Contents

Preface xxi
Acknowledgments xxiv
About the Authors 1

CHAPTER 1 Introduction to the Atmosphere

2

Introduction 3

Weather and Climate 4

The Earth's Major Surface Features 5

Making an Atmosphere: Gases and Gravity 5

Atmospheric Evolution and Composition 6

Variable Gases and Aerosols 8

Carbon Dioxide Cycle 8

Hydrologic Cycle 10

Methane 12

Chlorofluorocarbons 13

Aerosols 13

Atmospheric Pressure and Density 15

Basic Concepts 15

Barometric Pressure and Sea-Level Pressure 16

Dividing up the Atmosphere 18

The Troposphere 20

The Stratosphere 29

The Mesosphere and Thermosphere 21



© Milosz Aniol/ShutterStock, Inc.

CONTENTS ix

An Introduction to Weather Maps 22	
Basic Concepts 22 The Station Model 23	
Time Zones 25	
Weather Watches, Warnings, and Advisories 27	
Putting It All Together 28	
Summary 28	
Key Terms 30	
Review Questions 30	
Observation Activities 31	
Box 1-1 Moist Air Is Lighter Than Dry Air 7	
Box 1-2 The Ideal Gas Law 16	
Box 1-3 Why Do Your Ears Pop? 18	
,	
CHAPTER 2 The Energy Cycle	70
CHAPTER 2 The Energy Cycle	32
Introduction 33	
Force, Work, and Heat 33	
Transferring Energy in the Atmosphere 36	
Conduction: Requires Touching 36	
Convection: Hot Air Rises 37	
Temperature Advection: Horizontal Movement 37	
Latent Heating: Changing the Phase of Water 38	
Radiative Heat Transfer: Exchanging Energy with Space 39	
The Sun and the Seasons 47	
Angle of Incidence of the Sun's Energy 49	
Length of Daylight 49	
Path of Solar Energy Through the Atmosphere 53	
Radiative Properties of the Atmosphere 53	
The Greenhouse Effect 54	
Greenhouse Warming: The Basics 56	
The Global Average Energy Budget: Energy Is Transferred from the Surface	
to the Atmosphere 56	
Radiative Forcing 59	
Putting It All Together 59	
Summary 59	
Key Terms 60	
Review Questions 60 Observation Activities 61	
Box 2-1 Ozone 44	
Box 2-2 Satellite Images 55	
CHAPTER 3 Temperature	62
Introduction 63	
Surface Temperature 64	
Surface Energy Budget 65	
Global Distribution of Temperature 65	
Temperature Cycles 67	
Annual Temperature Cycle 68	
Interannual Temperature Variations 74	
Diurnal Temperature Cycle 78	



© Carlos S. Pereyra/age fotostock

Temperature Variation with Height: Lapse Rates and Static Stability 83

Adiabatic Cooling and Warming 84

The Environmental Lapse Rate and Static Stability 85

Temperature Inversions 87

Wind-Chill Temperature 89

Temperature and Agriculture 91

Growing Degree Days 92

Heating and Cooling Degree Days 92

Putting It All Together 93

Summary 93

Key Terms 93

Review Questions 94

Observation Activities 95

Box 3-1 Volcanoes and Temperature 77

Box 3-2 Record Heat Across the United States 82

Box 3-3 Temperature and Your Health 91

CHAPTER 4 Water in the Atmosphere

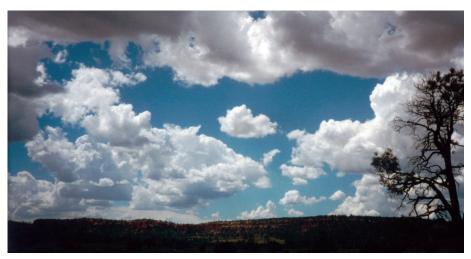
96

Introduction 98

Evaporation: The Source of Atmospheric Water 99



© Dudarev Mikhail/ShutterStock, Inc.



