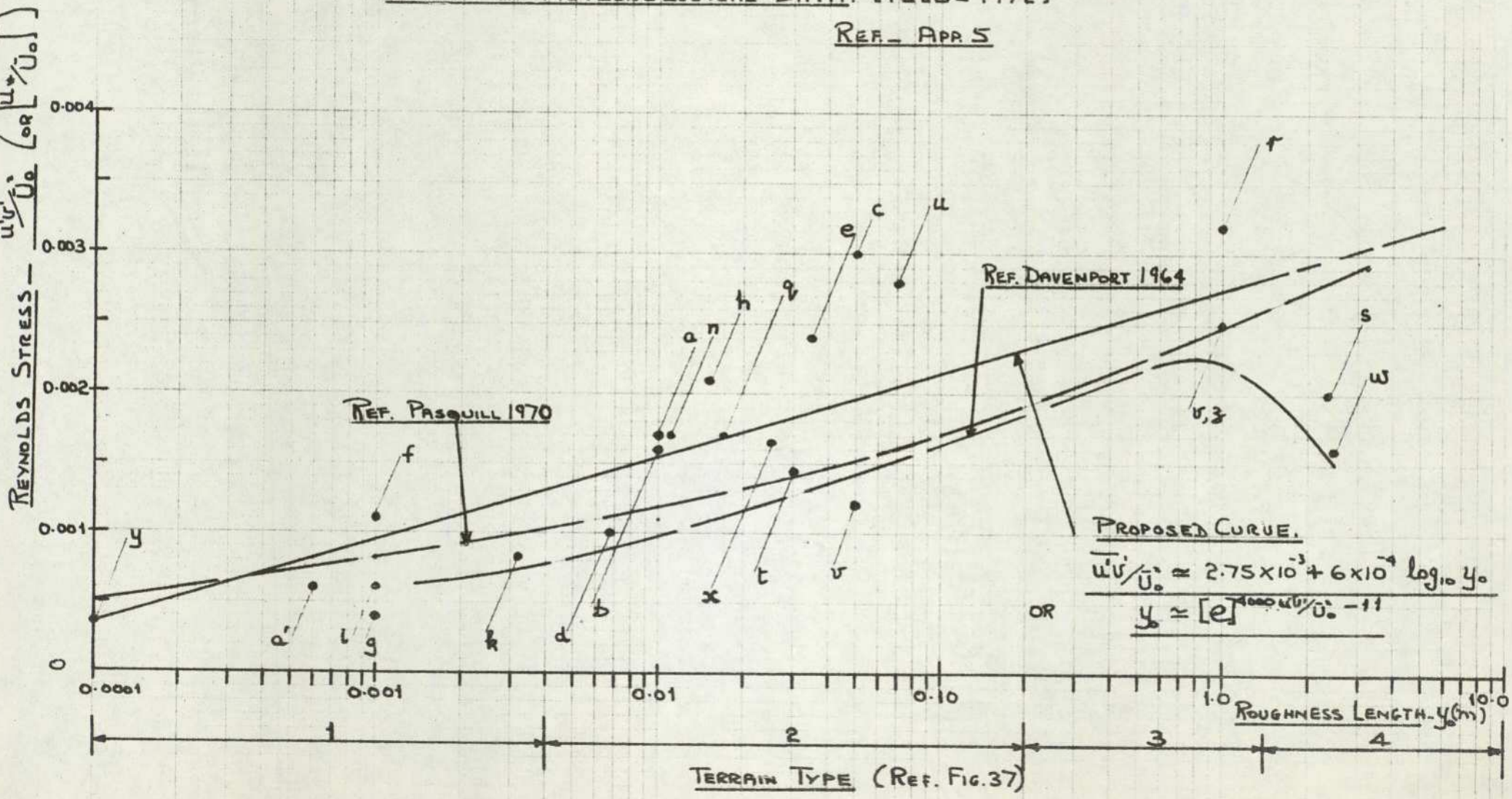
