

Weather: A Concise Introduction

From a world-renowned team at the Department of Atmospheric Sciences at the University of Washington, Seattle, *Weather: A Concise Introduction* is an accessible and beautifully illustrated text covering the foundations of meteorology in a concise, clear, and engaging manner. Designed to provide students with a strong foundation in the physical, dynamical, and chemical processes taking place in the atmosphere, this introductory textbook will appeal to students with a wide range of mathematical and scientific backgrounds.

This textbook provides a practical approach to the study of meteorology. It features a single case study of a midlatitude cyclone that is referred to throughout the whole book to illustrate the basic principles driving atmospheric dynamics and phenomena; boxes on more advanced topics; appendices for additional coverage; chapter summaries listing the “take-home” points discussed; review questions and visual analysis exercises; and color figures and charts clearly illustrating the fundamental concepts. Key terms are evident throughout, and a glossary explains the terms that students will need to understand and become familiar with.

Gregory J. Hakim has undergraduate degrees in Mathematics and Atmospheric Science and a PhD in Atmospheric Science from the University at Albany, State University of New York. He joined the Department of Atmospheric Sciences at the University of Washington in 1999, where he served as Department Chair from 2012 to 2017 and is currently a Professor. He is also a leading scientist in the areas of weather analysis, predictability, and dynamics, and his research interests include weather and climate prediction, hurricanes, past climates, and polar circulation patterns.

He has served on the advisory panel for the Directorate of Geosciences at the National Science Foundation, as Chair of the advisory panel for the Mesoscale and Microscale Meteorology Laboratory at the National Center for Atmospheric Research (NCAR), as a member of the NCAR Advisory Panel, as a member of the NCAR Strategic Planning Council, and as Chair of the University Corporation for Atmospheric Research’s President’s Advisory Committee on University Relations.

Jérôme Patoux earned a Master in Environmental Engineering from the University of Texas at Austin and a PhD in Atmospheric Science from the University of Washington. He has been funded by the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), the Office of Naval Research (ONR), and the National Oceanic and Atmospheric Administration (NOAA). He has taught undergraduate introductory meteorology for many years and has been funded by the NSF to develop weather and climate curriculum. He is a former faculty member from the Department of Atmospheric Sciences at the University of Washington and currently teaches in the Education Division of the Museum of Science and Industry in Chicago.

Weather

A Concise Introduction



Second Edition

GREGORY HAKIM

University of Washington

JÉRÔME PATOUX

University of Washington



CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom
One Liberty Plaza, 20th Floor, New York, NY 10006, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India
103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781108832717
DOI: 10.1017/9781108963688

© Gregory J. Hakim and Jérôme Patoux 2022

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2022

Printed in the United Kingdom by TJ Books Limited, Padstow Cornwall

A catalogue record for this publication is available from the British Library.

ISBN 978-1-108-83271-7 Hardback
ISBN 978-1-108-96559-0 Paperback

Additional resources for this publication at www.cambridge.org/weather2

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Contents

List of Boxes	<i>page x</i>		
Preface	xi		
Introduction	xiii		
CHAPTER 1 Weather Variables	1		
1.1 Temperature	1	2.2.1 Isotherms and Temperature Maps	23
1.1.1 Heat and Temperature	2	2.2.2 Temperature Fronts	24
1.1.2 Thermometers	3	2.2.3 Isobars and Pressure Maps	25
1.1.3 Temperature Measurements	4	2.2.4 Highs, Lows, Ridges, and Troughs	25
1.1.4 Temperature Scales	4		
1.1.5 Radiosonde Profiles	5		
1.2 Pressure	6	2.3 Upper-Level Maps	28
1.2.1 Force and Pressure	7	2.4 Radar	30
1.2.2 Atmospheric Pressure	8	2.5 Satellites	32
1.2.3 Vertical Distribution of Pressure	8	2.5.1 Visible Satellite Images	33
1.2.4 Barometers	10	2.5.2 Infrared Satellite Images	33
1.2.5 Pressure Units	11	2.5.3 Water Vapor Images	36
1.2.6 Some Useful Numbers	11	2.5.4 Geostationary Satellites	36
		2.5.5 Polar-Orbiting Satellites	39
1.3 Wind	12	Summary	42
1.3.1 Measuring Wind	12	Review Questions	42
1.3.2 Reporting Wind	13	Appendix 2.1 Important Satellite Cloud Signatures	44
1.3.3 Additional Sources of Wind Information	14	CHAPTER 3 Our Atmosphere: Origin, Composition, and Structure	46
1.4 Precipitation	15	3.1 Aspect	46
1.5 Weather Stations	15	3.2 Composition	46
Summary	17	3.3 Origin and Evolution	48
Review Questions	18	3.4 Future Evolution	51
Appendix 1.1 Instruments and the Birth of Modern Science	19	3.5 Vertical Structure	53
		Summary	56
CHAPTER 2 Spatial Representations of Weather Data	20	Review Questions	56
2.1 The Station Model	20	Appendix 3.1 Dynamic Equilibrium	58
2.2 Surface Maps	23	CHAPTER 4 Heat and Energy Transfer	59
		4.1 Conduction	60

