



# CONTENTS

CONTRIBUTORS.....	ix
FOREWORD .....	xi
PREFACE .....	xv

## Part I. Numerical Weather Prediction

### Medium-Range Forecasting at the ECMWF

LENNART BENGTTSSON

1. Introduction .....	3
2. The Physical and Mathematical Basis for Medium-Range Forecasting .	5
3. Numerical Methods and Modeling Technique .....	7
4. Observations, Their Use and Importance.....	15
5. Operational Application and Results .....	24
6. Problems and Prospects in Numerical Weather Prediction.....	35
7. Concluding Remarks .....	50
References.....	51

### Extended Range Forecasting

K. MIYAKODA AND J. SIRUTIS

1. Introduction .....	55
2. An Evolution of 10-Day Forecast Performance.....	56
3. Examples of Monthly Forecasts.....	65
4. A Projection of Seasonal Forecasts .....	79
5. Postscript.....	82
References.....	83

### Predictability

J. SHUKLA

1. Introduction .....	87
2. Classical Predictability Studies .....	89
3. Predictability of Space–Time Averages.....	110
4. Some Outstanding Problems .....	116
5. Concluding Remarks .....	119
References.....	121

## Data Assimilation

W. BOURKE, R. SEAMAN, AND K. PURI

1. Introduction .....	123
2. Evolution of Assimilation and the FGGE .....	125
3. Components of Four-Dimensional Assimilation Systems .....	131
4. Characteristics of Some Current Assimilation Schemes .....	138
5. Role of Four-Dimensional Assimilation in Research and Operations ...	143
6. Conclusion .....	151
References .....	151

## Part II. Mesoscale Dynamics

### Predictability of Mesoscale Atmospheric Motions

RICHARD A. ANTHES, YING-HWA KUO, DAVID P. BAUMHEFNER,  
RONALD M. ERRICO, AND THOMAS W. BETTGE

1. Introduction .....	159
2. Classic Predictability Experiments and Their Relationship to Mesoscale Predictability .....	164
3. Preliminary Predictability Study with a Mesoscale Model .....	165
4. Discussion and Comparison with a Predictability Study Using a Global Model .....	195
5. Summary and Conclusions .....	198
References .....	200

### Thermal and Orographic Mesoscale Atmospheric Systems— An Essay

ROGER A. PIELKE

1. Introduction .....	203
2. Summary of Major Research Accomplishments .....	204
3. Research Areas .....	216
4. Eventual Goals .....	218
References .....	219

### Advances in the Theory of Atmospheric Fronts

I. ORLANSKI, B. ROSS, L. POLINSKY, AND R. SHAGINAW

1. Introduction .....	223
2. Baroclinic Waves and Fronts .....	225

3. Mature Front .....	229
4. What Observed Features Can Be Explained by Theory? .....	233
5. What Other Processes Are Important in Frontogenesis?.....	237
References.....	250

### Part III. Tropical Dynamics

#### Numerical Modeling of Tropical Cyclones

YOSHIO KURIHARA

1. Introduction .....	255
2. Numerical Models of Hurricanes .....	256
3. Numerical Simulation of Tropical Cyclones.....	261
4. Some Challenging Issues in the Future .....	276
Appendix. GFDL Hurricane Models.....	278
References.....	280

#### Numerical Weather Prediction in Low Latitudes

T. N. KRISHNAMURTI

1. Introduction .....	283
2. Initialization: Dynamic, Normal Mode, and Physical.....	291
3. Parameterization of Physical Processes.....	306
4. Medium-Range Prediction of Monsoon Disturbances.....	314
5. On the Prediction of the Quasi-Stationary Component .....	323
6. Scope of Future Research .....	330
References.....	331

### Part IV. Turbulence and Convection

#### Sub-Grid-Scale Turbulence Modeling

J. W. DEARDORFF

1. Introduction: The Need for Grid-Scale Reynolds Averaging .....	337
2. The Effect of Grid-Volume Reynolds Averaging.....	338
3. The Sub-Grid-Scale Eddy Coefficient .....	340
4. Recent Developments .....	341
5. Future Outlook.....	341
References.....	342

## Ensemble Average, Turbulence Closure

GEORGE L. MELLOR

1. Introduction .....	345
2. The Turbulence Macroscale and Turbulence Closure .....	347
3. Averaging Distance for Measurements in the Atmosphere and Oceans and for Numerical Models .....	354
4. Numerical Modeling Applications and Horizontal Diffusion .....	355
5. Concluding Remarks .....	356
References .....	357

## The Planetary Boundary Layer

H. A. PANOFSKY

1. General Characteristics .....	359
2. The Equations in the PBL .....	364
3. The Surface Layer .....	367
4. First- and Second-Order Closures .....	377
5. Boundary-Layer Models .....	380
6. Boundary-Layer Parameterization .....	383
References .....	383

## Modeling Studies of Convection

YOSHI OGURA

1. Introduction .....	387
2. Bénard–Rayleigh Convection .....	388
3. Complexity of Convection in the Atmosphere .....	391
4. Shallow Moist Convection .....	392
5. Deep Moist Convection .....	397
6. Feedback Effects of Cumulus Clouds on Larger-Scale Environments ..	408
7. Concluding Remarks .....	413
References .....	416

