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ATMOSPHERIC TURBULENCE

Models and Methods for Engineering Applications

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To Nancy and Elizabeth

FOREWORD

The authors kindly asked me in the preliminary stages what I thought about their writing a book of this sort. My response was enthusiastic for a number of reasons.

First, over the past several decades engineering activities have invaded the atmosphere to an increasing extent. This is true in space, in air transportation, in communications, in the design of tall buildings and long bridges, in the release of pollutants, in wind energy, and so on. The need for engineers to know more about the atmosphere clearly has been increasing in leaps and bounds. It is now not only useful that this understanding be developed, but also critical.

Second, the knowledge of the atmosphere is moving so rapidly it is difficult for engineers to climb on board and gain the insight and the ability to make the simplifications often required for engineering purposes. This is especially true of atmospheric turbulence, the central subject of this book. A guide to the fundamentals by meteorologists sympathetic to engineering requirements is therefore invaluable.

Third, the authors are themselves internationally respected for their contributions to the frontline of meteorological research during the past several highly productive decades. Their extensive involvement with engineering applications has made them aware of needs and sympathetic to engineering constraints.

This book should find an important role at the interface between engineering and the atmosphere. It will significantly improve the mixing and exchange of momentum between these fields.

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PREFACE

Atmospheric scientists have recognized the importance of turbulence since the beginning of the century. It was clear that the energy budget of the atmosphere required the conversion of large-scale motions into turbulence before dissipation into heat. Meteorologists also recognized the importance of turbulence in the transfer of moisture and sensible heat near the ground, and it was obvious that air pollutants were dispersed by turbulence.

As a result, meteorologists concentrated on turbulent transport and its effect on the distribution of averaged atmospheric variables. Initially, there was little interest in the statistical properties of turbulence, such as the probability distributions and spectral densities of turbulent motions.

Now we have learned that these quantities allow us to describe and predict certain features of turbulence. Moreover, it is precisely these statistical quantities that are needed to assess and predict the effects of the wind and turbulence on the dynamic response of structures and aircraft. For this reason, engineers are now interested in the statistical properties of atmospheric turbulence. They have found that atmospheric turbulence is more complex than the wind-tunnel turbulence more traditionally studied in engineering and fluid dynamics because of the importance of convection at the Earth's surface and the smaller effects of the Earth's rotation.

Today, both meteorologists and engineers must be able to estimate statistical properties of atmospheric turbulence from relatively accessible quantities, such as the wind speed, the vertical temperature distribution close to the ground, and terrain features.

Rational methods for providing such estimates were created in the 1940s and 1950s as a result of hypotheses proposed by Monin and Obukhov and by Kolmogorov. Primarily as a result of these theories, one of us (Panofsky) teamed up with Professor John L. Lumley to produce *Structure of Atmospheric Turbulence*, published in 1964. Lumley provided the theoretical background and Panofsky analyzed the statistical results then available in accordance with the theoretical framework. By 1964, there had been one major observational program over simple terrain (at O'Neill, Nebraska) and many separate studies over more complex terrain and on towers.

Since 1964 several independent developments have occurred, particularly in regard to observations. Several major measurement programs have taken place over uniform terrain, some extending to much greater heights than the O'Neill observations. Systematic investigations of flow and turbulence over differing types of complex terrain have been concluded. As a result, much of the statistical material described by Lumley and Panofsky is now out-of-date, and the book is no longer in print. The theoretical material, on the other hand, has not changed significantly since 1964.

Today, there is no single place where engineers can find the most accurate models for atmospheric spectra and variances. Consequently, the purpose of this volume goes beyond bringing the material of the earlier book up-to-date. In the first place, it is directed at both practicing engineers and meteorologists. The first three chapters provide a reasonably rigorous treatment of the basic physics and statistics underlying the properties of atmospheric turbulence. Chapters 4–11 are self-sufficient, and give, after a very brief summary of the basic meteorological equations, an up-to-date treatment of statistical properties of atmospheric turbulence, with emphasis on the behavior close to the ground. Some of the recent developments of theory and observations in the higher turbulent layers are included, as well as a chapter concerning theory and practice of estimation of pollution concentration. This section is also useful as a text on atmospheric turbulence and diffusion for meteorologists and other physical scientists. Finally, the last three chapters are addressed specifically to engineers and deal with calculating response of systems to turbulent forcing.

Thus the book has two distinct purposes: (1) to serve as an summary of the current knowledge of the statistical characteristics of atmospheric turbulence and (2) to serve as a introduction to methods required to apply these statistics to practical-engineering problems. To aid the engineer or meteorologist, an appendix summarizes estimation techniques.