4.2	Convection	60	5.7.3	Radiosonde Profiles	94
4.3	Radiation	61	5.7.4	Back to Relative Humidity	95
4.3.1	The Nature of Electromagnetic Radiation	62	5.7.5	How to Saturate	96
4.3.2	Temperature and Radiation	62		Summary	97
4.4	Radiative Interactions	63		Review Questions	97
4.4.1	Absorption	63	CHAPTER 6	Cloud Formation	99
4.4.2	Reflection	65	6.1	Adiabatic Processes	100
4.4.3	Scattering	66	6.2	Adiabatic Processes in the Atmosphere	102
4.4.4	Radiative Equilibrium	66	6.3	Dry Adiabatic Lapse Rate	103
4.4.5	Selective Absorbers	68	6.4	Relative Humidity during Adiabatic Processes	104
4.4.6	A Window to the Sky	70	6.5	Moist Adiabatic Lapse Rate	105
4.4.7	The Greenhouse Effect	71	6.6	Orographic Lifting	106
4.5	Radiation and Weather	73	6.7	Lifting by Convergence	110
4.5.1	Heat Imbalance	73	6.8	Frontal Lifting	111
4.5.2	Seasonal Variations	75	6.9	Atmospheric Stability and Clouds	111
4.5.3	Diurnal Variations	76	6.9.1	Stable Air	112
4.5.4	The Influence of Clouds	78	6.9.2	Unstable Air and Thermals	113
4.5.5	Land–Ocean Contrasts	78	6.9.3	Stable vs. Unstable	113
	Summary	80	6.9.4	Fair-Weather Cumulus Clouds	115
	Review Questions	81	6.9.5	Conditional Instability and Cumulonimbus	118
CHAPTER 5	Water	83		Summary	121
5.1	The Water Cycle	83		Review Questions	121
5.2	Saturation	84	Appendix 6.1	A Cloud Family Album	123
5.3	Humidity	85	Appendix 6.2	Skew-T, Log-P Diagram	127
5.4	Relative Humidity	86	CHAPTER 7	Precipitation	130
5.5	Humidity and Temperature	87	7.1	Warm vs. Cold Clouds	130
5.5.1	Relative vs. Absolute Humidity	88	7.2	Collision and Coalescence	131
5.5.2	Condensation	89			
5.6	Dew Point Temperature	91			
5.7	Applications of the Dew Point Temperature	92			
5.7.1	Surface Weather Maps	92			
5.7.2	Meteograms	92			

7.3 Ice-Crystal Growth	132	9.4 Some Large-Scale Circulations	171
7.4 Precipitation Types	135	9.4.1 West Coast vs. East Coast	171
Summary	137	9.4.2 Antarctica	172
Review Questions	138	9.4.3 The Sahel	172
Appendix 7.1 Some Optical Phenomena	139	9.4.4 The Indian Monsoon	175
CHAPTER 8 Wind	141	9.4.5 El Niño	176
8.1 Force and Acceleration	141	9.4.6 The Madden–Julian Oscillation	180
8.2 Pressure Gradient Force	142	Summary	181
8.3 Sea Breeze and Land Breeze	143	Review Questions	183
8.4 Coriolis Force	144	Appendix 9.1 Winds of the World	185
8.5 Geostrophic Wind	146	CHAPTER 10 Air Masses, Fronts, and	186
8.6 Gradient Wind	149	Midlatitude Cyclones	
8.7 Surface Winds	150	10.1 Air Masses	186
8.8 Friction	152	10.2 Fronts	187
8.9 Topography	155	10.2.1 Stationary Fronts	188
8.9.1 Mountain Breeze and Valley Breeze	155	10.2.2 Cold Fronts	188
8.9.2 Katabatic Winds	157	10.2.3 Warm Fronts	188
Summary	158	10.2.4 Occluded Fronts	189
Review Questions	159	10.2.5 Large-Scale Influences on	
Appendix 8.1 History in Motion	160	Cyclone Structure, and the	
CHAPTER 9 Global Wind Systems	161	T-bone Model	190
9.1 The Averaged Atmosphere	162	10.3 Midlatitude Cyclone Development	191
9.1.1 Surface Temperature	162	10.3.1 The Life Cycle of a	
9.1.2 Upper-Level Heights	163	Midlatitude Cyclone	191
9.1.3 Surface Pressure	167	10.3.2 Vertical Structure of Cyclones	192
9.1.4 Precipitation	167	10.3.3 The February 2014 Cyclone	195
9.2 The Single-Cell Model	169	10.3.4 Where Do Cyclones Form?	197
9.3 The Three-Cell Model	170	Summary	204
		Review Questions	205
		Appendix 10.1 Southern Hemisphere	
		Midlatitude Cyclones	207
		Appendix 10.2 The Bergen School	
		of Meteorology	208
		CHAPTER 11 Thunderstorms	209
		and Tornadoes	
		11.1 Ordinary Thunderstorm	210