INDEX .....	423
-------------	-----





# MEDIUM-RANGE FORECASTING AT THE ECMWF

LENNART BENGTTSSON

*European Centre for Medium Range Weather Forecasts  
Reading, England*

1. Introduction . . . . .	3
2. The Physical and Mathematical Basis for Medium-Range Forecasting . . . . .	5
3. Numerical Methods and Modeling Technique. . . . .	7
3.1. Basic Equations . . . . .	7
3.2. Numerical Formulation . . . . .	10
3.3. Radiation and Clouds . . . . .	13
3.4. The Planetary Boundary Layer . . . . .	13
3.5. Moist Convection . . . . .	14
3.6. Nonconvective Parameterization. . . . .	14
3.7. Surface Values . . . . .	15
4. Observations, Their Use and Importance . . . . .	15
5. Operational Application and Results . . . . .	24
5.1. Northern Hemisphere Forecasts . . . . .	27
5.2. Tropical and Southern Hemisphere Forecasts. . . . .	30
6. Problems and Prospects in Numerical Weather Prediction. . . . .	35
7. Concluding Remarks . . . . .	50
References . . . . .	51





# PREDICTABILITY

J. SHUKLA

*Center for Ocean–Land–Atmosphere Interactions  
Department of Meteorology  
University of Maryland  
College Park, Maryland*

1. Introduction . . . . .	87
2. Classical Predictability Studies . . . . .	89
2.1. Simple Models . . . . .	89
2.2. Observations (Analog) . . . . .	91
2.3. General Circulation Models . . . . .	93
3. Predictability of Space–Time Averages. . . . .	110
3.1. Dynamical Predictability . . . . .	111
3.2. Boundary-Forced Predictability. . . . .	112
3.3. Prospects for Dynamical Extended-Range Forecasting. . . . .	115
4. Some Outstanding Problems . . . . .	116
4.1. Mean (Climate Drift) and Transient Predictability. . . . .	116
4.2. Observational Errors and Model Errors . . . . .	117
4.3. Predictability of Predictability . . . . .	118
5. Concluding Remarks . . . . .	119
References. . . . .	121



# DATA ASSIMILATION

W. BOURKE, R. SEAMAN, and K. PURI

*Bureau of Meteorology Research Centre  
Melbourne, Australia*

1. Introduction . . . . .	123
2. Evolution of Assimilation and the FGGE . . . . .	125
3. Components of Four-Dimensional Assimilation Systems . . . . .	131
3.1. Observational Data Base . . . . .	131
3.2. Optimum Interpolation (OI) . . . . .	132
3.3. Model Initialization . . . . .	134
3.4. Prediction Models . . . . .	136
4. Characteristics of Some Current Assimilation Schemes . . . . .	138
4.1. Continuous Assimilation . . . . .	139
4.2. Intermittent Assimilation . . . . .	141
5. Role of Four-Dimensional Assimilation in Research and Operations . . . . .	143
5.1. Research Implications of Four-Dimensional Assimilation . . . . .	146
5.2. Research on Four-Dimensional Assimilation Procedures . . . . .	147
5.3. Long-Term Operational Implications of Four-Dimensional Assimilation . . . . .	149
6. Conclusion. . . . .	151
References. . . . .	151



# PREDICTABILITY OF MESOSCALE ATMOSPHERIC MOTIONS

RICHARD A. ANTHES  
YING-HWA KUO  
DAVID P. BAUMHEFNER  
RONALD M. ERRICO  
THOMAS W. BETTGE

*National Center for Atmospheric Research\*  
Boulder, Colorado*

1. Introduction . . . . .	159
1.1. Pessimistic Outlook for Mesoscale Predictability Based on Atmospheric Spectra and Turbulence Theory . . . . .	161
1.2. Counterarguments and More Optimistic Points of View . . . . .	163
2. Classic Predictability Experiments and Their Relationship to Mesoscale Predictability . . . .	164
3. Preliminary Predictability Study with a Mesoscale Model . . . . .	165
3.1. Observed Atmospheric Evolution 10–11 April 1979 . . . . .	166
3.2. Summary of Model . . . . .	167
3.3. Introduction of Perturbation on Initial Conditions. . . . .	172
3.4. Results of Numerical Simulations . . . . .	175
4. Discussion and Comparison with a Predictability Study Using a Global Model . . . . .	195
5. Summary and Conclusions . . . . .	198
References. . . . .	200



# **THERMAL AND OROGRAPHIC MESOSCALE ATMOSPHERIC SYSTEMS—AN ESSAY**

**ROGER A. PIELKE**

*Department of Atmospheric Science  
Colorado State University  
Fort Collins, Colorado*

1. Introduction . . . . .	203
2. Summary of Major Research Accomplishments . . . . .	204
2.1. Thermal Mesoscale Systems . . . . .	205
2.2. Orographic Mesoscale Models . . . . .	212
3. Research Areas . . . . .	216
4. Eventual Goals . . . . .	218
References. . . . .	219





