Written by a group of international experts in their field, this book is a review of Lagrangian observation, analysis and assimilation methods in physical and biological oceanography. In recent years a large number of floating and drifting research buoys have been deployed in the global oceans to study the state of the ocean and its variation in terms of water mass properties, circulation and heat transport. Lagrangian techniques are required to analyze the data from these buoys.

This multidisciplinary text contains observations, theory, numerical simulations, and analysis techniques. It presents new results on nonlinear analysis of Lagrangian dynamics, the prediction of particle trajectories, and Lagrangian stochastic models. It includes chapters on floats and drifters, Lagrangian-based analysis methods and models in marine biology, the statistics of particle trajectories in the ocean, numerical simulations and their relationship with classical turbulence results, and nonlinear Lagrangian-based theory for studying ocean transport and particle trajectories. The book contains historical information, up-to-date developments, and speculation on future developments in Lagrangian-based observations, analysis, and modeling of physical and biological systems.

Containing contributions from experimentalists, theoreticians, and modelers in the fields of physical oceanography, marine biology, mathematics, and meteorology this book will be of great interest to researchers and graduate students looking for both practical applications and information on the theory of transport and dispersion in physical systems, biological modeling, and data assimilation.
Cover illustration: The cover depicts the abrupt breakup of a large ocean eddy in the Gulf of Mexico. Eddy Fourchon was tracked by assimilating satellite data into the University of Colorado version of the Princeton Ocean Model (developed by L. H. Kantha). Lagrangian analysis by researchers at the University of Delaware (led by A. D. Kirwan, Jr.) and the City University of New York (A. C. Poje) produced the time sequence of marked particles in the middle of the Gulf between July 28 and August 17, 1998. On July 28, Fourchon appears to be a typical large elliptical ocean eddy. Over the next two and a half weeks, interactions with nearby mesoscale features split the core in half. The larger colored region is determined by computing the Lagrangian boundaries of the eddy on the initial day with red/yellow assigned to those particles within the eddy which eventually split to the north/south respectively. The contrasting inscribed circles show the stirring inherent in each sub-region during the evolution. Figure design by Patrick Fagan.
LAGRANGIAN ANALYSIS AND PREDICTION OF COASTAL AND OCEAN DYNAMICS

Edited by

ANNALISA GRIFFA
Rosenstiel School of Marine and Atmospheric Science
University of Miami
Istituto di Scienze Marine, Consiglio Nazionale Ricerche, La Spezia, Italy

A. D. KIRWAN, JR.
University of Delaware

ARTHUR J. MARIANO
Rosenstiel School of Marine and Atmospheric Science
University of Miami

TAMAY M. ÖZGÖKMEN
Rosenstiel School of Marine and Atmospheric Science
University of Miami

THOMAS ROSSBY
Graduate School of Oceanography
University of Rhode Island
Contents

List of contributors \hfill page vi
Preface \hfill xi

1 Evolution of Lagrangian methods in oceanography \hfill 1
2 Measuring surface currents with Surface Velocity Program \hfill 39
drifters: the instrument, its data, and some recent results
3 Favorite trajectories \hfill 68
4 Particle motion in a sea of eddies \hfill 89
5 Inertial particle dynamics on the rotating Earth \hfill 119
6 Predictability of Lagrangian motion in the upper ocean \hfill 136
7 Lagrangian data assimilation in ocean general \hfill 172
circulation models
8 Dynamic consistency and Lagrangian data in \hfill 204
oceanography: mapping, assimilation, and optimization schemes
9 Observing turbulence regimes and Lagrangian dispersal \hfill 231
properties in the oceans
10 Lagrangian biophysical dynamics \hfill 275
11 Plankton: Lagrangian inhabitants of the sea \hfill 349
12 A Lagrangian stochastic model for the dynamics of a stage \hfill 401
structured population. Application to a copepod population
13 Lagrangian analysis and prediction of coastal and ocean \hfill 423
dynamics (LAPCOD)

Index \hfill 480

The color plates are situated between pages 228 and 229.
Contributors

Amy S Bower
Department of Physical Oceanography
Woods Hole Oceanographic Institute
Woods Hole, MA 02543
USA

Annalisa Bracco
Department of Physical Oceanography
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
USA

