Fundamentals of Physics and Chemistry of the Atmosphere

Guido Visconti

with CD-ROM

Springer

Guido Visconti

Fundamentals of Physics and Chemistry of the Atmosphere

With 272 Figures and 14 Tables

DI 40
551.510 ; 551.510.41
551.511
551.521.1 , 551.521.14

341/4135 INSTITUT
FÜR METEOROLOGIE U. KLIMATOLOGIE
UNIVERSITÄT HANNOVER
HERRENHÄUSER STR. 2 · 30419 HANNOVER

Springer

Contents

1 Introduction 1

1.1 The Essential Information 1
1.2 Thermal Equilibrium 6
1.2.1 The Radiative Time Constant 9
1.3 Thermal Structure and Atmospheric Dynamics 11
1.3.1 Slowly Rotating Planets 12
1.3.2 Fast Rotating Planets 13
1.4 Conclusions 16

2 Thermodynamics of the Atmosphere 19

2.1 Simple Laws 19
2.1.1 The Scale Height 20
2.1.2 The Potential Temperature 21
2.1.3 Static Stability 22
2.2 The Thermodynamics of Water Vapor 23
2.2.1 The Equation of Clausius-Clapeyron 23
2.3 Some Effects of Water Vapor 24
2.3.1 Tephigram or Thermodynamic Diagram 27
2.3.2 The Conditional Convective Instability 30
2.4 The Distribution of Water Vapor on the Planets 32
2.4.1 Was the Atmosphere Drier During the Ice Age? 36

3 Radiation: The First Steps 39

3.1 The Definition of Radiometric Variables 39
3.2 Solar Radiation 40
3.3 Scattering and Absorption of Solar Radiation 45
3.3.1 Rayleigh Scattering 45
3.3.2 The Absorption of Solar Radiation 49
3.4 Infrared Radiation 52
3.4.1 The Equation of Radiative Transfer 54
3.4.2 The Radiative – Convective Atmosphere 57
3.4.3 The Runaway Greenhouse 59

4 Origin and Evolution of the Atmospheres 63

4.1 The Relevant Data 63
4.2 An Inventory of the Volatile Elements 65
4.3 A Simple Model for the Nebula 67
4.4 The Chemical Composition of the Planets 70
4.5 The Escape Mechanisms 73
4.5.1 The Jeans Escape 74
4.5.2 The Diffusive Transport in the Atmosphere 77
4.5.3 The Hydrodynamic Escape 82
4.6 The Steam Atmosphere 84

5 The First Laws of Motion 91

5.1 Scales and Orders of Magnitude 91
5.2 The Equations We Absolutely Need 93
5.2.1 The Total Derivative 93
5.2.2 The Continuity Equation 95
5.2.3 Pressure Forces 97
5.2.4 Friction Forces 97
5.2.5 The Coriolis Acceleration 99
5.2.6 The Equations of Motion in an Inertial System 101
5.3 Vorticity and Circulation 103
5.3.1 Some Properties of Vorticity and Circulation 105
5.3.2 The Sea Breeze 108
5.3.3 Some Other Local Winds 109

6 A Few Simple Applications 113

6.1 The Isobaric Coordinate System 113
6.1.1 The Continuity Equation in Isobaric Coordinates 115
6.2 The Geostrophic Motion 115
6.2.1 The Geostrophic Streamfunction 119
6.2.2 The Quasi-Geostrophy: The Isallobaric Wind 120
6.3 The Thermal Wind 122
6.3.1 Thermal Wind and Vorticity 124
6.3.2 A Few More Things About Geostrophic Wind 128
6.4 The Natural Coordinate System 130

7 The Atmospheric Motions 135

7.1 The Rossby Waves 135
7.2 The Vorticity Equation 140

7.3 The Thermodynamic Equation 145
7.4 The Isentropic Coordinate System 147
7.4.1 The Vorticity Equation in Isentropic Coordinates 150
7.5 The Ertel Potential Vorticity 151
7.5.1 The Application of the Potential Vorticity 153
7.5.2 Ozone and Vorticity 155
7.5.3 More on Rossby Waves 156
7.6 The Non-stationary Solutions 158
7.6.1 Numerical Solutions of a Flow Above an Obstacle: The Stationary Case 159
7.6.2 Numerical Solutions of a Flow Above an Obstacle: the Non-stationary Case 162

