Someshwar Das · Wei-Kuo Tao
Editors

Severe Storms

Anatomy, Early Warning Systems and Aftermath in Changing Climate Scenarios

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ISBN 978-981-97-7074-8 ISBN 978-981-97-7075-5 (eBook)
https://doi.org/10.1007/978-981-97-7075-5

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Foreword

Having 30 years experience working on the development and community support of widely used atmospheric models, MM5 and WRF, I am an ardent believer in shared knowledge, especially in such an important area for humanity as severe storms. I know that Someshwar Das and Wei-Kuo Tao are bringing years of numerical weather modeling accomplishments to gathering chapters of a highly needed Monograph for anyone who wants to sample the forefront of current knowledge in the wide range of topics relevant to observing, understanding, modeling, and forecasting severe storms, and their impacts now and in the future climate.

Those of us who have worked in this area of meteorological research are fully aware of the complexities of every aspect of severe storms; how they develop, their internal dynamics and thermodynamics, their evolution and lifetimes, and their impacts. Furthermore, they differ globally under different environments and climates, and this Monograph gives a sense of that through its strongly international flavor.

Mesoscale convective systems occur in a variety of environments globally, and much research has been done on their climatology and impacts. In mountainous areas, such as the Himalayas, Rockies, Alps, and Andes, orography plays a large role in how these systems develop and interact with slopes and river basins. In flatter areas, organized systems can wreak havoc along long tracks.

Over the past few decades, satellites, radar, aircraft, and ground-based observations have used increasingly sophisticated methods to observe severe storms in terms of their real-time and climatological occurrence and their internal structures. Now casting and warnings rely heavily on a good observing network and real-time communication of observations. Given the impact of severe storms on society, the improvement of national observing networks of radars and mesonets in developing areas of the world is a crucial part of advancements in public safety. Preparedness for disasters such as flooding and severe storms is a large factor in mitigating their impacts. The link between forecasters and emergency managers must be able to reliably communicate forecast risks to the end users. The forecast product is crucial in maintaining the level of trust needed for this to be effective.

Observations of severe storms are also increasingly being used in high-resolution storm-resolving forecast systems as data assimilation techniques have advanced enough to incorporate developed storms into the model's initial conditions via real-time satellite and radar information. Short-range prediction via a rapid-cycling data assimilation system is becoming more common at operational centers and is suited to the short range of deterministic predictability with such stochastic systems. As the range extends beyond a few hours, ensemble forecasts become the main tool to enable forecasters to see what can happen within the growing uncertainty envelope. Ensembles should represent both model and analysis uncertainties to encompass the range of possible outcomes. Other prediction aspects such as hail size or lightning risk that are not directly modeled may make use of offline physical models using the forecast output or machine learning trained on past events and forecasts with the same model.

The development of high-resolution forecast models also benefits from microphysical observations obtained from radar and in situ aircraft. Microphysical properties vary globally, not just due to the thermodynamics of the environment, but also due to the presence of pollutants or dust where local effects need to be considered as these may sometimes strongly modify the storm characteristics. In storm-resolving models, much of the variability among models in simulating severe storms is down to the variability in representing microphysical processes, especially the particle properties and their evolution. Predicting rainfall intensity or hail relies on adequate microphysics schemes. Hail, surface wind, and lightning are dangerous aspects of severe storms and there is now much more understanding of these processes that is helping models to forecast these more reliably.

Climate change is already occurring and has detectable and accelerating trends even over the last 50 years. The global large-scale circulation is changing and will continue to do so for decades into the future with magnitudes of change that just multiply what has happened so far. How this change affects important systems such as the Indian monsoon and extreme rainfall events is a major topic of research. Projections for the future indicate more rainfall and larger extremes but also seasonal changes that remain uncertain. This will of course impact water resources and agriculture as well as urban climates for billions of people and to increasing degrees related to how much and how quickly the climate is permitted to change.

This Monograph has addressed the important topics that I have outlined above by showing current knowledge in the science and some best practices in forecasting related to severe storms. It is a commendable collection of works by experts in all the topics.

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Preface

Severe Storms continue taking their toll on human lives and economy even though there has been considerable advancement in the prediction models. This book is focused on local severe thunderstorms causing intense lightning, strong winds and torrential rainfall, dust storms, hailstorms, tornadoes, and cloudbursts.

The local Severe Storms disrupt the routine life, and have devastating impacts on agriculture, aviation, surface transportation, electricity, power, communication, essential services, and other socio-economic sectors. It is estimated that lightning due to severe storms kills more people than hurricanes, earthquakes, and floods and is the biggest contributor to accidental deaths due to natural causes. A global survey on the mortality and economic losses due to severe storms indicates that over half a million people died and economic losses of US Dollar 521 billion occurred during 1970–2019 (WMO report, 2021). The IPCC (2021) projects an increase in the severity and frequency of severe storms in future due to climate change. As climate shocks become more common, better forecasting and early warning is a critical need for decision-making, such as when to plan and when to flee. According to UN, currently, one-third of the people in the world, especially in the Least Developed Countries and Small Island Developing States, are still not covered by early warning systems.

