Contents

Foreword xvii
Preface xix
Acknowledgments xxi
List of symbols and definitions xxvii

1. Introduction 1
1.1 Scope and background 1
1.2 Layout of the book 4

2. Nature of the Problem 8
2.1 Introduction 8
2.2 Basic concepts of thermodynamic systems 9
2.2.1 State of a system, extensive and intensive properties
2.2.2 Classification of thermodynamic systems
2.2.3 Forced and free behavior of open systems
2.2.4 Random systems
2.3 Components of the climate system 13
2.3.1 Atmosphere
2.3.2 Hydrosphere
2.3.3 Cryosphere
2.3.4 Lithosphere
2.3.5 Biosphere
2.4 The climate system 18
2.4.1 The nature of the climate system
2.4.2 The climate state
2.4.3 Climate variability
2.5 Feedback processes in the climate system 26
2.5.1 Feedback concepts
2.5.2 Applications to the climate system
2.5.3 Some examples

3. Basic Equations for the Atmosphere and Oceans 32
3.1 Equation of continuity 32
3.2 Equations of motion 34
3.2.1 Frictional effects
3.2.2 Filtering of the basic equations for the atmosphere
3.2.3 Filtering of the basic equations for the oceans

3.3 Vorticity equation 42
3.3.1 Some definitions of vorticity
3.3.2 General vorticity equation
3.3.3 Vorticity equation of the horizontal motion
3.4 Thermodynamic energy equation and some applications 46
3.4.1 First law of thermodynamics
3.4.2 Static stability
3.4.3 Potential vorticity
3.4.4 The thermodynamic energy equation and the local rate of change of temperature
3.5 Equation of state 51
3.5.1 Atmosphere
3.5.2 Oceans
3.5.3 Barotropy and baroclinicity
3.6 Equation of water vapor 58
3.7 Summary of the basic equations in Lagrangian and Eulerian form ... 58

4. Various Decompositions of the Circulation 61
4.1 Transient and stationary eddies 61
4.1.1 Time and horizontal resolutions of the circulation
4.1.2 Vertical resolution of the circulation
4.2 Spectral analysis of meteorological fields 65
4.2.1 Spectral analysis in space and time
4.2.2 Limitations of sampling
4.3 Empirical orthogonal function analysis 67

5. The Data 70
5.1 Observational networks 70
5.1.1 Atmospheric data
5.1.2 Oceanic data
5.1.3 Satellite data
5.1.4 International field projects
5.2 Data processing techniques 81
5.2.1 Atmospheric data
5.2.2 Oceanic data
5.2.3 Satellite data
5.3 Objective analysis methods 84
5.3.1 Atmospheric analyses
5.3.2 Reliability of the atmospheric analyses
5.3.3 Oceanic analyses
5.4 Other atmospheric data sets 88

6. Radiation Balance 91
6.1 Introduction 91
6.1.1 Nature of solar and terrestrial radiation
6.1.2 Global radiation balance
6.2 Physical radiation laws 95
6.2.1 Planck's law
6.2.2 Stefan-Boltzmann law
6.2.3 Wien displacement law
6.2.4 Kirchhoff's law
6.2.5 Beer-Bouger-Lambert law
6.3 Solar radiation 98
6.3.1 Solar spectrum and solar constant
6.3.2 Distribution of solar radiation at the top of the atmosphere
6.3.3 Aerosols
6.3.4 Absorption of solar radiation

.... 42
6.3.5 Scattering of solar radiation
6.3.6 Effects of clouds on solar radiation
6.3.7 Solar radiation at the earth's surface
6.4 Terrestrial radiation 104
.... 46
6.4.1 Introduction
6.4.2 Absorption and emission spectra of atmospheric gases
6.4.3 Rotational and vibrational bands
6.4.4 Spectral lines—Lorentz formula
6.4.5 Transmissivity functions
6.4.6 Band models
.... 51
6.4.7 Nonhomogeneous paths
6.5 Radiative transfer 110
6.5.1 Schwarzchild equation
6.5.2 Radiative transfer equation
.... 58
6.6 Radiation balance of the atmosphere 114
... 58
6.7 Radiation balance at the earth's surface 116
... 61
6.8 Observed radiation balance 117
.... 61
6.8.1 Radiation balance of the earth
6.8.2 Global distribution of the radiation balance

