SEVERE CONVECTIVE STORMS AND TORNADOES

Observations and Dynamics

Howard B. Bluestein

Springer

PRAXIS

Severe Convective Storms and Tornadoes

Observations and Dynamics

Howard B. Bluestein

Severe Convective Storms and Tornadoes

Observations and Dynamics

Springer

Published in association with
Praxis Publishing
Chichester, UK

PRAXIS

Professor Howard B. Bluestein
School of Meteorology
University of Oklahoma
Norman
Oklahoma
U.S.A.

SPRINGER–PRAXIS BOOKS IN ENVIRONMENTAL SCIENCES

ISBN 978-3-642-05380-1 ISBN 978-3-642-05381-8 (eBook)
DOI 10.1007/978-3-642-05381-8
Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2012943848

© Springer-Verlag Berlin Heidelberg 2013
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Cover design: Jim Wilkie
Project management: OPS Ltd., Gt. Yarmouth, Norfolk, U.K.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Contents

Dedication ix

Preface xi

Acknowledgments xiii

List of figures xv

List of abbreviations and acronyms xxv

1 Introduction 1
- 1.1 Basic definition of severe convective storms and scope of the material 1
- 1.2 A brief history of severe storm field programs and numerical modeling efforts 3
  - 1.2.1 Field programs and instrument development 3
  - 1.2.2 Numerical model simulation experiments 22
- 1.3 Methods to be employed 23
- 1.4 General monographs and books 24
- 1.5 References and bibliography 25

2 The basic equations 27
- 2.1 The equations of motion. 27
  - 2.1.1 The horizontal equation of motion 27
  - 2.1.2 Buoyancy and the vertical equation of motion: defying gravity 28
- 2.2 Thermodynamics 32

2.3 Conservation of mass, and the Boussinesq and anelastic approximations . . . 34
  2.3.1 The Boussinesq approximation . . . 36
  2.3.2 Anelastic approximation . . . 37
  2.3.3 Water substance . . . 38
2.4 The vorticity and circulation equations . . . 41
2.5 The divergence equation and the buoyancy force . . . 45
  2.5.1 Buoyancy-induced and dynamically induced pressure perturbations . . . 46
  2.5.2 Retrieval of pressure and buoyancy fields from the wind field . . . 51
  2.5.3 Quantitative analysis of a buoyant sphere in a resting environment . . . 53
2.6 Ertel's potential vorticity . . . 60
2.7 The Exner function as a vertical coordinate, potential temperature as a thermodynamic variable, and the pseudo-incompressible continuity equation . . . 60
2.8 Simple, idealized models of dry convection: plumes and bubbles . 63
  2.8.1 Similarity models of plumes and thermals . . . 65
  2.8.2 The plume dynamical model . . . 66
2.9 Introduction to Rayleigh–Bénard convection . . . 71
  2.9.1 Convection in a resting atmosphere without rotation . . . 73
  2.9.2 Convection in a resting atmosphere with rotation . . . 80
  2.9.3 Convection in a linearly sheared atmosphere without rotation . . . 83
2.10 Response of a Boussinesq atmosphere to heat sources . . . 85
2.11 Similarity of fluid dynamics equations to electromagnetic equations . . . 90
2.12 General monographs and books . . . 90
2.13 References and bibliography . . . 90

3 Ordinary-cell convective storms . . . 95
3.1 Observations and dynamics . . . 96
  3.1.1 Conditional instability and the initiation of deep convection . . . 96
  3.1.2 Entrainment and convective initiation . . . 98
  3.1.3 Observed life cycle and vertical velocity . . . 104
3.2 Gust fronts and downdrafts . . . 120
  3.2.1 Gust fronts in the absence of vertical wind shear . . . 120
  3.2.2 Gust fronts in the presence of vertical shear: RKW theory 146
  3.2.3 Gravity waves forced by a density current . . . 153
3.3 Multicell convective storms . . . 153
3.4 General monographs and books . . . 158
3.5 References and bibliography . . . 160

4 Supercells 165
- 4.1 Supercells and the bulk Richardson number 166
- 4.2 Observed supercell behavior and early theories 173
- 4.3 Observed supercell structure: cloud features, precipitation distribution, polarimetric radar–observed parameters, and wind and temperature fields 176
  - 4.3.1 The main updraft in supercells 176
  - 4.3.2 Downdrafts: forward-flank downdraft and the rear-flank downdraft 185
  - 4.3.3 Precipitation type and distribution 205
- 4.4 The production of mid-level rotation. 209
- 4.5 Interaction of vertical shear with updrafts/downdrafts forced by buoyancy: linear and nonlinear pressure effects 213
  - 4.5.1 Convective storm dynamics for straight hodographs . . . 219
  - 4.5.2 Convective storm dynamics for curved hodographs 226
  - 4.5.3 Straight vs. curved hodograph dynamics: two paradigms. 230
  - 4.5.4 Sensitivity of simulated supercell structure to environmental thermodynamic and cloud microphysics parameters . 237
- 4.6 The Deep Convergence Zone (DCZ) 240
- 4.7 The production of low-level rotation 240
  - 4.7.1 The "owl horn" echo 246
- 4.8 The life cycle of the mesocyclone and cyclic mesocyclogenesis . . 246
- 4.9 Supercell structure and behavior in relation to inhomogeneities in the environment, and interactions with neighboring storms and surface boundaries 252
  - 4.9.1 Neighboring cell interaction 252
  - 4.9.2 Movement across outflow boundaries or fronts 255
- 4.10 Rotating downdrafts in convective storms 256
- 4.11 General monographs and books. 258
- 4.12 References and bibliography 258

5 Mesoscale convective systems 265
- 5.1 Formation 266
- 5.2 Morphology 273
- 5.3 The dynamics and thermodynamics of mature MCS squall lines 292
- 5.4 The production of vortices in MCSs 296
- 5.5 General monographs and books. 304
- 5.6 References and bibliography 304

6 Tornadoes 307
- 6.1 Basic observational aspects of tornadoes 307
- 6.2 Tornado climatology 326
- 6.3 Tornado research 332
- 6.4 Types of tornadoes and tornado-like vortices 334
- 6.5 Tornado vortex formation: tornadogenesis 342

