Kamaljit Ray
M. Mohapatra
B.K. Bandyopadhyay
L.S. Rathore *Editors*

High-Impact Weather Events over the SAARC Region

Springer

High-Impact Weather Events over the SAARC Region

Kamaljit Ray • M. Mohapatra
B.K. Bandyopadhyay • L.S. Rathore
Editors

High-Impact Weather Events over the SAARC Region

Springer

Editors
Kamaljit Ray
Nowcasting Unit
India Meteorological Department
Mausam Bhawan, Lodhi Road
New Delhi, India

M. Mohapatra
Cyclone Warning Division
India Meteorological Department
Mausam Bhawan, Lodhi Road
New Delhi, India

B.K. Bandyopadhyay
India Meteorological Department
Mausam Bhawan, Lodhi Road
New Delhi, India

L.S. Rathore
India Meteorological Department
Mausam Bhawan, Lodhi Road
New Delhi, India

Co-published by Springer International Publishing, Cham, Switzerland, 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—printed book sold and distributed by Capital Publishing Company, 7/28, Mahaveer Street, Ansari Road, Daryaganj, New Delhi 110 002, India.

ISBN 978-3-319-10216-0 ISBN 978-3-319-10217-7 (eBook)
DOI 10.1007/978-3-319-10217-7
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014955791

© Capital Publishing Company 2015
This work is subject to copyright. All rights are reserved by Capital Publishing Company, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Capital Publishing Company. Permissions for use may be obtained through Capital Publishing Company. Violations are liable to prosecution under the respective Copyright Law.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

High impact weather events are an inherent aspect of the climate system and are of different spatial and temporal scales. They have the potential to cause significant loss of life and property and a major disruption in communication and transport. Understanding the patterns of extreme weather events has assumed even more importance in recent years in the scenario of global climate change. Because of the significance of the extreme weather events in India, the India Meteorological Department, Ministry of Earth Sciences, Government of India, in collaboration with SMRC, Bangladesh, took the initiative to organize the SAARC Seminar on 'High Impact Weather Events over SAARC Region' during 2–4 December, 2013, in New Delhi, India, in order to shed light on the scientific basis and the complexities inherent in combating these events.

The objective of this seminar was to create a forum for discussion on the causes and consequences of high impact weather events in the SAARC member countries, to promote research activities with a view to make better understanding of the high impact weather phenomena and improve their forecasting to minimize loss of lives and properties of this region.

The broad thematic areas of the seminar were:

1. Climatology of high impact weather events
2. The dynamics of extreme events—improving forecasts in the current climate
3. High impact weather events/extreme events under changing climate
4. Consequence of high-impact weather events on the economy, infrastructure and society in various SAARC countries

Papers were received from scientists and National Hydrometeorological Service representatives from SAARC countries and a number of institutions like IIT, IITM, NCMRWF, IISc etc. from India. About 70 delegates from different SAARC countries participated in the seminar. During the seminar, there were nine technical sessions, a panel discussion and the concluding session. There were nine lead talks by eminent scientists in the field of heavy rains, thunderstorms, cyclones and temperature extremes. A number of recommendations emerged after the seminar in each area of specialization.

The panelists agreed that, research being an important component of IMD, it should give special emphasis to high impact weather events, particularly impacts and prediction of heat waves and thunderstorms. More research work was required to make use of DWR data through calibration, validation and networking. Based on remote sensing data, flood and drought hazard proneness needs to be evaluated for SAARC region. There was a need for hazard and vulnerability analysis and climatology of HIWE for SAARC region. In case of heavy rains, there is the need to use rainfall forecasts in a hydrological model to generate surface run-off and thus chance of flooding. The need of high resolution mesoscale models with an interactive land surface model and data assimilation to generate heavy rainfall forecasts was discussed. The panel felt that more sensitivity studies on regional meso scale models was needed to understand the basic mechanism of rainfall over different regions as a result of interaction of monsoon circulation, transient systems, orography and mid-latitude interactions. A number of papers were presented on tropical cyclones and the committee stressed on application of DT to microwave imageries, microwave sounders to estimate the intensity of TC, augmentation of observational network in SAARC region, including surface and upper air observations. The committee stressed on a standard operational mechanism for exchange of data and information among SAARC member countries. Regarding the lack of ground-based observations, space-based observation through satellite was to be utilized maximum for monitoring of high impact weather events including rainfall, temperature extremes, winds etc. Need of a structured system of forecasting and warnings over SAARC region using High Resolution Ensemble for Short Range NWP models for nowcasts, regional cooperation through Severe Weather FDP, and standard operating procedure for all elements of monitoring, prediction and warning was stressed upon.