11.2 Severe Thunderstorm	211	13.5 From Forecast Grids to Reliable Forecast Values	248
11.3 Lightning and Thunder	213	13.6 Making a Forecast	250
11.4 Supercells	215	13.6.1 Medium- to Long-Range Forecasting	251
11.5 Tornadoes	217	13.6.2 Seasonal Outlook	252
11.5.1 Description	217	Summary	252
11.5.2 Tornado Development	217	Review Questions	254
11.5.3 Tornado Alley	220	Appendix 13.1 Data Assimilation: From Observations to Weather Forecast Grids	255
Summary	222		
Review Questions	224		
CHAPTER 12 Tropical Cyclones	226	CHAPTER 14 Air Pollution	256
12.1 Facts and Figures	227	14.1 Pollutants	256
12.2 Tropical Cyclone Structure	228	14.1.1 Gases and Compounds	257
12.3 Tropical Cyclone Development	233	14.1.2 Particulates	257
12.3.1 Tropical Easterly Wave	233	14.1.3 Air Quality	258
12.3.2 Tropical Depression	233	14.1.4 Photochemical Smog	258
12.3.3 Tropical Storm	234	14.2 Wind and Stability	259
12.3.4 Tropical Cyclone (Hurricane)	234	14.3 Large-Scale Patterns	262
12.3.5 Tropical Cyclone Decay	234	14.4 Topography	263
12.4 Tropical Cyclone Hazards	235	Summary	263
12.5 Conditions for Tropical Cyclone Development	236	Review Questions	264
Summary	236	CHAPTER 15 Climate Change and Weather	266
Review Questions	237	15.1 Past and Future	267
Appendix 12.1 In the Eye of the Storm	239	15.2 Changing Composition	269
CHAPTER 13 Weather Forecasting	240	15.3 A Warmer World	269
13.1 Weather Forecasts and Uncertainty	241	15.4 An Altered Water Cycle	270
13.2 Prognostic Equations	241	15.5 Changing Global Wind Systems	272
13.3 Ensemble Forecasting	244	15.6 Midlatitude and Tropical Cyclones in a Warmer World	273
13.4 Chaos and Weather Prediction	247		

15.7 Beyond Weather	273	Appendix: Contiguous United States	
		Reference Map	279
15.8 The Forecast	274	Glossary	280
Summary	275	References	292
Review Questions	276	Credits	293
Appendix 15.1 Modeling Earth's Climate	278	Index	297

Boxes on Advanced Topics

1.1 The Law of Conservation of Energy	2	4.5 Feedback Loops	73
1.2 Meteorology in Times of War	6	5.1 Dalton's Law	86
1.3 The Law of Conservation of Mass	7	5.2 The Birth of Thermodynamics	89
1.4 The Ideal Gas Law	8	6.1 Fog	101
1.5 A Compressible Atmosphere	9	6.2 The First Law of Thermodynamics	102
1.6 The Law of Conservation of Momentum	12	6.3 The First Law of Thermodynamics, Revisited	105
2.1 A (Simplified) Weather Station Model	21	6.4 Buoyancy and Archimedes' Principle	112
2.2 Adjustment of Pressure to Mean Sea Level	27	6.5 Stability	114
2.3 Women in Meteorological Science and Engineering	33	7.1 From Polar Research to Plate Tectonics	133
3.1 Photosynthesis and the Carbon Cycle	50	7.2 Ice Crystals	136
3.2 Chapman Reactions	51	8.1 The Coriolis Force	146
3.3 The Discovery of the Ozone Hole	54	8.2 Geostrophic Balance	148
4.1 Radiation Laws	64	8.3 Balance of Forces and Geostrophic Wind	149
4.2 Applications of Scattering	67	8.4 Curved Flow	150
4.3 Radiation and Temperature	68	8.5 Highs and Lows	152
4.4 Selective Absorption and Emission of Radiation	69	8.6 Surface Winds	153
		11.1 The Fujita Scale	218

Preface

Having taught introductory classes on weather many times, we came to see the need for a textbook on the subject that covers the foundations of meteorology in a concise, clear, and engaging manner. We set out to create an informative, cost-effective text that meets the needs of students who may not have any background in mathematics and science. The result – *Weather: A Concise Introduction* – is an introductory meteorology textbook designed from scratch to provide students with a strong foundation in the physical, dynamical, and chemical processes taking place in the atmosphere.

