TURBULENCE IN THE ATMOSPHERE

This book provides a modern introduction to turbulence in the atmosphere and in engineering flows. Based on over 40 years of research and teaching, John Wyngaard's textbook is an excellent introduction to turbulence for advanced students and a reference work for researchers in the atmospheric sciences. Part I introduces the concepts and equations of turbulence. It includes a rigorous introduction to the principal types of numerical modeling of turbulent flows. Part II describes turbulence in the atmospheric boundary layer. Part III covers the foundations of the statistical representation of turbulence and includes illustrative examples of stochastic problems that can be solved analytically. Student exercises are included at the ends of chapters, and worked solutions are available online for use by course instructors. The book is an invaluable introduction to turbulence for advanced students and researchers in academia and industry in the atmospheric sciences and meteorology, as well as related fields in aeronautical, mechanical and environmental engineering, oceanography, applied mathematics, and physics.

John Wyngaard's experience in turbulence research and teaching spans the Air Force Cambridge Research Laboratories, the Wave Propagation Laboratory of the National Oceanographic and Atmospheric Administration (NOAA) in Boulder, the Atmospheric Analysis and Prediction Division of the National Center for Atmospheric Research (NCAR), and the Department of Meteorology at Pennsylvania State University, where he developed a sequence of courses on turbulence. This book is based on those courses. He has published over 100 refereed journal papers covering theoretical, observational, and numerical modeling aspects of engineering and geophysical turbulence.

Cambridge University Press
978-0-521-88769-4 - Turbulence in the Atmosphere
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Frontmatter
More information

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CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore,
São Paulo, Delhi, Dubai, Tokyo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521887694

First published 2010

Printed in the United Kingdom at the University Press, Cambridge

A catalog record for this publication is available from the British Library

Library of Congress Cataloging-in-Publication Data

Wyngaard, John C.
Turbulence in the atmosphere / John C. Wyngaard.
p. cm.
ISBN 978-0-521-88769-4 (Hardback)
1. Atmospheric turbulence. I. Title.
QC880.4.T8W96 2009
551.55–dc22
2009035697

ISBN 978-0-521-88769-4 Hardback

Additional resources for this publication at www.cambridge.org/9780521887694

Contents

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More information

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Preface

I doubt if many students have started out to be a "turbulence person." I suspect it usually just happens, perhaps like meeting the person you marry. I was an engineering graduate student, nibbling at convective heat transfer, when a friend steered me to a turbulence course taught by John Lumley. It was not rollicking fun – we went through Townsend's *The Structure of Turbulent Shear Flow* page by page – but it was a completely new field.

I began to explore the turbulence literature, particularly that by the heavy hitters of theoretical physics and applied mathematics. To my engineering eyes it was impregnable; I would need much more coursework before I could even put it in a context. Today I can understand why those theoretical struggles continue. Phil Thompson, a senior scientist in the early NCAR[†] explained it this way:

> Lots of people have tried to develop a fundamental theory of turbulence. Some very well known people have given up on it. But I just can't give up on it – it's like a beautiful mistress. You know that she treats you badly, she's being ornery, but you just can't stay away from her. So periodically, this question comes up again in my mind, and I keep casting about for some different and simple and natural way of representing the motion of a fluid, and some way of treating the analytical difficulties. And I seem to get a little bit closer sometimes …

When I was finishing my Ph.D. I began looking for a job. Hans Panofsky, whose 1964 book with John steered me toward atmospheric turbulence, kindly gave me a list of four prospects. The most intriguing was the Boundary-Layer Branch of Air Force Cambridge Research Laboratories, as it was then called. Led by the indefatigable Duane Haugen, they were in the final stages of planning a field measurement program on atmospheric surface-layer turbulence. It was as if the job were designed for me. I accepted their $12,822 per year offer.