Considering the significant findings presented in the seminar by various delegates and the recommendations made in the seminar, it was decided to publish the selected papers presented during the seminar as a book after the peer review of the manuscripts.

This book deals with recent advances in our understanding and prediction of cyclone, severe thunderstorms, squalls, heat and cold waves and heavy rainfall, based on the latest observational and NWP modeling platform. The chapters are based on four broad high impact weather events i.e. thunderstorms, cyclones, heavy rains, and drought and temperature. They are authored by leading experts both in research and operational fields.

The book reviews research work, future needs, forecasting skills and societal impacts of above extreme weather events and is relevant to weather forecasters, managers, graduate students and provides high-quality reference material for the users.

As editors of this volume, we are highly thankful to all the authors for their efforts and cooperation in bringing out this publication. We are thankful to SMRC, Dhaka, for approving publishing of this book. We are also thankful to the Advisory Council, National Organizing Committee, SMRC Organizing Committee and Local Organizing Committee for successfully organizing the SAARC Seminar during 2–4 December in New Delhi, India. Authors also thank the Ministry of Earth Sciences for facilitating the organization of the seminar.

New Delhi, India

Kamaljit Ray
M. Mohapatra
B.K. Bandyopadhyay
L.S. Rathore

Contents

Part I Thunderstorms

Study of Severe Thunderstorms over Bangladesh and Its Surrounding Areas During Pre-monsoon Season of 2013 Using WRF-ARW Model 3
Md. Abdul Mannan, Md. Nazmul Ahasan, and Md. Shah Alam

Assimilation of Doppler Weather Radar Data Through Rapid Intermittent Cyclic (RIC) for Simulation of Squall Line Event over India and Adjoining Bangladesh 23
Kuldeep Srivastava, Vivek Sinha, and Rashmi Bharadwaj

Impact of Data Assimilation in Simulation of Thunderstorm Event over Bangladesh Using WRF Model 35
Nazlee Ferdousi, Sujit K. Debsarma, Md. Abdul Mannan, and Md. Majajul Alam Sarker

Numerical Simulation of a Hailstorm Event over Delhi, India on 28 Mar 2013 49
A. Chevuturi and A.P. Dimri

Simulation of Mesoscale Convective Systems Associated with Squalls Using 3DVAR Data Assimilation over Bangladesh 63
Mohan K. Das, Someshwar Das, and Md. Mizanur Rahman

Simulation of Severe Convective Weather Events over Southern India Using WRF Model 73
S. Stella and Geeta Agnihotri

Part II Tropical Cyclones

Early Warning Services for Management of Cyclones over North Indian Ocean: Current Status and Future Scope 87
M. Mohapatra, B.K. Bandyopadhyay, Kamaljit Ray, and L.S. Rathore

Development of NWP-Based Cyclone Prediction System for Improving Cyclone Forecast Service in the Country 111
S.D. Kotal, Sumit Kumar Bhattacharya, S.K. Roy Bhowmik, and P.K. Kundu

Interannual and Interdecadal Variations in Tropical Cyclone Activity over the Arabian Sea and the Impacts over Pakistan 129
Wash Dev Khatri, Zhi Xiefei, and Zhang Ling

Impact of Cloud Microphysics and Cumulus Parameterisation on Meso-scale Simulation of TC Sidr over the Bay of Bengal Using WRF Model 147
Md. Mahbub Alam