Our efforts have been preceded by the work of hundreds of scientists and engineers; we have referred to those articles and books that we have used in preparing this book and have not attempted to provide a thorough review or bibliography. In many cases, we use classical or well-known material without reference.

We acknowledge support for parts of this work from the National Science Foundation; the Department of Energy; Risø National Laboratory, Denmark; Meteorology Research, Inc.; and of course, from Penn State. Our friend, Leif Kristensen of Risø helped us to improve the manuscript and A. M. Yaglom, Soviet Academy of Sciences, provided comments. The list of friends and colleagues who have helped us try to understand turbulence is much too long to reproduce—they have our gratitude, nonetheless. Any errors are our very own.

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University Park, Pennsylvania
October 1983

TABLE OF SYMBOLS

$\overline{(\ )}$	ensemble average (3.2.5)
$(\ )'$	a deviation from a mean or steady value
$\dot{(\ )}$	temporal derivative
$\dfrac{d}{dt}$	material derivative (2.1.2)
a	universal constant for inertial range (longitudinal wind component)
a_i	coherence decay constant in ith direction (9.2.5)
a_n	Fourier coefficients (12.5.13)
b	universal constant in inertial range relation for scalars
B	Bowen ratio of sensible to latent heat flux (4.4.1)
c_p, c_V	specific heats (Table 2.1)
C_ϕ	structure constant for ϕ (8.3.33)
$C_{u,v}(\omega)$, $\mathrm{Co}(f)$	cospectral density (3.7.24) (8.6.1)
$\mathrm{Coh}(f)$	coherence (9.2.1) [also $\Gamma_{u,v}(\omega)$]
d	displacement length (6.1.7)
D_ϕ	structure function for ϕ (8.3.32)
e	turbulent energy per unit mass (4.4.1)
$E\{\ \}$	expected value (3.1.1)
$E(\kappa)$	energy spectral density averaged over spheres in κ space (3.7.53)
f	Coriolis parameter $2\Omega \sin\phi$ (Ω, earth's rate of rotation; ϕ, latitude) (Table 2.1)
f	frequency in cycles per unit time (1 Hz = 1 cycle/sec) (4.1.1)
$f(t)$	forcing function (12.2.1)
$f(T)$	normalized dispersion function (10.4.17)
F_j	flux in the jth direction (4.7.5)
$F(x)$	longitudinal dispersion function (10.1.5)

g	acceleration of gravity (Table 2.1)
$G(y)$	lateral dispersion function (10.1.5)
$\underline{\underline{G}}$	equality under the Gaussian assumption
h	mixing depth
h	height of interface (6.12.1)
H	vertical flux of enthalpy (commonly called vertical heat flux) (4.7.3)
$H(z)$	vertical dispersion function (10.1.5)
k_a	von Karman constant (Section 5.1.1)
k_1	one-dimensional wavenumber in x direction (8.3.1)
$K(,)$	ensemble covariance function (3.2.8)
$K( )$	stationary covariance function
K_h	eddy heat conductivity (4.7.3)
K_m	eddy viscosity (4.7.8)
$l_i \sim L_i/4$	spatial scale in ith direction (2.3.12–13)
l.i.m.	limit in mean (3.6.8–9)
L	Monin–Obukhov length (6.4.5)
n	normalized frequency fz/V (Section 8.2)
n_i	normalized frequency fz_i/V (Section 8.2)
n_m	value of n at which $fS(f)$ has a maximum (8.4.3)
N	refractive index (8.3.32)
N^2	Brunt–Väisälä frequency squared (2.4.3)
$N(X)$	number of exceedances of X per unit time (13.4.3)
p	pressure (Table 2.1)
p	power in power law for wind profile (6.3.1)
$p( )$	probability density function (3.1.4)
$\mathrm{Pr} = \nu/k$	Prandtl number (Section 2.5)
$P( )$	probability distribution function (3.1.9)
q	specific humidity (Table 2.1)
q	source strength in mass/length · time (10.1.3)
q_*	scaling parameter for specific humidity in Monin–Obukhov scaling (6.10.5)
$Q_{u,v}(\omega)$, Quad(f)	quadrature spectral density (3.7.25)
$R(,)$	ensemble correlation function (3.2.13)
$R( )$	stationary correlation function (4.6.2)
Rb	Bulk Richardson number (6.7.3)
R	gas constant for dry air (287 J kg^{-1} deg^{-1}) (Table 2.1)
Re_t	Reynolds number for turbulence (6.2.15a)

