

# Contents

Preface XV

## 1 Turbulent Atmosphere 3

Threats from the Sky 4

Reasons for Concern 5

Earth's Atmosphere 7

### Focus on 1.1 Connections to Climate

#### Volcanoes' Importance in Shaping Earth's Atmosphere and Climate 10

Properties of the Atmosphere 13

Air Temperature 13

Temperature Scales 14

Vertical Profile of Air Temperature 15

Additional Layers of the Atmosphere 16

Air Pressure 17

### Focus on 1.2 Instruments

#### Air Pressure and Barometers 19

Wind 20

Moisture 22

Humidity, Relative Humidity, and Dew Point 23

### Focus on 1.3 A Physical Process

#### Rising Air Produces Clouds 24

Hydrologic Cycle 24

Extremes of Weather and Climate 26

Summary 31

Key Terms 32

Review Questions 32

## 2 Energy That Drives the Storms 35

Energy and Heat Transfer 36

Latent Heat—The Hidden Warmth 37

Conduction 38

Convection 39

### Focus on 2.1 Extreme Weather

#### Comparing Energy in Storms 40

Radiation 41

### Focus on 2.2 Focus on Forecasting

#### Predicting UV Rays and Sunburning 42

Energy Balancing Act—Absorption, Emission, and Equilibrium 45

Greenhouse Gases and the Greenhouse Effect 45

Enhancement of the Greenhouse Effect 48

Warming the Air from Below 49

Shortwave Radiation Streaming from the Sun 49

Earth's Annual Energy Balance 51

Why Earth Has Seasons 53

### Focus on 2.3 Extreme Weather

#### Space Weather and Its Impact on Earth 54

Seasons in the Northern Hemisphere 56

### Focus on 2.4 Connections to Climate

#### Is December 21 Really the First Day of Winter? 59

### Focus on 2.5 Connections to Climate

#### A Year Without a Summer? 61

Seasons in the Southern Hemisphere	62
Summary	62
Key Terms	62
Review Questions	63

## 3 Extreme Temperature and Humidity 65

Daily Temperatures and Cycles	66
Daytime Warming	66
Extreme High Temperatures	67
Nighttime Cooling	70
Extreme Cold Temperatures	71
Daily Temperature Variations	72

### Focus on 3.1 Instruments

Measuring Temperature	74
Regional Temperature Variations	76

### Focus on 3.2 Connections to Climate

When It Comes to Temperature, What's Normal?	77
--	----

### Humidity 82

Vapor Pressure	83
Relative Humidity	83
High Dew Points Mean Humid Air	85
Dew-Point Extremes	87
Dry Air with a High Relative Humidity	87

### Focus on 3.3 A Physical Process

Humid Air and Dry Air Do Not Weigh the Same	88
---	----

### Focus on 3.4 Instruments

Measuring Humidity	89
--------------------	----

Weather Extremes and Human Discomfort	90
Wind and the feeling of Cold	90
Cold, Damp Weather	91
Humidity—A Real Factor in How Hot or Cold We Feel	91

### Focus on 3.5 A Physical Process

A Thousand Degrees and Freezing to Death	92
--	----

The Heat Index	93
Extreme Humidity in the Home	94

### Heat Waves 94

Extreme Heat Waves	94
Preparing for Future Heat Waves	95

### Summary 96

### Key Terms 97

### Review Questions 97

## 4 Condensation in the Atmosphere 101

The Formation of Dew, Frost, and Haze	102
Fog	103

### Focus on 4.1 A Physical Process

Why Are Headlands Usually Foggier than Beaches?	105
---	-----

### Foggy Weather 107

### Clouds 110

### Focus on 4.2 Extreme Weather

#### When Fog Turns to Smog 110

Classification of Clouds	111
High Clouds	112
Middle Clouds	113
Low Clouds	114
Clouds with Vertical Development	116
Unique Clouds	120
Clouds as Observed from Space	123

### Focus on 4.3 Instruments

#### The Fourth Generation of GOES: New Windows on the Atmosphere 124

### Focus on 4.4 Extreme Weather

#### Casting the Eyes of Satellites on Clouds 128

### Summary 128

### Key Terms 130

### Review Questions 130

## 5 Clouds and Stability 133

Atmospheric Stability 134  
Determining Atmospheric Stability 135

**Focus on 5.1 Forecasting**  
**Forecasting Tools That Link to Stability** 136

A Stable Atmosphere 137

**Focus on 5.2 A Physical Process**  
**Stability and Subsidence Inversions** 140

An Unstable Atmosphere 141  
A Conditionally Unstable Atmosphere 142  
Other Causes of Instability 144