Giuseppe Buffoni
ENEA
Santa Teresa – Lerici
La Spezia I-19100
Italy

Jim Carton
University of Maryland
Stadium Drive
College Park, MD 20742-0001
USA

Luca R Centurioni
Scripps Institute of Oceanography
9500 Gilman Drive
La Jolla, CA 92093-0213
USA

Toshio Chin
RSMAS/MPO
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149
USA

Curtis A Collins
Code Oc/Co
Department of Oceanography
Naval Postgraduate School
833 Dyer Road
Monterey, CA 93943-5122
USA

Robert K Cowen
RSMAS/MBF
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149
USA
List of contributors

Heather Furey
Department of Physical Oceanography
Woods Hole Oceanographic Institute
Woods Hole, MA 02543
USA

Newell Garfield
San Francisco State University
Geosciences Dept.
3152 Paradise Drive
Tiburon, CA 94920
USA

Annalisa Griffa
RSMAS/MPO
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149
USA

Semyon Grodsky
Department of Meteorology
University of Maryland
College Park, MD 20742
USA

Gary L Hitchcock
RSMAS/MBF
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149
USA

Kayo Ide
Institute of Geophysics & Planetary Physics
UCLA
Los Angeles, CA 90095-1567
USA

Christopher Jones
University of North Carolina at Chapel Hill
CB #32350
UNC-CH
Chapel Hill, NC 27599
USA

YooYin Kim
Scripps Institute of Oceanography
9500 Gilman Drive
La Jolla, CA 92093-0213
USA

Vassiliki Kourafalou
RSMAS/MPO
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149
USA

Leonid Kuznetsov
Applied Mathematics
University of North Carolina at Chapel Hill
(Phillips Hall 362)
Chapel Hill, NC 27599
USA
List of contributors

Matthias Lankhorst
Leibniz-Institut für Meereswissenschaften
(IFM-GEOMAR)
Dusternbrooker Weg 20
Kiel D-24105
Germany

Dong-Kyu Lee
Department of Marine Sciences
Busan National University
Busan 609-735
South Korea

Thomas N Lee
RSMAS/MPO
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149
USA

Rick Lumpkin
Atlantic Oceanographic & Meteorological Lab
NOAA/AOML/PhOD
4301 Rickenbacker Causeway
Miami, FL 33149
USA

Svend-Aage Malmberg
Marine Research Institute
1 Hafrannsoknahofnunin
PO Box 1390
Skulgata 4
Reykjavik 121
Iceland

Arthur J Mariano
RSMAS/MPO
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149
USA

Maria Grazia Mazzocchi
Stazione Zoologica A. Dohrn
Villa Communale
Napoli I-80121
Italy

Anne Molcard
LSEET
University of Toulon
Forte Santa Teresa
La Spezia I-19036
Italy

Pearn P Niiler
Scripps Institute of Oceanography
9500 Gilman Drive
La Jolla, CA 92093-0213
USA

Donald B Olson
RSMAS/MPO
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149
USA

Tamay Ö zgökmen
RSMAS/MPO
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149
USA
List of contributors

Nathan Paldor
Hebrew University of Jerusalem
Institute of Earth Sciences
Edmund Safra Campus, Givat Ram
Jerusalem 92509
Israel

Sara Pasquali
CNR-IMATI
via Bassini, 15
Milano I-20133
Italy

Claudia Pasquero
Earth System Science Dept.
University of California
3224 Croul Hall
Irvine, CA 92697-3100
USA

Mayra C Pazos
Atlantic Oceanographic &
Meteorological Lab
NOAA/AOML/PhOD
4301 Rickenbacker Causeway
Miami, FL 33149
USA

Leonid Piterbarg
University of Southern California
Kaprielian Hall, Room 108
3620 Vermont Avenue
Los Angeles, CA 90089-2532
USA

Pierre-Marie Poulain
Istituto Nazionale di Oceanografia e
di Geofisica
Sperimentale (OGS)
Borgo Grotta Gigante 42/c
Trieste I-34010
Italy

Antonello Provenzale
Institute of Atmospheric Sciences &
Climate
CNR
Corso Fiume, 4
Torino I-10133
Italy

Thomas A Rago
Department of Oceanography
Naval Postgraduate School
833 Dyer Road, Rm 328
Monterey, CA 93943
USA

Thomas Rossby
University of Rhode Island
Graduate School of Oceanography
Kingston, RI 02881
USA

