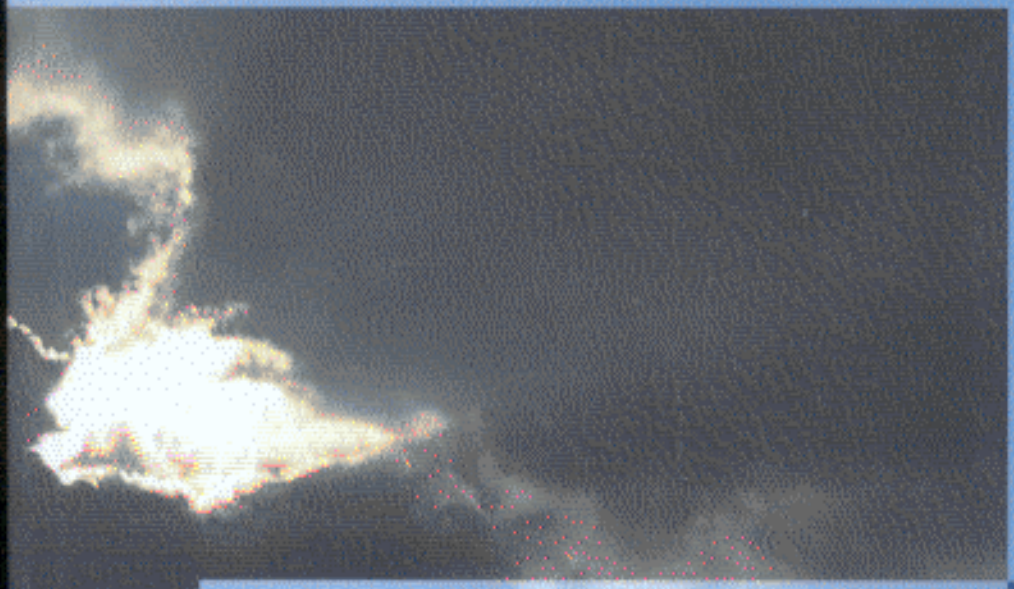

An Introduction to Atmospheric Physics

David G. Andrews

CAMBRIDGE

Contents

Preface ix

1 Introduction 1

1.1 The atmosphere as a physical system 1
1.2 Atmospheric models 4
1.3 Two simple atmospheric models 5
1.3.1 A simple radiative model 5
1.3.2 A simple model of the greenhouse effect 6
1.3.3 Global warming 8
1.4 Some atmospheric observations 9
1.4.1 The mean temperature and wind fields 9
1.4.2 Gravity waves 13
1.4.3 Rossby waves 14
1.4.4 Ozone 16
1.5 Weather and climate 18
References 19

2 Atmospheric thermodynamics 21

2.1 The ideal gas law 21
2.2 Atmospheric composition 22
2.3 Hydrostatic balance 24
2.4 Entropy and potential temperature 27
2.5 Parcel concepts 29
2.6 The available potential energy 33
2.7 Moisture in the atmosphere 35
2.8 The saturated adiabatic lapse rate 40
2.9 The tephigram 43
2.10 Cloud formation 45
References 50
Problems 51

3 Atmospheric radiation 55

3.1 Basic physical concepts 56
3.1.1 The Planck function 57
3.1.2 Local thermodynamic equilibrium 60
3.2 The radiative-transfer equation 61
3.2.1 Radiometric quantities 61
3.2.2 Extinction and emission 63
3.2.3 The diffuse approximation 66
3.3 Basic spectroscopy of molecules 67
3.3.1 Vibrational and rotational states 67
3.3.2 Line shapes 70
3.4 Transmittance 73
3.5 Absorption by atmospheric gases 75
3.5.1 The solar spectrum 75
3.5.2 Infra-red absorption 76
3.5.3 Ultra-violet absorption 77
3.6 Heating rates 79
3.6.1 Basic ideas 79
3.6.2 Short-wave heating 80
3.6.3 Long-wave heating and cooling 82
3.6.4 Net radiative-heating rates 83
3.7 The greenhouse effect revisited 85
3.8 A simple model of scattering 88
References 90
Problems 90

4 Basic fluid dynamics 97

4.1 Mass conservation 98
4.2 The material derivative 99
4.3 An alternative form of the continuity equation 101
4.4 The equation of state for the atmosphere 103
4.5 The Navier–Stokes equation 103
4.6 Rotating frames of reference 105
4.7 Equations of motion in coordinate form 108
4.7.1 Spherical coordinates 108
4.7.2 Approximations to the spherical equations 109
4.7.3 Tangent-plane geometry 110
4.8 Geostrophic and hydrostatic approximations 111
4.8.1 The thermal windshear equations 113
4.8.2 A circular vortex: gradient–wind balance 114
4.9 Pressure coordinates and geopotential 115
4.10 The thermodynamic energy equation 117
References 118
Problems 118

5 Further atmospheric fluid dynamics 123

5.1 Vorticity and potential vorticity 123
5.2 The Boussinesq approximation 126
5.2.1 Linearised equations and energetics 129
5.3 Quasi-geostrophic motion 130
5.4 Gravity waves 133
5.5 Rossby waves 137
5.6 Boundary layers 141
5.6.1 General considerations 141
5.6.2 The laminar Ekman layer 144
5.7 Instability 146
5.7.1 Baroclinic instability 147
5.7.2 Barotropic instability 151
References 152
Problems 153

6 Stratospheric chemistry 157

6.1 Thermodynamics of chemical reactions 157
6.2 Chemical kinetics 159
6.3 Bimolecular reactions 161
6.4 Photodissociation 164
6.5 Stratospheric ozone 165
6.5.1 Chapman chemistry 165
6.5.2 Catalytic cycles 167
6.6 The transport of chemicals 167
6.7 The Antarctic ozone hole 171
References 174
Problems 174

7 Atmospheric remote sounding 177

7.1 Atmospheric observations 177
7.2 Atmospheric remote sounding from space 178
7.2.1 Thermal emission measurements 179
7.2.2 Backscatter measurements 186
7.3 Atmospheric remote sounding from the ground 188
7.3.1 The Dobson ozone spectrophotometer 188
7.3.2 Radars 190
7.3.3 Lidars 195
References 196
Problems 197

8 Atmospheric modelling 203

8.1 The hierarchy of models 203
8.2 Numerical methods 205
8.3 Uses of complex numerical models 207

8.4 Laboratory models 209
8.5 Final remarks 211
8.5.1 The height of the tropopause 211
8.5.2 The middle-atmosphere temperature field 212
8.5.3 The Antarctic ozone hole 212
References 213

Appendix A Useful physical constants 215

Appendix B Derivation of the equations of motion in spherical coordinates 217

Appendix C Solutions and hints for selected problems 219

Bibliography 223
Index 227