Edited by :

U.C. Mohanty

Sundararaman G. Gopalakrishnan

Advanced Numerical Modeling and Data Assimilation Techniques for Tropical Cyclone Prediction

Springer

Advanced Numerical Modeling and Data Assimilation Techniques for Tropical Cyclone Prediction

Advanced Numerical Modeling and Data Assimilation Techniques for Tropical Cyclone Prediction

Edited by

U.C. Mohanty

*School of Earth, Ocean and Climate Sciences
Indian Institute of Technology Bhubaneswar
Bhubaneswar, India*

and

Sundararaman G. Gopalakrishnan

*Hurricane Research Division
Atlantic Oceanographic Meteorological Laboratory, NOAA
Miami, Florida*

Springer

A C.I.P. Catalogue record for this book is available from the Library of Congress.

ISBN 978-94-024-0894-2 (HB)

ISBN 978-94-024-0896-6 (e-book)

Copublished by Springer,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands
with Capital Publishing Company, New Delhi, India.

Sold and distributed in North, Central and South America by Springer,
233 Spring Street, New York 10013, USA.

In all other countries, except SAARC countries—Afghanistan, Bangladesh,
Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka—sold and distributed by
Springer, Haberstrasse 7, D-69126 Heidelberg, Germany.

In SAARC countries—Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal,
Pakistan and Sri Lanka—sold and distributed by Capital Publishing Company,
7/28, Mahaveer Street, Ansari Road, Daryaganj, New Delhi, 110 002, India.

www.springer.com

Printed on acid-free paper

All Rights Reserved

© 2016 Capital Publishing Company

No part of this work may be reproduced, stored in a retrieval system, or
transmitted in any form or by any means, electronic, mechanical, photocopying,
microfilming, recording or otherwise, without written permission from the
Publisher, with the exception of any material supplied specifically for the purpose
of being entered and executed on a computer system, for exclusive use by the
purchaser of the work.

Printed in India.

Preface

Tropical cyclones (TCs), also known as hurricanes in the Atlantic and typhoons in the west Pacific, are one of the deadliest and costliest natural disasters known to humankind. On an average, about 80-90 TCs form globally every year. The Northwest Pacific Ocean is the most active basin, with an average frequency of 20-30 TCs annually. The genesis of TCs over the North Indian Ocean (including the Bay of Bengal and Arabian Sea, together known as the Indian seas) is bimodal, with the primary maximum of cyclonic activity occurring in the post-monsoon season (October–December) and the secondary maximum occurring in the pre-monsoon season (April–May). The typical duration of a TC over the North Indian Ocean is 5–6 days, with severe cyclonic storm intensity persisting for 2–3 days in comparison to six days for the global average. Yet, this subcontinent accounts for the highest number of cyclone-related fatalities. Of the 23 recorded most deadly TCs over the last 300 years (more than 10,000 fatalities), 20 were formed over the Bay of Bengal. Recent studies show that the majority of TC-related deaths are attributed to inland freshwater flooding and storm surge. Although average annual deaths from TCs affecting the USA have decreased over the 20th century, property damages and loss due to TCs have always been on an increase. Five TCs, Hurricanes Sandy (2012), Katrina (2005), Ike (2008), Wilma (2005) and Andrew (1992) have alone resulted in net damages exceeding 300 billion dollars.

Research and operational agencies around the globe have been continually striving towards improving TC forecasts to save life and property. Although TC track forecasts have improved significantly in recent years, intensity and rainfall forecasts remain a foremost challenge. The high casualties due to TCs may be attributed to various factors including geographic conditions, the limitation of observations in data-sparse ocean regions to initialize and verify models, prediction systems for improved guidance, i.e., intensity and structure forecasting, inaccurate initial conditions from global forecasting systems, and understanding of physical processes within and around the TCs.

The National Oceanic and Atmospheric Administration (NOAA) has made significant advances in TC intensity forecasting through development of the high-resolution Hurricane Weather Research and Forecasting (HWRF) model and its associated data assimilation techniques pioneered at the National Centers for Environmental Prediction (NCEP) and the Atlantic Oceanographic and Meteorological Laboratory (AOML) under the Hurricane Forecast Improvement Program (HFIP). For instance, intensity forecasts from HWRF have improved by about 25% since 2012. The HWRF model has also evolved to become a global TC forecasting system. Nevertheless, much work remains to be done: from TC genesis to rapid intensification to weakening over the ocean and decay over land—our knowledge and understanding is limited. Questions still remain on how to improve numerical models and data assimilation techniques to further improve predictions of these killer storms, as well as questions about the key observations available to improve guidance.

