

Contents

| | |
|--|-------------|
| Preface | xiii |
| Notation | xvii |
| PART I FUNDAMENTALS OF GEOPHYSICAL FLUID DYNAMICS | 1 |
| 1 Equations of Motion | 3 |
| 1.1 Time Derivatives for Fluids | 3 |
| 1.2 The Mass Continuity Equation | 7 |
| 1.3 The Momentum Equation | 11 |
| 1.4 The Equation of State | 13 |
| 1.5 Thermodynamic Relations | 14 |
| 1.6 Thermodynamic Equations for Fluids | 21 |
| 1.7 Thermodynamics of Seawater | 30 |
| 1.8 Sound Waves | 40 |
| 1.9 Compressible and Incompressible Flow | 41 |
| 1.10 The Energy Budget | 42 |
| 1.11 An Introduction to nondimensionalization and Scaling | 46 |
| Appendix A: Thermodynamics of an Ideal gas from the Gibbs function | 47 |
| Appendix B: The First Law of Thermodynamics for Fluids | 49 |
| 2 Effects of Rotation and Stratification | 55 |
| 2.1 Equations of Motion in a Rotating Frame | 55 |
| 2.2 Equations of Motion in Spherical Coordinates | 59 |
| 2.3 Cartesian Approximations: The Tangent Plane | 69 |
| 2.4 The Boussinesq Approximation | 70 |
| 2.5 The Anelastic Approximation | 75 |
| 2.6 Pressure and other Vertical Coordinates | 79 |
| 2.7 Scaling for Hydrostatic Balance | 83 |
| 2.8 Geostrophic and Thermal Wind Balance | 87 |
| 2.9 Gradient Wind Balance | 94 |
| 2.10 Static Instability and the Parcel Method | 97 |
| Appendix A: Asymptotic Derivation of the Boussinesq Equations | 101 |

| | | |
|----------------|---|------------|
| 3 | Shallow Water Systems | 105 |
| 3.1 | Dynamics of a Single Shallow Layer of Fluid | 105 |
| 3.2 | Reduced Gravity Equations | 110 |
| 3.3 | Multi-Layer Shallow Water Equations | 112 |
| 3.4 | From Continuous Stratification to Shallow Water | 114 |
| 3.5 | Geostrophic Balance and Thermal Wind | 118 |
| 3.6 | Form Stress | 119 |
| 3.7 | Conservation Properties of Shallow Water Systems | 120 |
| 3.8 | Shallow Water Waves | 123 |
| 3.9 | Geostrophic Adjustment | 127 |
| 3.10 | Isentropic Coordinates | 134 |
| 3.11 | Available Potential Energy | 137 |
| 4 | Vorticity and Potential Vorticity | 143 |
| 4.1 | Vorticity and Circulation | 143 |
| 4.2 | The Vorticity Equation | 145 |
| 4.3 | Vorticity and Circulation Theorems | 147 |
| 4.4 | Vorticity Equation in a Rotating Frame | 153 |
| 4.5 | Potential Vorticity Conservation | 156 |
| 4.6 | Potential Vorticity in the Shallow Water System | 162 |
| 4.7 | Potential Vorticity in Approximate, Stratified Models | 163 |
| 4.8 | The Impermeability of Isentropes to Potential Vorticity | 165 |
| 5 | Geostrophic Theory | 171 |
| 5.1 | Geostrophic Scaling | 171 |
| 5.2 | The Planetary-Geostrophic Equations | 176 |
| 5.3 | The Shallow Water Quasi-Geostrophic Equations | 180 |
| 5.4 | The Continuously Stratified Quasi-Geostrophic System | 187 |
| 5.5 | Quasi-Geostrophy and Ertel Potential Vorticity | 195 |
| 5.6 | Energetics of Quasi-Geostrophy | 198 |
| 5.7 | The Ekman Layer | 201 |
| PART II | WAVES, INSTABILITIES AND TURBULENCE | 213 |
| 6 | Wave Fundamentals | 215 |
| 6.1 | Fundamentals and Formalities | 215 |
| 6.2 | Group Velocity | 220 |
| 6.3 | Ray Theory | 224 |
| 6.4 | Rossby Waves | 226 |
| 6.5 | Rossby Waves in Stratified Quasi-Geostrophic Flow | 231 |
| 6.6 | Energy Propagation and Reflection of Rossby Waves | 234 |
| 6.7 | Group Velocity, Revisited | 240 |
| 6.8 | Energy Propagation of Poincaré Waves | 244 |
| | Appendix A: The wkb Approximation for Linear Waves | 247 |
| 7 | Gravity Waves | 251 |
| 7.1 | Surface Gravity Waves | 251 |
| 7.2 | Shallow Water Waves on Fluid Interfaces | 257 |
| 7.3 | Internal Waves in a Continuously Stratified Fluid | 259 |
| 7.4 | Internal Wave Reflection | 268 |