6.5.1 Tornado-like vortices in a vortex chamber 342
6.5.2 Stretching of pre-existing vertical vorticity 344
6.5.3 Tilting of horizontal vorticity into the vertical, followed by stretching underneath an updraft 347
6.5.4 The dynamic pipe effect and the vertical propagation of vortices 352
6.5.5 Role of downdrafts in enhancing and transporting vorticity 354
6.5.6 Negative viscosity 356
6.5.7 Two-celled mesocyclones and shear instabilities 357
6.5.8 Cyclic tornadogenesis 357
6.5.9 Counter-rotating tornado pairs 359
6.6 Vortex dynamics 360
6.6.1 Vortex structure 363
6.6.2 Maximum possible wind speeds in tornadoes 383
6.7 Economic and societal impacts 404
6.8 Unresolved problems and challenges for future research, with suggestions for improved measurement capabilities 405
6.9 General monographs and books 407
6.10 References and bibliography 407

7 Forecasting and future work 417
7.1 Short-range forecasting 417
7.1.1 Ingredients-based forecasting 417
7.1.2 Model-based forecasting 421
7.1.3 Evaluations of forecast skill 423
7.2 Forecasting and climate change 424
7.3 Future research 425
7.4 General monographs and books 426
7.5 References and bibliography 427

Appendix: Doppler radar analysis techniques 429

Index 439

To the memory of my late mother and father,
to my wife Kathleen, and
to whoever put the bop in the bop shoo-bop.
If severe convection be the food of love, play on

Preface

During the World's Exposition in Chicago in 1893, Frederick Turner Jackson delivered a talk entitled "The Significance of the Frontier in American History". As the frontier of new land to be explored was coming to an end, he raised the question of how American society might change in response to its end. The severe convection "frontier" in the U. S. is steadily disappearing now because—with the advent of the Internet, cellphone technology, and cable television channels devoted exclusively to the weather—severe convective storms and tornadoes are being observed and documented all the time, even in remote places, by both meteorologists and non-meteorologists alike, and made available for mass viewing. Observing a tornado used to be a very rare occurrence.

While the observational severe convection frontier is disappearing, the knowledge frontier is still with us, as is the beauty of severe convective phenonmena. I wrote this book in response to a need for updated material for a graduate course on convective clouds and storms, with an emphasis on severe convective storms and tornadoes, that I have taught at the University of Oklahoma roughly once every other year for the past three decades. It has become very difficult for students to learn just from my class lectures and journal articles covering more than three decades. This course has evolved considerably, especially in the last decade and a half, with the advent of mobile Doppler radars and more sophisticated numerical models. It is hoped that this text will be useful not only to students, but also as a reference for researchers and forecasters.

The contents of this book are heavily influenced by an introductory course on convection taught by Prof. Norm Phillips at MIT in 1970, but not fully appreciated by the author then, and by the American Meteorological Society's (AMS) 1963 monograph on *Severe Local Storms*, edited by Dave Atlas, which contains seminal contributions by the editor, Ted Fujita, Chester Newton, and Frank Ludlam, among others. While there have been more recent contributions such as the latest, updated AMS monograph on severe local storms, which contains disparate contributions from many authors, Kerry Emanuel's textbook on many types of convection (but without an emphasis on severe convection or tornadoes), and Bob Houze's textbook on clouds (which covers a very broad range of topics), I felt compelled to produce a work from my own perspective as an avid observationalist and participant in over three decades of storm chasing, mainly with mobile instruments. This text should be considered a work in progress; since the pace of research in severe convective storms and tornadoes is rapid, I encourage the student and other readers to keep abreast of more recent journal articles. Despite this book's assured obsolescence in a relatively short time, I hope that most of the core dynamical issues addressed herein will be "current" for much longer.

No attempt has been made to be all inclusive; some topics have been ignored altogether and the student/reader must look elsewhere for detailed treatments on, for example, moist thermodynamics, cloud and precipitation microphysics, numerical modeling techniques for convective clouds, data assimilation techniques for cloud models, objective analysis of data, lightning and other electrical phenomena, radar meteorology, and shallow convection. By doing so it is hoped that the topics discussed herein will be adequate for a one-semester course. Students can take more specialized courses on the topics not covered in detail or ignored altogether. It is also recognized that there may be some overlap between the topics covered in this text and some topics covered in mesoscale meteorology courses (e.g., density currents and gravity waves may also be considered purely mesoscale phenomena and not exclusively associated with convection). Density currents are most frequently driven by water phase changes in convective clouds, so they are detailed here; gravity waves, on the other hand, frequently occur in the absence of convection, so we do not detail their dynamics.

To a better understanding of the wind and rain and hail ...

