Atmospheric Convection

Kerry A. Emanuel

ATMOSPHERIC CONVECTION

Kerry A. Emanuel
Center for Meteorology and Physical Oceanography
Massachusetts Institute of Technology

293/3623 INSTITUT
FÜR METEOROLOGIE U. KLIMATOLOGIE
UNIVERSITÄT HANNOVER
HERRENHÄUSER STR. 2 - 30419 HANNOVER

New York Oxford
OXFORD UNIVERSITY PRESS
1994

CONTENTS

Part I. DRY CONVECTION

1. General Principles, 3
   - 1.1. Definition of convection, 3
   - 1.2. The buoyancy force, 4
   - 1.3. The Boussinesq and anelastic approximations, 8

   Exercises, 13

2. Convection from local sources, 14
   - 2.1. The similarity approach and definitions of thermals and plumes, 14
   - 2.2. Turbulent plumes originating from a maintained point source, 16
   - 2.3. Turbulent plumes originating from a maintained line source, 18
   - 2.4. Turbulent convection from an instantaneous point source (thermals), 19
   - 2.5. Turbulent starting plumes, 21
   - 2.6. Laminar plumes originating from a maintained point source, 21
   - 2.7. Turbulent convection in stably stratified fluid, 25
   - 2.8. Experiments and observations, 35

   Exercises, 40

3. Global convection: the Rayleigh-Benard problem and dry convective boundary layers, 47
   - 3.1. Linear stability analysis of Rayleigh convection: the original Rayleigh problem, 49
   - 3.2. Parallel-plate convection with insulating boundaries, 60
   - 3.3. Inclusion of rotational effects, 65
   - 3.4. Parallel-plate convection in shear flows, 73
   - 3.5. Nonlinear parallel-plate convection, 82
   - 3.6. Convective boundary layers, 89

   Exercises, 97

Part II. MOIST THERMODYNAMICS AND STABILITY

4. Moist thermodynamic processes, 107
   - 4.1. Moisture variables, 107
   - 4.2. Thermodynamics of unsaturated moist air, 109
   - 4.3. Virtual and density temperatures, 111
   - 4.4. Phase equilibrium of water substance, 113
   - 4.5. Conserved moist thermodynamic variables, 117
   - 4.6. Processes leading to saturation in the atmosphere, 125
   - 4.7. Reversible and pseudoadiabatic processes, 130
   - 4.8. Microphysical considerations, 133
   - 4.9. Thermodynamics of the ice phase, 138

   Exercises, 139

5. Graphical techniques, 145
   - 5.1. Thermodynamic diagrams, 145
   - 5.2. Conserved-variable diagrams, 148

   Exercises, 162

6. Stability, 165
   - 6.1. Static stability of moist, unsaturated air, 165
   - 6.2. Static stability of cloudy air, 166
   - 6.3. Stability to finite-amplitude displacements: the parcel method, 168
   - 6.4. Stability diagrams, 173
   - 6.5. The "slice Method," 175
   - 6.6. Available potential energy of barotropic moist atmospheres, 179
   - 6.7. Remarks on conditional versus potential instability, 185

   Exercises, 185

Part III. LOCAL PROPERTIES OF MOIST CONVECTION

7. Observed characteristics of nonprecipitating cumuli, 191
   - 7.1. Measurement of clouds, 191
   - 7.2. Kinematic structure of nonprecipitating cumuli, 192
   - 7.3. Distributions of cloud water, temperature, and mixing ratio in nonprecipitating cumuli, 196
   - 7.4. Inferences about entrainment and mixing from conserved-variable diagrams, 199

7.5. Organization of nonprecipitating cumuli, 205
Exercises. 208

8. Theory of mixing in cumulus clouds, 215
8.1. Instabilities of cloud-clear air interfaces 215
8.2. Velocity and length scales associated with mixing in cumuli, 221
Exercises, 228

9. Observed characteristics of precipitating convection, 230
9.1. The common convective shower and thunderstorm, 230
9.2. Intense convective storms, 235
9.3. Squall lines, 257
9.4. Cloud clusters and mesoscale convective complexes, 266
Exercises, 271

10. Numerical modeling of convective clouds, 280
10.1. General considerations, 280
10.2. Basic equations suitable for cloud models, 285
10.3. Representation of subgrid-scale motions, 286
10.4. Representation of cloud microphysical processes, 297
10.5. Boundary and initial conditions, 307
10.6. An example of a numerical simulation, 320
Exercises, 324

11. Dynamics of precipitating convection, 329
11.1. The response of stratified fluids to heat sources, 329
11.2. Deep convective scales and quasi-equilibrium versus triggered convection, 333
11.3. Dynamic effects of falling precipitation, 338
11.4. Nonlinear dynamics of squall lines, 353
11.5. Dynamics of three-dimensional precipitating convection, 372
11.6. Classification of precipitating convection, 387
Exercises, 388

12. Slantwise convection, 392
12.1. Centrifugal convection, 392

12.2. Theory of slantwise convection, 398
12.3. Observational evidence of slantwise convection, 409
Exercises, 413

Part IV. Global moist convection

13. Stratocumulus and trade-cumulus boundary layers, 421

13.1. Fog, 421
13.2. Equilibrium mixed layers, 424
13.3. Stratocumulus-topped mixed layers, 432
13.4. Trade-cumulus boundary layers, 443
Exercises, 460

14. Deep convective regimes, 463

14.1. Thermodynamic structure, 463
14.2. Quasi-equilibrium, 479
Exercises, 486

15. Interaction of convection with large-scale flows, 488

15.1. Effect of moist convection on large-scale variables, 488
15.2. Properties of convective ensembles deduced from atmospheric sounding arrays, 497
15.3. Elementary aspects of the interaction between convection and large-scale atmospheric circulations, 509
Exercises, 520

16. Cumulus representation in numerical models, 524

16.1. General considerations, 524
16.2. Convective representations based on moisture budgets, 526
16.3. Adjustments schemes, 533
16.4. Penetrative convection schemes based on cloud models, 539
16.5. Validation of convective representations, 553
Exercises, 557

Appendix 1. Water and thermodynamic variables, 560

Appendix 2. Thermodynamic constants and parameters, 565

Index, 569