ATMOSPHERIC TURBULENCE AND MESOSCALE METEOROLOGY

Bringing together leading researchers, this volume surveys recent developments in the fields of atmospheric turbulence and mesoscale meteorology, with particular emphasis on the areas pioneered by Douglas K. Lilly.

Numerical simulation is an increasingly important tool for improving our understanding of a wide range of atmospheric phenomena. The first part of this book looks at the development of theoretical and computational analyses of atmospheric turbulent flows, and reviews current research advances in this area. Chapters in the second part look at various aspects of mesoscale weather phenomena: from the numerical forecasting of individual thunderstorms to understanding how mountains affect local weather and climate.

Researchers and graduate students will find the book to be an excellent resource summarizing the development of techniques as well as current and future work in the fields of atmospheric turbulence and mesoscale meteorology.

Evgeni Fedorovich specialises in the dynamics of atmospheric boundary layers. He has authored or co-authored numerous articles in meteorology, fluid dynamics, and geophysics. In 1998 he co-edited *Buoyant Convection in Geophysical Flows* (Kluwer) having organised a NATO Advanced Study Institute meeting with the same name.

Richard Rotunno has spent most of the last 25 years at the National Center for Atmospheric Research in Boulder, Colorado, where he has been Senior Scientist since 1989. For his work directed at the understanding needed to make progress in the forecasting of mesoscale weather phenomena he received the Jule G. Charney award of the American Meteorological Society in 2004.

With a background in electrical engineering, Bjorn Stevens has extensively studied the dynamics of shallow cumulus convection. In recognition of his contributions to the field, he was presented with the Clarence Leroy Meisinger award by the American Meteorological Society in 2002.

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Scientific Research Inspired by Doug Lilly

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Preface

Nature is not particularly generous when it comes to producing individuals with both great intellectual and humanitarian qualities. Douglas K. Lilly, or simply Doug, is a rare example of a person who essentially combines these two virtues.

As will become apparent from the scientific articles collected in this volume, Doug has earned an outstanding reputation worldwide for the very high caliber of his contributions to the fields of meteorology and geophysical fluid dynamics. Less evident, but not less striking, is the dignity of his character, his modesty, and his dedication to truth. Of pioneering stock, Doug still embodies the best of the pioneering spirit: vision, individualism, fearlessness, and obliviousness of authority. His fairness of judgements co-existing with his friendliness to colleagues and dedication to students has become almost legendary. Doug has made many friends throughout the years at the various places where he has worked, and is respected and admired by students and prominent scientists alike.

This collective volume, dedicated to Doug on the occasion of his 75th birthday, begins by focusing on Doug the man. His biography, written by K. Kanak, a recent Ph.D. student of Doug, traces his scientific evolution by incorporating recollections of several people, who worked with Doug, beginning with those of J. Smagorinsky, Doug's post-doc advisor. Doug's fundamental work on the numerical simulation of turbulence dates back to his interactions with Smagorinsky and K. Bryan while at the Geophysical Fluid Dynamics Laboratory (GFDL) in the late 1950s and early 1960s. In the latter part of the 1960s, Doug went to the National Center for Atmospheric Research (NCAR), where he continued to develop his interests in numerical simulation in collaboration with J. Deardorff. During that period of his career, Doug began nurturing interest also in observational techniques for measuring atmospheric turbulent flows. D. Lenschow, who worked closely with Doug during those years, reflects upon this interest in his recollection note.

In the early 1980s, Doug left NCAR to become Professor of Meteorology at the University of Oklahoma (OU). While at OU, Doug developed strong ties to the

National Severe Storms Laboratory (NSSL) of the National Oceanic and Atmospheric Administration (NOAA). He directed the OU/NOAA Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) and was a co-founder of OU's Center for the Analysis and Prediction of Storms (CAPS). These various endeavors of Doug are highlighted in the biography through the recollections of P. Lamb, K. Droegemeier, and J. Kimpel, who worked closely with Doug while he was at OU.

The bulk of this book, however, focuses on the impact of Doug's scientific contributions. Individual chapters in Part I: *Atmospheric turbulence* and Part II: *Mesoscale meteorology* represent invited contributions from renowned experts in these two areas, whose careers, either directly or indirectly, were touched by interactions with Doug. Consequently, both the contents of and works cited in each chapter serve as testaments to Doug's scientific contributions. At the same time, the chapter sequence defines a course in atmospheric dynamics on scales ranging from the micro to the meso, which should be of interest to graduate students or beginning scientists who perhaps have never heard of Doug, as well as to seasoned practitioners interested in the latest assessment of advances in the fields of atmospheric turbulence and mesoscale meteorology.

For instance, it should be readily apparent from the *Atmospheric turbulence* chapters that the thread of Doug's ideas is deeply woven into the fabric of modern research on the topic. These chapters serve both to introduce and to reflect upon the birth of an entirely new scientific methodology – the numerical simulation of atmospheric turbulent flows. The birth of this new methodology raises novel questions, such as:

- How does one rationalize simulation?
- How should simulations be optimally constructed, and then used?
- In what ways can simulations be integrated with established methodologies such as experiments, observations, and more traditional theoretical work?