This textbook is unique in that it

- ▶ provides a concise and practical approach to understanding the atmosphere;
- ▶ introduces the basic physical laws early on and then ties them together with a single case study spanning the book;
- ▶ presents weather analysis tools early in the book to allow instructors to engage in discussions of current weather in tandem with the basic concepts, thus attracting and retaining student interest; and
- ▶ facilitates students' learning and understanding of the fundamental aspects of weather analysis and forecasting, as well as practical skills, through a careful description of the forecasting process. Modern methods, such as ensemble forecasting, are central to the approach.

Features

Case Study: February 2014 Cyclone

The main concepts of the book are illustrated in Chapters 2–13 by a single case study: a midlatitude cyclone that swept through the eastern half of the United States between February 19 and 22, 2014. This rich case study serves as a common thread throughout the book, allowing students to study it from multiple perspectives. Viewing the storm in the context of different topics provides a familiar setting

for mastering new subjects and for developing a holistic understanding of midlatitude cyclones.

Boxes on More Advanced Topics

Instructors have the option of including more advanced coverage through use of boxes that provide insights on various topics. For example, in Chapter 1, “Weather Variables,” boxes include an in-depth description of the four laws of physics that are central to the study of the atmosphere. The book contains 33 boxes, affording instructors the opportunity to tailor the level of the material that they present to students in their course.

Appendixes for Additional Coverage

End-of-chapter appendixes include additional material on important cloud signatures found in satellite imagery; the concept of dynamic equilibrium; cloud classification; the Skew-T, Log-P diagram; some optical phenomena; southern hemisphere midlatitude cyclones; and historical insights on instruments and the birth of modern science, the laws of motion, the general circulation models, the Bergen School of meteorology, the structure of tropical cyclones, data assimilation in numerical weather prediction, and the modeling of Earth's climate.

Summaries and Review Questions

A summary of key points and review questions have been included at the end of each chapter so that students can confirm that they have understood the significant take-away facts and ideas.

Figures, Charts, and Maps

Figures have been designed to convey the key concepts in a simple and self-explanatory way, keeping in mind that clean representations of information are more helpful to students than complex drawings. Graphs

and maps have been created with real data as much as possible, obtained from NOAA, NASA, ECMWF, and similar research-quality sources referenced in the text.

Key Terms and Glossary

The main text contains terms (in bold) that students need to understand and become familiar with. Many of these terms are listed in the Glossary at the back of the book. The Glossary allows the reader to look up terms easily whenever needed and can also be used to review important topics and key facts.

SI Units

We have consistently used SI units throughout the book, while providing alternative units whenever possible or relevant.

Organization

The first two chapters provide a general overview of key variables and weather maps used by meteorologists, which facilitates daily weather map discussions early in the course. We have found that motivating lecture topics with real-time examples using weather map discussions is a very effective way to engage students in the lecture material, and it allows instructors to introduce aspects of weather forecasting at their discretion well in advance of discussing the material more completely in Chapter 13. As a result, students are more invested in adding to their knowledge, which builds systematically toward understanding and predicting weather systems.

Chapters 3–8 provide foundational material on the composition and structure of the atmosphere, along with the application of the laws of classical physics to emphasize and explain the role of energy, water, and wind in weather systems.

Chapters 9–12 apply the foundational material to understanding the general circulation of the

atmosphere (Chapter 9), midlatitude cyclones and fronts (Chapter 10), thunderstorms (Chapter 11), and tropical cyclones (Chapter 12).

Chapters 13–15 build further on the first 12 chapters by applying the concepts developed to explain processes that affect how weather forecasts are made (Chapter 13), air pollution (Chapter 14), and climate change (Chapter 15).

Instructor Resources

A companion website at www.cambridge.org/weather contains PowerPoint slides of the figures in the text as well as a testbank of questions.

