

Atmospheric Dynamics

In his book, John Green presents a unique personal insight into the fundamentals of fluid mechanics and atmospheric dynamics. Generations of students have benefited from his lectures, and this book, many years in the making, is the result of his wide teaching and research experience.

The theory of fluid flow has developed to such an extent that very complex mathematics and models are currently used to describe it, but many of the fundamental results follow from relatively simple considerations: these classic principles are derived here in a novel, distinctive, and at times even idiosyncratic, way. In order to resist blindly following the ever more complex computer simulations of atmospheric dynamics, the author advocates that students need to keep in touch with these fundamental derivations and thought processes. These self-same lower level derivations can then often be useful in developing strategies for creation of more complex systems.

John Green's book is an introduction to fluid mechanics in the atmosphere for students and researchers that are already familiar with the subject, but who wish to extend their knowledge and philosophy beyond the currently popular development of conventional undergraduate instruction.

JOHN GREEN graduated in mathematics from Imperial College, London, where he also received a PhD from the Meteorology Department, and went on to become Reader in Meteorology. He is now a lecturer in fluid dynamics and mathematical modelling of natural processes at the School of Environmental Sciences, University of East Anglia. He has published extensively, mainly in the *Royal Meteorological Society Quarterly Journal* and the popular journal *Weather*, and has been awarded the Buchan prize of the Royal Meteorological Society for work on baroclinic instability and thunderstorms.

Cambridge Atmospheric and Space Science Series

Editors

Alexander J. Dessler
John T. Houghton
Michael J. Rycroft

Titles in print in this series

M. H. Rees
Physics and chemistry of the upper atmosphere

Roger Daley
Atmosphere data analysis

Ya. L. Al'pert
Space plasma, Volumes 1 and 2

J. R. Garratt
The atmospheric boundary layer

J. K. Hargreaves
The solar-terrestrial environment

Sergei Sazhin
Whistler-mode waves in a hot plasma

S. Peter Gary
Theory of space plasma microinstabilities

Martin Walt
Introduction to geomagnetically trapped radiation

Tamas I. Gombosi
Gas kinetic theory

Boris A. Kagan
Ocean-atmosphere interaction and climate modelling

Ian N. James
Introduction to circulating atmospheres

J. C. King and J. Turner
Antarctic meteorology and climatology

J. F. Lemaire and K. I. Gringauz
The Earth's plasmasphere

Daniel Hastings and Henry Garrett
Spacecraft-environment interactions

Thomas E. Cravens
Physics of solar system plasmas

John Green
Atmospheric dynamics

Atmospheric Dynamics

John Green



Cambridge University Press
0521616964 - Atmospheric Dynamics
John Green
Frontmatter
[More information](#)

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK
40 West 20th Street, New York NY 10011-4211, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain
Dock House, The Waterfront, Cape Town 8001, South Africa

<http://www.cambridge.org>

© Cambridge University Press 1999

This book is in copyright. Subject to statutory exception
and to the provisions of relevant collective licensing agreements,
no reproduction of any part may take place without
the written permission of Cambridge University Press.

First published 1999
First paperback edition 2004

Typeset in Times 10.25/13.5pt, in 3B2 [κw]

A catalogue record for this book is available from the British Library

Library of Congress Cataloguing-in-Publication Data

Green, John (John Sydney Adcock), 1934–
Atmospheric dynamics / John Green.
p. cm. – (Cambridge atmospheric and space science series)
Includes index.
ISBN 0 521 24975 9 hardback
1. Dynamic meteorology. 2. Atmospheric physics. 3. Fluid
mechanics. I. Title. II. Series.
QC860.G66 1999
551.5' 15–dc21 97–43007 CIP

ISBN 0 521 24975 9 hardback
ISBN 0 521 61696 4 paperback

Contents

Introduction 1

Chapter 1 Description of atmospheric motion systems 3

- 1.1 Introduction 3
- 1.2 Spectrum of motion 4
- 1.3 How isolated phenomena appear in wavenumber-space 7
- 1.4 Repeated phenomena 9
- 1.5 Contribution of phenomena to the global kinetic energy spectrum 10
- 1.6 What do we learn? 11
- 1.7 Good and bad descriptions of phenomena 12

Chapter 2 Notation 18

- 2.1 What we mean by notation 18
- 2.2 The substantial derivative 18
- 2.3 The ordinary derivative 20
- 2.4 Remaining confusion 20
- 2.5 The hydrostatic equation 21
- 2.6 Pressure as vertical coordinate 22
- 2.7 Other coordinates 24
- 2.8 General transformation of coordinates 25

Chapter 3 Fundamental equations 26

- 3.1 Momentum 26
- 3.2 Rotating axes 28
- 3.3 Motion independent of longitude 29
- 3.4 Continuity of mass 31
- 3.5 Continuity of energy 32
- 3.6 Dry adiabatic 33
- 3.7 Wet adiabatic 34
- 3.8 Thermodynamic processes 35
- 3.9 Energetics 36
- 3.10 Completeness 37
- 3.11 Vorticity 38
- 3.12 The terms in the vorticity equation 39
- 3.13 Circulation 40
- 3.14 The shallow atmosphere 41
- 3.15 Some other forms of the vorticity equation 42

Chapter 4 Nearly horizontal atmosphere 44

- 4.1 Nature of approximation 44
- 4.2 Nearly horizontal atmosphere analysed 45
- 4.3 The linearised equations 46
- 4.4 Boundary conditions 50
- 4.5 Application to the real atmosphere 51
- 4.6 What do we expect to see? 53
- 4.7 Simplified solutions 53
- 4.8 Elastic waves eliminated 54
- 4.9 Compressible-Boussinesq 55
- 4.10 Hydrostatic approximation alone 56
- 4.11 Quasi-geostrophic motion and Rossby waves 57

