

MESOSCALE DYNAMICS

Mesoscale weather systems are responsible for numerous natural disasters, such as damaging winds, blizzards, and flash flooding. A fundamental understanding of the underlying dynamics involved in these weather systems is essential in forecasting their occurrence. This book provides a systematic approach to this subject, and covers a more complete spectrum of mesoscale dynamics than other texts.

The opening chapters introduce the basic equations governing mesoscale weather systems and their approximations. The subsequent chapters cover four major areas of mesoscale dynamics: wave dynamics, moist convection, front dynamics, and mesoscale modeling. Wave dynamics covers wave generation and maintenance, orographically forced flow, and thermally forced flow. The moist convection part covers mesoscale instabilities, isolated storms, mesoscale convective systems, orographic precipitation, and introduces tropical cyclone dynamics. The dynamics of synoptic-scale fronts, mesoscale fronts, and jet streaks are discussed in the front dynamics part. The last part of the book introduces basic numerical modeling techniques, parameterizations of major physical processes, and the foundation for mesoscale numerical weather prediction.

Mesoscale Dynamics is an ideal reference on this topic for researchers in meteorology and atmospheric science. This book could also serve as a textbook for graduate students, and it contains over 100 problems, with password-protected solutions available to instructors at www.cambridge.org/9780521808750. Modeling projects, providing hands-on practice for building simple models of stratified fluid flow from a one-dimensional advection equation, are also described.

YUH-LANG LIN's research in mesoscale dynamics and modeling includes moist convection, orographic effects on airflow and weather systems, gravity waves, tropical, lee and coastal cyclogenesis, storm dynamics, wake vortex, aviation turbulence, forest fire, and modeling of the Martian atmosphere.

Cambridge University Press
978-0-521-80875-0 - Mesoscale Dynamics
Yuh-Lang Lin
Frontmatter
[More information](#)

MESOSCALE DYNAMICS

By Yuh-Lang Lin



CAMBRIDGE
UNIVERSITY PRESS

Cambridge University Press
978-0-521-80875-0 - Mesoscale Dynamics
Yuh-Lang Lin
Frontmatter
[More information](#)

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521808750

© Cambridge University Press 2007

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 2007

Printed in the United Kingdom at the University Press, Cambridge

A catalog record for this publication is available from the British Library

ISBN-978-0-521-80875-0 hardback

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

<i>Preface</i>	<i>page xi</i>
1 Overview	1
1.1 Introduction	1
1.2 Definitions of atmospheric scales	3
1.3 Energy generation and scale interactions	7
1.4 Predictability	10
References	11
2 Governing equations for mesoscale motions	12
2.1 Introduction	12
2.2 Derivation of the governing equations	12
2.3 Approximations to the governing equations	17
References	20
Problems	20
3 Basic wave dynamics	22
3.1 Introduction	22
3.2 Basic wave properties	24
3.3 Sound waves	28
3.4 Shallow water waves	29
3.5 Pure gravity waves	37
3.6 Inertia-gravity waves	43
3.7 Wave reflection levels	50
3.8 Critical levels	54
Appendix 3.1	60
References	62
Problems	63
4 Mesoscale wave generation and maintenance	64
4.1 Introduction	64
4.2 Wave generation mechanisms	64
4.2.1 Density impulses and moist convection	66
4.2.2 Mesoscale instabilities	71

4.2.3	Geostrophic adjustment	74
4.2.4	Nonlinear interactions	85
4.3	Wave maintenance mechanisms	85
4.3.1	Linear wave ducting mechanism	86
4.3.2	Solitary wave mechanism	91
4.3.3	Wave-CISK mechanism	97
4.4	Energy propagation and momentum flux	101
	References	104
	Problems	107
5	Orographically forced flows	109
5.1	Flows over two-dimensional sinusoidal mountains	109
5.2	Flows over two-dimensional isolated mountains	115
5.2.1	Uniform basic flow	115
5.2.2	Basic flow with variable Scorer parameter	121
5.2.3	Trapped lee waves	122
5.3	Nonlinear flows over two-dimensional mountains	125
5.3.1	Nonlinear flow regimes	125
5.3.2	Generation of severe downslope winds	131
5.4	Flows over three-dimensional mountains	138
5.4.1	Linear theory	139
5.4.2	Generation of lee vortices	144
5.5	Flows over larger mesoscale mountains	152
5.5.1	Rotational effects	152
5.5.2	Lee cyclogenesis	157
5.5.3	Orographic influence on cyclone track	167
5.6	Other orographic effects	170
5.6.1	Effects on frontal passage	170
5.6.2	Coastally trapped disturbances	173
5.6.3	Cold-air damming	174
5.6.4	Gap flow	176
	Appendix 5.1	177
	References	179
	Problems	183
6	Thermally forced flows	184
6.1	Two-dimensional flows	184
6.1.1	Steady flows over a sinusoidal heat source	184
6.1.2	Steady flows over an isolated heat source	190
6.2	Transient flows	193
6.2.1	Flow responses to pulse heating	193
6.2.2	Flow responses to steady heating	196
6.3	Applications to mesoscale circulations	198
6.3.1	Density current formation and propagation	198