One year later we carried out the 1968 Kansas experiment, perhaps the most ambitious such field program up to that time. The data analyses engaged us for

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[†] National Center for Atmospheric Research, Boulder, Colorado.

several years. Owen Coté and I, with the plotting and programming assistance of Jack Izumi and Jean O'Donnell, mapped out perhaps the first observational analyses of the conservation equations for stress and scalar flux in a turbulent flow. Chandran Kaimal did his inimitable spectral analyses. Visitor Joost Businger oversaw the analysis of the flux-mean profile relations over the wide range of stability conditions. Henk Tennekes and I found that velocity derivative statistics in the huge Reynolds number Kansas turbulence were off the older charts, but in accord with the newer thinking of the Russian school. Those were heady times.

We returned to the field in 1973, in the very flat farming country of northwestern Minnesota. In collaboration with a British Met Office group we reached deep into the boundary layer with sensors on the tethering cable of a World War II surplus barrage balloon. It stayed up for several weeks, despite the best late-night efforts of rifle-toting cowboys, until it was brought down by a gust front. Part II discusses some of the insights gained from these field programs.

Today's main types of turbulent-flow models – large-eddy simulation and second-order closure (Chapters 5 and 6) – were in their infancy in 1970. I remember discovering with Owen Coté the myriad ways a second-order-closure model could misbehave – negative variances, violations of Schwartz's inequality, … What we thought were obviously better closures gave poorer results. We saw the early hopes of universal second-order closures dashed in buoyancy-dominated flows. We developed a wariness about turbulence modeling. As Ronald Reagan later said, "Trust, but verify."

Anyone who has developed models of the second-moment equations (Chapter 5), discovered how poorly they can behave, and then in fatigue and discouragement wondered how Nature keeps variances positive, can appreciate this story:

> Some years ago, during the hall talk at a break in an NCAR meeting, a prominent senior scientist became impatient with a mathematician's fussing over obscure details of an equation. "Hell," he blurted, "in the atmospheric sciences we don't even know what the equations are."

The applied turbulence field seems different today. Numerical modeling of turbulent flows is a dominant technology used by a second- or even third-generation community. Programmers have ensured that the codes don't misbehave like they used to. Geophysical observations have not kept pace with the model predictions, nor could they have; modeling and observational work have cruelly different time scales. Now less likely to be rooted in personal experience, wariness of modeling seems to be diminishing.

Recently I previewed a video of the EPA Fluid-Modeling Facility before showing it in my class on atmospheric dispersion. The FMF, as it is called, is located in Raleigh, NC, and contains low-speed wind tunnels, a stratified towing tank, and a replica of the Deardorff–Willis convection tank (Chapter 11). The FMF is a world-class facility put together largely by Bill Snyder beginning about 1970.

The video shows visualizations of plume dispersion, wind-tunnel turbulence, and stably stratified flow around obstacles. Two students stopped briefly to watch, and as they left one said to the other, "That was before we had computer modeling."

Fortunately, EPA management recognizes the FMF's strengths and continues its funding for observations central to the testing and improving of dispersion models.

For a generation born into personal computing, numerical modeling is a natural research medium. Models are widely and instantly available, some through vendors, others being in the public domain. But in a time when observational work seems increasingly out of fashion, when a "sixth sense" about the behavior of turbulence is becoming rare, models can be easily misused and misinterpreted. We have no "Modeler General"; the models have no warning labels.

I suspect this lack of wariness about modeling is an experiential issue, not a generational one. I recall attending an AMS-EPA workshop on air-quality modeling in the 1980s. At one point the discussion focused on the performance of the standard Gaussian-plume air-quality model in fair weather, flat terrain, quasi-steady conditions. The question was asked: "How well do the model predictions of ground-level concentration downwind of a point source agree with one-hour measurements?" A crusty old air-quality "consultant," as they are called, who had enjoyed a long, successful practice, didn't hestitate in answering: "Within ten percent." No doubt that was his honest belief, but we now know it was wrong by more than an order of magnitude. The community hadn't yet focused on such considerations.

