

INTERNATIONAL GEOPHYSICS SERIES • VOLUME 44

Storm and Cloud Dynamics

William R. Cotton
Richard A. Anthes



Storm and Cloud Dynamics

William R. Cotton

DEPARTMENT OF ATMOSPHERIC SCIENCE
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

Richard A. Anthes

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
BOULDER, COLORADO



ACADEMIC PRESS, INC.

Harcourt Brace Jovanovich, Publishers

San Diego New York Berkeley Boston
London Sydney Tokyo Toronto

Contents

Preface	ix
---------	----

Chapter 1 Clouds

1.1 Introduction	1
1.2 The Classification of Clouds	2
1.3 Cloud Time Scales, Vertical Velocities, and Liquid-Water Contents	5
References	10

Part I Fundamental Concepts and Parameterizations

Chapter 2 Fundamental Equations Governing Cloud Processes

2.1 Introduction	13
2.2 General Equations	13
2.3 Scale Analysis and Approximate Equations	28
2.4 The Vertical Coordinate	41
References	45

Chapter 3 On Averaging

3.1 Introduction	47
3.2 Ensemble Average	48
3.3 Grid-Volume Average	49
3.4 The Generalized Ensemble Average	50
3.5 Average Equations by the “Top-Hat” Method	52
3.6 An Example of the Reynold’s Averaging Procedure	54
3.7 First-Order Closure Theory	57
3.8 Higher Order Closure Theory	60

3.9 Partial Condensation over an Averaging Volume or Averaging Domain	68
3.10 Implications of Averaging to the Interpretation of Model-Predicted Data	76
References	76

Chapter 4 The Parameterization or Modeling of Microphysical Processes in Clouds

4.1 Introduction	79
4.2 General Theory of the Microphysics of “Warm” Clouds	80
4.3 Parameterizations of Warm-Cloud Physics	90
4.4 Fundamental Principles of Ice-Phase Microphysics	100
4.5 Parameterization of Ice-Phase Microphysics	117
4.6 Impact of Cloud Microphysical Processes on Cloud Dynamics	134
References	138

Chapter 5 Radiative Transfer in a Cloudy Atmosphere and Its Parameterization

5.1 Introduction	148
5.2 Absorption, Reflectance, Transmittance, and Emittance in the Clear Atmosphere	151
5.3 Shortwave Radiative Transfer in a Cloudy Atmosphere	152
5.4 Longwave Radiative Transfer in a Cloudy Atmosphere	161
5.5 Radiative Influences on Cloud Particle Growth	163
5.6 Radiative Characteristics of Clouds of Horizontally Finite Extent	164
5.7 Aerosol Effects on the Radiative Properties of Clouds	169
5.8 Parameterization of Radiative Transfer in Clouds	174
5.9 Summary	185
References	186

Chapter 6 Cumulus Parameterization and Diagnostic Studies of Convective Systems

6.1 Introduction	190
6.2 Relationship between Cumulus Convection and Larger Scale Atmospheric Variables	192
6.3 Mathematical Framework	199
6.4 Diagnostic Studies of the Effects of Cumulus Convection on the Environment	211
6.5 Cumulus Parameterization Schemes	258
References	295

Part II The Dynamics of Clouds

Chapter 7 Fogs and Stratocumulus Clouds

7.1 Introduction	303
7.2 Types of Fog and Formation Mechanisms	303

7.3 Radiation Fog Physics and Dynamics	305
7.4 Valley Fog	314
7.5 Marine Fog	316
7.6 Stratocumulus Clouds	328
7.7 Arctic Stratus Clouds	362
References	364

Chapter 8 Cumulus Clouds

8.1 Introduction	368
8.2 Boundary Layer Cumuli—An Ensemble View	369
8.3 Organization of Cumuli	391
8.4 The Observed Structure of Individual Cumuli	407
8.5 Entrainment and Downdraft Initiation in Cumuli	417
8.6 The Role of Precipitation	430
8.7 The Role of the Ice Phase	431
8.8 Cloud Merger and Larger Scale Convergence	437
References	446

Chapter 9 Cumulonimbus Clouds and Severe Convective Storms

9.1 Introduction	455
9.2 Descriptive Storm Models and Storm Types	455
9.3 Updrafts and Turbulence in Cumulonimbi	463
9.4 Downdrafts: Origin and Intensity	478
9.5 Low-Level Outflows and Gust Fronts	492
9.6 Theories of Storm Movement and Propagation	497
9.7 Mesocyclones and Tornadoes	521
9.8 Hailstorms	540
9.9 Rainfall from Cumulonimbus Clouds	559
9.10 Thunderstorm Electrification and Storm Dynamics	564
References	577

Chapter 10 Mesoscale Convective Systems

10.1 Introduction	593
10.2 Mesoscale Convective Systems	593
10.3 Characteristics of Midlatitude Mesoscale Convective Systems	630
10.4 Genesis of Mesoscale Convective Systems	677
10.5 Tropical Cyclones	690
References	707

Chapter 11 The Mesoscale Structure of Extratropical Cyclones and Middle and High Clouds

11.1 Introduction	714
11.2 Large-Scale Processes that Determine Mesoscale Features	714

11.3 Mesoscale Structure of Extratropical Cyclones	723
11.4 Middle- and High-Level Clouds	744
References	783

Chapter 12 The Influence of Mountains on Airflow, Clouds, and Precipitation

12.1 Introduction	788
12.2 Theory of Flow over Hills and Mountains	788
12.3 Orogenic Precipitation	823
12.4 Orographic Modification of Extratropical Cyclones and Precipitation	833
12.5 Distribution of Supercooled Liquid Water in Orographic Clouds	847
12.6 Efficiency of Orographic Precipitation and Diurnal Variability	857
References	863
<i>Epilogue</i>	871
<i>Index</i>	873
<i>International Geophysics Series</i>	881