Contents

Preface ix
Symbols xi

1 Purposes and value of geophysical fluid dynamics 1

2 Fundamental dynamics 8
   2.1 Fluid dynamics 8
      2.1.1 Representations 8
      2.1.2 Governing equations 9
      2.1.3 Boundary and initial conditions 13
      2.1.4 Energy conservation 14
      2.1.5 Divergence, vorticity, and strain rate 16
   2.2 Oceanic approximations 18
      2.2.1 Mass and density 19
      2.2.2 Momentum 22
      2.2.3 Boundary conditions 24
   2.3 Atmospheric approximations 27
      2.3.1 Equation of state for an ideal gas 27
      2.3.2 A stratified resting state 29
      2.3.3 Buoyancy oscillations and convection 31
      2.3.4 Hydrostatic balance 34
      2.3.5 Pressure coordinates 35
   2.4 Earth’s rotation 39
      2.4.1 Rotating coordinates 41
      2.4.2 Geostrophic balance 43
      2.4.3 Inertial oscillations 47
## Contents

3 Barotropic and vortex dynamics

3.1 Barotropic equations
   3.1.1 Circulation
   3.1.2 Vorticity and potential vorticity
   3.1.3 Divergence and diagnostic force balance
   3.1.4 Stationary, inviscid flows

3.2 Vortex movement
   3.2.1 Point vortices
   3.2.2 Chaos and limits of predictability

3.3 Barotropic and centrifugal instability
   3.3.1 Rayleigh's criterion for vortex stability
   3.3.2 Centrifugal instability
   3.3.3 Barotropic instability of parallel flows

3.4 Eddy–mean interaction

3.5 Eddy viscosity and diffusion

3.6 Emergence of coherent vortices

3.7 Two-dimensional turbulence

4 Rotating shallow-water and wave dynamics

4.1 Rotating shallow-water equations
   4.1.1 Integral and parcel invariants

4.2 Linear wave solutions
   4.2.1 Geostrophic mode
   4.2.2 Inertia-gravity waves
   4.2.3 Kelvin waves

4.3 Geostrophic adjustment

4.4 Gravity wave steepening: bores and breakers

4.5 Stokes drift and material transport

4.6 Quasigeostrophy

4.7 Rossby waves

4.8 Rossby-wave emission
   4.8.1 Vortex propagation on the $\beta$-plane
   4.8.2 Eastern boundary Kelvin wave

5 Baroclinic and jet dynamics

5.1 Layered hydrostatic model
   5.1.1 Two-layer equations
   5.1.2 $N$-layer equations
   5.1.3 Vertical modes
Contents

5.2 Baroclinic instability
  5.2.1 Unstable modes 156
  5.2.2 Upshear phase tilt 160
  5.2.3 Eddy heat flux 161
  5.2.4 Effects on the mean flow 162

5.3 Turbulent baroclinic zonal jet 164
  5.3.1 Posing the jet problem 164
  5.3.2 Equilibrium velocity and buoyancy structure 167
  5.3.3 Zonal momentum balance 171
  5.3.4 Potential vorticity homogenization 177
  5.3.5 Meridional overturning circulation and mass balance 177
  5.3.6 Meridional heat balance 180
  5.3.7 Maintenance of the general circulation 181

5.4 Rectification by Rossby-wave radiation 182

6 Boundary-layer and wind-gyre dynamics 186
  6.1 Planetary boundary layer 186
    6.1.1 Boundary-layer approximations 187
    6.1.2 The shear boundary layer 192
    6.1.3 Eddy-viscosity closure 196
    6.1.4 Bottom Ekman layer 197
    6.1.5 Oceanic surface Ekman layer 201
    6.1.6 Vortex spin down 205
    6.1.7 Turbulent Ekman layer 206
  6.2 Oceanic wind gyre and western boundary layer 213
    6.2.1 Posing the gyre problem 215
    6.2.2 Interior and boundary-layer circulations 219
    6.2.3 Application to real gyres 224
    6.2.4 Turbulent baroclinic wind gyres 228

Afterword 233
Exercises 234
References 243
Index 245

Colour plate section appears between pages 94 and 95