**Focus on 5.3 A Physical Process**  
**Atmospheric Stability and Windy Afternoons—  
Hold Onto Your Hat** 145

Cloud Development and Stability 146  
Convection and Clouds 146  
Topography and Clouds 149

**Focus on 5.4 A Physical Process**  
**Exhaust and Pollution** 150

Changing Cloud Forms 152  
Summary 154  
Key Terms 154  
Review Questions 155  
Online Learning 155

## 6 Precipitation Extremes 157

Precipitation Processes 158  
Collision and Coalescence Process 158  
Ice-Crystal Process 160  
Cloud Seeding and Precipitation 162  
Precipitation in Clouds 164  
Precipitation Types 164  
Rain 164

**Focus on 6.1 A Physical Process**  
**Are Raindrops Tear-Shaped?** 165

**Focus on 6.2 A Physical Process**  
**Acid in the Sky** 166  
Snow 168  
The Effect of a Snowfall 170  
Sleet, Freezing Rain, and Ice Storms 172

**Focus on 6.3 Extreme Weather**  
**Lake-Effect (Enhanced) Snows** 172  
Snow Grains and Snow Pellets 175

**Focus on 6.4 Extreme Weather**  
**Aircraft Icing—A Hazard to Flying** 175  
Hail 176

Precipitation—Extreme Events 178  
The Influence of Mountains 178  
Extreme Wet and Dry Regions 179  
Too Much Rain—Floods and Flash Floods 181  
When It Doesn't Rain—Drought and the Palmer  
Index 183

**Focus on 6.5 Extreme Weather**  
**The Terrifying Flash Flood in the Big Thompson  
Canyon** 183

**Focus on 6.6 Instruments**  
**Doppler Radar and Precipitation** 184  
Some Notable Droughts 185  
African Drought 186  
North American Drought 187

Summary 188  
Key Terms 188  
Review Questions 189

## 7 Motions in the Atmosphere 191

Horizontal Pressure Changes and Wind 192  
Surface and Upper-Level Charts 194  
Isobaric (constant pressure) MAPS 196

### Focus on 7.1 A Physical Process

**The Atmosphere Obeys the Gas Law** 196

Surface and Upper-Air Map 197

Why the Wind Blows 198

Newton's LAws of Motion 198

### Focus on 7.2 Instruments

**Flying Along a Constant Pressure Surface—When the Air Temperature Drops, Look Out for Mountaintops** 199

Forces That Influence the Wind 200

Pressure Gradient Force 200

Coriolis Force 202

How the Wind Blows 204

Straight-Line Flow Aloft 204

### Focus on 7.3 A Physical Process

**Estimating Wind Direction and Pressure Patterns Aloft by Watching Clouds** 205

Curved Winds Around Lows and Highs Aloft 206

Winds on Upper-Level Charts 207

### Focus on 7.4 Connections to Climate

**Winds Aloft in the Southern Hemisphere** 209

Surface Winds 210

Vertical Motions and Storms 211

### Focus on 7.5 Instruments

**Measuring Winds** 212

The Influence of Extreme Winds 215

Strong Winds Blowing over Land 215

Extreme Winds and Water 217

Windy Places 218

Extreme Winds 218

Wind and Energy 220

### Focus on 7.6 Connections to Climate

**Reducing Future Climate Change Through Clean Wind Energy** 221

Summary 222

Key Terms 222

Review Questions 222

## 8 Wind Systems 225

General Circulation of the Atmosphere 226

Single-Cell Model 226

Three-Cell Model 227

Average Surface Winds and Pressure: The Real World 229

The General Circulation and Precipitation Patterns 231

### Focus on 8.1 Connection to Climate

**The Climate Impacts of Wind Patterns and Surface Ocean Currents** 232

Winds Aloft 234

Jet Streams 235

### Focus on 8.2 Focus on Forecasting

**Weather Models—Looking into the Future** 238

### Focus on 8.3 Extreme Weather

**Aircraft Turbulence—Fasten Your Seat Belts** 240

Local Wind Systems and Extremes 241

Monsoon Winds 241

Sea and Land Breezes 243

### Focus on 8.4 Extreme Weather

**North America's Own Monsoon** 245

Mountain and Valley Breezes 246

Katabatic Winds 247

Chinook (Foehn) Winds 248

Santa Ana Winds 250

Desert Winds 252

Other Extreme Winds of interest 254

Summary 255

Key Terms 255

Review Questions 256

## 9 Air Masses and Fronts 259

Air Masses 260

Source Regions 260

Classification 261

Air Masses of North America 261

Continental Polar (cP) and Continental Arctic (cA)