Eddy Angular Momentum Fluxes in Relation with Intensity Changes of Tropical Cyclones Jal (2010) and Thane (2011) in North Indian Ocean 165
S. Balachandran and B. Geetha

Impact of Initial and Boundary Conditions on Mesoscale Simulation of Bay of Bengal Cyclones Using WRF-ARW Model 179
K.S. Singh and M. Mandal

Performance of Global Forecast System for the Prediction of Intensity and Track of Very Severe Cyclonic Storm 'Phailin' over North Indian Ocean 191
V.R. Durai, S.D. Kotal, S.K. Roy Bhowmik, and Rashmi Bhradwaj

Part III Heavy Rains

Observational Analysis of Heavy Rainfall During Southwest Monsoon over India 207
Pulak Guhathakurta

Long Term Trends in the Extreme Rainfall Events over India 229
D.S. Pai and Latha Sridhar

Diagnostic Study of Heavy Rainfall Events in Monsoon Season over Northern Part of Bangladesh Using NWP Technique 241
Md. Abdul Mannan and Md. Mahbub Alam

Analysis of Increasing Heavy Rainfall Activity over Western India, Particularly Gujarat State, in the Past Decade 259
Manorama Mohanty, Kamaljit Ray, and Kalyan Chakravarthy

Simulation of Heavy Rainfall Event over Gujarat During September 2013 277
S.I. Laskar, S.D. Kotal, S.K. Bhattacharya, and S.K. Roy Bhowmik

Simulation of Rainfall over Uttarakhand, India, in June Using WRF-ARW Model and Impact of AIRS Profiles 287
Sqn Ldr Prabodh Shukla, Wg Cdr Anil Kumar Devrani, and Sqn Ldr Himanshu Singh

Incessant Rainfall Event of June 2013 in Uttarakhand, India: Observational Perspectives 303
M.R. Ranalkar, H.S. Chaudhari, G.K. Sawaisarje, A. Hazra, and S. Pokhrel

Convergence of Synoptic and Dynamical Conditions Responsible for Exceptionally Heavy Rainfall over Uttarakhand, India 313
Charan Singh

Changes in Rainfall Concentration over India During 1871–2011 325
Naresh Kumar and A.K. Jaswal

Identifying the Changes in Rainfall Pattern and Heavy Rainfall Events During 1871–2010 over Cherrapunji 335
Pulak Guhathakurta, Preetha Menon, and N.B. Nipane

Part IV Drought and Temperature

Agricultural Drought Assessment: Operational Approaches in India with Special Emphasis on 2012 349
S.S. Ray, M.V.R. Sesha Sai, and N. Chattopadhyay

Trends in Extreme Temperature Events over India During 1969–2012 365
A.K. Jaswal, Ajit Tyagi, and S.C. Bhan

Analysis of Extreme High Temperature Conditions over Uttar Pradesh, India 383
Ramesh Chand and Kamaljit Ray

Use of Remote Sensing Data for Drought Assessment: A Case Study for Bihar State of India During Kharif, 2013 399
K. Choudhary, Inka Goel, P.K. Bisen, S. Mamatha, S.S. Ray, K. Chandrasekar, C.S. Murthy, and M.V.R. Sesha Sai

Index 409

About the Editors

Dr. Kamaljit Ray is presently the Incharge of Nowcasting Unit of India Meteorological Department. She was instrumental in starting the All India Nowcast of thunderstorms in 2013 for 120 cities covered by Doppler weather radar network of IMD. She was also a faculty member in the Gujarat University, Department of Physics Electronics and Space Science. She has more than 21 years of experience in meteorological services, research and forecasting and has about 25 research publications in peer-reviewed journals and proceedings.

Dr. M. Mohapatra is Head of Cyclone Warning Division of India Meteorological Department and also looks after the activities of WMO recognized Regional Specialised Meteorological Centre for Tropical Cyclones at IMD, New Delhi. His main research interests include high impact weather events including tropical cyclones. He has 21 years of experience in meteorological services and research and is the author of 50 research papers published in peer-reviewed journals. He has received a number of recognitions including 25th Biennial Mausam Award and Young Scientist Award of Ministry of Earth Sciences (MoES), Government of India, for his research contributions in the field of atmospheric sciences.