Volfango Rupolo
ENEA
via Anguillarese, 301
Roma I-00060
Italy
<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Address</th>
<th>City, Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edward H Ryan</td>
<td>RSMAS/MPO</td>
<td>University of Miami</td>
<td>Miami, FL</td>
</tr>
<tr>
<td></td>
<td>4600 Rickenbacker Causeway</td>
<td>Florida 33149</td>
<td>USA</td>
</tr>
<tr>
<td>Vitalii A Sheremet</td>
<td>Graduate School of Oceanography</td>
<td>University of Rhode Island</td>
<td>Narrangansett, RI 02882 USA</td>
</tr>
<tr>
<td>Hedinn Valdimarsson</td>
<td>Marine Research Institute</td>
<td>1 Hafrannsoknansofnunin</td>
<td>Reykjavik, Iceland</td>
</tr>
<tr>
<td>Jeffrey B Weiss</td>
<td>Dept. of Atmospheric &amp; Oceanic Science</td>
<td>University of Colorado</td>
<td>Boulder, CO 80309-0311 USA</td>
</tr>
<tr>
<td>Elizabeth Williams</td>
<td>RSMAS/MPO</td>
<td>University of Miami</td>
<td>Miami, FL 33149 USA</td>
</tr>
<tr>
<td>Walter Zenk</td>
<td>Leibniz-Institut fur Meereswissenschaften</td>
<td>Ozeanographie</td>
<td>Kiel, Germany</td>
</tr>
<tr>
<td></td>
<td>Dusternbrooker Weg 20</td>
<td></td>
<td>D-24105 Kiel, Germany</td>
</tr>
</tbody>
</table>
Preface

This book has been motivated by the recent surge in the density and availability of Lagrangian measurements in the ocean, recent mathematical and methodological developments in the analysis of such data to improve forecasts and transport characteristics of ocean general circulation models, and numerous applications to dispersion of biological species. Another source of motivation has been the Lagrangian Analysis and Prediction of Coastal and Ocean Dynamics (LAPCOD) workshops (www.rsmas.miami.edu/LAPCOD/meetings.html).

The main purpose of this book is to conduct a review of Lagrangian observations, analysis and assimilation methods in physical and biological oceanography, and to present new methodologies on Lagrangian analysis and data assimilation, and new applications of Lagrangian stochastic models from biological dispersion studies. Some of the chapters included in this volume were presented at LAPCOD workshops, while others have been specifically written for this collection. Given the size of the Lagrangian field, the present work cannot be considered as an exhaustive effort, but one which is aimed to cover many of the central research topics. It was our intent to maintain a good balance between historical and state-of-the-art developments in Lagrangian-based observations, theory, numerical modeling and analysis techniques.

This book seems to be a first of its kind because the central theme is the Lagrangian viewpoint for studying the transport phenomena in oceanic flows. Another unique and timely aspect of this book is its multidisciplinary nature with contributions from experimentalists, theoreticians, and modelers from diverse fields such as physical oceanography, marine biology, mathematics, and meteorology.

The book starts with a historical perspective of the development and application of Lagrangian methods, while more recent measurements and results
are presented in Chapter 2. Some striking examples of Lagrangian trajectories are depicted by a collection of authors in Chapter 3. A number of new theoretical approaches to understand and describe particle motion are outlined in Chapters 4, 5, 6, and 9. New methods for assimilating Lagrangian data in ocean models to improve their forecast are described in Chapters 7 and 8. A suite of applications of Lagrangian techniques to transport of biological species are given in Chapters 10 to 12. Finally, we close with an extensive observational and theoretical review of Lagrangian techniques that were presented in the three LAPCOD workshops held in 2000, 2002, and 2005.

We would like to express special thanks to Dr. Manuel Fiedeiro from the US Office of Naval Research (ONR) for sponsoring much of the research presented in this book, while fostering collaboration between many groups of researchers and initiating LAPCOD workshops. We also thank Dr. Jerry Miller from ONR-London for supporting some of the LAPCOD workshops. Special thanks are also due to Edward Ryan, who has dedicated countless days to help organize this book. We also thank anonymous reviewers for many useful suggestions to help improve the chapters, and for maintaining a quality standard of scientific work. Finally, we thank all the scientists who have played important roles in the advancement of Lagrangian observations and analysis, but are not directly represented in this book.

Annalisa Griffa, Denny Kirwan, Arthur Mariano, Tamay Özgökmen and Tom Rossby