Howie "Cb" Bluestein
Norman, OK and Boulder, CO
December 2011

Acknowledgments

As the Beatles once sang, "I get high with a little help from friends." So be it for this book. Many colleagues, friends, and students contributed in various ways to this text. At the University of Oklahoma (OU) I am indebted to the chairs of the School of Meteorology the late Rex Inman, and Jeff Kimpel, Claude Duchon, Bill Beasley, Fred Carr, and Dave Parsons and to OU colleagues Kelvin Droegemeier, Pete Lamb, and OU president David L. Boren for their support. Much of my research funding has come from the National Science Foundation with the aid of the late Ron Taylor, and Steve Nelson and Brad Smull. I thank the reviewers of research proposals and manuscripts who have anonymously supported and assisted my work and that of my students. Colleagues and friends Rich Rotunno and Morris Weisman at NCAR, and John Brown at NOAA, in Boulder, have provided many years of stimulating scientific and recreational interaction and assistance with various aspects of this work. Lance Bosart at the University of Albany/SUNY has for years been an enabler of weather addicts such as me while at the same time holding me accountable to the advancement of science. The late Bob Burpee (formerly at the Hurricane Research Division and National Hurricane Center in Miami) was always supportive of my convective interests. I am particularly thankful for the many graduate and undergraduate students at OU over the years, too numerous to list in entirety, who have chased storms with me both formally as part of their courses of research and informally just for the fun of it. Teaching has always been a two-way street and the students have willingly shared their enthusiasm for meteorological phenomena of the buoyant, rotational, and violent kind. Graduate students Jana Houser, Jeff Snyder, Mike French, Robin Tanamachi, Vivek Mahale, Chris Weiss, David Dowell, and Matthew Kramar were "instrumental" in conducting our field experiments using mobile Doppler radars. Rodger Brown at NSSL, Keith Browning (ret.), Dave Atlas (ret.), and Jerry Brotzge at OU assisted with fact checking and other matters. I also thank collaborators Al Bedard (formerly at NOAA WPL), the late Wes Unruh (formerly at LANL), Andy Pazmany (formerly at the University of Massachusetts and currently at ProSensing), the late Bob McIntosh (formerly at U. Mass.), Steve Frasier (U. Mass.), Bob Bluth (NPS), Ivan PopStefanija (ProSensing), and others for support with in situ instruments and radars over the years. The late Joanne Simpson at EML in Miami was kind enough to take me, as a graduate student, on a flight into and out of big thunderstorms over central Florida during her randomized cloud-seeding experiment. Dave Jorgensen (NSSL) and Roger Wakimoto (formerly at UCLA and currently at NCAR) made it possible for me to participate in data collection on the NOAA P-3 and ELDORA aircraft, respectively. Joe Golden (formerly at NOAA) kindly allowed me to fly around waterspouts with him. OU colleagues Brian Fiedler and Al Shapiro have generously provided time to discuss various scientific problems. I appreciate Kerry Emanuel's (MIT) support over the years, especially during an extended visit to MIT, and for the example he has set for research excellence. His textbook on convection and the work and textbook on clouds by Bob Houze (University of Washington) and Bob's research have represented standards to which I have aspired. Much inspiration has come from the work of the late Ted Fujita (formerly at the University of Chicago), and Don Burgess, Bob Davies-Jones and his colleagues at NSSL. The late Pauline Austin and Speed Geotis (formerly at MIT) freely exchanged ideas about convection when I was in graduate school; Speed entertained me during a stint on the R.V. *Gillis* in the Intertropical Convergence Zone in the western north Atlantic during GATE in the late summer of 1974, when I operated the onboard radar. Norm Phillips' "notes" at MIT also played an important role in this textbook. I thank Ed Kessler, the first director of NSSL, for suggesting that I move to Norman to study severe convective storms and tornadoes and my advisor at MIT, the late Fred Sanders for providing the mentoring necessary to set me on my convective way. Finally, I thank Clive Horwood and Romy Blott at Praxis Publishing and Robert Doe at Springer Publishing for their support, Jim Wilkie for designing the cover, and Neil Shuttlewood for his expert copyediting.

Figures

1.1–1.10 A non-exhaustive gallery of photographs of people and instruments involved in severe local storms research 4–13
1.11 Waterspouts and tornadoes as seen from airborne platforms 16
1.12 Illustration of pseudo dual-Doppler analysis technique as wind vectors are resolved at fixed points in space from intersecting oblique beams, but at slightly different times 19
2.1 Idealized illustration of Archimedean buoyancy for a box of fluid 30
2.2 Hailstone that fell in Vivian, SD on July 23, 2010 40
2.3 An idealized illustration of positive vorticity about the y-axis 42
2.4 An idealized illustration of the generation of vorticity about the y-axis when buoyancy decreases in the x-direction 43
2.5 An idealized illustration of circulation computation 44
2.6 An idealized illustration of how an air parcel that is accelerated upward by positive buoyancy is opposed by a downward-directed perturbation pressure gradient force 48
2.7 An idealized illustration of the way in which the aspect ratio of a buoyant air parcel affects how much air must be moved out above it and in beneath it 50
2.8 The buoyancy distribution from (2.72) and the perturbation pressure field associated with it 51
2.9 Spherical coordinates 54
2.10 Qualitative depiction of the acceleration field induced by a buoyant, spherical bubble 58
2.11 Qualitative depiction of the perturbation pressure field induced by a buoyant, spherical bubble 59
2.12 Idealized representations and photographs of convection. 64
2.13 Example of a top hat profile for vertical velocity and buoyancy. 67
2.14 Variations of mean radius, mean buoyancy, and a measure of upward vertical mass flux as a function of height in the MTT steady-state plume in a neutral environment for a Gaussian profile in mean vertical velocity and mean buoyancy 70

2.15 Bénard–Rayleigh-like convection represented by cells of clouds over the Gulf of Mexico and cumulus clouds over land 72
2.16 Setup for Rayleigh–Bénard convection 74
2.17 Cloud streets over land as viewed from an aircraft 84
2.18 Evidence of clear-air boundary rolls by a radar and a lidar 86–7
2.19 Idealized illustration of the tilting of horizontal vorticity associated with horizontal convective rolls into the vertical by ascending air along a dryline 87
2.20 Illustration of where convection might be preferentially initiated along a surface boundary 88–9
3.1 Illustration of how some significant thermodynamic parameters are computed from a sounding using as an example a sounding ahead of the dryline 97
3.2a Elevated convection 100
3.2b Altocumulus castellanus 101
3.3 Schematic illustrating forced lift over a surface front, an outflow boundary, or orography 102
3.4 Illustration of entrainment of environmental air into a cloud 102
3.5 Cumulonimbus anvil 103
3.6 Illustration of how low-level convergence reduces static stability in a stable atmosphere 105
3.7 Anvil domes at the tops of convective storms 106
3.8 Schematic of airflow over a dome at the top of a convective storm 107
3.9 Waves in the anvil of a convective storm as seen by satellite 107
3.10 Idealized illustration of dynamic horizontal perturbation pressure gradient forces along the sides of an anvil dome 108
3.11 Color-enhanced infrared signatures at anvil top 108
3.12 Cloud base in a supercell that has striations like an orographic wave cloud and orographic wave clouds in the lee of the Rockies just west of Ward, CO 110
3.13 Example of a "CAPE robber" 111
3.14 Vertical velocity measurements made in a hailstorm in southeastern Montana by the T-28 instrumented aircraft during CCOPE 113
3.15 Measurements of vertical velocity, based on the ascent rate of a radiosonde, inside a tornadic supercell in the Texas Panhandle and a comparison with estimated vertical velocity based on parcel theory 113
3.16 Long anvils 115
3.17 Cumulonimbus with a symmetrical, mushroom-like anvil in eastern Oklahoma 116
3.18 Orphan anvil, Ft. Lauderdale, FL 117
3.19a Stages in the life of a Byers–Braham, ordinary-cell convective storm 118
3.19b Byers–Braham conceptual model of an ordinary-cell convective storm . . . 119
3.20 Gust front passage 122–3
3.21 Illustration of the baroclinic generation of a vortex ring about a region of evaporatively cooled air embedded within an ambient region of warm air, in a tornadic supercell in eastern Oklahoma 123
3.22 Sense of horizontal vorticity near the ground underneath a precipitation-laden downdraft in a convective storm over Oklahoma City, OK. 124
3.23 Dry microburst over southwestern Kansas as viewed from the NOAA P-3 aircraft, and Ted Fujita's single-Doppler analysis of a dry microburst that caused two commercial airlines to abort while landing at Denver's Stapleton Airport 125

