LABORATORY SIMULATION OF ATMOSPHERIC

MOTIONS IN THE LOWEST ONE HUNDRED METERS

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Summary

The simulation of motion in the atmospheric surface layer by low-speed, wind-tunnel flows is discussed. Similarity parameters and wind-tunnel characteristics required for simulation of small- and micro-scale atmospheric motions are stated. Comparisons of vertical distributions of mean velocity for different thermal conditions, turbulence power spectra, energy dissipation rates, and intensity of the vertical component of turbulence are made for wind-tunnel and atmospheric data -- data taken in the thick turbulent boundary layer (1 m) produced by flow over a long test-section floor (20 m) show good agreement with atmospheric data.

Time and length scaling factors for small and large scale turbulence are established through the use of similarity agreements utilizing the energy dissipation rate per unit of mass ϵ.

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Introduction

Simulation of atmospheric motions in the lowest one hundred meters by laboratory flows is desirable from several points of view. From a scientific perspective, laboratory flows which are faithful models of atmospheric prototypes can be systematically studied under controlled geometrical, dynamical and thermal conditions to produce new knowledge about geophysical systems. From an engineering or applied perspective, simulated atmospheric flows in the laboratory are of value in experimental efforts to establish the dynamic behavior of structures, to predict the diffusion of heat and mass for various environmental circumstances, to study the scattering of electromagnetic energy, and to explore many other interactions between atmospheric motions and man's activities on the surface of his planet.

The remarks in this paper are confined to what is commonly called small-scale and micro-scale atmospheric motions. A restriction to small-scale motions limits the distances for which simulation is considered to those giving large values of the Rossby number or, in other words, flows in which the Coriolis acceleration is a minor factor in determining the flow. Horizontal distances are thus limited to about 150 km. Micro-scale motions are defined to be the turbulent motions embedded in the small-scale mean motion.

Nonuniformity of the small-scale mean motion occurs both in horizontal and in vertical directions. Horizontal nonuniformity is influenced strongly by terrain nonuniformity while nonuniformity in the vertical direction is conditioned by surface shear stress and vertical heat flux. Simulation of these nonuniformities is discussed for steady flow of the surface layer.

Turbulence structure -- the micro-scale motion -- is characterized by numerous measures of which length scales, intensities, energy spectra, and turbulent energy dissipation are of primary importance. Comparisons of such quantities for laboratory and atmospheric data have been made in an exploratory sense at the Fluid Dynamics and Diffusion Laboratory of Colorado State University. These studies which are described in Ref. 1, reveal that much research remains to be accomplished before atmospheric turbulence structure can be simulated with a high degree of confidence; however, the special type of wind tunnel developed at Colorado State University produces turbulent boundary-layer flows having the desired characteristics.

Symbols

Symbol	Definition	Dimensions
g	gravitational acceleration	Lt^{-2}
h	reference height	L
k	Karman constant or wave number	- or L^{-1}
m	subscript designating model flow	-
p	subscript designating prototype flow	-
t	time	t
u	turbulent velocity fluctuation in mean flow direction	Lt^{-1}
$\overline{u^2}$	time mean of u^2	L^2t^{-2}
w	turbulent velocity fluctuation in vertical direction	Lt^{-1}
w'	$(\overline{w^2})^{1/2}$	Lt^{-1}
C	constant	-
C_p	Specific heat at constant pressure	$QL^{-3}T^{-1}$
$E(k)$	three-dimensional energy spectrum	L^3t^{-2}
$E_1(k)$	one-dimensional energy spectrum	L^3t^{-2}
F	force	F
H	turbulent heat flux	$QL^{-2}t^{-1}$
L	Monin-Obukov stability length	L
L_x	integral scale of in direction of mean flow	L

Symbols - continued

Symbol	Definition	Dimensions
L_d	scale length for small scale turbulence	L
L	scale length for large scale turbulence	L
Q	thermal energy	Q
Ri	Richardson number	-
T	mean absolute temperature	T
U	mean local wind speed	Lt^{-1}
U_a	mean ambient wind speed	Lt^{-1}
U_*	shear velocity	Lt^{-1}
V	mean reference wind speed	Lt^{-1}
Z	vertical distance above surface	L
Z_o	aerodynamic surface roughness	L
β	constant	-
δ	boundary-layer thickness	L
ϵ	turbulent energy dissipation rate per unit of mass	L^2t^{-3}
ν	kinematic viscosity of fluid	L^2t^{-1}
ρ	mass density of fluid	ML^{-3}
τ_o	surface shear stress	FL^{-2}

Army Meteorological Wind Tunnel

If the laboratory data referred to in this paper are to be fully appreciated, a brief comment on the wind tunnel in which they were obtained should be made. The motivating idea leading to the design of this unique facility was to provide a long test section so that a thick turbulent boundary layer can develop in a natural manner. Figure 1 shows this laboratory facility.