Air Masses 261

Extremely Cold Outbreaks 263

Modification of Cold Air Masses 264

<b>Focus on 9.1 Extreme Weather</b>	
<b>The Siberian Express of December 1983</b>	265
Maritime Polar (mP) Air Masses	266
Maritime Tropical (mT) Air Masses	267
<b>Focus on 9.2 Extreme Weather</b>	
<b>Atmospheric Rivers as Extreme Precipitation Producers</b>	271
Continental Tropical (cT) Air Masses	272
<b>Focus on 9.3 Extreme Weather</b>	
<b>A Scorching by Noon in June</b>	274
Fronts	275
Stationary Fronts	276
Cold Fronts	276
Typical Cold Fronts	277
"Back Door" Cold Fronts	279
A Strong Cold Front	280
Warm Fronts	281
<b>Focus on 9.4 Extreme Weather</b>	
<b>The Extraordinary Cold Front of 1836</b>	282
<b>Focus on 9.5 A Physical Process</b>	
<b>Warm Fronts and Ice Storms</b>	284
The Dryline	284
Occluded Fronts	286
Upper-Air Fronts	288
Summary	289
Key Terms	289
Review Questions	290

## 10 Mid-Latitude Cyclonic Storms 293

Polar Front Theory	294
Stages of a Developing Storm	294
Where Do Mid-Latitude Cyclones Tend to Form?	296
<b>Focus on 10.1 Extreme Weather</b>	
<b>A Notorious Storm Follows the Mid-Latitude Cyclone Model</b>	297
<b>Focus on 10.2 Extreme Weather</b>	
<b>Nor'Easters</b>	299
Developing Mid-Latitude Cyclones	300
The Roles of Convergence and Divergence	300
<b>Focus on 10.3 A Physical Process</b>	
<b>A Closer Look at Convergence and Divergence</b>	301
Waves in the Westerlies	302
Upper-Air Support for the Developing Storm	303
The Role of the Jet Stream	304
<b>Focus on 10.4 A Physical Process</b>	
<b>Jet Streaks and Storms</b>	306
Conveyor Belt Model of Mid-Latitude Cyclones	307
Extreme Weather and Mid-Latitude Cyclones	308
Extreme Cold and Snowfall—The March Storm of 1993	308
Extreme Wind—The Columbus Day Storm of October 1962	312
Blizzards	313
Quantifying the Impact of Snowfall	315
Forecasting Weather by Tracking Mid-Latitude Cyclones	316

### **Focus on 10.5 Extreme Weather**

#### **Blizzard Safety Tips 316**

- Polar Lows 320
- Summary 321
- Key Terms 321
- Review Questions 321

## **11 Thunderstorms 325**

- Thunderstorm Development 326
  - Ordinary Cell Thunderstorms 327
  - Multicell Thunderstorms 329
    - The Gust Front 330
    - Microbursts 331
    - Heat Bursts 334
  - Squall-line Thunderstorms 334
  - Mesoscale Convective Complexes 336

### **Focus on 11.1 Extreme Weather**

#### **The Devastating Power of Derechos 337**

- Supercell Thunderstorms 338
- Thunderstorms and the Dryline 342
- Pyrocumulonimbus 343
- Distribution of Thunderstorms 343
- Lightning and Thunder 345
  - How Far Away Is the Lightning? Start Counting 346
  - Electrification of Clouds 347
  - The Lightning Stroke 347
  - The Different Types of Lightning 349

### **Focus on 11.2 A Physical Process**

#### **ELVES in the Atmosphere 350**

- When Lightning Strikes 352
- Lightning Detection and Suppression 353

### **Focus on 11.3 Extreme Weather**

#### **The Deadly Danger of Lightning 354**

- Summary 356
- Key Terms 357
- Review Questions 357

## **12 Tornadoes 359**

- What Is a Tornado? 360
- Tornado Life Cycle 362
- Tornado Occurrence and Distribution 363
- Tornado Winds 366