	<i>Contents</i>	vii
	6.3.2 Heat island circulations	199
	6.3.3 Moist convection	201
	6.3.4 Gravity wave generation and propagation	201
6.4	Effects of shear, three dimensionality, and rotation	203
	6.4.1 Two-dimensional shear flows	203
	6.4.2 Three-dimensional nonrotating flows	207
	6.4.3 Three-dimensional rotating flows	211
6.5	Dynamics of sea and land breezes	215
	6.5.1 Linear theories	216
	6.5.2 Nonlinear numerical studies	219
6.6	Dynamics of mountain–plains solenoidal circulations	221
	Appendix 6.1	224
	References	224
	Problems	227
7	Mesoscale instabilities	229
	7.1 Wave energy transfer through instabilities	230
	7.2 Integral theorems of stratified flow	233
	7.2.1 Governing equations	233
	7.2.2 Miles’ theorem	236
	7.2.3 Howard’s semicircle theorem	236
7.3	Static, conditional, and potential instabilities	238
	7.3.1 Static instability	238
	7.3.2 Conditional instability	244
	7.3.3 Potential instability	249
7.4	Kelvin–Helmholtz instability	252
7.5	Inertial instability	253
7.6	Symmetric instability	256
	7.6.1 Dry symmetric instability	257
	7.6.2 Moist symmetric instability	260
7.7	Baroclinic instability	265
	References	268
	Problems	271
8	Isolated convective storms	272
	8.1 Dynamics of single-cell storms and downbursts	272
	8.2 Dynamics of multicell storms	276
	8.3 Effects of shear and buoyancy	283
	8.3.1 Effects of shear on cold outflow	283
	8.3.2 Effects of buoyancy	289
8.4	Dynamics of supercell storms	293
	8.4.1 General characteristics	293
	8.4.2 Effects of unidirectional shear	297
	8.4.3 Storm splitting	300

8.4.4	Storm rotation and propagation	304
8.4.5	Effects of directional shear	307
8.5	Tornado dynamics	309
8.5.1	Supercell tornadogenesis	309
8.5.2	Nonsupercell tornadogenesis	313
8.5.3	Tornado vortex dynamics	315
	References	318
	Problems	320
9	Mesoscale convective systems	322
9.1	Squall lines and rainbands	323
9.1.1	Squall line classifications	323
9.1.2	Formation mechanisms	328
9.1.3	Maintenance mechanisms	332
9.1.4	Squall line movement	335
9.1.5	Rainbands	336
9.2	Mesoscale convective complexes	338
9.2.1	General characteristics	338
9.2.2	Formation and development mechanisms	341
9.3	Tropical cyclones	347
9.3.1	General characteristics	347
9.3.2	Tropical cyclogenesis	349
9.3.3	Intensity and mesoscale structure	360
9.3.4	Tropical cyclone movement	370
	References	373
	Problems	377
10	Dynamics of fronts and jet streaks	379
10.1	Kinematics of frontogenesis	380
10.2	Dynamics of two-dimensional frontogenesis	387
10.2.1	Geostrophic momentum approximation	387
10.2.2	Frontogenesis and cross-frontal circulations	389
10.3	Frontogenesis and baroclinic waves	394
10.4	Moist and frictional effects on frontogenesis	401
10.5	Other types of fronts	405
10.5.1	Upper-level frontogenesis	405
10.5.2	Drylines	413
10.6	Jet streak dynamics	420
10.6.1	Upper-level jet streaks	420
10.6.2	Low-level jets	433
	References	437
	Problems	441