Re	Reynolds number (Section 2.5)
Rf	flux Richardson number (4.4.2)
Ri	gradient Richardson number (4.4.3) (4.4.4)
$R_v(\tau)$	Lagrangian correlation of lateral component (10.4.9)
S_q	Source of q (2.1.3)
$S_\phi(f)$, $S_\phi(k_1)$	spectral densities of ϕ as functions of frequency or wave number in units of ϕ^2 per unit frequency or unit wave number
$S_\phi(n)$	spectral density of ϕ as function of dimensionless frequency in units of ϕ^2
t	time (Table 2.1)
T	temperature (Table 2.1)
T	integral time scale (8.1.1)
T_*	temperature scaling parameter for Monin–Obukhov scaling (6.10.4)
$T(\omega) = \|\hat{W}(\omega)\|^2$	transfer function (13.2.7)
u	velocity component in x direction (also used for $\bar{u}$ in Chapter 6ff) Table (2.1)
U	steady solution (2.3.3)
$U = \bar{u}$	mean wind speed in x direction (4.5.1)
u_*	friction velocity (or surface friction velocity in equilibrium) (Section 6.1)
v	velocity component in y direction (Table 2.1)
$\mathbf{u}, \mathbf{v} = (u, v, w)$	vector velocity (Table 2.1; p. 143)
V	volume (2.2.1)
V	mean wind speed (often used for $\bar{u}$ because it is measured more easily) after (4.5.1)
V_g	geostrophic wind speed
w	velocity component in z direction (Table 2.1)
w_*	scaling velocity in mixed-layer scaling (5.1.13)
$W(\tau)$	response or weighting function (12.2.3)
$\mathbf{x} = (x, y, z)$	spatial coordinates $\mathbf{x} = (x_1, x_2, x_3)$
X, Y, Z	displacements along wind direction (Section 10.4.3.1)
$y(t)$	response variable (12.2.1)
z_0	roughness length (Section 6.2, Tables 6.1, 6.2)
z_i	height of lowest inversion (Section 5.1)

α	horizontal wind direction (7.1.1)
β	ratio of Lagrangian to Eulerian scales (Pasquill's β) (Section 4.6)
γ	lapse rate ($= -\partial T/\partial z$) (4.4.4)
γ_d	dry adiabatic lapse rate, 9.8°C/km (4.3.4)
$\Gamma_{u,v}(\omega)$	coherence (3.7.31) [also Coh(f)]
$\delta(\ )$	Dirac's delta function (3.4.23)
Δx, Δy, Δz	separations of observations (Chapter 9)
ε	rate of dissipation of turbulent energy into heat (4.4.1)
η	dissipation length (8.2.1)
θ	potential temperature (2.1.11); [$\theta \simeq (T_0 + \gamma_d(z - z_0)$] (6.10.1)
$\theta(\omega)$	phase angle (3.7.28)
θ	vertical wind direction (4.1.2)
κ	angular wave number
λ_n	eigenvalues (12.5.9)
$\Lambda_{u,v}(\omega)$	cross spectrum (3.7.23)
μ_n	nth moment $\mu_n = E(\ )^n$
ν	molecular viscosity (8.2.1)
ρ	density (Table 2.1)
σ_ϕ	standard deviation of variable ϕ; ensemble definition (3.2.5), see also (4.1.1)
τ	time lag
τ, $\boldsymbol{\tau}$	stress [often $\tau = \tau(0)$] (6.2.1)
$\phi_{ij}(\kappa)$	spatial spectral density function (3.7.46)
ϕ_n	eigenfunctions (12.5.9)
$\phi_x(\ )$	characteristic function of variable x (3.3.4)
ϕ_i	normalized standard deviations of ith velocity component (7.3.7)
ϕ_h	normalized potential temperature gradient (6.10.5)
ϕ_m	normalized vertical wind shear (5.1.9, Table 6.3)
ϕ_q	normalized vertical gradient of scalar q (7.4.6)
ϕ_T	normalized standard deviation of temperature (Section 7.4.1)
ϕ_ε	normalized dissipation (8.3.4)
$\Phi(\omega)$	energy spectral density (3.7.3)
χ	pollutant concentration (mass per unit volume) (10.1.1)
χ_q	rate of destruction of fluctuations of scalars by molecular action (8.3.14)
χ_T	rate of destruction of temperature fluctuations by molecular heat conduction (4.4.7)

ψ_h	universal function in diabatic surface layer temperature profile (6.10.11)
ψ_m	universal function in diabatic surface layer wind profile (6.5.6) (Table 6.3)
ψ_q	universal function in diabatic surface layer profile of specific humidity (6.10.15)
ψ_ε	normalized dissipation, mixed-layer scaling (8.5.7)
ω	frequency in radians per unit time
Ω	earth's angular velocity
Ω	response frequency (13.2.10–11)

CONTENTS

PART ONE FOUNDATIONS OF TURBULENCE THEORY

PART TWO OBSERVED PROPERTIES OF ATMOSPHERIC TURBULENCE