8 The Planetary Boundary layer 165

8.1 Turbulence and Diffusion 165
8.2 Turbulent Friction 168
8.2.1 The Mixing Length 170
8.3 The Surface Layer 172
8.4 The Ekman Layer 175
8.5 The Secondary Circulation 179
8.5.1 Spin-Down in a Teacup 181
8.6 The Transfer of Sensible and Latent Heat 183
8.6.1 The Fluxes in Presence of Vegetation 185
8.7 Turbulent Diffusion from Discrete Sources 187
8.7.1 The Characteristics of Smoke Plumes 187
8.7.2 The Gaussian Plume 190

9 Aerosols and Clouds 193

9.1 Sources of Atmospheric Aerosols 193
9.2 The Size Distribution of Atmospheric Aerosols 195
9.3 Nucleation and Growth 197
9.3.1 Nucleation from Water Vapor Condensation 198
9.3.2 The Growth by Condensation 200
9.3.3 Droplet Growth by Collision and Coalescence 202
9.3.4 The Statistical Growth 204
9.4 Formation and Growth of Ice Crystals 205
9.5 A Few Things About Radar 210
9.6 Stratospheric Aerosols 214
9.6.1 The Sulfate Aerosol layer 214
9.6.2 Polar Stratospheric Clouds (PSC) 216

10 Waves in the Atmosphere 219

10.1 Some Properties of the Waves 219
10.2 Gravity Waves in Shallow Water 221
10.3 Orographic Waves 223
10.4 Internal Gravity Waves 226
10.5 Three Dimensional Rossby Waves 229
10.6 The Physics of Gravity Waves 232
10.6.1 The Equation of Quasi Geostrophic Potential Vorticity 232
10.6.2 The Eliassen-Palm Flux 234
10.6.3 Energetics of Gravity Waves 236
10.7 Breaking, Saturation and Turbulence in the Upper Atmosphere 238

11 The Data on the Atmospheric Circulation 245

11.1 The General Features 245
11.2 The Energy Budget of the Atmosphere 248
11.2.1 Forms of Energy 251
11.2.2 Decomposition of Transport 254
11.2.3 The Details of the Energy Budget 255
11.3 The Mean Zonal Circulation 257

12 Theories on the General Circulation of the Atmosphere 263

12.1 The Equatorial Circulation 263
12.1.1 Gill's Symmetric Circulation 263
12.1.2 The Non-linear Symmetric Circulation 267
12.1.3 The Inviscid Symmetric Circulation 270
12.2 The General Circulation: A Reductionist Approach 274
12.2.1 The Inertial Instability 276
12.2.2 A Comparison Among the Planets 277
12.3 The Middle Latitude Circulation 278
12.3.1 The Baroclinic Instability: Qualitative Treatment 279
12.3.2 The Baroclinic Instability: The Eady Problem 281
12.3.3 The Baroclinic Instability: The Charney Problem 286
12.3.4 The Baroclinic Instability: Two Levels Model 287
12.4 Energetics of the Baroclinic Waves 292
12.4.1 Energy in the Two Levels Model 295
12.4.2 The Parameterization of Transport 297

13 Radiation for Different Uses 301

13.1 Parameterization of Gaseous Absorption 301
13.1.1 The Ozone Absorption 302
13.1.2 The Water Vapor Absorption 304
13.2 The Interaction of Solar Radiation with Particulates in the Atmosphere ... 307
13.2.1 Optical Properties of the Particles 309
13.2.2 Phase Functions and Mie Scattering 315
13.3 Radiative Transfer in the Presence of Scattering 316
13.3.1 A Few Simple Applications of the δ-Eddington Approximation 320
13.4 The Transfer of Infrared Radiation 323
13.4.1 The Formal Solution 323
13.5 Molecular Spectra 324
13.5.1 Spectral Line Shape 326
13.6 Models for the Line Absorption 328
13.6.1 A Formulation of the Infrared Flux 330
13.6.2 The Band Absorptivities According to Cess and Ramanathan 331
13.7 δ-Eddington in the Infrared 333

14 Simple Climate Models 335

14.1 Energy Budget 335
14.2 Zero Dimensional Models and Feedback 336
14.3 One Dimensional Energy Balance Climate Models 341
14.3.1 The North Model 342
14.3.2 The Stability of the One Dimensional Model 346
14.3.3 The Sellers Model 348
14.4 The radiative - convective models 350
14.4.1 The Radiative-Convective Models and the Greenhouse Effect 355
14.4.2 Can We Put Together the Radiative-Convective and Energy Balance Climate Models? 357