7. Observed Mean State of the Atmosphere 131
.... 65
7.1 Atmospheric mass and pressure 131
7.1.1 Mass balance
7.1.2 Distribution of mass in terms of pressure
.... 67
7.2 Mean temperature structure of the atmosphere 137
... 70
7.2.1 Global distribution of the temperature
.... 70
7.2.2 Vertical structure of the temperature
7.2.3 Variability of the temperature
7.3 Mean geopotential height structure of the atmosphere 144
7.3.1 Vertical structure of the geopotential
7.3.2 Variability of the geopotential height
7.4 Mean atmospheric circulation 149
.... 81
7.4.1 Introduction
7.4.2 Global distribution of the circulation
7.4.3 Vertical structure of the circulation
7.4.4 Variability of the circulation
.... 84
7.5 Mean kinetic energy in the atmosphere 162
7.5.1 Global distribution of the kinetic energy
7.5.2 Vertical structure of the kinetic energy
7.6 Precipitation, evaporation, runoff, and cloudiness 165
... 88
7.6.1 Precipitation
7.6.2 Evaporation
... 91
7.6.3 Surface runoff
.... 91
7.6.4 Cloudiness

8. Observed Mean State of the Oceans 176
... 95
8.1 Mean temperature structure of the oceans 176
8.1.1 Global distribution of the temperature
8.1.2 Vertical structure of the temperature
8.1.3 Variability of the temperature
8.2 Mean salinity structure of the oceans 187
8.2.1 Global distribution of the salinity
... 98
8.2.2 Vertical structure of the salinity
8.3 Mean density structure of the oceans 190
8.3.1 Global distribution of the density
8.3.2 Vertical structure of the density

8.4 Mean ocean circulation 196
8.4.1 Global distribution of the surface circulation
8.4.2 Vertical structure of the circulation
8.5 Surface kinetic energy of the oceans 206

9. Observed Mean State of the Cryosphere 207
9.1 Role of the cryosphere in the climate 207
9.2 General features of the cryosphere 210
9.3 Ice sheets and glaciers 211
9.4 Sea ice 212
9.5 Snow 214
9.6 Permafrost 215

10. Exchange Processes Between the Earth's Surface and the Atmosphere 216
10.1 Introduction 216
10.2 Energy budget at the surface 217
10.2.1 Energy fluxes at an ideal surface
10.2.2 Energy budget of a layer
10.3 Development of the planetary boundary layer 222
10.3.1 Some characteristic features of the planetary boundary layer
10.3.2 Generation and maintenance of atmospheric turbulence
10.3.3 Effects of stability
10.4 Exchange of momentum 226
10.4.1 Eddy correlation approach
10.4.2 Gradient-flux approach
10.4.3 Mixing-length approach and wind profiles
10.4.4 Bulk aerodynamic method
10.5 Transfer of mechanical energy into the oceans 231
10.6 Exchange of sensible heat 232
10.7 Exchange of water vapor, evaporation 233
10.7.1 Eddy correlation, gradient-flux, and bulk transfer methods
10.7.2 Energy balance method
10.7.3 Combined approaches, Penman formula
10.8 Formation of atmospheric aerosol 240

11. Angular Momentum Cycle 241
11.1 Balance equations for angular momentum 241
11.1.1 Introduction
11.1.2 Angular momentum in the climatic system
11.1.3 Angular momentum in the atmosphere
11.1.4 Volume integrals
11.1.5 Modes of transport
11.2 Observed cycle of angular momentum 255
11.2.1 Angular momentum in the atmosphere
11.2.2 Angular momentum exchange between the atmosphere and the underlying surface
11.2.3 Cycle of angular momentum in the climatic system
11.2.4 Angular momentum exchange between the oceans and the lithosphere

12. Water Cycle 270
12.1 Formulation of the hydrological cycle 270
12.1.1 Introduction
12.1.2 Water in the climatic system

12.2 Equations of hydrology 273
12.2.1 Classic equation of hydrology
12.2.2 Balance equation for water vapor
12.2.3 Modes of water vapor transport
12.3 Observed atmospheric branch of the hydrological cycle 278
12.3.1 Water vapor in the atmosphere
12.3.2 Transport of water vapor
12.3.3 Divergence of water vapor
12.4 Synthesis of the water balance 297
12.5 Hydrology of the polar regions 302
12.5.1 Equations of hydrology including vapor, liquid, and solid water substance
12.5.2 Observed water budget of the polar regions