	<i>Contents</i>	ix
11	Dynamics of orographic precipitation	442
11.1	Orographic influence on climatological distribution of precipitation	442
11.2	Orographic modification of preexisting disturbances	446
11.2.1	Passage of troughs	447
11.2.2	Passage of midlatitude cyclones and fronts	451
11.2.3	Passage of tropical cyclones	453
11.2.4	Common ingredients of orographic precipitation	458
11.3	Formation and enhancement mechanisms	461
11.3.1	Stable ascent mechanism	462
11.3.2	Release of moist instabilities	466
11.3.3	Effects of mountain geometry	470
11.3.4	Combined thermal and orographic forcing	471
11.3.5	Seeder–feeder mechanism	472
11.3.6	Dynamical–microphysical interaction mechanism	475
11.4	Control parameters and moist flow regimes	477
11.4.1	Control parameters	477
11.4.2	Moist flow regimes	478
	References	484
12	Basic numerical methods	489
12.1	Introduction	489
12.2	Finite difference approximations of derivatives	491
12.3	Finite difference approximations of the advection equation	495
12.3.1	Two-time-level schemes	496
12.3.2	Three-time-level schemes	504
12.4	Implicit schemes	508
12.5	Semi-Lagrangian methods	511
	Appendix 12.1	514
	References	515
	Problems	516
	Modeling projects	516
13	Numerical modeling of geophysical fluid systems	518
13.1	Grid systems and vertical coordinates	518
13.1.1	Grid systems	520
13.1.2	Vertical coordinates	526
13.2	Boundary conditions	528
13.2.1	Lateral boundary conditions	528
13.2.2	Upper boundary conditions	530
13.2.3	Lower boundary conditions	537
13.3	Initial conditions and data assimilation	539
13.4	Nonlinear aliasing and instability	547
13.5	Modeling a stratified fluid system	551

13.6	Predictability and ensemble forecasting	555
	References	557
	Problems	561
	Modeling project	561
14	Parameterizations of physical processes	563
14.1	Reynolds averaging	563
14.2	Parameterization of planetary boundary layer processes	568
14.2.1	Parameterization of the surface layer	570
14.2.2	Parameterization of the PBL	572
14.3	Parameterization of moist processes	579
14.3.1	Parameterization of microphysical processes	580
14.3.2	Cumulus parameterization	585
14.4	Parameterizations of radiative transfer processes	594
14.4.1	Introduction	594
14.4.2	Longwave radiation	598
14.4.3	Shortwave radiation	601
	References	605
	Problems	609
	<i>Appendices</i>	610
	A. <i>List of symbols</i>	610
	B. <i>Nomenclature</i>	615
	<i>Index</i>	618

Preface

Mesoscale weather systems, such as thunderstorms, mesoscale convective systems, supercells, fronts, jet streaks, gravity waves, severe downslope winds, low-level jets, sea breezes, heat island circulations, and clear air turbulence, are responsible for numerous natural disasters, such as blizzards, torrential rain, flash flooding, damaging winds, and aviation accidents. Thus, a fundamental understanding of their underlying dynamics, the mesoscale dynamics, is essential to help forecast their occurrence. Although textbooks are available in individual subdisciplines such as cloud dynamics, storm dynamics, convection, and synoptic-dynamic meteorology, there are no textbooks which take a systematic approach and cover a more complete spectrum of the mesoscale dynamics. In particular, due to the rapid advancements in research in the past three decades or so, there is a need for a mesoscale dynamics textbook.

The text is presented in four parts: wave dynamics, moist convection, front dynamics, and mesoscale modeling. There are no clear boundaries among these parts. In the opening chapters, the basic equations governing mesoscale weather systems and their approximations are introduced. The wave dynamics include wave generation and maintenance, orographically forced flow, and thermally forced flow. The moist convection part includes mesoscale instabilities, isolated storms, mesoscale convective systems, and orographic precipitation. Traditionally, tropical cyclones are not viewed as a mesoscale phenomenon due to the wide range of scales involved in their genesis, movement, circulations, and convective systems. However, we may also view a hurricane or typhoon as an intense, rotating convective system once it has formed. Thus, for completeness, tropical cyclone dynamics are briefly introduced in the moist convection part of the text. The front dynamics covers dynamics of large scale fronts, mesoscale fronts, and jet streaks.