What causes the local severe storms so furious? How can we predict their intensity, location, and time of occurrence accurately at sufficient lead time? Accurate prediction of severe storms is still a challenge to the Atmospheric Scientists. Such questions are addressed in this book. For understanding a physically evolving system like a thunderstorm, we need to observe the system through various approaches, develop techniques to forecast its evolution in short, medium, and long-time scales, and develop policies for disaster mitigation in the aftermath of the event. These are discussed in three parts containing 26 chapters in the monograph titled *Severe Storms: Anatomy, Early Warning Systems and Aftermath in Changing Climate Scenarios* by leading scientists across the world.

The observational aspects of the severe storms through satellite, radar, aircraft, and ground-based network of stations are discussed in the first part of the book consisting of 8 chapters. The numerical modeling and data assimilation techniques are discussed in the second part consisting of 12 chapters for the development of early warning system, and finally the outlook of the severe storms in a changing climate, their socio-economic impacts, and policies for disaster mitigation are discussed in the third part of the book consisting of 6 chapters.

The first theme consisting of eight chapters focuses on using satellite (TRMM PR, GPM DPR, INSAT-3D/R), ground-based Radar (Doppler/Dual polarization), aircraft, and in situ measurements to improve our understanding of the physical processes (dynamic, thermodynamic and microphysics) associated with severe storms. These observations are for different types of storms and over different geographic locations. Observation of electric field, Maxwell current, and disdrometers also provide the lightning and raindrop size distributions, respectively.

The second theme consists of twelve chapters that focus on numerical model simulations including the impact of the data assimilation on forecasting severe storms. The impact of the model horizontal resolution, hailstorm dynamic, and hail characteristics, atmospheric boundary layer, low- and high-level moisture characteristics, diurnal cycle, monsoon lows, intra-seasonal oscillations, and extreme precipitation events on severe storms are presented. There is one chapter discussing the use of AI in lightning forecasting. All chapters also emphasized the importance of observations (i.e., Mesonet meteorological observations, radar reflectivity and radial velocity, and lidar profiling data, using high spatial and temporal radar-gauge merged precipitation data).

The third theme consists of six chapters that focus on the severe storms in the changing climate and their impact on societal and disaster risk reduction. These papers used observations (gridded rainfall data, satellite), re-analysis, and CMIP6 to address the impact of future climate change on severe storm developments. The solar storm and its characteristics, and cloud-radiation interaction; land-ocean feedback on extreme weather systems are discussed.

We would like to thank all the authors of the book for contributing the chapters that include the state-of-the-art of the subject and the latest findings of their research. We thank Dr. Amitava Bandopadhyay, Director General of the Centre for Science and Technology of the Non-Aligned and Other Developing Countries (NAM S&T Centre) for taking initiative for the publication of the Monograph, and Ms. Jasmeet Kaur Baweja, Programme Officer, NAM S&T Centre for her support throughout the process.

We hope that the Monograph will be a useful resource guide for research scientists, policymakers, and students to understand the "Severe Storms" and minimize the knowledge and technology gaps especially among the scientific community and policymakers for disaster mitigation, thereby minimizing the loss of lives and economy due to Severe Storms.

New Delhi, India — Someshwar Das
Maryland, USA — Wei-Kuo Tao

Introduction

Thunderstorms are among the nature's most spectacular phenomenon. They occur almost everywhere on the earth's surface. Depending on their intensity, they can produce cool showers or torrential rainfall, pleasant downdrafts or damaging winds, hails, lightning strikes, and can cause deaths and loss of properties. It is estimated that at any given time about 2000 thunderstorms are taking place on the globe (http://www.nssl.noaa.gov/education/svrwx101/thunderstorms/). While they occur both during the summer and the winter seasons, their frequency is highest during the pre-monsoon season over the Indian subcontinent. During the pre-monsoon season, severe thunderstorms generally travel from northwest to southeast direction over the east and northeast parts of countries such as India and Bangladesh. Therefore, they are also called the Nor'westers.

The thunderstorms and dust storms severely disrupt the routine human life, transportation, electricity, and other essential services. Livestock are particularly vulnerable to severe storms. Hailstorms can cause heavy damage to crops and vegetation. Secondary hazards like snapping of electric poles due to uprooting of trees, disruption of communication links, etc. are also attributed to thunderstorms. Most of the damages from thunderstorms occur due to strong winds, lightning strikes, hail stones, and flash floods caused by heavy rains. The cloudburst that occurs in the mountains, leads to exceptionally heavy rainfall and sudden flash floods in the streams and rivers, leading to breaching of the banks and overflowing of dams over the plain areas.