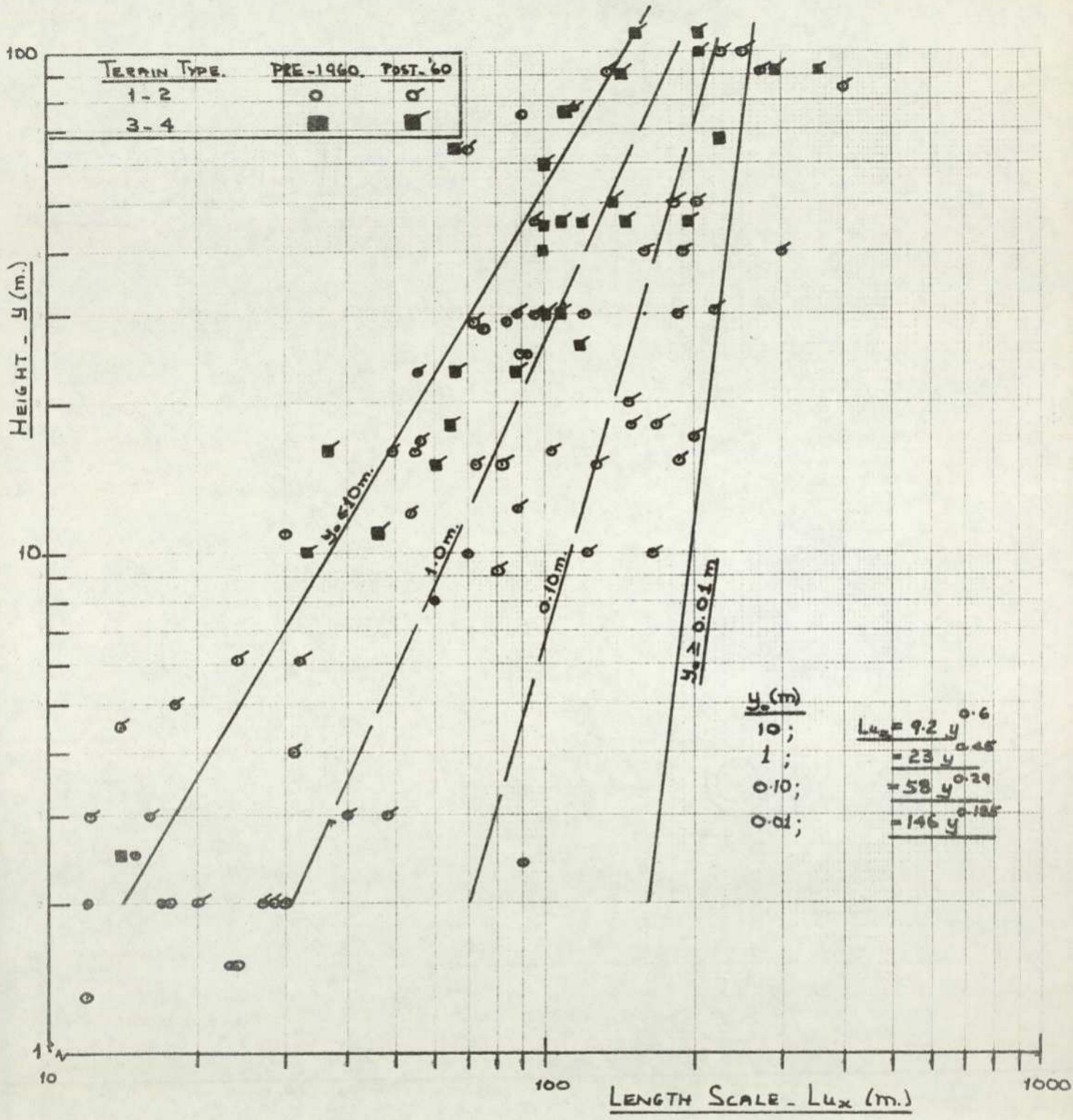


