A Short Course in CLOUD PHYSICS

Third Edition

R. R. Rogers & M. K. Yau



A Short Course in Cloud Physics

THIRD EDITION

ьу R. R. ROGERS

and

M. K. YAU Department of Meteorology, McGill University, Canada



Contents

Intro	oduction	xiii
1.	Thermodynamics of Dry Air	1
	Atmospheric composition	1
	Equation of state for dry air	1
	The first law of thermodynamics	2
	Special processes	6
	Entropy	7
	Meteorological thermodynamic charts	8
	FIODEINS	11
2.	Water Vapor and its Thermodynamic Effects	12
	Equation of state for water vapor	12
	Clausius-Clapeyron equation	12
	Moist air : its vapor content	16
	Thermodynamics of unsaturated moist air	18
	Ways of reaching saturation	19
	Pseudoadiabatic process	21
	Adiabatic liquid water content	23
	Problems	25
	Tiobenis	. 20
3.	Parcel Buoyancy and Atmospheric Stability	28
	Hydrostatic equilibrium	28
	Dry adiabatic lapse rate	29
	Buoyant force on a parcel of air	30
	Stability criteria for dry air	30
	The pseudoadiabatic lapse rate	32
	Stability criteria for moist air	32
	Horizontal restoring forces	33
	Geostrophic wind and geostrophic wind shear	36
	Slantwise displacement	38
	Symmetric instability	39
	Baroclinic instability	41
	Geopotential	41
	Problems	42

4.	Mixing and Convection	44
	Mixing of air masses	44
	Convective condensation level	47
	Modification of the elementary theory	48
	Problems	57
5.	Observed Properties of Clouds	60
	Sizes of clouds and cloud systems	60
	Cloud droplet spectra	72
	Microstructure of stratus clouds	74
	Likelihood of ice and precipitation in clouds	75
	Microstructure of large continental storm clouds	77
	1100101115	19
6.	Formation of Cloud Droplets	81
	General aspects of cloud and precipitation formation	81
	Nucleation of liquid water in water vapor	84
	Problems	89 96
	 Openential and the second se Second second se	
7.	Droplet Growth by Condensation	99
	Diffusional growth of a droplet	99
	I he growth of droplet populations Some corrections to the diffusional growth theory	105
	Problems	112
8.	Initiation of Rain in Nonfreezing Clouds	121
	Setting the stage for coalescence	122
	Droplet growth by collision and coalescence	124
	Statistical growth: the Telford model	131
	Statistical growth: the stochastic coalescence equation	137
	Condensation plus stochastic coalescence	143
	Concluding remarks	143
	Problems	148
9.	Formation and Growth of Ice Crystals	150
	Nucleation of the ice phase	150
	Experiments on heterogeneous ice nucleation	153
	Aunospheric ice nuclei	154

Contents

x

	The ice phase in clouds	156
	Diffusional growth of ice crystals	158
	Further growth by accretion	163
	The ice crystal process versus coalescence	166
	Problems	169
10.	Rain and Snow	170
	Drop-size distribution	170
	Drop breakup	172
	Distribution of snowflakes with size	180
	Aggregation and breakup of snowflakes	182
	Precipitation rates Problems	182
	Trobenis	183
11.	Weather Radar	184
	Principles of radar	184
	The radar equation	187
	The weather radar equation	188
	Relation of Z to precipitation rate	190
	Problems	191
		193
12.	Precipitation Processes	196
	Stratiform precipitation	197
	Showers	203
	Precipitation theories	206
	Mesoscale structure of rain	209
	Acidic precipitation	217
	Problems	218
	a to produce	220
12	Server St. NY 1	
15.	Severe Storms and Hall	222
	Life cycle of the thunderstorm cell	222
	Severe thunderstorms	226
	Hail growth	234
	Problems	235
		231
14.	Weather Modification	340
	Stimulation of rain and anon	240
	Cloud dissipation	241
	Hail suppression	243
	Problems	243
		211

Contents xi

xii Col	ntents
---------	--------

15.	Numerical Cloud Models	246
	The governing equations One-dimensional models Two-dimensional models Three-dimensional models Model evaluation	247 249 253 259 266
Refe	rences	269
Арр	endix	277
Ansi	wers to Selected Problems	278
Inde	х .	285
Othe	er Titles in the Series in Natural Philosophy	291

13. Consequent and the sequence of particular sequence of the sequence of t

error separated pel error to da repa