To share state-of-the-art understanding and forecasting techniques acquired in recent years by NOAA and its partnering institutions in the US and India, a six-day advanced workshop and training session titled the “Advanced Indo-US Workshop and Colloquium on Modeling and Data Assimilation for Tropical Cyclone Predictions” was organised jointly by the Indian Institute of Technology (IIT) Delhi and IIT Bhubaneswar, at Bhubaneswar, Odisha, India during 9–14 July 2012. Sponsors included the Indo-US Science and Technology Forum (IUSSTF), Council of Scientific and Industrial Research (CSIR), Ministry of Earth Science (MoES), IIT Delhi, IIT Bhubaneswar, NOAA, and the National Science Foundation (NSF). Their contributions are duly acknowledged.

The week-long workshop brought together ten eminent scientists from NOAA and US universities, one from Australia, and five from India. It also brought together four NSF-sponsored students from the US and 27 young scientists and students from various organisations across India including the India Meteorological Department (IMD), National Centre for Medium Range Weather Forecasting (NCMRWF), Indian National Centre for Ocean Information Services (INCOIS), Indian Institute of Tropical Meteorology (IITM), Indian Air Force, Indian Navy, Indian Space Research Organisation (ISRO), Indira Gandhi Centre for Atomic Research (IGCAR), IITs, and various Indian universities. The workshop consisted of 36 hours of lectures and 10 hours of colloquium, with extended hours for discussion and interaction amongst the resource experts and participants. The workshop accomplished its primary goal of capacity building and infrastructure sharing under the NOAA (US)-MoES (India) agreement on weather and climate sciences. In addition, the exchange of state-of-the-art knowledge and prediction techniques immensely benefited not only the participants but also the resource experts from all countries involved.

In consideration of the significant findings and recommendations presented at the workshop, it was decided to publish a special textbook

covering several important aspects of TCs such as observations, analysis and prediction. The textbook was envisioned to serve as a teaching and reference material resource at universities/academic institutions for post-graduate students and researchers around the world. It has been designed to provide a broad outlook on recent advances in observations, assimilation and modeling of TCs with detailed and advanced information on genesis, intensification, movement and storm surge prediction. Specifically, it focusses on (i) state-of-the-art observations for advancing TC research, (ii) advances in numerical weather prediction for TCs, (iii) advanced assimilation and vortex initialization techniques, (iv) ocean coupling, (v) current capabilities to predict TCs, and (vi) advanced research in physical and dynamical processes in TCs. It is also expected to stimulate critical thinking for cyclone forecasters and researchers, managers, policy makers, and graduate and post-graduate students to carry out future research in the field of TCs.

As editors of this special textbook, we are highly thankful to all the authors for their efforts and cooperation in bringing out this publication. We are sincerely thankful to Dr. Jian-Wen Bao, Prof. Noel Davidson, Dr. Alexandre O. Fierro, Prof. T.N. Krishnamurti, Dr. Frank D. Marks, Jr., Prof. Michael T. Montgomery, Prof. Dev Niyogi, Dr. Vijay Tallapragada, Dr. Da-Lin Zhang, and Prof. Fuqing Zhang for making their valuable time available for the lecture series in India and for dedicating considerable time and effort to compiling their lecture notes into textbook materials. In addition, Dr. Sujata Pattanayak, Dr. Ashish Routray and Dr. Richard M. Yablonsky are acknowledged for their contributions and considerable effort in preparation of the book chapters. Thanks are due to Indian experts, viz. Prof. S.K. Dube, Dr. C.M. Kishtawal, Dr. M. Mohapatra, and Dr. S.K. Roy Bhowmik, who spared their valuable time to provide lectures at the workshop. We are also sincerely thankful to all reviewers, viz. Prof. D.V. Bhaskar Rao, Dr. Someswar Das, Dr. John P. George, Dr. S.C. Kar, Dr. Frank Marks, Dr. D.R. Sikka and Dr. (AVM) Ajit Tyagi for their continued efforts in assessing and adding value to this material. We along with Prof. D. Niyogi and Prof. T.N. Krishnamurti gratefully acknowledge the U.S. National Science Foundation grant AGS-1239642 (Program Director: Dr. A. Bamzai) which supported the participation and visit of graduate students and postdoctoral scientists from the US in the workshop. We are also sincerely thankful to Prof. S. Tripathy, Head, School of Earth, Ocean and Climate Sciences, and his colleague, Dr. Sandeep Pattanaik, for their countless efforts in hosting the workshop in a grand manner at IIT Bhubaneswar. Dr. Krishna K. Osuri has contributed significantly in editorial process during preparation of the textbook materials and his dedicated efforts are duly acknowledged. Our special thanks to Capital Publishing Company for their untiring editorial efforts to bring the monograph to its present state.