13. Energetics 308
13.1 Basic forms of energy 308
13.2 Energy balance equations 310
13.2.1 Introduction
13.2.2 The climate equations
13.2.3 Volume integrals
13.2.4 Globally averaged climate equations
13.3 Observed energy balance 319
13.3.1 Diabatic heating in the atmosphere
13.3.2 Energy in the atmosphere
13.3.3 Transport of atmospheric energy
13.3.4 Energy in the oceans
13.3.5 Transport of oceanic energy
13.3.6 Synthesis of the energy balance
13.4 Energetics of the polar regions 353
13.4.1 Formulation of the energy budget
13.4.2 Observed energy budget in atmospheric polar caps
13.4.3 Observed energy budget in ocean–land–ice polar caps
13.4.4 Synthesis of the polar energetics

14. The Ocean–Atmosphere Heat Engine 365
14.1 Availability of energy in the atmosphere 365
14.2 Availability of energy in the ocean 370
14.3 Balance equations for kinetic and available potential energy 373
14.3.1 Formal derivation of the balance equations
14.3.2 Balance equations for mean and eddy kinetic energy in the atmosphere
14.3.3 Balance equations for mean and eddy available potential energy in the atmosphere
14.4 Observed energy cycle in the atmosphere 379
14.4.1 Spatial distributions of the energy and energy conversions
14.4.2 The energy cycle
14.5 Maintenance and forcing of the zonal-mean state of the atmosphere 385
14.5.1 Introduction
14.5.2 Interactions between the eddies and the zonal-mean state
14.5.3 Eliassen-Palm flux
14.5.4 Modified momentum and energy equations
14.5.5 Forcing of the mean meridional circulation
14.5.6 Some examples of E–P flux diagrams
14.6 Observed energy cycle in the oceans 393
14.6.1 Spatial distributions of the energy components
14.6.2 The energy cycle

15. Entropy in the Climate System 401
15.1 Introduction 401
15.2 Balance equation of entropy 403
15.3 Observed entropy budget of the atmosphere 407
15.3.1 Global entropy budget
15.3.2 Regional entropy budgets

16. Interannual and Interdecadal Variability in the Climate System 412
16.1 Introduction 412
16.2 Quasibiennial oscillation 413
16.2.1 Observed features
16.2.2 Possible solar-QBO-climate connections
16.3 ENSO phenomenon 415
16.4 Regional teleconnections 426
16.5 Interdecadal fluctuations and trends 433
16.5.1 Anthropogenic influences
16.5.2 Atmospheric gases
16.5.3 Surface temperature
16.5.4 Upper air temperatures
16.6 Some special climatic phenomena 444

17. Mathematical Simulation of Climate 450
17.1 Introduction 450
17.2 Mathematical and physical structure of climate models 451
17.2.1 Basic parameters of a climate model
17.2.2 Model equations
17.2.3 Necessity of using numerical integrations
17.2.4 Parameterizations
17.2.5 Nature of the mathematical solutions
17.3 Hierarchy of climate models 463
17.4 General circulation models 464
17.4.1 Some general features
17.4.2 The development of general circulation modeling
17.4.3 Coupled ocean–atmosphere models
17.5 Statistical dynamical models 467
17.5.1 Energy balance models
17.5.2 Radiative–convective models
17.5.3 Two-dimensional statistical dynamical models
17.6 Uses and applications of models 473
17.6.1 Some general remarks
17.6.2 Data assimilation and network testing
17.6.3 Modeling of the hydrological cycle
17.6.4 Modeling of the ENSO phenomena
17.6.5 Modeling of the CO_2 effects
17.6.6 Effects of mountains and the simulation of an ice-age climate
17.6.7 Sensitivity to changes in astronomical parameters

Appendix A: Analysis in Terms of Fourier Components 481
A1. Introduction 481
A2. The Fourier spectrum 482

. 401
.. 401
.. 403
.. 407

A3. Multiplication and Parseval theorems 484
A4. Spectral functions of the meteorological variables and equations 487
A4.1. Linear quantities
A4.2. Quadratic quantities
A4.3. Meteorological equations

Appendix B: Analysis in Terms of Empirical Orthogonal Functions (EOF's) 492

. 412
.. 412
.. 413

B1. The problem 492
B2. Solution of the problem 493
B3. Variability of two-dimensional vector fields 496

.. 415
. 426
. 433

References 497

. 444

Name Index 509

. 450
. 450
. 451

Subject Index 513

. 463
. 464

. 467

. 473

. 481
. 481
. 482