| | | |
|-----------|--|------------|
| 7.5 | Internal Waves in a Fluid with Varying Stratification | 271 |
| 7.6 | Internal Waves in a Rotating Frame of Reference | 276 |
| 7.7 | Topographic Generation of Internal Waves | 283 |
| 7.8 | Acoustic-Gravity Waves in an Ideal Gas | 293 |
| 8 | Linear Dynamics at Low Latitudes | 297 |
| 8.1 | Co-existence of Rossby and Gravity Waves | 298 |
| 8.2 | Waves on the Equatorial Beta Plane | 303 |
| 8.3 | Ray Tracing and Equatorial Trapping | 314 |
| 8.4 | Forced-Dissipative Wavelike Flow | 316 |
| 8.5 | Forced, Steady Flow: the Matsuno–Gill Problem | 321 |
| | Appendix A: Nondimensionalization and Parabolic Cylinder Functions | 330 |
| | Appendix B: Mathematical Relations in the Matsuno–Gill Problem | 333 |
| 9 | Barotropic and Baroclinic Instability | 335 |
| 9.1 | Kelvin–Helmholtz Instability | 335 |
| 9.2 | Instability of Parallel Shear Flow | 337 |
| 9.3 | Necessary Conditions for Instability | 345 |
| 9.4 | Baroclinic Instability | 347 |
| 9.5 | The Eady Problem | 351 |
| 9.6 | Two-Layer Baroclinic Instability | 356 |
| 9.7 | A Kinematic View of Baroclinic Instability | 363 |
| 9.8 | The Energetics of Linear Baroclinic Instability | 367 |
| 9.9 | Beta, Shear and Stratification in a Continuous Model | 369 |
| 10 | Waves, Mean-Flows, and their Interaction | 379 |
| 10.1 | Quasi-Geostrophic Wave–Mean-Flow Interaction | 380 |
| 10.2 | The Eliassen–Palm Flux | 383 |
| 10.3 | The Transformed Eulerian Mean | 387 |
| 10.4 | The Non-Acceleration Result | 394 |
| 10.5 | Influence of Eddies on the Mean-Flow in the Eady Problem | 399 |
| 10.6 | Necessary Conditions for Instability | 403 |
| 10.7 | Necessary Conditions for Instability: Use of Pseudoenergy | 406 |
| 11 | Basics of Incompressible Turbulence | 413 |
| 11.1 | The Fundamental Problem of Turbulence | 413 |
| 11.2 | The Kolmogorov Theory | 416 |
| 11.3 | Two-dimensional Turbulence | 423 |
| 11.4 | Predictability of Turbulence | 433 |
| 11.5 | Spectra of Passive Tracers | 437 |
| 12 | Geostrophic Turbulence and Baroclinic Eddies | 445 |
| 12.1 | Differential Rotation in Two-dimensional Turbulence | 445 |
| 12.2 | Stratified Geostrophic Turbulence | 454 |
| 12.3 | A Scaling Theory for Geostrophic Turbulence | 460 |
| 12.4 | Phenomenology of Baroclinic Eddies in the Atmosphere and Ocean | 464 |