15 The Application of the Simple Climate Models 359

15.1 The Climate System 359
15.2 The Solar Radiation and the Orbital Parameters 363
15.3 Some Experimental Data on the Ice Ages 366
15.4 The 100 kyear Cycle and the Lithosphere – Atmosphere Coupling 369
15.5 Stochastic Resonance 374
15.6 The Global Warming: A Simple Exercise 378
15.6.1 The Near Future Climate of the Earth as a Problem of Electrical Engineering 378

15.7 The General Circulation Models 384
15.7.1 The Model Equations 385
15.7.2 The Performances of the GCMs 387

16 Chemistry of the Troposphere 393

16.1 Introduction 393
16.2 A Chemistry Refresher 394
16.3 The Minor Gas Inventory 397
16.3.1 Methane 399
16.3.2 Nitrous Oxide 399
16.3.3 Atmospheric Chlorine 400
16.4 The Biogeochemical Cycle for Carbon 403
16.4.1 Carbonate/CO_2 System: A Bit of Marine Chemistry 405
16.4.2 How Long Will the Biosphere Survive? 410
16.5 Chemistry of the Troposphere 414
16.5.1 Methane Oxidation 416
16.5.2 The Chemistry of Urban Air 418
16.5.3 The Atmospheric Sulfur Cycle 422
16.6. Modes of a Chemical System 424
16.7 Transport of Chemical Species in the Troposphere 427

17 Dynamics of the Middle Atmosphere 431

17.1 Thermal Structure of the Stratosphere 431
17.2 The Eulerian Mean Circulation 433
17.2.1 The Transformed Eulerian Mean 435
17.2.2 An Attempt to Understand the Origin of the Residual Circulation ... 437
17.2.3 The Sudden Stratospheric Warming 438
17.3 Tracers Transport in the Stratosphere 440
17.3.1 The Two-Dimensional Diffusion Coefficients 442
17.3.2 Self Consistent Transport in Two Dimensions 445
17.3.3 Troposphere–Stratosphere Exchange 447
17.3.4 Eddies and the Troposphere–Stratosphere Flux 449
17.4 Transport in Isentropic Coordinates 452
17.4.1 Stratospheric Dynamics and Ertel potential vorticity 453
17.4.2 The Slope of the Tracers 455
17.4.3 The Tracer Correlation: Age of Air and Transport 458
17.4.4 The Conservative Coordinates 463

18 Stratospheric Chemistry 469

18.1 The Ozone Distribution 470

18.2 The Homogeneous Ozone Chemistry 472
18.2.1 The Catalytic Cycles in the Gaseous Phase 474
18.2.2 The Odd Hydrogen Catalytic Cycle 475
18.2.3 The Odd Nitrogen Catalytic Cycle 477
18.2.4 The Bromine and Chlorine Catalytic Cycles 478
18.2.5 The Effects of the Catalytic Cycles 480
18.3 Heterogeneous Chemistry 483
18.4 The Perturbations to the Ozone Layer 486
18.4.1 The Global Ozone Trend 488
18.4.2 Natural and Anthropogenic Perturbations: Volcanic Eruptions 491
18.4.3 Natural and Anthropogenic Perturbations: The Effect of Aviation 497
18.5 Polar Ozone 500
18.5.1 The Theory of the Polar Ozone 502

19 Chaos in the Atmosphere **507**

19.1 Simple Examples from the Theory of Dynamical Systems 507
19.1.1 The Poincarè Section 508
19.1.2 Fractal Dimension 510
19.2 The Climate 512
19.3 Is El Niño Chaotic? 517
19.4 Dimensions of Weather and Climate Attractors 521

Appendix A 525

A.1 Constructing a Tephigram 525

Appendix B 529

B.1 Flow Over an Obstacle: The Numerical Solution 529

Appendix C 541

C.1 The Quasi Geostrophic Potential Vorticity in log-p Coordinates 541
C.2 The Eliassen and Palm Flux Terms 541
C.3 Energy and EP Flux 542
C.4 The WKB Approximation 543
C.5 The Numerical Solution to the Wave Equation 544

Appendix D 553

D.1 Band Parameterization for CO_2, O_3 and H_2O 553

Appendix E **555**

E.1 A Listing for the North's Spectral Model 555
E.2 Program for the Sellers Model 559

Appendix F **565**

F.1 The Model for Stochastic Resonance 565
F.2. The FORTRAN Program 566

Symbols **569**

References **573**

Subject Index **586**