Acknowledgments

We thank NOAA, NASA, and ECMWF for providing access to data and images; Reto Knutti, Jan Sedlacek, and Urs Beyerle for providing access to IPCC data; Rick Kohrs from the University of Wisconsin–Madison for providing global composite satellite imagery; and Paul Sirvatka from the College of DuPage for providing radar imagery.

We also thank Ángel Adames, Becky Alexander, Ileana Blade, Peter Blossey, Michael Diamond, Ralph Foster, Dargan Frierson, Qiang Fu, Dennis Hartmann, Paul Markowski, Cliff Mass, Lynn McMurdie, Max Menchaca, Yumin Moon, Scott Powell, Virginia Rux, David Schultz, Justin Sharp, Brian Smoliak, Mike Warner, Steve Warren, Rachel White, Darren Wilton, Matt Wyant, and Qi Zhong, as well as 13 anonymous reviewers, for their help in preparing this book.

This project would not have come to life without the support, help, influence, and constructive criticism from many fellow professors, teaching assistants, and students. We cannot acknowledge them all here by name, but we thank them nevertheless for the important role they have played in shaping the development of this book.

Introduction

Why should we study our atmosphere? Why should we learn about the causes and mechanisms of our weather? Weather affects our daily life: the clothes we wear (rain coat, shorts, hat, should we take an umbrella or sunglasses . . . ?), the means of transportation we choose (walk, take a bus, ride our bike . . . ?), our activities (ski, sail, water our plants, read a book in a coffee shop . . . ?), and probably more. But beyond our daily concerns, weather affects society at large. Schools close when snow impedes traffic. Visitors to ski resorts might be more impatient for snow, while the ski instructors will be keeping an eye on the possibility of avalanches. Rangers are concerned with fog, thunderstorms, and flash floods. Fire patrols look for weather patterns that are conducive to forest fires (dryness, wind). Electricity providers are concerned by windstorms that can damage the infrastructure of the electrical grid and, on larger timescales, also need to plan how weather will affect upcoming energy needs (minimum temperatures impact heating, while maximum temperatures impact air conditioning). Weather averages, such as prevailing winds, the typical temperature range, and mean precipitation determine how we build our homes and what locations are sensitive to extreme events, such as droughts, floods, hurricanes, and tornadoes. On longer timescales, we can ask how humans are changing the atmosphere and what those changes imply for the weather and climate of the future.

To start answering those questions, we need to understand how the atmosphere works. We need to identify the basic processes that drive the atmosphere and the laws that govern atmospheric processes. By doing so, we will be able to explain the weather phenomena we experience around the year and throughout the world. Furthermore, we will be able to apply these laws to the current state of the atmosphere and *predict* how it will evolve in the future.

There is a lot of value in becoming a knowledgeable observer of the atmosphere. After reading this book, you will look at the sky differently, and you will gain an



understanding of weather and climate that will make you more attentive to the world around you. You will have a basic understanding of weather phenomena – of cyclones, thunderstorms, and hurricanes – and you will understand the basic aspects of weather forecasting. You will see beyond the weather forecast you get on your phone, radio, TV, or the internet, and you will be able to make your own forecast in many situations.

Weather and Climate

Before we continue, let us clarify an important distinction between weather and climate. **Weather** is the *condition of the atmosphere at a particular time and location*. Weather varies on timescales of minutes to days. **Climate**, by contrast, is an *average of the weather*. It varies

on timescales of decades to centuries and beyond. In this textbook, we will be concerned mostly with weather – even though many of the concepts have direct application to climate.

Getting Started

Our exploration of weather will start with a quick overview of important weather elements that we can observe or measure and that we can analyze. The choice of variables to observe is influenced by the laws of physics that govern the atmosphere. As we will see shortly, the atmosphere is made of *matter* (air, water, etc.), it contains *energy* (heat), and it is in *motion* (wind, convection). Our understanding of weather is based on the fundamental notion that matter, energy, and motion obey *conservation laws*. To apply these conservation laws to the atmosphere requires observations of

temperature (conservation of energy), pressure (conservation of mass), and wind (conservation of momentum), along with humidity, precipitation, and clouds. One step at a time, and one building block over another, we will then investigate the physical processes that underlie the atmosphere at work. Finally, we will articulate these processes together to build a picture of weather systems, such as midlatitude cyclones, thunderstorms, and hurricanes. In doing so, we will follow the precepts of René Descartes, who advocated, as early as 1637, that every difficult problem should be divided into small parts and that one should always proceed from the more simple to the more complex. This cornerstone of the scientific method, still in favor today, will be an important aspect of our exploration as we elaborate a thorough understanding of the atmosphere from its most fundamental constituents at the molecular scale to its most complex inner workings as a system for moving heat at the global scale.