| | | |
|-----------------|--|------------|
| 13 | Turbulent Diffusion and Eddy Transport | 473 |
| 13.1 | Diffusive Transport | 473 |
| 13.2 | Turbulent Diffusion | 475 |
| 13.3 | Two-Particle Diffusivity | 480 |
| 13.4 | Mixing Length Theory | 484 |
| 13.5 | Homogenization of a Scalar that is Advected and Diffused | 487 |
| 13.6 | Diffusive Fluxes and Skew Fluxes | 490 |
| 13.7 | Eddy Diffusion in the Atmosphere and Ocean | 493 |
| 13.8 | Thickness and Potential Vorticity Diffusion | 502 |
| PART III | LARGE-SCALE ATMOSPHERIC CIRCULATION | 509 |
| 14 | The Overturning Circulation: Hadley and Ferrel Cells | 511 |
| 14.1 | Basic Features of the Atmosphere | 511 |
| 14.2 | A Steady Model of the Hadley Cell | 516 |
| 14.3 | A Shallow Water Model of the Hadley Cell | 524 |
| 14.4 | Asymmetry Around the Equator | 525 |
| 14.5 | Eddy Effects on the Hadley Cell | 528 |
| 14.6 | Non-local Eddy Effects and Numerical Results | 532 |
| 14.7 | The Ferrel Cell | 534 |
| 15 | Zonally-Averaged Mid-Latitude Atmospheric Circulation | 539 |
| 15.1 | Surface Westerlies and the Maintenance of a Barotropic Jet | 540 |
| 15.2 | Layered Models of the Mid-Latitude Circulation | 549 |
| 15.3 | Eddy Fluxes and an Example of a Closed Model | 562 |
| 15.4 | A Stratified Model and the Real Atmosphere | 566 |
| 15.5 | Tropopause Height and the Stratification of the Troposphere | 572 |
| 15.6 | A Model for both Stratification and Tropopause Height | 579 |
| | Appendix A: TEM for the Primitive Equations in Spherical Coordinates | 581 |
| 16 | Planetary Waves and Zonal Asymmetries | 585 |
| 16.1 | Rossby Wave Propagation in a Slowly Varying Medium | 585 |
| 16.2 | Horizontal Propagation of Rossby Waves | 588 |
| 16.3 | Critical Lines and Critical Layers | 594 |
| 16.4 | A wKB Wave–Mean-Flow Problem for Rossby Waves | 598 |
| 16.5 | Vertical Propagation of Rossby waves | 599 |
| 16.6 | Vertical Propagation of Rossby Waves in Shear | 606 |
| 16.7 | Forced and Stationary Rossby Waves | 609 |
| 16.8 | Effects of Thermal Forcing | 615 |
| 16.9 | Wave Propagation Using Ray Theory | 621 |
| 17 | The Stratosphere | 627 |
| 17.1 | A Descriptive Overview | 627 |
| 17.2 | Waves in the Stratosphere | 634 |
| 17.3 | Wave Momentum Transport and Deposition | 639 |
| 17.4 | Phenomenology of the Residual Overturning Circulation | 642 |
| 17.5 | Dynamics of the Residual Overturning Circulation | 644 |
| 17.6 | The Quasi-Biennial Oscillation | 652 |
| 17.7 | Variability and Extra-Tropical Wave–Mean-Flow Interaction | 663 |

