



Thermodynamics of
**Atmospheres
& OCEANS**

JUDITH A. CURRY & PETER J. WEBSTER



INTERNATIONAL GEOPHYSICS SERIES, VOLUME 65



Thermodynamics of Atmospheres and Oceans

Judith A. Curry and Peter J. Webster
PROGRAM IN ATMOSPHERIC AND OCEANIC SCIENCES
DEPARTMENT OF AEROSPACE ENGINEERING
UNIVERSITY OF COLORADO
BOULDER, COLORADO
USA

332/4064 INSTITUT
FÜR METEOROLOGIE U. KLIMATOLOGIE
UNIVERSITÄT HANNOVER
HERRENHAUSER STR. 2 - 30419 HANNOVER



ACADEMIC PRESS

San Diego London Boston
New York Sydney Tokyo Toronto

Contents

<i>Preface</i>	x
<i>Acknowledgements</i>	xiv
<i>Publisher's Credits</i>	xv

Part I Basic Concepts

Chapter 1 Composition, Structure, and State

1.1	Composition of the Atmosphere	3
1.2	Composition of the Ocean	5
1.3	Pressure	6
1.4	Density	8
1.5	Temperature	10
1.6	Kinetic-Molecular Model of the Ideal Gas	13
1.7	Equation of State for Air	18
1.8	Equation of State for Seawater	21
1.9	Compressibility and Expansion Coefficients	23
1.10	Hydrostatic Equilibrium	26
	Notes	
	Problems	

Chapter 2 First and Second Laws of Thermodynamics

2.1	Work	35
2.2	Heat	38
2.3	First Law	39
2.4	Applications of the First Law to Ideal Gases	44
2.5	Entropy	48
2.6	Second Law	52
2.7	Equilibrium and the Combined First and Second Laws	55
2.8	Calculation of Thermodynamic Relations	57
2.9	Heat Capacity	59
2.10	Dry Adiabatic Processes in the Atmosphere	65
2.11	Adiabatic Processes in the Ocean	68
	Notes	71
	Problems	71

Chapter 3 Transfer Processes

3.1	Time-dependent Thermodynamics	74
3.2	Radiant Energy	76
3.3	Radiative Transfer	81
3.4	Diffusive Transfer Processes	85
3.5	Turbulence and Turbulent Transport	89
3.6	Time-dependent Equations for the Ocean and Atmosphere	92
	Notes	94
	Problems	94

Chapter 4 Thermodynamics of Water

4.1	Molecular Structure and Properties of Water	96
4.2	Thermodynamic Degrees of Freedom	100
4.3	Phase Equilibria	104
4.4	Atmospheric Humidity Variables	112
4.5	Colligative Properties of Water Solutions	114
4.6	Simple Eutectics	123
	Notes	126
	Problems	127

Chapter 5 Nucleation and Diffusional Growth

5.1	Surface Tension	129
5.2	Nucleation of the Liquid Phase	131
5.3	Nucleation of the Ice Phase	140
5.4	Diffusional Growth of Cloud Drops	142
5.5	Ice Crystal Morphology and Growth	149
5.6	Formation of the Initial Sea Ice Cover	151
5.7	Formation of Sea Ice Transition and Columnar Zones	154
	Notes	156
	Problems	156

Part II Applications**Chapter 6** Moist Thermodynamic Processes in the Atmosphere

6.1	Combined First and Second Laws	160
6.2	Isobaric Cooling	163
6.3	Cooling and Moistening by Evaporation of Water	168

6.4	Saturation by Adiabatic, Isobaric Mixing	170
6.5	Saturated Adiabatic Cooling	172
6.6	The Ice Phase	179
6.7	Conserved Moist Thermodynamic Variables	181
6.8	Aerological Diagrams	185
	Notes	189
	Problems	189

Chapter 7 Static Stability of the Atmosphere and Ocean

7.1	Stability Criteria	191
7.2	Stability of a Saturated Atmosphere	196
7.3	Processes Producing Changes in Stability	200
	Notes	204
	Problems	204

Chapter 8 Cloud Characteristics and Processes

8.1	Cloud Classification and Characteristics	207
8.2	Precipitation Processes	209
8.3	Radiative Transfer in a Cloudy Atmosphere	220
8.4	Fogs, Stratus Clouds, and Stratocumulus Clouds	230
8.5	Cumuliform Clouds	236
8.6	Parameterization of Cloud Microphysical Processes	241
	Notes	244
	Problems	245

Chapter 9 Ocean Surface Exchanges of Heat and Freshwater

9.1	Ocean Surface Energy Budget	247
9.2	Ocean Surface Salinity Budget	257
9.3	Ocean Surface Buoyancy Flux	260
9.4	Air Mass and Upper Water Mass Modification	262
	Notes	265
	Problems	265

Chapter 10 Sea Ice, Snow and Glaciers

10.1	Large-scale Morphology of Sea Ice	267
10.2	Ice Thickness Distribution	271
10.3	Evolution of the Salinity Profile in Sea Ice	273

10.4	Thermal Properties of Sea Ice	276
10.5	Optical Properties of Sea Ice and Snow	279
10.6	Surface Energy Balance over Snow and Sea Ice	282
10.7	Growth and Decay of Sea Ice	285
10.8	Metamorphosis of Surface Snow	291
10.9	Glaciers	293
	Notes	296
	Problems	297

Chapter 11 Thermohaline Processes in the Ocean

11.1	Radiative Transfer in the Ocean	299
11.2	Skin Temperature and the Diffusive Surface Layer	301
11.3	Surface Density Changes and the Ocean Mixed Layer	302
11.4	Instability and Mixing in the Ocean Interior	309
11.5	Oceanic Convection and Deep Water Formation	318
11.6	Global Thermohaline Circulations	324
	Notes	328
	Problems	329

Part III Special Topics

Chapter 12 Global Energy and Entropy Balances

12.1	Planetary Radiation Balance	331
12.2	Global Heat Engine	337
12.3	Entropy and Climate	342
12.4	Global Hydrologic Cycle	347
	Notes	349
	Problems	349

Chapter 13 Thermodynamic Feedbacks in the Climate System

13.1	Introduction to Feedback and Control Systems	352
13.2	Radiation Climate Sensitivity and Feedbacks	354
13.3	Water Vapor Feedback	358
13.4	Cloud-radiation Feedback	366
13.5	Snow/Ice-albedo Feedback	374
13.6	Thermodynamic Control of the Tropical Ocean Warm Pool	378
13.7	High-latitude Ocean Feedbacks	383
	Notes	385

Chapter 14 Planetary Atmospheres

14.1 Atmospheric Composition and Mass	386
14.2 Vertical Structure of Planetary Atmospheres	393
14.3 Planetary Energy Balance	403
14.4 Water on the Terrestrial Planets	411
14.5 Cloud Physics of the Terrestrial Planets	417
14.6 Cloud Physics of the Jovian Planets	418
14.7 Surface Ice	422
Notes	424
Problems	424

Appendices

A. Notation	425
B. Physical Constants	437
C. Units and Their SI Equivalents	439
D. Atmospheric Humidity Tables	440
E. Atmospheric Thermodynamic Chart	442
F. Properties of Seawater	444

<i>Answers to Selected Problems</i>	446
<i>References</i>	450
<i>Index</i>	456