

Meteorology Understanding the Atmosphere

Steven A. Ackerman

University of Wisconsin, Madison

John A. Knox

University of Georgia

B 155

DX: 551. 525.2, 551.571, 551.577, 551.593 551. 513, 551. 515.2, 551. 515.3, 551. 515.1 551. 515.4, 551. 509, 551. 585, 551. 583, 551.510. 41, 551. 524.34

JYY Y 161 INSTITUT
FÜR METEOROLOGIE U. KLIMATOLOGIE
UNIVERSITÄT HANNOVER

HERRENHÄUSER STR. 2 - 30419 HANNOVER



Brief Contents

C H A P T E R	Ī	Introduction to the Atmosphere	I
СНАРТЕК	2	The Energy Cycle	26
C H A P T E R	3	Temperature	56
C H A P T E R	4	Water in the Atmosphere	84
C H A P T E R	5	Observing the Atmosphere	126
CHAPTER	6	Atmospheric Forces and Wind	158
СНАРТЕК	7	Global-Scale Winds	188
СНАРТЕК	8	Atmosphere—Ocean Interactions:	
		El Niño and Tropical Cyclones	208
СНАРТЕК	9	Air Masses and Fronts	249
СНАРТЕК	10	Extratropical Cyclones and Anticyclones	270
C H A P T E R	ΙΙ	Thunderstorms and Tornadoes	306
C H A P T E R	12	Small-Scale Winds	338
C H A P T E R	13	Weather Forecasting	36 I
C H A P T E R	14	Past and Present Climates	400
CHAPTER	15	Human Influences on Climate	430
		Glossary	457
		Index	475
		Credits	483

vii



Contents

Снартек і			
Introduction to the Atmosphere			
Introduction 1			
Weather and Climate 1			
The Earth's Major Surface			
Features 3			
Making an Atmosphere: Gases and			
Gravity 3			
Atmospheric Evolution and			
Composition 4			
Trace Gases and Aerosols 5			
BOX 1.1: Most Air Is Lighter Than Dry Air 5			
Carbon Dioxide Cycle 6			
Hydrologic Cycle 8			
Methane 9			
Chlorofluorocarbons 10			
Aerosols 11			
Atmospheric Pressure and			
Density 12			

Basic Concepts 12

B O X 1.2:

Pressure and Altitude

The Ideal Gas Law 14

Dividing up the Atmosphere B O X 1.3: Why Do Your Ears Pop? 16 An Introduction to Weather Maps 18 Basic Concepts 18 The Station Model 19 Time Zones 21 Weather Watches, Warnings, and Advisories 23 Summary 24 Key Terms 25 Review Questions 25 Web Activities 25 CHAPTER 2 The Energy Cycle 26 Introduction 27 Force, Work, and Heat 27 Transferring Energy in the Atmosphere 30 Conduction: Requires Touching 30 Convection: Hot Air Rises 31



Heat Advection: Horizontal Movement
of Air 31

Latent Heating: Changing the Phase of
Water 32

Adiabatic Cooling and Warming:
Expanding and Compressing
Air 33

Diabatic Cooling and Warming:
Adding and Subtracting Heat 35

Radiative Heat Transfer: Exchanging
Energy with Space 36

B O X 2.1: Ozone 42

The Sun Supplies Energy to

Earth 44

Radiative Properties of the

Atmosphere 47

The Greenhouse Effect 49

Greenhouse Warming: The Basics 50

The Global Average Energy Budget:

Heat Is Transferred from the

Surface to the Atmosphere 50

B O X 2.2:

Monitoring the Earth's Energy
Budget 52

Summary 53
Key Terms 54
Review Questions 54
Web Activities 55

Temperature 56
Introduction 57
Surface Temperature 57
Surface Energy Budget 58
Temperature Cycles 59
Annual Temperature Cycle 60
Interannual Temperature

Variations 66

B O X 3.1:
Volcanoes and Temperature 68

Diurnal Temperature Cycle 70

BOX 3.2:
Record Cold and Record Heat Across
the United States 73

Temperature Variation with Height 74



Lapse Rates and Stability 74
Temperature Inversions Near the
Ground 76
Wind-Chill Temperature 79