3.24 Model of the characteristics of the morning and evening soundings favorable for dry-microburst activity over the High Plains, and model of the thermodynamic descent of a dry microburst from cloud base 126

3.25 Wet-microburst sounding at Oklahoma City, OK 127

3.26 Z_{DR} hole in a microburst in Alabama as depicted by data from the NCAR CP-2 Doppler radar during MIST 128

3.27 Meteogram from a surface station in the Oklahoma Mesonet of a heat burst 130

3.28 Conceptual model of a heat burst as a deformation of a shallow, cool, stable layer at the surface by a descending current of warm, dry air from aloft. . 131

3.29a Cumulonimbus mammatus 132

3.29b Close-up views of mammatus in western Oklahoma, from the NOAA P-3 aircraft, and at Boulder, CO 133

3.30 Ground-based, Ka-band, vertically pointing Doppler radar observations of cumulonimbus mammatus in north central Manitoba, Canada 134

3.31 Ground-based, W-band, vertically pointing Doppler radar observations of cumulonimbus mammatus in South Florida 134

3.32 Mammatus under the anvil of a cumulonimbus cloud which are attached to striations or are organized in lines 135

3.33 Idealized vertical cross section across a cold pool of air near the surface . 137

3.34 Haboob in Arizona 138

3.35 Idealized representation of features in an atmospheric density current associated with a gust front in a convective storm, as seen in a vertical cross section, and the corresponding changes in meteorological parameters at the surface 139

3.36 Illustration of how the cold side/warm side–directed, hydrostatic pressure gradient force decreases with height in a density current 140

3.37 Vertical cross section of idealized density current, in which a cold (dense) pool having a density ρ_2 and depth h propagates into an environment of less density ρ_1 and depth H 140

3.38 Illustration showing how gust front relative flow is decelerated as it encounters an adverse, dynamic pressure gradient force 142

3.39 Illustration of how air flowing up and over a cold pool behaves like air flowing up and over an airfoil, and underside of air flowing up and over a cold pool: the "Whale's Mouth" in north central Oklahoma 143

3.40 Idealized illustration of how a buoyant updraft may be influenced by vertical wind shear and/or a cold pool 147

3.41 Vertical cross section across the leading edge of the cold pool, showing the domain used over which the steady-state, frictionless, horizontal vorticity equation in flux form is integrated 148

3.42 Demonstration of "optimum" orientation of flow normal to a cold outflow from a precipitating convective cloud when environmental shear is as indicated by the vertical profile of gust front relative winds below $z = h$. 149

3.43 As in Figure 3.37, but at the right edge of the domain the flow is uniform and from the right at speed c above $z = h_0$ 151

3.44 Idealized depiction of the vertical cross section of clouds and radar echoes in a multicell convective storm, as seen in the plane of the mean vertical shear vector or, equivalently, from the right side of the storm with respect to its motion; and multicell convective storm in eastern Colorado 154

3.45 Photographs of multicell convective storms 155

3.46 Conceptual model of the three stages in the life cycle of an ordinary convective cell within a mature, multicellular, squall line mesoscale convective system 156
3.47 Conceptual model of stages in the discrete propagation of a multicellular squall line in the forward direction (to the right) as high-frequency gravity waves are forced by the squall line and are trapped beneath the forward anvil 157
3.48 Idealized illustration of "strong" evolution, "weak" evolution, and "quasi-steady" evolution in a convective storm. 158
3.49 Illustration of discrete propagation in a multicell convective storm. 159
3.50 Example of a case in which the cell motion is the same as that of the mean wind, and discrete propagation occurs along a gust front oriented in a meridional direction, so that the storm motion vector lies to the right of the mean wind 159
3.51 Illustration of how the movement of a cold pool relative to the movement of a growing cell results in a phase shift of the buoyancy-induced vertical circulation of the growing cell with respect to the buoyancy-induced vertical circulation of a new cell, such that it is suppressed from above by a subsiding branch of the older cell 160
4.1 Cumulus congestus being sheared off as it develops during several spurts of growth in central Oklahoma. 168
4.2 Thermodynamic composite sounding and hodograph for right-front quadrant in hurricanes. 170
4.3 Idealized illustration of air at mid-levels catching up with and flowing around an updraft inside which lower values of westerly momentum have been advected upward 171
4.4 Illustration of the "Magnus effect" as a clockwise-spinning baseball experiences a force that deflects it to the right 174
4.5 One of the first illustrations of how boundary-layer horizontal vorticity associated with vertical shear could be tilted onto the vertical as fluid parcels in the boundary layer are tilted upward. 175
4.6 Supercell, as viewed from ahead and approximately to the right of storm motion 177
4.7 Storm-relative winds at 400 m AGL, synthesized from an early dual-Doppler radar analysis using fixed site radars operated by NSSL in central Oklahoma 178
4.8 An early simulation of a supercell using the Klemp–Wilhelmson numerical cloud model 179
4.9 Vault observed in a supercell by a radar in central Oklahoma: vertical cross section of radar echo; the vertical scale is exaggerated, and vault/BWER, WER, and "echo overhang" observed in a supercell in north central Oklahoma. 180
4.10 Idealized model of the WER, BWER, and echo overhang in a supercell. . 181
4.11a Examples of crescent-shaped BWERs in supercells in eastern Colorado . . 182
4.11b Examples of crescent-shaped BWERs in supercells in the Oklahoma Panhandle. 183
4.12 Example of a Z_{DR} column in a vertical cross section through a supercell in central Oklahoma 184
4.13 As for Figure 4.12, but for a K_{DP} column 186
4.14 Hook echoes in supercells, and (g) soundings on days when there were tornado outbreaks 187–93