Gross operating conditions of the wind tunnel have the following characteristics:

Ambient wind speed U_a : 0.5-37 m/sec
Ambient turbulence intensity: 0.1 per cent
Max. temperature differences at 1.5 m/sec:

$$T_{\text{cold floor}} - T_{\text{hot air}} = -65°C$$

$$T_{\text{hot floor}} - T_{\text{cold air}} = 105°C$$

Most of the data referred to were taken at the downstream portion of the test-section approximately 20 m from the entrance and about 12 m from the beginning of the thermally controlled floor section. Reference 2 describes the wind tunnel in detail; however, the following flow characteristics at a wind speed of about 9 m/sec are useful to keep in mind:

Boundary-layer thickness δ	:	$70 < \delta < 110$ cm (depends on floor roughness)
Turbulence integral scale L_x	:	11 cm at $Z = \delta/2$
Taylor's micro-scale	:	0.9 cm at $Z = \delta/2$
Richardson number Ri	:	$-0.8 < Ri < 0.3$ at $Z = 3$ cm ($U_a = 1.5$ m/sec)

Requirements for Laboratory Simulation of the Atmospheric Surface Layer

An examination of the governing equations of motion and the equation for conservation of energy gives parameters which must be equal in both the laboratory and the field for similarity in the strict sense. The parameters and auxiliary condition which must be matched are shown in Fig. 2. In addition, the boundary conditions, including surface temperature and roughness variation with position and ambient turbulence intensity, must be similar.

Meeting all of these requirements simultaneously is generally impossible; therefore, a compromise with strict similarity is necessary. The important problem which must be faced is to determine the conditions under which equality of certain parameters can be relaxed without introducing serious error in the laboratory flow. By limiting the flow extent to under 150 km, equality of the Rossby numbers is no longer a necessity. If air is used for the laboratory flow the Prandtl numbers and specific heat ratios are automatically equal. Since the Froude number and Richardson number for thermally stratified flows are equivalent, the major parameters remaining to be matched are the Reynolds number and the Richardson number. By an adequately designed heating and cooling system an equality of Richardson numbers is possible. Therefore, the Reynolds number, because of the necessity to use length scale ratios up to about 1:1000, presents the major difficulty in achieving strict similarity.

Spatial Nonuniformity of the Mean Wind Field (small-scale motions)

A. Variation in the horizontal due to topographic features.

Topographic features and large structures may produce variation of the surface wind field. If these features are "sharp-edged", models scaled to 1:1000 or even 1:5000 (Ref. 3) give good simulation of the mean wind field in spite of the Reynolds number differing by three orders of magnitude. The reason for successful flow simulation in these cases is that the basic flow pattern no longer is a function of Reynolds numbers (for sufficiently high values) but depends only on the geometry.

An example of such simulation is reported in Ref. 4 and is shown in Fig. 3. Comparison of the model flow with actual field data gave excellent agreement. The main lesson to be learned from these experiences is that strict equality of the Reynolds number for model and prototype flows is not necessary in order to achieve similarity of gross flow patterns over objects having sharp edges.

B. Variations in the vertical direction due to shear and thermal structure

Variation of wind speed in the vertical direction is in general complex; therefore, simulation has been studied primarily for the "ideal" case. By "ideal" is meant flows over level plane areas where topographic effects discussed in section A are negligible and buoyancy forces have no component parallel to the surface.

Mean velocity profiles under a variety of thermal stability conditions have been measured in the thick turbulent boundary layer at about 20 m from the test section entrance. These vertical distributions are compared with field data taken during project Prarie Grass in Fig. 4. The basis for comparison is the log-linear relationship

$$\frac{U}{U_*} = \frac{1}{k} \left| \ln \frac{Z}{L} + \beta \frac{Z}{L} + C \right|$$

in which the Monin-Obukov stability length $L = \dfrac{-U_*^3 C_p T}{kgH}$ is the reference length and the shear velocity $U_* = (\tau_o/\rho)^{\frac{1}{2}}$ is the reference velocity. The agreement of the two sets of data reveal that the mean flows are similar over at least the lower one-third of the wind-tunnel boundary layer. The corresponding height in the atmosphere may vary from about 20 to 200 m.