Temperature and Agriculture

B O X 3.3: Temperature and Your Health 81

80

Summary 82
Key Terms 82
Review Questions 82
Web Activities 83

CHAPTER 4

Water in the Atmosphere 84

Introduction 85

Evaporation: The Source of

Atmospheric Water 86

Measuring Water Vapor in the

Air 86

Mixing Ratio 87

Vapor Pressure 88

Relative Humidity 89

B O X 4.1:
Atmospheric Moisture and Your
Health 90

Dew Point/Frost Point 92

Condensation and Deposition: Cloud

Formation 94

Solute and Curvature Effects 94

Nucleation 95

Cloud Particle Growth by

Condensation and Deposition 96

Fog Formation 96

Lifting Mechanisms That Form

Clouds 99

Cloud Classification 101

Low Clouds 101

Precipitating Clouds 105

Middle Clouds 106

High Clouds 108

Clouds and the Greenhouse

Effect 110

Cloud Composition 112

Precipitation 112

Precipitation Growth in Warm

Clouds 113

B O X 4.2:

Controlling the Weather 113

Precipitation Growth in Cold

Clouds 114

Precipitation Types 117

Clouds and Precipitation Near

Mountains 122

Summary 124



Key Terms 124
Review Questions 125
Web Activities 125

Observing the Atmosphere 126
Introduction 127
Meteorological Observations 127
Direct Measurements of Surface
Conditions 127

The Meteogram 128

Temperature 129

Humidity 130

Pressure 130

Wind 131

Precipitation 132

Direct Measurements of Upper-Air Weather Observations 132 Indirect Methods of Observing Weather 133 Laws of Reflection and Refraction 133

B O X 5.2: Twinkle, Twinkle, Little Star 135 Scattering 136 Multiple Scattering and Climate
Change 137

ASOS Indirect Sensors 138
Meteorological Satellite
Observations 139
Interpreting Satellite Images 140
Radar Observations 144

Atmospheric Optics 147
Mirages 148
Halos 150

Mirages 148
Halos 150
Dispersion of Light 150
Green Flash 150
Sundogs 151
Sun Pillar 152
Rainbows 152
Coronas, Glories, and the Brocken
Bow 155

Summary 156
Key Terms 157
Review Questions 157
Web Activities 157

Atmospheric Forces and Wind 158
Introduction 159



Magnitude and Direction of Forces 159

Laws of Motion 160

Newton's First Law: Law of

Inertia 160

Newton's Second Law: Law of

Momentum 161

Forces That Move the Air 162 Gravitational Force 162

B O X 6.1:

Planes and Pressure Differences 162

Pressure Gradient Force 163

Pressure Gradient Force 163 Coriolis Force 165

B O X 6.2:

Down the Drain with the Rossby

Number—Clockwise or

Counterclockwise? 168

Centrifugal Force/Centripetal
Acceleration 168
Frictional Force

Putting Forces Together: Atmospheric

Force-Balances 170

Hydrostatic Balance 172

Geostrophic Balance, the Geostrophic

Wind, and Buys Ballot's Law 172

Gradient Balance and the Gradient

Wind 174

Adjustment to Balance 175

Guldberg–Mohn Balance and Buys
Ballot's Law Revisited 176
Observations of Upper-Level and
Surface Wind 176

BOX 6.3:
Wind and Waves 177

Putting Force-Balances Together: The Thermal Wind 179

Putting Horizontal and Vertical Winds

Together 181

Sea Breezes 181

Scales of Motion 183

Summary 185

Key Terms 186

Review Questions 186

Web Activities 187

CHAPTER 7

Global-Scale Winds 188

Introduction 189

What Are Conceptual Models? 190

Observations Our Model Should

Explain 191

A Simple Conceptual Model of Global Circulation Patterns 192



Marine Stratocumulus Cloud Regions 195

Upper-Air Midlatitude
Westerlies 199
The Poleward Transport of
Energy 201
Seasonal Variations 203

B O X 7.2:
Precipitation Patterns and
Topography 204

Monsoons 205
Summary 206
Key Terms 206
Review Questions 207
Web Activities 207

CHAPTER 8
Atmosphere—Ocean Interactions: El
Niño and Tropical Cyclones 208
Introduction 209
Oceanography 209

Ocean Temperature 211
Ocean Currents 212
El Niño 216
La Niña 221
Other Oscillations 222

Tropical Cyclones: Hurricanes and
Typhoons 223
What Are They? 223
What Do They Look Like? 224
How and Where Do They Form? 224
How Are They Structured? 228

