

Cambridge Atmospheric and Space Science Series



# Atmospheric Dynamics

John Green

D III 265

DK 551.511.3

# Atmospheric Dynamics

John Green

33214067 INSTITUT  
FÜR METEOROLOGIE U. KLIMATOLOGIE  
UNIVERSITÄT HANNOVER  
HERKENHAUSER STR. 2 - 30419 HANNOVER



**CAMBRIDGE**  
UNIVERSITY PRESS

# 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

- 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