Courtesy of Steven Ackerman

Measuring Water Vapor in the Air 100

Mixing Ratio 100 Vapor Pressure 100 Relative Humidity 102 Dew Point/Frost Point 105

Condensation and Deposition: Cloud Formation 107

Solute and Curvature Effects 107

Nucleation 108

Condensation Nuclei 108 Ice Nuclei 109 Cloud Particle Growth by Condensation and Deposition 109

Fog Formation 109

Radiation Fog 110 Advection Fog 110 Evaporation Fog 112 Upslope Fog 112

Lifting Mechanisms That Form Clouds 112

Static Stability and Cloud Development 113

The Saturated Adiabatic Lapse Rate 113 Conditionally Unstable Environments 115

Cloud Classification 115

Low Clouds 117 Precipitating Clouds 119 Middle Clouds 120 High Clouds 122

Clouds and the Greenhouse Effect 124

Cloud Composition 126

Precipitation 126

Precipitation Growth in Warm Clouds 126
Precipitation Growth in Cold Clouds 128
Precipitation Types 130
Clouds, Lapse Rates, and Precipitation Near Mountains 136

Putting It All Together 138

Summary 138 Key Terms 138 Review Questions 139 Observation Activities 141



Courtesy of Anne Pryor

Box 4-1 Atmospheric Moisture and Your Health 103

Box 4-2 Controlling the Weather 127

CHAPTER 5 Observing the Atmosphere

142

Introduction 143

Meteorological Observations 144

Direct Measurements of Surface Conditions 144

Temperature 146

Humidity 146

Pressure 147

Wind 148

Precipitation 148

Direct Measurements of Upper-Air Weather Observations 149

Indirect Methods of Observing Weather 150

Laws of Reflection and Refraction 151

Scattering 153

ASOS Indirect Sensors 156

Meteorological Satellite Observations 157

Interpreting Satellite Images 158

Radar Observations 162

Atmospheric Optics 167

Mirages 167

Halos 168

Dispersion of Light 169

Green Flash 171

Sundogs 171

Sun Pillar 171

Rainbows 172

Coronas 172

Glories 173

Putting It All Together 175

Summary 175

Key Terms 176







© John King/Alamy Images

CONTENTS xiii

Review Questions 176	
Observation Activities 177	
Box 5-1 The Meteogram 145	
Box 5-2 GPS and Water Vapor 147	
Box 5-3 Twinkle, Twinkle, Little Star 153	
Box 5-4 Multiple Scattering and Climate Change 155	
Box 5-5 Next Generation of Weather Satellites 158	
CHAPTER 6 ALL LES LIVE L	17.0
CHAPTER 6 Atmospheric Forces and Wind	178
Introduction 179	
Wind Basics 180	
Physics of Motion Basics 181	
Newton's Second Law of Motion 181	
Forces That Move the Air 181	
Gravitational Force 182	
Pressure Gradient Force (PGF) 182	
Centrifugal Force/Centripetal Acceleration 185	
Coriolis Force 185	
Frictional Force 187	
Putting Forces Together: Atmospheric Force-Balances 190	
Hydrostatic Balance 191	
Geostrophic Balance, the Geostrophic Wind, and Buys Ballot's Law 192	
Gradient Balance and the Gradient Wind 194	
Adjustment to Balance 195	
Guldberg-Mohn Balance and Buys Ballot's Law Revisited 196	
Observations of Upper-Level and Surface Wind 196	
Putting Force-Balances Together: The Thermal Wind 199	
Putting Horizontal and Vertical Winds Together 201	
Sea Breezes 201	
Scales of Motion 203	
Putting It All Together 205	
Summary 205	
Key Terms 206	
Review Questions 206	
Observation Activities 207	
Box 6-1 Going Down the Drain with the Rossby Number—Clockwise or Counterclockwise? 189	
Box 6-2 Wind and Wayes 197	
Box o 2 willia and waves 157	
CHAPTER 7 Global-Scale Winds	208
Introduction 209	
What Are Conceptual Models? 211	
Observations Our Model Should Explain 211	
A Simple Conceptual Model of Global Circulation Patterns 212	
Upper-Air Midlatitude Westerlies 219	
The Poleward Transport of Energy 223	
The Effects of Land 223	
Seasonal Variations 224	