B O X 8.1: The "Hurricane Hunters" 231

What Are the Different Stages of Their "Lives"? 232

BOX 8.2:
Naming Hurricanes 233

What Does a Year's Worth of Tropical
Cyclones Look Like? 236
How Do They Cause
Destruction? 239

How Do We Observe and Forecast Tropical Cyclones? Past, Present, and Future 242

B O X 8.3:
Bryan Norcross, TV Meteorologist
and Hero 244

Summary 246
Key Terms 246
Review Questions 246
Web Activities 247



CHAPTER 9
Air Masses and Fronts 249
Introduction 249
What Is an Air Mass? 249
Observations 249

Deadly Heat Waves 250

Air Mass Types 251

Air Mass Source Regions 253

Atmospheric Stability Revisited 253

Air Masses Affecting North

America 254

Maritime Polar Air Masses 254

Continental Polar Air Masses 255

Arctic Air Masses 256

Continental Tropical Air Masses 256

Maritime Tropical Air Masses 257

Air Mass Modification 258

Fronts 260

B O X 9.2:
Lake-Effect Snows 261

Cold Fronts 263

Warm Fronts 264

Stationary Fronts 266

Occluded Fronts 267

Drylines 268

Summary 268
Key Terms 269
Review Questions 269
Web Activities 269

Extratropical Cyclones and
Anticyclones 270
Introduction 271
A Time and Place of Tragedy 272
A Life Cycle of Growth and
Death 273
Day One: Birth of an Extratropical
Cyclone 274

Day One: Birth of an Extratropical
Cyclone 274
Typical Extratropical Cyclone
Paths 277

B O X 10.1:
Making Cyclones and Waves 278

Day Two: With the Fitz 278

Adult 280

Cyclones and Fronts: On the
Ground 281

Cyclones and Fronts: In the Sky 282

Back with the Fitz: A Fateful Course
Correction 284

Cyclones and Jet Streams 284



Day Three: The Mature

Cyclone 287

Bittersweet Badge of Adulthood: The

Occlusion Process 288

B O X 10.2: Cyclones and Water: Bomb and Bust 289

Hurricane West Wind 289
One of the Worst . . . 290
"Nosedive" 292

B O X 1 O . 3 :

Cyclone Winds in 3D: Belts, Slots, and
Squalls 293

Day Four (and Beyond): Death 296
The Cyclone 296
The Fitzgerald 297

The Sailors 298

The Extratropical Anticyclone 299

Anticyclones and Another Fitzgerald

Tragedy 301

High Pressure, Low Visibility 303

Summary 304

Key Terms 305

Review Questions 305

Web Activities 305

Thunderstorms and
Tornadoes 306
Introduction 307
What Is a Thunderstorm? 307
Thunderstorm Distribution 308
Factors Affecting Thunderstorm
Growth and Development 308
Types of Thunderstorms 312
Ordinary Single-Cell
Thunderstorm 312
Multicell Thunderstorm 314

CHAPTER II

The Tornado 320
Tornado Formation and Life
Cycle 320

Supercell Thunderstorm

318

B O X 1 1.1:
Storm Chasers 321
Radar Observations of Tornadoes

Tornado Winds 324
Tornado Distribution 326
The Waterspout 328

B O X 11.2: Severe Weather Safety 329

Other Thunderstorm Severe Weather 330 Lightning 330 324



Flash Floods and Flooding 332 Hail 334

Summary 336

Key Terms 336

Review Questions 336

Web Activities 337

CHAPTER 12

Small-Scale Winds 778
Introduction 339
Friction in the Air: Turbulent
"Eddies" 339

BOX 12.1:
Clean-Air Turbulence 341

A Tour of Small-Scale Winds 342
The East and South 342
Coastal Fronts and Cold-Air
Damming 342

B O X 1 2 . 2 :
The Windiest Place on Earth 343
Microbursts 344
Gravity Waves 345

The Midwest 348

Lake Breezes 348

Derechos 349

The Great Plains 350

Blue Northers 350

B O X 12.3:

Using Turbulence to Advantage: Snow Fences and Windbreaks 351 Chinooks 351

B O X 1 2 . 4 :
Dust Storms and the "Dust
Bowl" 352

The West 353

Mountain/Valley Breezes and

Windstorms 353

Dust Devils 354

Lenticular Clouds 355

Santa Ana Winds 356

von Kármán Vortex Street 357

The Big Picture 358
Summary 360
Key Terms 360
Review Questions 360
Web Activities 361