4.15 Conceptual model of the major vertical air currents in a supercell, and ensemble mean vertical velocity and storm-relative ensemble mean wind. . 194
4.16 Example of a "descending reflectivity core" in a supercell 195
4.17 Wall clouds. 196
4.18 Multiple RFD surges in a tornadic supercell 198
4.19 Three-dimensional conceptual model of the storm-relative airflow in a cyclonically rotating, right-moving supercell, showing how the mid-level airstream catches up with the storm and descends behind the rear-flank gust front. 199
4.20 Example of a differential reflectivity arc along the edge of the right-front flank of a supercell's FFD 199
4.21 Idealized illustration of how a supercell that formed in an environment of a clockwise-turning hodograph with height can lead to the enhancement of differential reflectivity Z_{DR} along the edge of the FFD on the right-front flank of the storm 200
4.22 Idealized illustration of some polarimetric signature in supercells and their locations within the storm 201
4.23 The smooth, striated, laminar appearance of the downshear side of the updraft tower of supercells, as viewed from ahead and to the right of the storm movement 202–4
4.24 Example of a DCZ in a supercell in the Texas Panhandle 205
4.25 Low-precipitation supercells 207
4.26 High-precipitation supercells. 208
4.27 Classic supercell. 209
4.28 Idealized representation of a horizontal cross section at low levels of features in an LP supercell, a classic supercell, and an HP supercell 210
4.29 Idealized illustration of how an updraft in an environment of westerly vertical shear tilts a vortex line pointing towards the north so that horizontal vorticity is converted into cyclonic vorticity south of anticyclonic vorticity north of the updraft; idealized illustration of how an updraft that deforms a θ_e surface upward so that there is a bulge/peak also deforms a vortex line upward because the vortex line must always lie on a surface of constant θ_e; and idealized illustration of how circulation in the vertical plane is advected and tilted upward to produce cyclonic circulation in the horizontal plane at mid-levels 211
4.30 A cyclonic–anticyclonic Doppler velocity shear couplet at mid-levels in a supercell in southwestern Oklahoma 214
4.31 Illustration of how updrafts propagate from where the downward-directed dynamic pressure gradient is increasing the most to where the upward-directed dynamic pressure gradient is increasing the most 215
4.32 Idealized example of a straight hodograph. 217
4.33 Illustration of cyclostrophic balance 219
4.34 Illustration of how the dynamic perturbation pressure is high upstream and low downstream from an updraft in a unidirectionally vertically sheared environment 220
4.35 Schematic representation of the splitting process in a unidirectionally sheared environment 221
4.36 Examples of storm-splitting in eastern Montana and as depicted by a sequence of images of radar reflectivity factor at low elevation angle 222–4

4.37 Numerical simulation of an isolated, splitting supercell for unidirectional and hybrid curved low, unidirectional aloft shear profiles 225
4.38 Hodograph in the Ekman layer in the absence of baroclinicity for a boundary-layer geostrophic wind that is southwesterly 226
4.39 Idealized illustration of how a new updraft is encouraged on the downshear side of an updraft and suppressed on the upshear side of an updraft by linear dynamic vertical perturbation pressure gradient forces in unidirectional shear in the presence of a buoyant updraft. 227
4.40 Illustration of half of a circle hodograph, for which the wind vector at any height points in the same direction as the horizontal vorticity vector and normal to the vertical shear vector 227
4.41 Illustration of how the circle hodograph in Figure 4.40, for which the hodograph curves in a clockwise manner with height, promotes new updraft growth to the right and suppresses new updraft growth to the left of the mean vertical shear. 228
4.42 As for Figure 4.41, but from nonlinear dynamic perturbation pressure gradient forces. 229
4.43 Hodograph at Norman, OK showing clockwise curvature from the surface to 2 km and counterclockwise curvature from 2 km to 7 km AGL 230
4.44 Examples of crosswise and streamwise vorticity 232
4.45 Illustration of the relationship between SREH and the area under the hodograph swept out by the storm-relative wind vector from $z = 0$ to $z = h$ 234
4.46 Idealized illustration of how moving the storm motion vector away from the hodograph increases SREH 235
4.47 Illustration of the computation of SREH between the ground and 3 km AGL for a quarter-circle hodograph having a radius of $10\,\mathrm{m\,s^{-1}}$ and a storm motion from the west to the east of $10\,\mathrm{m\,s^{-1}}$ 235
4.48 Supercells in the Gulf of Mexico off the west coast of Florida, in an outer rainband of Hurricane Ivan 237
4.49 An example of convective storms that produced funnel clouds near a cold, upper-level low in Oklahoma 238
4.50 Illustration of how low-level horizontal vorticity may be enhanced by an anvil-generated baroclinic zone due to a horizontal gradient in radiation . 241
4.51 Ensemble mean of the rate of baroclinic generation at 750 m AGL of storm-relative streamwise horizontal vorticity 242
4.52 Idealized illustration showing how streamwise vorticity associated with low-level vertical shear could be advected toward an updraft and tilted to produce a mesocyclone just above the ground. 243
4.53 Material circuit in the horizontal plane, around a low-level mesocyclone in a numerical simulation of a supercell traced back from when it was well defined at 90 min to 15 min earlier 244
4.54 Idealized illustration of how circulation about a vertical plane can be tilted onto the horizontal and advected downward to the ground 245
4.55 "Owl horn" echoes in supercells 247
4.56 Conceptual model of couplets of vorticity produced as streamwise vorticity is tilted upward and downward as it flows from right to left over a head at the edge of a cold pool at the rear of a supercell and then exits the cold pool at the left in a similar manner 248
4.57 Conceptual model of the "owl horn" echo. 249