U.C. Mohanty
Sundararaman G. Gopalakrishnan

Contents

Preface

v

Part 1: State-of-the-art Observations for Advancing TC Research

1. Advancing the Understanding and Prediction of Tropical Cyclones Using Aircraft Observations
Frank D. Marks, Jr. 3
2. Use of Satellite Observations in Tropical Cyclone Studies
C.M. Kishtawal 35

Part 2: Advances in Numerical Weather Predictions for Tropical Cyclones

3. Overview of the NOAA/NCEP Operational Hurricane Weather Research and Forecast (HWRF) Modelling System
Vijay Tallapragada 51
4. Physical Processes in Tropical Cyclone Models
Jian-Wen Bao 107
5. Sub-Grid Vertical Turbulent Mixing in the Atmospheric Boundary Layer
Jian-Wen Bao 145
6. Air-Sea Turbulent Flux Parameterizations in Tropical Cyclone Models
Jian-Wen Bao 167
7. Present State of Knowledge of Electrification and Lightning within Tropical Cyclones and Their Relationships to Microphysics and Storm Intensity
Alexandre O. Fierro 197
8. The Role of Land Surface Processes on Tropical Cyclones: Introduction to Land Surface Models
Dev Niyogi, Subashini Subramanian and Krishna K. Osuri 221

x Contents

9. The Role of Land Surface Processes on Extreme Weather Events: Land Data Assimilation System
Dev Niyogi, Krishna K. Osuri, S. Subramanian and U.C. Mohanty 247
10. Ocean Component of the HWRF Coupled Model and Model Evaluation
Richard M. Yablonsky 267

Part 3: Advanced Assimilation and Vortex Initialization Techniques

11. Introduction to Data Assimilation Techniques and Ensemble Kalman Filter
A. Routray, Krishna K. Osuri, S. Pattanayak and U.C. Mohanty 307
12. Data Assimilation and Predictability of Tropical Cyclones
Fuqing Zhang 331
13. Data Assimilation: Comparison and Hybridization between Ensemble and Variational Methods
Fuqing Zhang and Ashish Routray 361

Part 4: Monitoring and Prediction of Tropical Cyclones

14. Operational ACCESS-TC: Vortex Specification, 4DVAR Initialization, Verification and Structure Diagnostics
Noel Davidson, Yi Xiao, Harry Weber, Yimin Ma, Charlie Lok, Lawrie Rikus, Jeff Kepert, Peter Steinle, James Fraser and Radhika Kanase 385
15. Physical Initialization in Tropical Cyclone Forecasting
T.N. Krishnamurti, A. Jaya Kumar, Y.E.A. Raj and S.B Thampi 397
16. Monitoring and Forecasting of Tropical Cyclones over North Indian Ocean
M. Mohapatra 409
17. Operational Tropical Cyclone Forecasts Models at IMD and Their Performance
S.K. Roy Bhowmik 449
18. Tropical Cyclone Research over the North Indian Ocean: Impact of Data and Vortex Initialization in High Resolution Mesoscale Models
U.C. Mohanty, Krishna K. Osuri and Sujata Pattanayak 465
19. Superensemble Technique for Tropical Cyclone Prediction
T.N. Krishnamurti, S. Pattnaik and M. Mandal 497
20. Advanced Diagnostics for the HWRF Hurricane Modelling System
Thiago Quirino and Sundararaman G. Gopalakrishnan 517

Part 5: Advances in Tropical Cyclone Research

21. Introduction to Hurricane Dynamics: Tropical Cyclone Intensification	<i>Michael T. Montgomery</i>	537
22. Recent Advances in Tropical Cyclogenesis	<i>Michael T. Montgomery</i>	561
23. The Hurricane Boundary Layer	<i>Sundararaman G. Gopalakrishnan, C. Venkata Srinivas and Kieran T. Bhatia</i>	589
24. Balanced Dynamics in Tropical Cyclones	<i>Chanh Q. Kieu and Da-Lin Zhang</i>	627
25. Quasi-balanced Dynamics in Tropical Cyclones	<i>Chanh Q. Kieu and Da-Lin Zhang</i>	651
26. Using Budgets to Study Tropical Cyclones	<i>Wallace Hogsett and Da-Lin Zhang</i>	669
27. The Storm Surge Prediction over Bay of Bengal and Arabian Sea: A Review	<i>Sujata Pattanayak, U.C. Mohanty and S.K. Dube</i>	691
<i>Index</i>		725
<i>About the Editors</i>		737
<i>Contributors</i>		739