While the natural disasters cannot be prevented or controlled, the loss of lives and damage to property can be substantially minimized by issuing accurate forecast/advisories of the impending disasters through field observations, research, and the use of numerical modeling tools. Accurate and advanced advisories can greatly help the disaster mitigation managers to get sufficient lead time to initiate all the necessary preparedness and mitigation actions including evacuation measures which would help in reducing risks due to these disasters. The first step in the development of accurate warning system of severe storms is a proper understanding of their anatomy based on observations from the satellites, radars, aircrafts, and ground-based network of stations. The second step is the development of numerical modeling techniques and data assimilation in the model. The third step is the communication of the forecasts to the public, disaster mitigation agencies, and local administration giving sufficient lead time for disaster preparedness, evacuation, and other mitigation measures.

Considering the scientific importance of the subject and its socio-economic significance, particularly for the countries of the Global South, the Centre for Science and Technology of the Non-Aligned and Other Developing Countries (NAM S&T Centre), New Delhi have brought out this publication titled *Severe Storms—Anatomy, Early Warning Systems and Aftermath in Changing Climate Scenarios.*

The Monograph is divided into three parts comprising chapters contributed by leading experts from various parts of the world. The first two parts of the book present the current understanding of the anatomy and early warning system of severe storms. Further, due to the uncertainties of the effects of climate change on the earth, it is important to deliberate on what the frequency and severity of the severe storms could be in the future. In order to address this, a few chapters have been included in the third part of the book which present the outlook of severe storms in the changing climate scenarios based upon the climate model simulations and preparedness required for mitigation and management of disasters in the aftermath of such storms. The book also touches upon socio-economic implications of severe storms. The book contains 26 chapters contributed by authors from 11 countries and an Epilogue by the Editors.

I express my sincere gratitude to Dr. Jimy Dudhia, NSF National Centre for Atmospheric Research, Boulder, Colorado, USA for writing the "Foreword" of the Monograph.

The leading international scientific and academic publisher—Springer Nature, Singapore has published the Monograph. We are thankful to Dr. Loyola D'Silva, Executive Editor, Springer Nature for his encouragement and kind support; and Mr. Rajasekar Ganesan, Production Editor, Springer Nature, Chennai, India and other staff members of Springer team worldwide especially Ms. Bhagyalakshmee, Production Supervisor for handling all technical and administrative matters related to this publication. I am confident that our association with "Springer" would lead to many more such valuable collaborative endeavors in the future.

I would like to express my gratitude to the Editors, Dr. Someshwar Das, Former Adviser, Ministry of Earth Sciences, Govt. of India, New Delhi & Former Chair Professor of Atmospheric Science, Central University of Rajasthan, India and Dr. Wei-Kuo Tao, Emeritus Scientist, NASA/Goddard Space Flight Center, Greenbelt, Maryland, USA & Chair Professor, National Central University, Taiwan for their guidance, initiatives and efforts, and sharing their time in technical editing of the papers and designing the structure of this book.

In addition, I am grateful to all the experts for accepting our invitation and sparing their valuable time for reviewing the papers published in this book.

I express my gratitude to Mr. Madhusudan Bandyopadhyay, Senior Adviser, NAM S&T Centre for his kind advice and guidance in various stages of planning and execution of this book project. Further, I am thankful to Ms. Jasmeet Kaur Baweja, Senior Programme Officer, NAM S&T Centre for her significant contributions in coordinating this publication project.

I also acknowledge the interest, initiatives and support received from the entire team of the NAM S&T Centre. I am especially thankful to Mr. Pankaj Buttan, Data

Processing Manager; Mr. Rahul Kumra, Assistant Administrative Officer; Mr. Sunil Kumar, Accounts Manager, and Mr. Jayakumaran, Public Relations Manager, NAM S&T Centre for their support in bringing out this publication.

I am sure that this book would be a valuable reference material for the scientists, researchers and other professionals working in the areas of severe storms observations, modeling, and development of prediction and early warning systems.

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Contents

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The book provides information on the observational aspects of the severe storms through satellite, radar, aircraft, and ground based network of stations and these issues are discussed in the first part of the book consisting of 8 chapters. The numerical modelling and data assimilation techniques are discussed in the second part of the book aimed at development of Early Warning Systems (12 chapters) and finally the outlook of the severe storms in a changing climate scenario, their socio-economic impacts and policies for disaster mitigation are discussed in the third part of the book consisting of 6 chapters. This book is of great interest to atmospheric scientists and other researchers, practitioners, policy and decision makers, international institutions, governmental and non-governmental organizations, educators, as well as students.

ISBN 978-981-97-7074-8

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