The last part of the text is devoted to the introduction of mesoscale modeling and the foundation for mesoscale numerical weather prediction. Since the 1970s, numerical models have become an important tool for studying mesoscale weather systems, thus making it essential to understand the fundamental properties of numerical models. In this part of the text, we briefly introduce the basic knowledge on numerical

modeling techniques and parameterizations of major physical processes such as planetary boundary layer, cumulus convection, microphysical processes, and radiative transfer. This part of the text is not intended to replace advanced textbooks in mesoscale meteorological modeling or numerical weather prediction, but will instead provide the basic knowledge and background so that the readers have a better understanding of numerical schemes when they choose to use models to investigate mesoscale weather phenomena, rather than using a numerical model as a black box. The modeling exercise provides a hands-on practice for building a simple model of stratified fluid flow from a one-dimensional advection equation, two-dimensional shallow-water model, and three-dimensional shallow-water model.

This textbook is based on two graduate courses, mesoscale dynamics and mesoscale modeling, taught by the author at the Department of Marine, Earth, and Atmospheric Sciences of the North Carolina State University since 1987. It is designed for a two-semester course in mesoscale dynamics at graduate level. It may also be used for a one-semester graduate course focused on mesoscale wave dynamics by using material from Chapters 1 through 7, on moist convection and front dynamics by using material from Chapters 1 through 3 and Chapters 8 through 11, or on mesoscale modeling by using material from Chapters 1 through 3 and Chapters 12 through 14. I have assumed that students should have a fundamental understanding of basic dynamic meteorology or geophysical fluid dynamics. Although I have attempted to provide as many references as possible, there are still many papers that have been left out of the text. The webpage at: <http://www.cambridge.org/9780521808750> will be used by the author to communicate with the readers.

I would like to acknowledge Professor Ron Smith for introducing mountain meteorology and relevant mesoscale dynamics to me when I was a Ph.D. student at Yale University. Also, I would like to acknowledge Professor Harry Orville at the South Dakota School of Mines and Technology for teaching me cloud modeling and dynamics and getting me involved in the development of a microphysical parameterization scheme (LFO scheme) which was later adopted as a major scheme in cloud, mesoscale, and numerical weather prediction models. I also benefited from attending the 1982 summer school on mesoscale meteorology in France (sponsored by NATO), where I learned a wide range of mesoscale meteorology from lecturers and fellow attendees. I would also like to extend thanks to the students in my mesoscale dynamics and mesoscale modeling/numerical weather prediction classes in North Carolina State University, especially Hye-Yeong Chun, Ron Weglarz, Mike Kiefer, Heather Reeves, Paul Suffern, Chad Ringley, Chenjie Huang, Dave Vollmer, Kelly Mahoney, Karl Pfeiffer, and Sen Chiao, who have contributed useful suggestions in the text and exercises that have improved the quality of the book. I am indebted to all of my colleagues who have made thorough reviews and comments on the manuscript of the book, which has greatly improved the quality of the text and are highly appreciated. These include Shu-Hua Chen, Min-Dah Chou, Jay Charney, Hye-Yeong Chun, Ching-Yuang Huang, Jerry Janowitz, Mike Kaplan, Steve Koch, Gary Lackmann,

Hsin-Mu Lin, Matt Parker, Rich Rotunno, Dave Schultz, Roger Smith, Wen-Yih Sun, Miguel Teixeira, Si-Chee Tsay, Ken Waight, Ron Weglarz, Chun-Chieh Wu, Qin Xu, Ming Xue, Ming-Jen Yang, Sandra Yuter and Fuqing Zhang. I would also like to thank Robert Mera, Michelle Lin, and Ron Weglarz for their technical editing of the manuscript and Ya-Hui Lin for her skillful drafting of the figures and patience in doing so. Jessica Lin has also assisted the drafting of the figures. The detailed copy-editing by Jon Billam is appreciated. Parts of the book reflect my own research on mesoscale dynamics and modeling, which has been sponsored by the National Science Foundation, National Aeronautics and Space Administration, Office of Naval Research, Air Force Research Laboratory, Forest Service Office of Air Force Scientific Research, and National Oceanic and Atmospheric Administration.

Finally, the encouragement, support, and love from my wife, Emily, and my daughters, Michelle and Jessica, have made it easier to go through the long writing process. I would like to dedicate this book to them.