

Ideal and Real Atmospheric Boundary Layers



Mathias W. Rotach
Albert A.M. Holtslag



IDEAL AND REAL ATMOSPHERIC BOUNDARY LAYERS

MATHIAS W. ROTACH

Department of Atmospheric and Cryospheric Sciences, University of Innsbruck, Innsbruck, Austria

ALBERT A.M. HOLTSLAG

Wageningen University, Wageningen, Netherlands



ELSEVIER



ACADEMIC PRESS

An imprint of Elsevier

Academic Press is an imprint of Elsevier
125 London Wall, London EC2Y 5AS, United Kingdom
525 B Street, Suite 1650, San Diego, CA 92101, United States
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

Copyright © 2025 Elsevier Inc. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

Publisher's note: Elsevier takes a neutral position with respect to territorial disputes or jurisdictional claims in its published content, including in maps and institutional affiliations.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: www.elsevier.com/permissions.

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

ISBN 978-0-323-95957-5

For information on all Academic Press publications
visit our website at <http://www.elsevier.com/books-and-journals>

Publisher: Candice Janco
Acquisitions Editor: Jennette McClain
Editorial Project Manager: Teddy A Lewis
Production Project Manager: Paul Prasad Chandramohan
Cover Designer: Greg Harris

Typeset by STRAIVE, India



Contents

Preface	ix	6.3 Practical approach	62
List of symbols and acronyms	xi	6.4 Monin-Obukhov similarity theory for the surface layer	64
1. Introduction		6.5 Scaling regimes	67
1.1 The Atmospheric Boundary Layer	1	References	75
1.2 Phenomenological overview	4	7. Turbulence spectra	
1.3 Surface energy budget and the daily cycle	10	7.1 Introduction to spectral analysis	77
References	12	7.2 Energy cascade	80
		7.3 Kolmogorov hypotheses	81
		7.4 Spectra and co-spectra	82
		7.5 Application of spectral information	89
		References	90
		8. Observing and modeling atmospheric boundary layers	
		8.1 Measurements, post processing and useful diagnostics	91
		8.2 Modeling and parameterization	103
		References	108
		9. The neutral boundary layer	
		9.1 The surface layer	114
		9.2 Ekman boundary layer wind profile and depth	115
		9.3 Boundary layer resistance law	116
		9.4 Alternative boundary layer wind profile	118
		9.5 Turbulence in neutral boundary layers	119
		References	121
		10. The convective boundary layer	
		10.1 Introduction	123
		10.2 Turbulent mixing of heat and momentum	125
		10.3 Modeling convective boundary layers	128
		10.4 Land-atmosphere interactions and formation of boundary layer clouds	130
		10.5 Surface layer wind gradients and profiles	134
		References	136
		11. The stable boundary layer	
		11.1 Introduction	139
		11.2 The wind profile	139
		11.3 The temperature profile	142
		11.4 Modeling stable boundary layers	144
		11.5 Turbulence in stable boundary layers	145
		11.6 Stable boundary layer depth	147

I

Ideal atmospheric boundary layers

2. A brief introduction to atmospheric turbulence

2.1 The turbulence syndrome	17
2.2 The Reynolds number	19
2.3 Laminar vs. turbulent flows	20
2.4 Tools to describe turbulent atmospheric flows	24
References	25

3. Statistical treatment of turbulence

3.1 Averaging, stationarity and homogeneity	27
3.2 Taylor hypothesis	31
3.3 Reynolds decomposition	32
3.4 Covariances and their physical meaning	32
3.5 Other turbulence variables	36
References	38

4. Conservation equations for turbulent flows

4.1 Conservation equations for mean variables in a turbulent flow	39
4.2 Conservation equations for higher order moments	44
4.3 The closure problem	46
References	48

5. Turbulent kinetic energy and dynamical stability

5.1 TKE-equation	49
5.2 Dynamic stability measures	54
5.3 Turbulence potential energy	57
References	59

6. Similarity theory

6.1 Motivation	61
6.2 Scaling and similarity	61

11.7 Small-scale processes in the SBL and their interaction with SBL dynamics	148
References	149

II

Real atmospheric boundary layers

12. Non-ideal boundary layers

12.1 Overview	155
12.2 Non-horizontally homogeneous surfaces	157
12.3 Large roughness elements—Very rough surfaces	159
12.4 Influence of orography	160
References	163

13. Surface inhomogeneity and heterogeneity effects

13.1 Overview	165
13.2 Simple two-surface systems	166
13.3 Heterogeneous surfaces	173
13.4 Assessing surface influence	177
References	182

14. Flow over rough surfaces

14.1 General considerations	185
14.2 Mean profiles	191
14.3 Scaling in the roughness sublayer above the canopy	201
References	204

15. Exchange processes within vegetated and urban canopies

15.1 Coherent structures	207
--------------------------	-----

15.2 Mixing layer analogy	212
15.3 A unified roughness sublayer theory	215
15.4 Canopy impacts on urban dispersion modeling	222
References	226

16. Boundary layers over orography

16.1 Introduction to mountain boundary layers	229
16.2 Idealized flow regimes: Flows on sloped surfaces	232
16.3 Idealized flow regimes: Valley and slope wind circulations	236
16.4 Idealized flow regimes: Flow over Gentle Hills	240
References	252

17. Characteristics of real terrain mountain boundary layers

17.1 Horizontal inhomogeneity of the MoBL	255
17.2 Vertical structure of the MoBL	262
17.3 Turbulence structure of the MoBL	269
17.4 Similarity in the MoBL	273
17.5 Exchange to the free troposphere	280
References	284

18. Observing and modeling real atmospheric boundary layers

18.1 Observational challenges in complex terrain	289
18.2 Challenges for numerical modeling over complex terrain	299
18.3 Synthesis	308
References	309

Index

315