These questions form the subtext of nearly a half-century of research by Doug Lilly. They should continue to interest current and future generations of students, researchers, and practitioners involved in atmospheric turbulence research and its applications.

This idea of Doug that numerical simulation represents a new frontier for explorations of turbulence is eloquently articulated in the overview chapter by J. Wyngaard, wherein he discusses Doug's strategy for numerical simulation, which he calls a bold "three-phase plan of attack." With one exception, the other chapters in Part I (and many chapters in Part II, especially the contribution by J. Klemp and W. Skamarock) help to exemplify implementation of this plan. In particular, the use of Direct Numerical Simulation (DNS) to study fundamental problems in turbulence research, which J. Wyngaard credits with revitalizing the field, is exemplified in the article on two-dimensional and stratified turbulence by J. McWilliams. The continuing efforts to rationalize Large Eddy Simulation (LES), which is the most active area of turbulence research, and the contributions of Doug in this respect are reviewed and extended in the chapter by J. Wyngaard and that by C. Higgins, C. Meneveau, and M. Parlange. As another example of the implementation of Doug's strategy, the chapter by C.-H. Moeng, B. Stevens, and P. Sullivan shows how LES is being used to study basic problems pertaining to cloud-topped mixed layers. The only chapter to deviate from this three-phase strategy is illustrative in that it focuses on the history of a simple theoretical framework for studying a rich and complex geophysical problem: the stratocumulus mixed layer. This framework, known as mixed-layer theory, was developed by Doug and is reviewed in the chapter by D. Randall and W. Schubert.

However, it remains the centerpiece of efforts to use numerical simulation to understand stratocumulus-topped boundary layers. As such, it reminds us that Doug's contributions to an emerging scientific methodology are probably no more than the byproduct of a brilliant scientist searching to understand and explain phenomena.

Introducing the chapters in Part II, it is worth recalling that Doug did his Ph.D. work on buoyant convection in 1959, when mesoscale meteorology had yet to become a common term describing research on phenomena occurring on spatial scales of less than approximately 1000 kilometers and time scales of less than about a day [see Fujita, T. (1963). Analytical mesometeorology: a review. In *Severe Local Storms*, Meteorological Monographs No. 27, **5**, American Meteorological Society, 77–125, for the history of the term "mesometeorology"]. In non-technical terms, mesoscale meteorology is the science of the weather phenomena that are directly experienced by human beings. The examples of such phenomena are thunderstorms, cold fronts, strong local winds, fog and rain, etc. Doug's deep interest in and enthusiasm for these weather phenomena have had such a great influence that it is probably no exaggeration to say that mesoscale meteorology, as we know it today, is largely his creation.

The science of mesoscale meteorology, as developed by Doug Lilly, was based on the pursuit of innovative observational technologies, recognition of the vast potential of computer simulations to aid in the interpretation and forecasting of the small-scale weather systems and, finally, a skilled use of analytical theory. As both scientist and scientific manager, Doug pursued all of these areas with great vigor and, consequently, many of the things we take for granted today, such as computer models of thunderstorms and aircraft measurements of mesoscale air motions, are a direct consequence of his leadership.

In Part II we have included a broad selection of topics, to which Doug has made fundamental contributions. He both pioneered simulations of atmospheric convection through his early work and fostered its later development through to the experimental forecasting of individual thunderstorms. The chapter by J. Klemp and W. Skamarock and that by J. Sun address recent advances in these respective areas. Doug also made fundamental contributions through theory, modeling, and novel use of observations to the understanding of how mountains affect weather and climate; the chapter by R. Smith likewise addresses some of the newer findings in that field. In mesoscale meteorology, Doug's curiosity knew no bound, and he tried his hand at just about everything in this area at one time or another. The chapter by K. Emanuel tells the interesting tale of Doug Lilly's influence on Emanuel's tropical cyclone research. Finally, Doug had the knack of recognizing a problem before the rest of us knew it was a problem. Such was the case with explaining the atmospheric energy spectra over a very large range of scales. The chapter by K. Gage chronicles the evolution of this field, in which Doug's original contribution continues to play an important role.

As John Wyngaard stated in his response to the invitation to contribute to the book, "Doug is not just another excellent scientist; he has changed the face of modern small-scale meteorology." Therefore, we expect that this book will be of significant interest to the meteorological community all over the world. Furthermore, since the book includes a variety of papers on fundamental aspects of turbulence and convection, we also anticipate interest from engineers, fluid dynamicists, oceanographers, and environmental scientists. We hope that the audience for the book will include researchers, university instructors, and first- or second-year graduate students in the fields of atmospheric dynamics, turbulence modeling and simulation, boundary-layer meteorology, air-pollution meteorology, convective storms, mountain meteorology, ocean dynamics, and computational fluid dynamics. Some operational meteorologists may be interested in reading the chapters on downslope windstorms and convective storm modeling. The book may also be used as a supplementary textbook for graduate courses in atmospheric turbulence and mesoscale meteorology, as well as a research compendium in these two areas.

The editors of this book gratefully acknowledge the assistance of Katharine Kanak and Bob Conzemius in editing the chapters and preparing figures for the book, and the help of Mark Laufersweiler in managing electronic versions of the book components. They are indebted to Katharine Kanak for the compilation of the Appendices.