4.58 Occlusion downdrafts. 250
4.59 Conceptual models of cyclic mesocyclogenesis and effects of hodograph shapes and lengths. 251
4.60 Idealized illustration showing how neighboring storms might interact according to how the mean vertical shear vector is oriented with respect to a line along which convective storms are triggered 253
4.61 Illustration of how the orientation of low-level vertical shear vector affects behavior along the leading edge of a cold pool. 254
4.62 Idealized illustration of how a supercell may behave as it crosses a cold pool 256
4.63 Idealized illustration of how a cyclonically rotating downdraft may form in a convective storm when the hodograph curves in a clockwise manner with height. 257
5.1 Radar reflectivity at low elevation angle for a broken and solid line of convective cells 267
5.2 Example of a squall line with a leading convective line and a trailing stratiform precipitation area over Arkansas 268
5.3 Idealized depiction of four types of squall line formation; example of broken line formation; idealized representation of a back-building squall line; and example of an embedded areal squall line 270–1
5.4 Evidence of a bore and/or solitary waves in Oklahoma as seen from satellite and radar 272
5.5 Conceptual model of sequence of events that occur when a nocturnal squall line propagates ahead of itself discretely as convection is initiated ahead of the leading convective line 273
5.6 Illustration of how a low-level jet oriented normal to a surface boundary such as an outflow boundary or front can lead to locally enhanced lift for triggering convection 274
5.7 The moist absolutely unstable layer in the growing portion of an MCS . . 275
5.8 Example of the upscale growth of an MCS from an initial isolated convective storm from a numerical simulation 276
5.9 The leading edge of an MCS in the Texas Panhandle 276
5.10 Vertical cross section through a squall line MCS 277
5.11 Symmetric mesoscale convective systems; asymmetric mesoscale convective system; and idealized depiction of symmetric and asymmetric mesoscale convective systems 278–9
5.12 Mesoscale convective systems whose leading convective line consists of individual cells whose major axes are oriented approximately normal to the leading line 281
5.13a Squall lines with mesoscale waves along the leading convective line 282
5.13b Squall line with wave and mesoscale vortex 283
5.14 Conceptual model of a mesohigh and wake low in an MCS 284
5.15 Idealized depiction of weak and strong surface horizontal pressure gradients in association with rear-inflow jets that continue forward toward the leading convective line or are blocked, respectively. 285
5.16 Conceptual model of the surface pressure, wind, and precipitation field associated with an asymmetric MCS 286
5.17 Linear MCS archetypes from initiation to maturity 287
5.18 Vertical profiles of layer mean storm-relative pre-MCS winds for linear MCS archetypes. 288

5.19 Idealized model of two-dimensional vertical circulation in a squall line. . . 289
5.20 Idealized depiction of the three stages in the evolution of an MCS. 293
5.21 Conceptual model of precipitation particle trajectories and mean vertical motions in a trailing stratiform MCS 294
5.22 A conceptual model of the mature structure of a long-lived squall line MCS for a descending rear-inflow jet and an elevated rear-inflow jet 295
5.23 Bow echoes as depicted by WSR-88D radars 298–9
5.24 Bookend vortices in a simulated squall line MCS 300
5.25 Schematic representation of an idealized two-dimensional counter-rotating vortex couplet showing the stronger flow induced in between the vortices. 300
5.26 Idealized illustration of how upward tilting of vorticity in the $-y$-direction associated with easterly vertical shear produces an anticyclonic vortex to the south and cyclonic vortex to the north 301
5.27 Idealized illustration of how small-scale counter-rotating vortices may be produced later in the life of a squall line MCS by the tilting of baroclinically generated horizontal vorticity in the $-y$-direction by an updraft and a downdraft 302
5.28 Idealized illustration showing how a downward-directed dynamic pressure gradient force is present above a mesovortex, which suppresses new updrafts and fractures the convective line 303
6.1 Early drawing of condensation funnels, underneath cumuliform clouds, associated with tornadoes, in the U. S. in 1882. 308
6.2a Old drawing of a tornado in the U. S. in 1884 308
6.2b Tornadoes with condensation funnels 309
6.2c As Figure 6.2b 310
6.3 Tornadoes with debris cloud at and just above the ground and a small funnel cloud at cloud base 311
6.4 Tornadoes surrounded by precipitation and partially obscured, when viewed looking to the south or southwest 312
6.5 Tornado damage in Moore, OK from a large tornado 313
6.6 Polarimetric radar debris signature in an EF5 tornado in Oklahoma 314
6.7 Tornado damage track over Massachusetts 315
6.8 Cyclonic–anticyclonic tornado pair near El Reno, OK 316
6.9 Examples of cyclonic–anticyclonic tornado pairs in cyclonically rotating, right-moving supercells. 317
6.10a Photographs of multiple-vortex tornadoes 318
6.10b Doppler radar imagery of multiple-vortex tornadoes. 319
6.11 Cycloidal marks in a field created by small-scale vortices in a tornado rotating around an axis of rotation associated with a larger vortex 320
6.12 Funnel cloud in a supercell over northwestern Oklahoma and funnel cloud underneath a line of moderate cumulus, Ft. Lauderdale, FL 321
6.13 Waterspouts 322
6.14 Tornadoes or funnel clouds over mountainous terrain. 323
6.15 Dust devils 324
6.16 Steam devil over Lake Thunderbird, Norman, OK, December 22, 1989 . . 324
6.17a Photographs of high-based funnel clouds. 325
6.17b U-shaped funnel underneath the anvil of a tornadic supercell in eastern Oklahoma. 326
6.18 Tornado climatology information (U. S.). 327

6.19 Tornado climatology information (worldwide) 328
6.20 Tornado threat in the U. S. by time of year 329
6.21 Composite High Plains severe convective storm parameter chart 330
6.22 Vertical cross section of estimated azimuthal wind speeds in a tornado from photogrammetric analysis debris and cloud tags in movies of the Dallas, TX tornado of April 2, 1957 333
6.23a Examples of vortices of different scales in and around a tornado 336
6.23b Photographs of tornadoes 337
6.24 Photographs of landspouts 338
6.25 Conceptual model of the life cycle of a non-supercell tornado 338
6.26 Conceptual model of the evolution of non-supercell tornadoes along a weak outflow boundary 339
6.27a Gustnadoes/non-supercell tornadoes along an outflow boundary of a non-supercell convective storm, during VORTEX2, in southwest Texas. 340
6.27b Doppler radar data from the U. Mass. mobile, W-band, Doppler radar of the storm shown in Figure 6.27a 341
6.28 Tornado along a QLCS in central Oklahoma as detected by a Collaborative Adaptive Sensing of the Atmosphere (CASA) Doppler radar. 343
6.29 Vortex lines in a tornado simulator 344
6.30 Radial profiles of azimuthally averaged azimuthal velocity, radial velocity, vertical vorticity, divergence, circulation, and radar reflectivity factor, from analyses of data collected at low elevation angle in a tornado in northern Kansas 345
6.31 Small-scale vortices along the rear-flank gust front of a supercell in north central Nebraska 348
6.32 Idealized illustration showing how baroclinically generated horizontal streamwise vorticity in the forward flank of a supercell can be tilted in the updraft and stretched underneath it, and how baroclinically generated horizontal anti-streamwise vorticity in the rear flank can be tilted by the downdraft and advected around the mesocyclone at the surface and stretched underneath the updraft. 349
6.33 Schematic showing how cyclonic vorticity may be generated, as a combination of tilting and baroclinic generation causes the vorticity of parcels to change from anticyclonic to cyclonic while descending in a downdraft . . . 351
6.34 Illustration of the dynamic pipe effect 353
6.35 Radar reflectivity and Doppler velocity for a tornado in Kansas 355
6.36 Example of tornadogenesis at the leading edge of a bulge in the rear-flank gust front 356
6.37 Cyclic tornadogenesis. 358
6.38 Left-moving, anticyclonically rotating supercell containing a meso-anticyclone and an anticyclonic tornado 359
6.39 Idealized illustration of how counter-rotating vortices can form in a supercell at the ends of an updraft associated with the flanking line and main updraft 360
6.40 Schematic of the “Ward” tornado simulator, and large tornado simulator at the Museum of Science and Industry in Chicago, IL. 361
6.41 The four characteristic regions of a tornado and their properties 365
6.42 Forces in the inertial layer, within the boundary layer. 366
6.43 Balance of forces in the friction layer 367
6.44 Cancellation of shear and curvature vorticity in a potential vortex 372