Under neutral thermal conditions (adiabatic in the atmosphere) the corresponding vertical variation of wind speed becomes

$$\frac{U}{U_*} = \frac{1}{k} \ln \frac{Z - Z_o}{Z_o} .$$

Therefore, under such conditions where the object to be studied has a height h less than the boundary-layer thickness δ one arrives at the similitude criteria of Jensen (5). This criteria is merely that the ratio of roughness heights for model and prototype $(Z_o)_m/(Z_o)_p$ must equal the length scale ratio determined by the height ratio of model and prototype structure h_m/h_p; i.e.,

$$\frac{h_m}{h_p} = \frac{(Z_o)_m}{(Z_o)_p}$$

Similarity comparisons for the outer part of the boundary layer have not been made. When sufficient field data become available, a velocity defect form such as proposed by Hama (6)

$$\frac{U_a - U}{U_*} = 9.6 \left(1 - \frac{Z}{\delta}\right)^2$$

which correlates laboratory data well for $0.15 < Z/\delta < 1$ is expected to also correlate the field data. Since δ is an unknown in the atmosphere a more practical form of the velocity-defect relationship can be taken as

$$\frac{U_h - U}{U_*} = C \left(1 - \frac{Z}{h}\right)^2$$

where C is expected to depend upon h and the ambient turbulence.

Turbulence Structure (micro-scale motions)

Efforts to simulate turbulent structure of the atmospheric surface layer in the laboratory is closely associated with the problem of producing a laboratory spectral energy distribution $E_1(k)$ which is similar to what is found in the atmosphere. If the one-dimensional energy spectra $E_1(k)$ are similar, then one can proceed to derive, on the basis of dimensional arguments, time and length scales relating the two flow fields.

Fortunately, close similarity of the one-dimensional energy spectra exists for boundary layer flows obtained in the downstream portion of the long meteorological wind tunnel. The data shown in Fig. 5 reveal close correspondence (including a significant inertial sub-range where $E_1(k) \propto k^{-5/3}$ excepting at small relative wave numbers $k/k_d = \frac{k}{\epsilon^{1/4}\nu^{-3/4}}$ where the boundary-layer thickness of the wind-tunnel flow limits the large-scale turbulent motions to being of order δ. Apart from limitation on large-scale turbulent motions, the significant energy-spectrum features are present in the laboratory flow provided the boundary layer can develop over a sufficiently long fetch.

If the small-scale turbulence structure over the outer 90 per cent of the boundary layer is acknowledged to closely approximate an isotropic turbulence field, dimensional arguments lead to a length scale relationship. Consider a field of turbulence in which the turbulence Reynolds number is moderately large. Should a volume of fluid moving downstream from a turbulence generating grid in a wind tunnel be followed, the turbulence structure (energy spectrum) is expected to depend only upon the energy dissipation per unit of mass ϵ, the kinematic viscosity ν and the time of travel t. As is indicated by Hinze (7, p. 137) these three quantities form a dimensionless group which must then be a constant; i.e.,

$$\frac{\epsilon t^2}{\nu} = \text{constant.}$$

In the boundary-layer flow under consideration the time t has little meaning in the sense of our model flow; therefore, we shall construct a time scale which depends on a characteristic velocity and length. Keeping in mind that the energy spectra are nearly similar for the two flows, a velocity derivable from this distribution should be selected for reference; therefore, the mean square longitudinal velocity fluctuation $\overline{u^2}$ becomes significant since it may be expressed as

$$\overline{u^2} = \int_0^\infty E_1(k)\, dk = \int_0^\infty E(k)\, dk$$

where $E(k)$ is the three-dimensional energy spectral function.

Defining a scale length as L_d, the dimensionless grouping obtained for the turbulence field may be expressed as

$$\frac{\epsilon L_d^2}{\overline{u^2}\nu} = \text{constant} .$$

Considering that ν is equal for both the laboratory and the atmospheric boundary layer, a statement relating the laboratory model length scale $(L_d)_m$ to the prototype atmospheric length scale $(L_d)_p$ can be made. This statement is

$$\frac{(L_d)_m}{(L_d)_p} = \left[\frac{(\epsilon/\overline{u^2})_p}{(\epsilon/\overline{u^2})_m}\right]^{1/2}$$