Chapter 5 Gravity waves 63

- 5.1 More realistic gravity waves 63
- 5.2 Adiabatic perturbation of steady flow 64
- 5.3 Refraction and reflection 65
- 5.4 Propagation of energy 67
- 5.5 Gravity waves generated by stationary flow over an obstacle 69
- 5.6 Gravity waves generated by an isolated obstacle 72
- 5.7 Trapped waves (lids lead to resonance) 74

Chapter 6 Shearing instability 76

- 6.1 Helmholtz instability 76
- 6.2 Helmholtz waves of finite amplitude 78
- 6.3 Short waves and viscosity 82
- 6.4 Short waves; distributed shear 83
- 6.5 Short waves and stratification 85
- 6.6 Energetics of sheared stratified overturning 86
- 6.7 Some generalities on shearing instability 87
- 6.8 Stratification outside the shear zone 87
- 6.9 Shear with gravitationally unstable stratification 90
- 6.10 Turbulence near the ground 91

Chapter 7 Vertical convection 93

- 7.1 Hydrostatics 93
- 7.2 Effect of molecular diffusivity 94
- 7.3 Really-shallow convection 97
- 7.4 Convection in shear 97
- 7.5 A possible linear selection process 98
- 7.6 Steady convective overturning 99
- 7.7 Updraught slope 101
- 7.8 Real convection 102

Chapter 8 Mesoscale motion 104

- 8.1 Definition of mesoscale 104
- 8.2 Above the logarithmic layer 105
- 8.3 The Taylor–Ekman layer 106
- 8.4 Communication with the free atmosphere 107
- 8.5 Two-dimensional analysis 109
- 8.6 The cold slab 109
- 8.7 Slow disturbance about a state of no motion 111
- 8.8 Continually balanced motion 113
- 8.9 Evolution of the mean flow 114
- 8.10 More general forcing 115

Chapter 9 Motion of large scale 117

- 9.1 Introduction 117
- 9.2 Scale analysis 117
- 9.3 Simplified equations 119

- 9.4 Potential vorticity 121
- 9.5 The parcel theory of baroclinic instability 122
- 9.6 Simplest baroclinic wave 123
- 9.7 Sloping boundaries 126
- 9.8 The slantwise nature of the convection 126
- 9.9 More general stability problems 127
- 9.10 Short waves 128
- 9.11 Integral constraints 131
- 9.12 Another integral relation 132
- 9.13 Completeness and the complex plane 133

Chapter 10 The forecast problem 134

- 10.1 Perturbations of inconstant shape: the missing baroclinic wave 134
- 10.2 A complete set of solutions 136
- 10.3 A complete solution 137
- 10.4 Rate of amplification of the inconstant wave 139
- 10.5 General baroclinic waves with two lids 140
- 10.6 Predictability 142

Chapter 11 Motion in a barotropic atmosphere 144

- 11.1 The barotropic quasi-geostrophic vorticity equation 144
- 11.2 Stationary waves 145
- 11.3 Lids lead to resonance 145
- 11.4 Surface friction 146
- 11.5 Friction at an upper lid 147
- 11.6 Very deep atmosphere 147
- 11.7 Upward propagation of energy 148
- 11.8 Propagation in the real atmosphere 151
- 11.9 Lateral dispersion 152
- 11.10 Longitudinal horizontal dispersion 153
- 11.11 Evolution of wavelike packets 157
- 11.12 Dispersion and dissipation 157

Chapter 12 Modelling 159

- 12.1 Philosophy 159
- 12.2 Simulation 159
- 12.3 Academic modelling 160
- 12.4 Mean planetary temperature 161

Contents

ix

- 12.5 Ice–albedo feedback 161
- 12.6 Two-dimensional ice–albedo feedback 163
- 12.7 Strategy in the use of numerical models 165
- 12.8 Physics and numerical gridpoint models 165
- 12.9 Linear computational instability 167
- 12.10 Non-linear computational instability 169

Chapter 13 Models 172

- 13.1 Types of models 172
- 13.2 Models with two levels 172
- 13.3 Two layers 176
- 13.4 Two parameters 178
- 13.5 Layer aspect of models 179
- 13.6 Spectral models 179
- 13.7 A simple spectral model 180
- 13.8 Some non-linear solutions 182
- 13.9 Non-linear baroclinic wave with friction 184
- 13.10 What do we learn from such exercises? 185

Chapter 14 Transport and mixing 186

- 14.1 Transfer 186
- 14.2 Mixing 187
- 14.3 Unresolved transport is not always mixing 188
- 14.4 Transfer of energy 189
- 14.5 Transfer of momentum 191
- 14.6 Chemicals 192
- 14.7 Diffusion and shear 192
- 14.8 Diffusion and deformation 194

Chapter 15 General circulation 196

- 15.1 Definition of general circulation 196
- 15.2 Zonal mean observed 197
- 15.3 Zonal mean dissected; thermodynamics 198
- 15.4 Zonal mean dissected; zonal component of momentum 200
- 15.5 Zonal mean dissected; meridional component of momentum 201
- 15.6 Horizontal transfer of momentum 202
- 15.7 A model of the general circulation; parameterisation 203
- 15.8 Some simple models of the general circulation 205

15.9	Stationary waves	207
15.10	More general transfer	208
	<i>Appendix</i>	211
	<i>Index</i>	212