CONTENTS

Monsoons 227	
Beyond Conceptual Models: Current Research in Global-Scale Winds 229	
Putting It All Together 228	
Summary 228 Key Terms 229	
Review Questions 229	
Observation Activities 229	
Box 7-1 Marine Stratocumulus Cloud Regions 216	
Box 7-2 Precipitation Patterns and Topography 225	
CHAPTER 8 Atmosphere-Ocean Interactions: El Niño	
and Tropical Cyclones	230
Introduction 231	
Oceanography 231	
Ocean Temperature 233	
Ocean Currents 234	
El Niño 237	
La Niña 242	
Other Oscillations 242	
Tropical Cyclones: Hurricanes and Typhoons 244	
What Are They? 244	
What Do They Look Like? 245 How and Where Do They Form? 246	
How Are They Structured? 247	
What Are the Different Stages of Their "Lives"? 249	
What Does a Year's Worth of Tropical Cyclones Look Like? The Record Year of 2005	255
How Do They Cause Destruction? 258	233
How Do We Observe and Forecast Tropical Cyclones? 261	
Long-Range Tropical Cyclone Forecasting 267	
Putting It All Together 269	
Summary 269	
Key Terms 270	
Review Questions 270	
Observation Activities 271	
Box 8-1 The "Hurricane Hunters" 250	
Box 8-2 Naming Hurricanes 252	
Box 8-3 Hurricanes and Dust Storms 262	
CHAPTER 9 Air Masses and Fronts	272
Introduction 273	
What Is an Air Mass? 274	
Observations 274	
Air Mass Types 276	
Air Mass Source Regions 277	
Atmospheric Stability and Air Masses 278	
Air Masses Affecting North America 279	
Maritime Polar Air Masses 279	
Continental Polar Air Masses 279	
Continental Arctic Air Masses 281	

Continental Tropical Air Masses 281 Maritime Tropical Air Masses 282

Air Mass Modification 282

Fronts 286

Cold Fronts 286 Warm Fronts 289 Stationary Fronts 292 Occluded Fronts 292 Drylines 293

Conceptual Models of Frontal Systems 294

Norwegian Cyclone Model 294 Shapiro-Keyser Cyclone Model 294

Putting It All Together 295

Summary 295 Key Terms 296 Review Questions 296 Observation Activities 297

Box 9-1 Deadly Heat Waves 274

Box 9-2 Lake-Effect Snows and Buffalo's "Aphid" Infestation 284



Courtesy of NASA Earth Observatory and MODIS Rapid Response Team at NASA GSFC

CHAPTER 10 Extratropical Cyclones and Anticyclones

298

Introduction 299

A Time and Place of Tragedy 300

A Life Cycle of Growth and Death 300

Day 1: Birth of an Extratropical Cyclone 303

Typical Extratropical Cyclone Paths 303

Day 2: With the Fitz 305

Portrait of the Cyclone as a Young Adult 308 Cyclones and Fronts: On the Ground 310

Cyclones and Fronts: In the Sky 312

Back with the Fitz: A Fateful Course Correction 312

Cyclones and Jet Streams 312

Day 3: The Mature Cyclone 317

Bittersweet Badge of Adulthood: The Occlusion Process 317

Hurricane West Wind 320

One of the Worst . . . 322

"Nosedive" 322

Day 4 (and Beyond): Death 323

The Cyclone 323 The *Fitzgerald* 326 The Sailors 327

The Extratropical Anticyclone 328

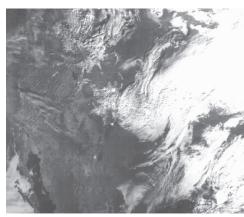
High Pressure, High Heat: The Deadly European Heat Wave of 2003 331

Putting It All Together 334

Summary 334 Key Terms 334 Review Questions 334 Observation Activities 335

Box 10-1 Making Cyclones and Waves 306

Box 10-2 Cyclone Winds in 3D: Belts and Slots 315



Courtesy of National Snow and Ice Data Center



Courtesy of Dr. Joseph Golden/NOAA

Box 10-3	Cyclones	and	Water:	Bomb	and Bust	319
----------	----------	-----	--------	------	----------	-----