6.45 Circulation in a potential vortex 373
6.46 Radial profile of azimuthal wind in a Rankine combined vortex 375
6.47 Radial profile of azimuthally averaged azimuthal wind component in a tornado in Kansas, and radial profile of azimuthal wind in a Burgers–Rott vortex 376
6.48 Radial profile of azimuthal wind in a Sullivan vortex 378
6.49 Weak-echo holes in a tornado and a dust devil 382
6.50 Small-scale vertical structure of weak-echo holes in tornadoes 383–4
6.51 Weak-echo column in a tornadic supercell near Greensburg, KS 385–6
6.52 Spiral bands of radar reflectivity around a tornado marked by a WEH in southeastern Wyoming 387
6.53 Idealized illustration of vertically propagating centrifugal waves in a stable vortex 390
6.54 An example of vortex breakdown in a laboratory vortex as a transition from a narrow, laminar rotating column below to a wider, turbulent column aloft 391
6.55 Idealized illustration of the relationship between swirl ratio and vortex structure in a tornado simulator 394
6.56 Double-walled condensation funnel in a tornado in southwestern Nebraska and hollow condensation ring in a waterspout in the Florida Keys 396
6.57 Idealized depiction of a vortex sheet 397
6.58 Secondary satellite vortices in a dust devil in northwest Texas 398
6.59 Idealized illustrations of force diagrams for various swirl ratios and radii, for steady-state, frictionless flow at a level surface, for a potential vortex characterized by angular momentum Γ 401
7.1 Box-and-whiskers plots of mixed-layer CAPE for all tornadoes, mixed-layer CAPE for all severe events, mixed-layer CIN for all tornadoes, mixed-layer CIN for all severe events, mixed-layer LCL for all tornadoes, and mixed-layer LCL for all severe events 419
7.2 Scatterplot of equilibrium level height vs. “effective bulk shear” for supercells and non-supercells 420
7.3 Box-and-whisker overlay plots of effective storm-relative helicity for various types of convective storms 421
7.4 Forecast parameters for distinguishing between tornado and non-tornado convective storm environments as a function of elevation 422
A.1 Geometry relating the positions of two radars and a point in Cartesian space to the distances from each radar to the target, the three components of the wind, and the terminal fall velocity 430
A.2 Area for which the between-beam angle β lies between β and 180° 431
A.3 FAST: scanning technique used by the airborne radar ELDORA and illustration of the pseudo dual-Doppler synthesis of the wind field for beams that trace out cones alternately in the fore and aft directions. 433
A.4 Comparison of the variation of the horizontally polarized radar reflectivity factor for hydrometeor type and size at the S band, C band, and X band for rain, for “dry hail”, and for “wet hail” 434

Abbreviations and acronyms

ARPS	Advanced Regional Prediction System
BAMEX	Bow Echo and MCV EXperiment
BWER	Bounded Weak Echo Region
CAPE	Convective Available Potential Energy
CAPS	Center for Analysis and Prediction of Storms
CCL	Convective Condensation Level
CCOPE	Cooperative COnvective Precipitation Experiment
CDI	Cloud-base Detrainment Instability
CIN	Convective INhibition
CINDE	Convective INitiation and Downburst Experiment
CISK	Conditional Instability of the Second Kind
COHMEX	COoperative Huntsville Meteorological EXperiment
COMET	Cooperative Program for Operational Meteorology, Education, and Training
COPS	Cooperative Oklahoma Profiler Study
CSU	Colorado State University
DCZ	Deep Convergence Zone
DOW	Doppler On Wheels
DPE	Dynamic Pipe Effect
DRC	Descending Reflectivity Core
EF	Enhanced Fujita
EL	Equilibrium Level
ELDORA	ELectra DOppler RAdar
FAA	Federal Aviation Administration
FAST	Fore–Aft Scanning Technique
FFD	Forward Flank Downdraft
GATE	GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment

GBVTD	Ground Based Velocity Track Display
HCR	Horizontal Convective Roll
HP	High Precipitation
IPV	Isentropic Potential Vorticity
JAWS	Joint Airport Weather Studies
JDOP	Joint Doppler Operational Project
LANL	Los Alamos National Laboratory
LCL	Lifting Condensation Level
LES	Large Eddy Simulation
LFC	Level of Free Convection
LLJ	Low Level Jet
LM	Left Moving
LP	Low Precipitation
M-CLASS	Mobile Cross chain LORAN Atmospheric Sounding System
MAUL	Moist Absolutely Unstable Layer
MCS	Mesoscale Convective System
MCV	Mesoscale Convective Vortex
MIST	MIcroburst and Severe Thunderstorm Project
MIT	Massachusetts Institute of Technology
MLCAPE	Mixed Layer or Mean Layer CAPE
MTT	Morton, Taylor, and Turner (1956)
MUCAPE	Most Unstable CAPE
MWR-05XP	Meteorological Weather Radar-2005, X-band, Phased Array
NCAR	National Center for Atmospheric Research
NEXRAD	NEXt generation RADar
NHRE	National Hail Research Experiment
NIMROD	Northern Illinois Meteorological Research on Downbursts
NOAA	National Oceanic and Atmospheric Administration
NOCM	Non Occluding Cyclic Mesocyclogenesis
NSSL	National Severe Storms Laboratory
NSSP	National Severe Storm Project
NST	Non Supercell Tornado
NWS	National Weather Service
OCM	Occluding Cyclic Mesocyclogenesis
OU	Oklahoma University
PGF	Pressure Gradient Force
PROFS	Program for Regional Observing and Forecasting Services
QLCS	Quasi-Linear (Mesoscale) Convective System
RAMS	Regional Atmospheric Modeling System
RASS	radio acoustic sounding system
RaXPol	Rapid-scan (mechanically scanning, not electronically scanning) polarimetric, X-band, Doppler radar
RFD	Rear Flank Downdraft
RFGF	Rear Flank Gust Front
RKW	Rotunno, Klemp, and Weisman