### **Focus on 12.1 Extreme Weather**

#### **The Weird World of Tornado Damage 367**

- Seeking Shelter 368
- The Fujita Scale 369

### **Focus on 12.2 Extreme Weather**

#### **The Evolution of Tornado Watches and Warnings 370**

- Tornado Outbreaks 372

- Tornado Formation 374
- Supercell Tornadoes 374

### **Focus on 12.3 Focus on Forecasting**

#### **Predicting Severe Thunderstorms and Tornadoes 378**

- Nonsupercell Tornadoes 380
- Waterspouts 381
- Observing Tornadoes with Doppler Radar 382

### **Focus on 12.4 Instruments**

#### **Takin' a Chase on the Wild Side 386**

- Summary 387
- Key Terms 387
- Review Questions 387

## **13 Hurricanes 391**

- Tropical Weather 392
- Hurricanes, Tropical Storms, and Other Tropical Cyclones 393
- Anatomy of a Hurricane 393
- Hurricane Lifecycle 396
  - The Right Environment 396
  - The Developing Storm 398
  - The Storm Dies Out 399
  - Hurricane Basins and Movement 400

<b>Focus on 13.1 A Physical Process</b>	
<b>How Do Hurricanes Compare with Middle-Latitude Cyclonic Storms?</b>	401
North Atlantic Hurricanes	403
East North Pacific Hurricanes	404
Naming Hurricanes and Tropical Storms	405
Devastating Winds, Flooding, and the Storm Surge	406
<b>Focus on 13.2 Instruments</b>	
<b>Investigating the Storm</b>	408
Classifying Hurricane Strength	409
Hurricane-Spawned Tornadoes	411
Hurricane Fatalities	412
Some Notable and Destructive Hurricanes	413
Galveston, 1900	413
New England, 1938	413
Camille, 1969	414
Hugo, 1989	414
Andrew, 1992	415
Katrina and Rita, 2005	416
<b>Focus on 13.3 Instruments</b>	
<b>Hunting Hugo</b>	416
Sandy, 2012	418
Michael, 2018	420
<b>Focus on 13.4 Extreme Weather</b>	
<b>The Record-Setting North Atlantic Hurricane Seasons of 2004 and 2005</b>	420
IDA, 2021	421
IAN, 2022	423
Devastating Tropical Cyclones Around the World	423
Hurricane Watches, Warnings, and Forecasts	424
<b>Focus on 13.5 Focus on Forecasting</b>	
<b>Forecasting Techniques for Hurricanes</b>	426
Modifying Hurricanes	427

Summary	428
Key Terms	429
Review Questions	429

## 14 Global Climate 433

The Many Climates of Earth	434
Global Temperature	434
Global Precipitation	436
<b>Focus on 14.1 Focus on Forecasting</b>	
<b>Predicting Weather across Timescales</b>	438
Climatic Classification—The Köppen System	440
The Global Pattern of Climate	440
Tropical Moist Climates (Group A)	441
Dry Climates (Group B)	446
Moist Subtropical Mid-Latitude Climates (Group C)	449
<b>Focus on 14.2 A Physical Process</b>	
<b>A Desert with Clouds and Drizzle</b>	450
Moist Continental Climates (Group D)	454
Polar Climates (Group E)	456
Highland Climates (Group H)	458
Atmosphere–Ocean Interactions and Climate Variability	459
El Niño, La Niña, and the Southern Oscillation	459
<b>Focus on 14.3 Connections to Climate</b>	
<b>Plant Hardiness Zones Are Shifting Northward</b>	460
Pacific Decadal Oscillation	466
Indian Ocean Dipole	466
North Atlantic Oscillation	467
Arctic Oscillation	467
Summary	468
Key Terms	469
Review Questions	469

# 15 Earth's Changing Climate 473

- Reconstructing Past Climates Through Paleoclimatology 474
- Climate Throughout the Ages 477
  - Temperature Trends During the Past 2000 Years 478
  - Temperature Trends During the Past 100-Plus Years 479

## Focus on 15.1 Connections to Climate The Ocean's Influence on Rapid Climate Change 480

- Natural Causes of Climate Change 483
  - Feedback Mechanisms 483
  - Plate Tectonics and Mountain Building 484
  - Variations in Earth's Orbit 485
  - Variations in Solar Output 488
  - Atmospheric Particles 489
- Human (Anthropogenic) Causes of Climate Change 492
  - Increases in Greenhouse Gases 492
  - Aerosols Injected into the Lower Atmosphere 492
  - Land Use Changes 493