# ADVANCES IN THE THEORY OF ATMOSPHERIC FRONTS

I. ORLANSKI, B. ROSS, L. POLINSKY, AND R. SHAGINAW

*Geophysical Fluid Dynamics Laboratory/NOAA  
Princeton University  
Princeton, New Jersey*

1. Introduction . . . . .	223
2. Baroclinic Waves and Fronts . . . . .	225
2.1. Quasi-Geostrophic Effects . . . . .	226
2.2. Semigeostrophic Effects . . . . .	228
2.3. Ageostrophic Effects . . . . .	228
3. Mature Front . . . . .	229
3.1. The Significance of Frontal Collapse . . . . .	229
3.2. Dynamic Balance in a Mature Front . . . . .	232
4. What Observed Features Can Be Explained by Theory? . . . . .	233
5. What Other Processes Are Important in Frontogenesis? . . . . .	237
5.1. Structure of the Cold Front . . . . .	237
5.2. Frontogenetical Terms . . . . .	244
References . . . . .	250



# NUMERICAL MODELING OF TROPICAL CYCLONES

YOSHIO KURIHARA

*Geophysical Fluid Dynamics Laboratory/NOAA  
Princeton University  
Princeton, New Jersey*

1. Introduction . . . . .	255
2. Numerical Models of Hurricanes . . . . .	256
2.1. Modeling Problems . . . . .	256
2.2. GFDL Hurricane Models . . . . .	258
3. Numerical Simulation of Tropical Cyclones . . . . .	261
3.1. Tropical Storm Genesis . . . . .	261
3.2. Intensification of Tropical Storms . . . . .	266
3.3. Structure of Hurricanes . . . . .	267
3.4. Spiral Bands and Comma Vortices . . . . .	271
3.5. Landfall of Hurricanes . . . . .	273
4. Some Challenging Issues in the Future . . . . .	276
4.1. Improvement of Numerical Models . . . . .	276
4.2. Basic Study . . . . .	276
4.3. Prediction of Tropical Cyclones . . . . .	277
Appendix. GFDL Hurricane Models . . . . .	278
References . . . . .	280



# NUMERICAL WEATHER PREDICTION IN LOW LATITUDES

T. N. KRISHNAMURTI

*Department of Meteorology  
Florida State University  
Tallahassee, Florida*

1. Introduction . . . . .	283
1.1 Scope of Simple Models Based on Conservation Laws . . . . .	285
2. Initialization: Dynamic, Normal Mode, and Physical . . . . .	291
2.1 Physical Initialization . . . . .	293
2.2 Humidity Analysis . . . . .	302
3. Parameterization of Physical Processes . . . . .	306
3.1. Parameterization of Cumulus Convection . . . . .	306
3.2. Radiative Parameterization . . . . .	313
4. Medium-Range Prediction of Monsoon Disturbances . . . . .	314
5. On the Prediction of the Quasi-Stationary Component . . . . .	323
6. Scope of Future Research. . . . .	330
References. . . . .	331



# THE PLANETARY BOUNDARY LAYER

H. A. PANOFSKY\*

*Department of Meteorology  
Pennsylvania State University  
University Park, Pennsylvania*

1. General Characteristics . . . . .	359
1.1. Definitions and Importance . . . . .	359
1.2. The Daytime Boundary Layer . . . . .	360
1.3. The PBL at Night . . . . .	361
1.4. The PBL in Strong Winds . . . . .	363
1.5. Complex Terrain . . . . .	363
2. The Equations in the PBL. . . . .	364
3. The Surface Layer . . . . .	367
3.1. Profiles and Fluxes over Homogeneous Terrain . . . . .	367
3.2. Variances . . . . .	370
3.3. Spectra and Cospectra . . . . .	372
4. First- and Second-Order Closures. . . . .	377
4.1. First-Order Closure . . . . .	377
4.2. Large-Eddy Exchange . . . . .	379
4.3. Second-Order Closure . . . . .	380
5. Boundary-Layer Models . . . . .	380
5.1. The Surface Layer over Complex Terrain. . . . .	380
5.2. Modeling the Whole PBL . . . . .	381
6. Boundary-Layer Parameterization . . . . .	383
References. . . . .	383





# MODELING STUDIES OF CONVECTION

YOSHI OGURA

*Department of Atmospheric Sciences  
University of Illinois  
Urbana, Illinois*

1. Introduction . . . . .	387
2. Bénard-Rayleigh Convection . . . . .	388
3. Complexity of Convection in the Atmosphere . . . . .	391
4. Shallow Moist Convection . . . . .	392
5. Deep Moist Convection. . . . .	397
5.1. Life Cycle of Air-Mass Thunderstorm Cells . . . . .	397
5.2. Mesoscale Convective Systems. . . . .	397
5.3. Simulations of Long-Lived Squall Lines . . . . .	399
5.4. Life Cycle of Mesoscale Convective Systems . . . . .	406
6. Feedback Effects of Cumulus Clouds on Larger-Scale Environments . . . . .	408
7. Concluding Remarks . . . . .	413
References. . . . .	416