CHAPTER 13

Weather Forecasting 361

Methods of Forecasting by

People 363

Folklore 363

Persistence and Climatology 364

B O X 13.1:

Personal Weather Forecasting 365



Trend and Analog 366

A Real Life-or-Death Forecast:
D-Day, June 1944 368

L.F. Richardson and the Dawn of
Numerical Weather
Forecasting 372

- B O X 1 3 . 2 :
 Modeling the Equations of the Air
 373
- B O X 1 3 . 3 : L.F. Richardson: Pioneer and Prophet 375

The Numerical Weather Prediction
Process, Then and Now 376
Step One: Weather Observations 376
Step Two: Data Assimilation 376
Step Three: Forecast Model
Integration 378

- B O X 1 3.4:
 "Blowing Up" a Forecast Model 381

 Step Four: Forecast Tweaking and
 Broadcasting 381
- B O X 1 3 . 5 :
 A Day in the Life of Private-Sector
 Meteorology 382

Modern Numerical Weather Prediction Models 382 Short-Range Forecast Models 384 Medium-Range Forecast Models 384 A Real Life-or-Death Forecast: The "Storm of the Century," March 1993 386 The Medium-Range Forecast 386 The Short-Range Forecast for Washington, D.C. 388 The Short-Range Forecast for Birmingham, Alabama 389 The Storm of the Century Appears 389 A Perfect Forecast 390 Nowcasting in D.C. 390 The Aftermath 390 Why Forecasts Still Go Wrong Today 392 Imperfect Data 392 Faulty "Vision" and "Fudges" 393 Chaos 394 Forecasts of Forecast Accuracy: Ensemble Forecasting 394 Pushing the Envelope: Numerical

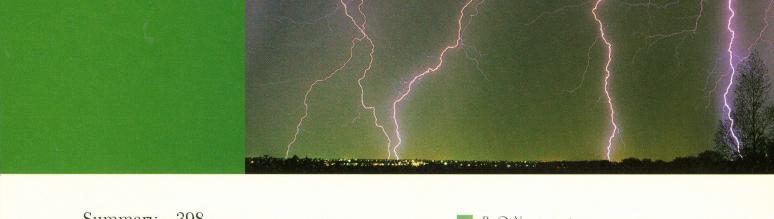
Nowcasts and Long-Range

396

Prediction

The Proper Perspective

396



Summary 398
Key Terms 398
Review Questions 398
Web Activities 399

CHAPTER 14

Past and Present Climates 400

Introduction 401

Defining Climate 401

Climate Controls 402

Classifying Today's Climate

Zones 402

Tropical Humid Climates (A) 404

Dry Climates (B) 405

Moist Subtropical and Midlatitude

Climates (C) 406

Severe Midlatitude Climates (D) 408

Polar Climates (E) 410

Highland Climates (H) 410

Past Climates: The Clues 411

Historical Data 411

Tree Rings 413

Pollen Records 413

B O X 1 4.1:

Dating Ancient Climates 414

Air Bubbles and Dust in Ice Sheets 414 B O X 14.2:

Glaciers and Icebergs 416

Marine Sediments 418

Fossil Records 418

Past Climates: The Change

Mechanisms 419

Volcanic Eruptions 419

Asteroid Impacts 419

Solar Variability 421

Variations of the Earth's Orbit:

Milankovitch Cycles 423

Plate Tectonics 423

Changes in Ocean Circulation

Patterns 426

Summary 428

Key Terms 429

Review Questions 429

Web Activities 429

CHAPTER 15

Human Influences on Climate 430

Introduction 431

Observations of Global

Warming 431

Feedback Mechanisms 432

Air Pollution 433

Acid Deposition 435



The Stratospheric Ozone
Hole 436
Changing Land Surfaces 439
Desertification 439
Urban Heat Islands 440
Greenhouse Gases and Global
Warming 442
Global Warming and Atmospheric
Water 442
Global Warming and the Oceans 443

BOX 15.1:
Contrails 444
Climate Modeling 445
Climate Change Assessment 449

Climate Change and Health 449
Climate Change and Coastal
Regions 450
Climate Change and Forests 451
Closure 452
Summary 454
Key Terms 454
Review Questions 454
Web Activities 454

Glossary 457 Index 475 Credits 483