## Focus on 15.2 Connections to Climate Nuclear Winter—Climate Change Induced by Nuclear 493

- Global Warming and Impacts 494
  - Recent Climate Change: Perspective 494
    - Radiative Forcing Agents 494
    - Climate Models and Recent Temperature Trends 495
  - Future Climate Change: Projections 495
    - Uncertainties About Greenhouse Gases 498

## Focus on 15.3 Focus on Forecasting Climate Models: How Do They Work? 500

- The Question of Clouds 500

## Focus on 15.4 Connections to Climate Ozone and the Ozone Hole: Their Influence on Climate Change 502

- The Ocean's Impact 503
- Impacts of Global Warming 503
  - Precipitation 503
  - Sea-Level Rise 506
  - Ocean Warming and Acidification 507
  - Changes in Sea and Land Ice 507
  - Changes in Ecosystems 507
- Connections to Extreme Weather 508
  - Extreme Temperature 508
  - Extreme Precipitation 508
  - Drought 509
  - Mid-Latitude Cyclonic Storms 509
  - Thunderstorms and Tornadoes 510
  - Hurricanes 510
  - Summary of Extreme Weather Events and Global Warmings 511

A Call for Change 512

## Focus on 15.5 Connections to Climate International Cooperation to Reduce Emissions 513

- Summary 514
- Key Terms 514
- Review Questions 515

**A** Units, Conversions, and Abbreviations 516

**B** Equations and Constants 519

**C** Weather Symbols and the Station Model 522

**D** Humidity and Dew-Point Tables (Psychrometric Tables) 524

**E** Köppen's Climatic Classification System 528

**F** Average Annual Global Precipitation 530

Additional Reading Material 532

Glossary 533

Index 545



**Extreme Weather and Climate, 2nd Edition.**  
**C. Donald Ahrens, Perry Samson,**  
**Kevin A. Reed**

SVP, Product: Cheryl Costantini

VP, Product: Thais Alencar

Sr. Product Director, Portfolio Product  
Management: Mark Santee

Associate Portfolio Product Director: Maureen  
McLaughlin

Product Assistant: Jeanette Ames

Learning Designers: Chris Doughman

Content Project Manager: Kugan Vasudevan

Content Manager: Anupam Bose,  
MPS Limited

Content Project Manager: Kugan Vasudevan

Digital Project Manager: Mark Hopkinson

Senior Director, Product Marketing: Danae April

Content Acquisition Analyst: Nichole Nalenz

Production Service: MPS Limited

Designer: Chris Doughman

Cover Image Source: Roberto Machado  
Noa/Moment/Getty Images

Copyright © 2025 Cengage Learning, Inc. ALL RIGHTS RESERVED.

WCN 01-100-393

No part of this work covered by the copyright herein may be reproduced or distributed in any form or by any means, except as permitted by U.S. copyright law, without the prior written permission of the copyright owner.

Unless otherwise noted, all content is Copyright © Cengage Learning, Inc.

Previous edition: © 2011

For product information and technology assistance, contact us at  
**Cengage Customer & Sales Support, 1-800-354-9706**  
or [support.cengage.com](http://support.cengage.com).

For permission to use material from this text or product, submit all  
requests online at [www.copyright.com](http://www.copyright.com).

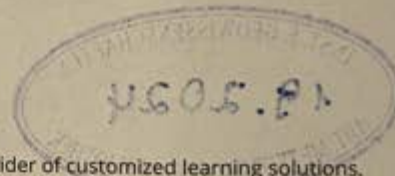
Library of Congress Control Number: 2023904918

Student Edition:

ISBN: 978-0-357-97687-6

**Cengage**

5191 Natorp Boulevard  
Mason, OH 45040  
USA



Cengage is a leading provider of customized learning solutions. Our employees reside in nearly 40 different countries and serve digital learners in 165 countries around the world. Find your local representative at [www.cengage.com](http://www.cengage.com).

To learn more about Cengage platforms and services, register or access your online learning solution, or purchase materials for your course, visit [www.cengage.com](http://www.cengage.com).

# Extreme Weather & Climate <sup>2e</sup>

**C. Donald Ahrens**

Emeritus, Modesto Junior College

**Perry Samson**


University of Michigan

**Kevin A. Reed**

Stony Brook University

α γ LEH2-AHR



 **Cengage**

Australia • Brazil • Canada • Mexico • Singapore  
United Kingdom • United States