| | | |
|----------------|---|------------|
| 18 | Water Vapour and the Tropical Atmosphere | 673 |
| 18.1 | A Moist Ideal Gas | 673 |
| 18.2 | The Distribution of Relative Humidity | 680 |
| 18.3 | Atmospheric Convection | 691 |
| 18.4 | Convection in a Moist Atmosphere | 695 |
| 18.5 | Radiative Equilibrium | 700 |
| 18.6 | Radiative-Convective Equilibrium | 703 |
| 18.7 | Vertically-Constrained Equations of Motion for Large Scales | 708 |
| 18.8 | Scaling and Balanced Dynamics for Large-Scale Flow in the Tropics | 711 |
| 18.9 | Scaling and Balance for Large-Scale Flow with Diabatic Sources | 714 |
| 18.10 | Convectively Coupled Gravity Waves and the MJO | 717 |
| | Appendix A: Moist Thermodynamics from the Gibbs Function | 720 |
| | Appendix B: Equations of Radiative Transfer | 724 |
| | Appendix C: Analytic Approximation of Tropopause Height | 725 |
| | | |
| PART IV | LARGE-SCALE OCEANIC CIRCULATION | 729 |
| | | |
| 19 | Wind-Driven Gyres | 731 |
| 19.1 | The Depth Integrated Wind-Driven Circulation | 733 |
| 19.2 | Using Viscosity Instead of Drag | 740 |
| 19.3 | Zonal Boundary Layers | 744 |
| 19.4 | The Nonlinear Problem | 745 |
| 19.5 | Inertial Solutions | 747 |
| 19.6 | Topographic Effects on Western Boundary Currents | 753 |
| | | |
| 20 | Structure of the Upper Ocean | 761 |
| 20.1 | Vertical Structure of the Wind-Driven Circulation | 761 |
| 20.2 | A Model with Continuous Stratification | 767 |
| 20.3 | Observations of Potential Vorticity | 770 |
| 20.4 | The Main Thermocline | 774 |
| 20.5 | Scaling and Simple Dynamics of the Main Thermocline | 776 |
| 20.6 | The Internal Thermocline | 779 |
| 20.7 | The Ventilated Thermocline | 785 |
| | Appendix A: Miscellaneous Relationships in a Layered Model | 796 |
| | | |
| 21 | The Meridional Overturning Circulation and the ACC | 801 |
| 21.1 | Sideways Convection | 802 |
| 21.2 | The Maintenance of Sideways Convection | 808 |
| 21.3 | Simple Box Models | 813 |
| 21.4 | A Laboratory Model of the Abyssal Circulation | 818 |
| 21.5 | A Model for Oceanic Abyssal Flow | 821 |
| 21.6 | A Model of Deep Wind-Driven Overturning | 829 |
| 21.7 | The Antarctic Circumpolar Current | 836 |
| 21.8 | A Dynamical Model of the Residual Overturning Circulation | 845 |
| 21.9 | A Model of the Interhemispheric Circulation | 853 |

| | | |
|-----------|---|------------|
| 22 | Equatorial Circulation and El Niño | 861 |
| 22.1 | Observational Preliminaries | 861 |
| 22.2 | Dynamical Preliminaries | 862 |
| 22.3 | A Local Model of the Equatorial Undercurrent | 865 |
| 22.4 | An Ideal Fluid Model of the Equatorial Undercurrent | 876 |
| 22.5 | An Introduction to El Niño and the Southern Oscillation | 886 |
| 22.6 | The Walker Circulation | 891 |
| 22.7 | The Oceanic Response | 893 |
| 22.8 | Coupled Models and Unstable Interactions | 895 |
| 22.9 | Simple Conceptual and Numerical Models of ENSO | 898 |
| 22.10 | Numerical Solutions of the Shallow Water Equations | 902 |
| | Appendix A: Derivation of a Delayed-Oscillator Model | 904 |
| | References | 909 |
| | Index | 936 |

In the main text, sections that are more advanced or that contain material that is peripheral to the main narrative are marked with a black diamond, \blacklozenge . Sections that contain material that is still not settled or that describe active areas of research are marked with a dagger, \dagger .