This book is based on the material in the graduate course in atmospheric turbulence I have taught for nearly 20 years at Penn State. Its four precepts are (1) engineering and geophysical turbulence have much in common; (2) our numerical models of turbulent flows, particularly those in the atmosphere, need effective representations of turbulence; (3) although the "turbulence problem" appears to be as unyielding as ever, we have learned much about *dealing with* turbulence; (4) users of turbulent-flow models should understand their foundations.

There are three self-contained parts. Part I, "A grammar of turbulence," covers the important attributes, concepts, rules, and tools of turbulence – those aspects that are common to all applications fields and are central to turbulence literacy. Done in a constant-density fluid, it begins with an overview of turbulence, including the contrast between its instantaneous and average properties, the averaging process and its convergence, the eddy velocity scale and turbulence spectrum, turbulent vorticity, and the eddy diffusivity. We then average the equations, over space or an ensemble of realizations, and discuss the turbulent fluxes this produces. There is a chapter each on the ensemble-average fluxes and their conservation equations, including their modeling by "second-order closure." A chapter on the space-averaged equations, the basis of large-eddy simulation, demonstrates the spectral energy cascade and explains the physical basis of the Kolmogorov hypotheses about the inertial

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More information

subrange. The final chapter covers the dissipative range, both as hypothesized in 1941 by Kolmogorov and more recently through dissipation-intermittency models, and two-dimensional turbulence as described through the Kolmogorov-like notions of Kraichnan and Batchelor.

Part II covers turbulence in the atmospheric boundary layer (ABL). The first chapter generalizes the equations of Part I to a variable density environment in a standard way, using a background-plus-deviation representation for density, temperature, and pressure. The background state is hydrostatic, buoyancy is handled through the Boussinesq approximation, and a conserved temperature is used that in its ultimate form allows phase change. The four subsequent chapters survey the structure and dynamics of the ABL, emphasizing for a non-meteorological audience those features that make its turbulence different from that in engineering flows. They also cover turbulence in the surface layer, and discuss in depth the physics and the efficacy of the Monin–Obukhov similarity hypothesis for its turbulence structure. There is a chapter on the convective boundary layer, whose turbulence physics and structure have been extensively studied in the field and through large-eddy simulation. The final chapter covers the stable ABL, which has some regimes in which turbulence structure and dynamics have a reasonably simple interpretation.

Part III, "Statistical representation of turbulence," includes a number of important statistical tools and concepts – probability densities and distributions, covariances, autocorrelations, spectra, and local isotropy – that are used in turbulence and other stochastic problems. It has a number of illustrative examples of stochastic problems that can be solved analytically, including the wavenumber-space dynamics of turbulence spectra; relating spectra in the plane to traditional spectra; and the effects of spatial averaging, sensor separation, crosstalk, and probe-induced flow distortion on turbulence measurements.

In the course of writing this book I received valuable input on technical matters from Bob Antonia, Bob Beare, Craig Bohren, Frank Bradley, Peter Bradshaw, Jim Brasseur, Joost Businger, Steve Clifford, Steve Derbyshire, Diego Donzis, Carl Friehe, Steve Hatlee, Reg Hill, Bert Holtslag, Tom Horst, Mark Kelly, Don Lenschow, Charles Meneveau, Chin-Hoh Moeng, Parviz Moin, Ricardo Munoz, Laurent Mydlarski, Bill Neff, Ray Shaw, K. R. Sreenivasan, Peter Sullivan, Dennis Thomson, Chenning Tong, Zellman Warhaft, Jeff Weil, Keith Wilson, P. K. Yeung, and Sergej Zilitinkevich, for which I am most grateful. I'd like to thank Lori Mattina for expertly and patiently crafting the figures, Ned Patton for kindly setting up the LATEX style files for me, and Peter Sullivan again for his generous and sustained assistance with LATEX. I am grateful to the AFCRL group – Duane Haugen, Chandran Kaimal, Owen Coté, Jack Izumi, Jim Newman, Jean O'Donnell, and Don Stevens – for my once-in-a-lifetime experience in the 1968 Kansas experiment. Finally, I thank John Lumley for inspiring my career in turbulence.