Box 10-4 Weather History Repeats Itself (Almost) 325

Box 10-5 Fitzgerald Sailors Lost at Sea 328

Box 10-6 Gordon Lightfoot, Songwriter—and Amateur Meteorologist 329

Box 10-7 The Groundhog Day Blizzard of 2011 331

CHAPTER 11 Thunderstorms and Tornadoes

336

Introduction 337

What Is a Thunderstorm? 338

Thunderstorm Distribution 339

Factors Affecting Thunderstorm Growth and Development 339

Lifting Mechanisms 341

Unstable Atmosphere and Stability Indices 341

Vertical Wind Shear 341

Low-Level Jet Stream and Inversions 342

Types of Thunderstorms 343

Ordinary Single-Cell Thunderstorms 343

Multicell Thunderstorms 345

Supercell Thunderstorms 348

Microbursts 350

The Tornado 352

Tornado Formation and Life Cycle 352

Radar Observations of Tornadoes 354

Tornado Winds 356

Tornado Debris 357

Tornado Distribution 358

Tornado Outbreaks 360

When a Tornado Hits a City: Joplin, Missouri 366

The Waterspout 367

Other Thunderstorm-Produced Severe Weather 367

Lightning 367

Flash Floods and Flooding 370

Hail 372



© Peter Wollinga/Dreamstime.com

CONTENTS xvii





Courtesy of NOAA

© Cailyn Lloyd

Putting It All Together 374

Summary 374 Key Terms 375 Review Questions 376 Observation Activities 377

Box 11-1 Storm Chasers 353

Box 11-2 Severe Weather Safety 361

Box 11-3 Tornado Safety: A Success Story 365

CHAPTER 12 Small-Scale Winds

378

Introduction 379

Friction in the Air: Turbulent "Eddies" 380

A Tour of Small-Scale Winds 381

The East and South 381

Coastal Fronts and Cold-Air Damming 381 Gravity Waves 384

The Midwest 386

Lake Breezes 386

Derechos 386

The Great Plains 387

Blue Northers 387 Heat Bursts 389

Chinooks 391

The West 392

Mountain/Valley Breezes and Windstorms 392

Dust Devils 393

Lenticular Clouds 393

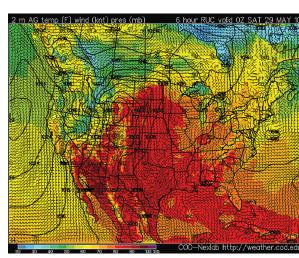
Santa Ana Winds 394

von Kármán Vortex Street 395

The Big Picture 395

Putting It All Together 396

Summary 396 Key Terms 396



© Ilene MacDonald/Alamy Images

CONTENTS

Review Questions 397	
Observation Activities 397	
Box 12-1 Clear-Air Turbulence 382	
Box 12-2 Using Turbulence to Advantage: Snow Fences and Windle	oreaks 388
Box 12-3 Dust Storms and the "Dust Bowl" 390	
CHAPTER 13 Weather Forecasting	398
Introduction 400	
Methods of Forecasting by People 400	
Folklore 400	
Persistence and Climatology 402	
Trend and Analog 404	
A Real Life-or-Death Forecast: D-Day, June 1944 406	
L. F. Richardson and the Dawn of Numerical Weather Forecasting	409
The Numerical Weather Prediction Process: Then and Now 411	
Step 1: Weather Observations 411	
Step 2: Data Assimilation 414	
Step 3: Forecast Model Integration 416	
Step 4: Forecast Tweaking and Broadcasting 418	
Modern Numerical Weather Prediction Models 419	
Short-Range Forecast Models 422	
Medium-Range Forecast Models 422	
A Real Life-or-Death Forecast: The "Storm of the Century," March	1993 423
The Medium-Range Forecast 423	
The Short-Range Forecast for Washington, DC 424	
The Short-Range Forecast for Birmingham, Alabama 425	
The Storm of the Century Appears 426 A Perfect Forecast 426	
Nowcasting in DC 427	
The Aftermath 427	
Why Forecasts Still Go Wrong Today 428	
Imperfect Data 428	
Faulty "Vision" and "Fudges" 428	
Chaos 429	
Ensembles, the Future of Forecasting 430	
Past: Ensembles and Extratropical Cyclone "Lothar," 1999 430	
Present: Ensembles Extend Our Reach 431	
Future: Models Talking to Models 433	
The Proper Perspective 435	
Putting It All Together 437	
Summary 437	
Key Terms 438	
Review Questions 438	
Observation Activities 439	
Box 13-1 Personal Weather Forecasting 403	
Box 13-2 Modeling the Equations of the Air 410	
Box 13-3 L. F. Richardson, Pioneer and Prophet 412	
Box 13-4 "Blowing Up" a Forecast Model 419	
Box 13-5 CSI: Weather 420	