The length L_d defined is entirely dependent upon the turbulence energy spectrum because ϵ can be written as

$$\epsilon = 2\nu \int_0^\infty k^2\, E(k)\, dk$$

therefore,

$$L_d^2 \propto \frac{2\int_0^\infty k^2\,E(k)\,dk}{\int_0^\infty E(k)\,dk}$$

Exploratory data have been collected in the wind tunnel (Ref. 8) and in the atmosphere (Ref. 9) which permit calculation of the length scales. Distributions of $\epsilon/\overline{u^2}$ are shown in Fig. 6 for both the wind-tunnel flow and the atmosphere. The distributions appear to be of the same form. If the ratio $(\epsilon/\overline{u^2})_p \,/\, (\epsilon/\overline{u^2})_m$ is computed for the outer portion of these profiles, the prototype length scale $(L_d)_p$ is 16 times larger than the model length scale $(L_d)_m$. A corresponding ratio of time scales is given by $t_m/t_p = (\epsilon_p/\epsilon_m)^{1/2}$. For these flows $t_m/t_p = (260/9300)^{1/2} = 1/6$. The scale ratios obtained by these arguments give a measure of the relative small scale characteristics for the two flows. The importance of scaling these small-scale micro motions depends upon the problem under study -- for flow around objects, say a cylinder of diameter d, where d_m or d_p is large compared to $(L_d)_m$ or $(L_d)_p$, respectively, similitude at this scale is relatively unimportant compared to similitude for the large-scale micro motions which we discuss in the next paragraph.

To examine similarity of the large-scale turbulence consider that

$$\epsilon \propto \frac{(\Delta U)^3}{L_\delta}$$

where ΔU is a gross mean velocity difference. On this basis, the ratio of large scale lengths becomes

$$\frac{(L_\delta)_m}{(L_\delta)_p} = \left(\frac{\Delta U_m}{\Delta U_p}\right)^3 \frac{\epsilon_p}{\epsilon_m}$$

For the wind-tunnel flow over the rough boundary and the atmospheric flow referred to in Fig. 6, the quantities on the right-hand side of the previous equation are as follows:

	prototype	model
ϵ (cm^2/sec^3)	260	9300
ΔU(m/sec)	16	9.15

Here ΔU is taken as the velocity where the vertical velocity gradient vanishes in both cases. The length-scale ratio then becomes

$$\frac{(L_\delta)_m}{(L_\delta)_p} = \frac{1}{190}$$

Accordingly, if the mean turbulent dissipation rates are known and the wind-speeds at approximately zero vertical wind gradient are known for both a laboratory and an atmospheric flow, it becomes possible to establish the relationship between height in the model and the prototype. The corresponding time-scale ratio for the large-scale turbulent motion becomes

$$\frac{t_m}{t_p} = \left(\frac{(L_\delta)_m}{(L_\delta)_p}\right)^{2/3} \left(\frac{\epsilon_p}{\epsilon_m}\right)^{1/3} .$$

These scale ratios become particularly significant when it is desired to simulate flow around structures or other phenomena which are sensitive to the large-scale micro motions or turbulence. To simulate flow around a structure using the atmospheric flow and wind-tunnel flow referred to here, the appropriate model scale would be approximately 1:200. Of course, the wind-tunnel boundary layer must be sufficiently thick to submerge the model.

In Fig. 7 data are shown which compare the behavior of the intensity of the vertical velocity fluctuations at 3 cm above the smooth wind-tunnel floor and 1 and 2 m above the earth's surface as affected by thermal stratification. These data which are presented in Ref. 10 show that the effects of thermal stratification are similar for the two flows. In the region where these data were taken ($Z < 0.1\ \delta$) the actual average height ratio of 1/50 is estimated to be approximately equal to $(Z_o)_m / (Z_o)_p$ for the two flows. The wind-tunnel data taken at $U = 150$ cm/sec appears to be strongly influenced by viscous forces; i.e., the Reynolds number $\frac{UZ}{\nu}$ is too small compared to the prototype value.

Summary

Mean flow characteristics and turbulence characteristics in the lowest 100 m of the atmosphere can be simulated in the laboratory if adequate wind-tunnel facilities are available. The wind-tunnel should have a long test section which will permit development of a turbulent boundary layer having a thickness at least equal to the height of any object, scaled to a practical size for study, which is to be placed in the flow. At a test section length of 20-30 m the spectrum of turbulence is similar excepting at the smallest wave numbers. If the energy dissipation rate and the ambient wind speed are known for a laboratory flow and an atmospheric flow, the scaling ratio for vertical heights or the large-scale turbulent motions can be established.

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