FIG. 65

ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA. (1880-1972)

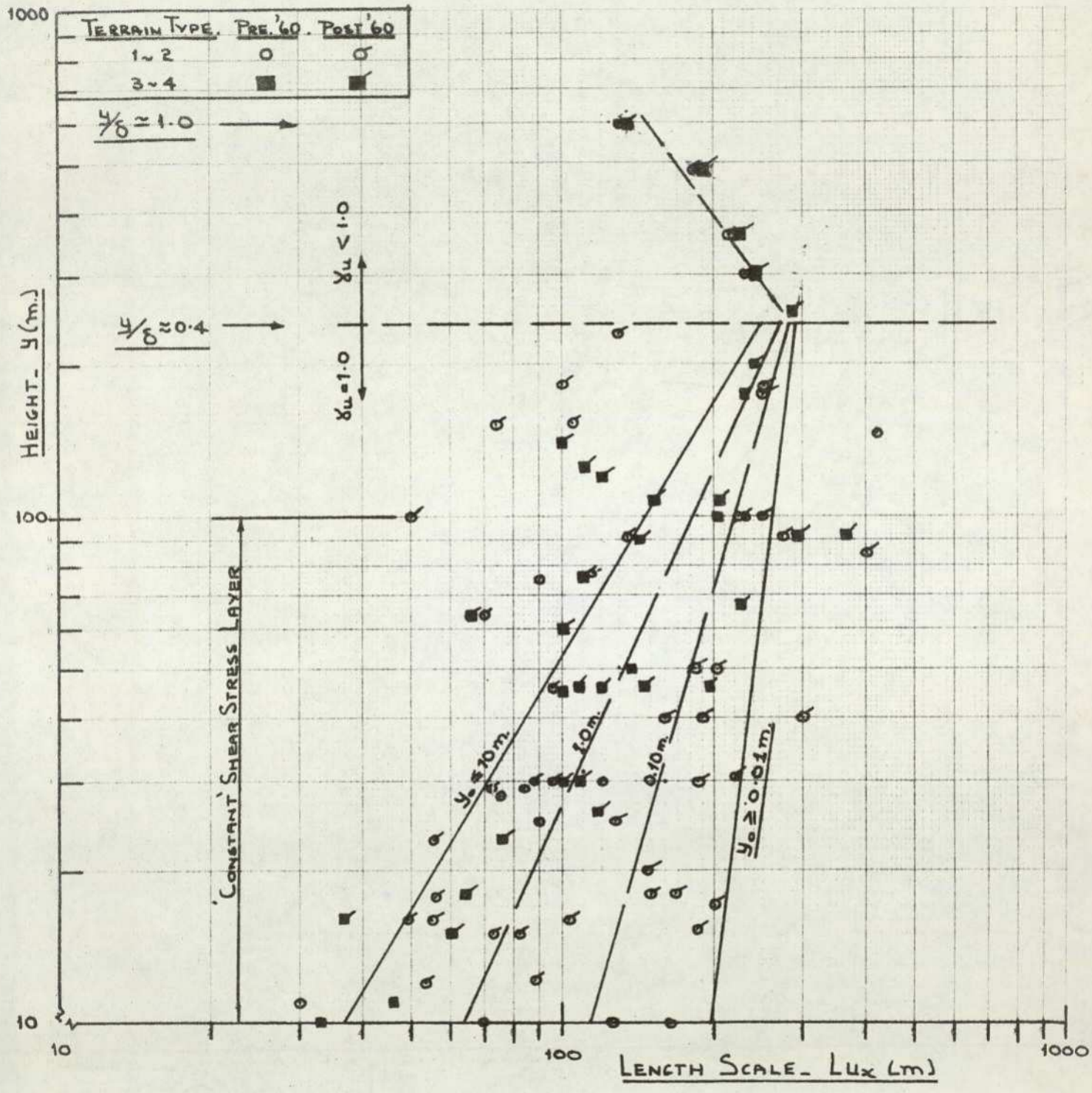
REF. - APP. 6



ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA. (1880-1972)

(REF. - APP 6.)



ATMOSPHERIC BOUNDARY LAYER SIMULATION.

SURVEY OF METEOROLOGICAL DATA. (1880-1972)

REF. - APP. 6