RM	Right Moving
RMW	Radius of Maximum Wind
ROTATE	Radar Observations of Tornadoes And Thunderstorms Experiment
RPV	Remotely Piloted Vehicle
SBCAPE	Surface Based CAPE
SESAME	Severe Environmental Storms And Mesoscale Experiment
SMART-R	Shared Mobile Atmospheric Research and Teaching Radar
SPC	Storm Prediction Center
SREH	Storm Relative Environmental Helicity
STEPS	Severe Thunderstorm Electrification and Precipitation Study
TDWR	Terminal Doppler Weather Radar
TIV	Tornado Intercept Vehicle
TOTO	TOtable Tornado Observatory
TRAP	Tornado Research Airplane Project
TVS	Tornado Vortex Signature
TWISTEX	Tactical Weather Instrumented Sampling in/near Tornadoes EXperiment
TWOLF	Truck-Mounted Wind Observing Lidar Facility
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
VAD	Velocity Azimuth Display
VORTEX	Verification of the Origins of Rotation in Tornadoes EXperiment
VSI	Value of a Statistical Injury
VSL	Value of a Statistical Life
WEC	Weak Echo column
WEH	Weak Echo "eye" or Hole
WER	Weak Echo Region
WPL	Wave Propagation Laboratory
WRF	Weather Research and Forecasting Model

1

Introduction

"... oh now feel it comin' back again
like a rollin' thunder chasing the wind
forces pullin' from the center of the earth again
I can feel it."
Lyrics from *Lighting Crashes* by Live

1.1 BASIC DEFINITION OF SEVERE CONVECTIVE STORMS AND SCOPE OF THE MATERIAL

Severe convective storms worldwide inflict damage to property and crops, disrupt air, sea, and ground travel and outdoor activity, and, in the most extreme cases, inflict injuries and even death. While the adjective "severe" generally refers to weather phenomena that produce damage, what is damaging to one type of structure may not be damaging to another, owing to differences in the integrity of construction and the nature of the underlying surface. In the U. S., "severe" weather associated with *local* storms (as opposed to storms that are much larger in scale such as extratropical and tropical cyclones) is defined more precisely by the Storm Prediction Center (SPC) of the National Weather Service (NWS) as having one or more of the following: tornadoes, winds equal to or in excess of $25.8\,\mathrm{m\,s^{-1}}$ (58 mph), or hail 2.5 cm (1 inch) or greater in diameter, regardless of whether or not there is actual damage; it is noted that prior to January 5, 2010 the minimum hail size criterion was only 1.9 cm (3/4 inch).

It is perhaps a shortcoming of the U. S. definition of severe weather that flooding and lightning are not included, even though each of these also may be responsible for damage, injuries, and death. To maintain a manageable focus, however, *this textbook discusses only the physics of the airflow and cloud and*

H.B. Bluestein, *Severe Convective Storms and Tornadoes: Observations and Dynamics*,
Springer Praxis Books, DOI 10.1007/978-3-642-05381-8_1, © Springer-Verlag Berlin Heidelberg 2013

precipitation distribution (with little regard for cloud particle type or precipitation type) in severe convective storms. The reader is directed elsewhere for detailed discussions of cloud microphysics and precipitation formation, including the formation of large hail (e.g., Knight and Knight, 2001), the hydrological consequences of excessive rainfall (i.e., flooding), and cloud electrification and its consequences (e.g., Williams, 2001). Forecasting techniques using numerical models initialized by observational data are also not covered in much detail, in part because at the time of this writing there is a flurry of activity using data assimilation techniques that is in a state of rapid flux and, consequently, attempts to detail them might not be useful, since the art and science of data assimilation are changing so rapidly.

The purpose of this textbook is to summarize what we have learned in approximately the last half-century about the kinematics and dynamics and, to a lesser extent, the thermodynamics of severe convective storms. I do not use the term "thunderstorm", because it is possible that a severe convective storm does not produce lightning and I would not want to exclude this class of storms from discussion. In addition, while the adjective "convective" simply denotes the movement of air in general, we generally use the adjective "convective" to denote small-scale movements of air in deep cumulus clouds or cumulonimbus clouds.

Advances in observing systems, particularly in radars, and advances in computer technology and numerical modeling techniques have stimulated and made possible fruitful studies of the structure and dynamics of severe convective storms. Through the analysis of observational data (from both quantitative measurements and from visual observations) and the results of controlled numerical experiments, the fundamental processes responsible for determining the convective storm type and the severe weather associated with each type of convective storm have been identified.

After a brief history in this chapter of the major field programs and numerical simulation experiments aimed at understanding the physical processes responsible for severe convective storms is given, the dynamical and, to a much lesser extent, the thermodynamic frameworks used to diagnose the behavior of severe convective storms are discussed mathematically and explained physically in Chapter 2. Thermodynamics is given short shrift because the details are mostly important for numerical modelers and numerical modeling is not a major focus of this book. Students and readers are referred elsewhere (e.g., Emanuel, 1994) and to many journal articles (see the reference lists for specific works) for further discussions on thermodynamics. Also, it is assumed that the reader has some knowledge of radar meteorology. Some additional information, however, is embedded within the main body of the text on the maturing area of polarimetric radar technology and its applications to severe convective storm studies.

The author believes that students will gain an increased appreciation for the theory after they have become aware of some of the major problems and solutions to them that have been grappled with and proposed by scientists, engineers, computer scientists, and amateur meteorologists and have become more acquainted with the actors involved in the scenes of the theater of severe storm meteorology.