CONTENTS xix

CHAPTER 14 Past and Present Climates

440

Introduction 441
Defining Climate 442
Climate Controls 442

Classifying Today's Climate Zones 442

Tropical Humid Climates 445

Dry Climates 445

Moist Subtropical and Mid-Latitude Climates 447

Severe Mid-Latitude Climates 449

Polar Climates 450

Past Climates: The Clues 451

Historical Data 451

Tree Rings 451

Pollen Records 453

Air Bubbles and Dust in Ice Sheets 455

Marine Sediments 455

Fossil Records 458

Past Climates: The Change Mechanisms 458

Volcanic Eruptions 459

Asteroid Impacts 460

Solar Variability 460

Variations of the Earth's Orbit: Milankovitch Cycles 463

Plate Tectonics 463

Changes in Ocean Circulation Patterns 465

Why Study Climates of the Past? 466

Putting It All Together 467

Summary 467

oullilliary 407

Key Terms 467

Review Questions 468

Observation Activities 469

Box 14-1 Dating Ancient Climates 454

Box 14-2 Glaciers and Icebergs 456



Courtesy of National Archives

CHAPTER 15 Human Influences on Climate

470

Introduction 471

Feedback Mechanisms 472

Human Impacts 473

Air Pollution 473

Aerosols and Clouds 477

Contrails 478

Acid Deposition 479

Stratospheric Ozone Hole 480

Changing Land Surfaces 483

Evidence of Global Warming 489

Atmosphere 490

Oceans 491

Cryosphere 492

Biosphere 495



© ribeiroantonio/ShutterStock, Inc.

The Intergovernmental Panel on Climate Change Assessment 496 The U.S. National Climate Assessment (NCA) 497

Putting It All Together 498

Summary 498 Key Terms 498 Review Questions 499 Observation Activities 499

Box 15-1 Taking an Unleaded Bite Out of Crime? 475

Box 15-2 Can a City Make It Rain? 488

CHAPTER 16 Climate Forecasting

500

Introduction 501

Weather Forecasts vs. Climate Forecasts 502

Monthly/Seasonal Climate Forecasts 503

Making Monthly/Seasonal Climate Forecasts 503 Interpreting Monthly/Seasonal Climate Forecasts 504

Long-Range Climate Forecasts 505

Making Long-Range Climate Forecasts with GCMs 506 Verifying Long-Range Climate Forecasts 507 A GCM Genealogy 508

Forecasts of Global Climate Change 510

IPCC Scenarios of Greenhouse Gas Emissions 510 Forecasts of Surface Temperature Changes 511 Forecasts of Precipitation Changes 514 Possible Impacts of Global Climate Change 514

Some Possible Societal Responses to Global Climate Change Forecasts 518

Kyoto Protocol 518 Carbon Trading and Taxing 520 Geoengineering 521

Perspectives on Global Climate Change 522

Closure 523

Putting It All Together 524

Summary 524 Key Terms 524 Review Questions 525 Observation Activities 525

Box 16-1 What Can I Do About Global Warming? 519

Appendices 526 Glossary 534 Index 564