B.K. Bandyopadhyay is Deputy Director General of Meteorology (Services), India Meteorological Department. He joined as a Research Scholar in Indian Institute of Tropical Meteorology, Pune, and during next 3 years, he was associated with research on microphysical characteristics of clouds. He joined India Meteorological Department in 1981 and was engaged in operational weather forecasting for past 30 years which mainly included cyclone and heavy rainfall warning services and allied meteorological research. He has made significant research contributions mainly on tropical cyclones. He has about 40 research publications in national and international journals.

Dr. L.S. Rathore is Director General of Meteorology, India, Meteorological Department and Permanent Representative of India with World Meteorological Organization. He is Co-Vice Chairman of Intergovernmental Board of Climate Services (IBCS) and former Vice President of Commission for Agriculture Meteorology, WMO, and presently on its management board. He is former chairman of SAARC Meteorological Research Centre, Dhaka, and also former President of Indian Meteorological Society and President of Association of Agro-meteorologists. He made significant contribution in setting up Integrated Agro-meteorological Service in India. He has 33 years of experience in meteorological services and research and has published about 100 research papers and seven books. He is recipient of Dr Lakhi Ram Memorial Award 2011 constituted by Society for Recent Development in Agriculture. He has been conferred Fellowship by Indian Meteorological Society.

Part I
Thunderstorms

Study of Severe Thunderstorms over Bangladesh and Its Surrounding Areas During Pre-monsoon Season of 2013 Using WRF-ARW Model

Md. Abdul Mannan, Md. Nazmul Ahasan, and Md. Shah Alam

1 Introduction

Bangladesh is located in the northeastern part of the Indian subcontinent and faces the Bay of Bengal in the south and the Meghalaya plateau in the northeast. Almost the entire country is less than 10 m above sea level and on a flat plane. Severe Thunderstorms (henceforth referred to simply as STS) frequently occur in Bangladesh during the pre-monsoon season from March to May, causing deaths and damage to property every year. In Bangladesh, STSs are classified depending on the magnitude of wind speed. The ones producing wind gusts above 42 m s^{-1} are defined as tornadoes, while those producing wind gusts ranging from 11 to 42 m s^{-1} are defined as 'nor'westers'. The term 'nor'wester' means that STS come mostly from the northwestern direction. Despite being highly arbitrary, such criteria for classifying STSs have been used in a number of climatological studies addressing STSs in Bangladesh (Yamane et al. 2008).

Chowdhury and Karmakar (1986) investigated the climatology of nor'westers and reported that nor'westers occurred most frequently in the north central region of Bangladesh during the pre-monsoon season, peaking in April. Yamane and Hayashi (2006) showed the seasonal variation of Convective Available Potential Energy (CAPE) and the vertical wind shear between the surface and the midlevel of the troposphere in Bangladesh using ERA-40. They showed that both CAPE and vertical wind shear are high during the pre-monsoon season with a peak in April. Brooks

Md.A. Mannan (✉) • Md.S. Alam
SAARC Meteorological Research Centre (SMRC), Dhaka, Bangladesh

Bangladesh Meteorological Department (BMD), Dhaka, Bangladesh
e-mail: mannan_u2003@yahoo.co.in

Md.N. Ahasan
Bangladesh Meteorological Department (BMD), Dhaka, Bangladesh

K. Ray et al. (eds.), *High-Impact Weather Events over the SAARC Region*,
DOI 10.1007/978-3-319-10217-7_1

et al. (2003) depicted that the atmospheric conditions displaying high CAPE and strong vertical wind shear are favourable for convective storms.

In Bangladesh, there has been little research on the environmental conditions of STS. Although some case studies of STS have been performed, but their environmental conditions have not been comprehensively studied. Convective parameters (e.g., CAPE) are useful tools for forecasting of STSs. Many statistical studies of convective parameters in the outbreak of STS have been conducted. Rasmussen and Blanchard (1998) showed statistical climatology of convective parameters in the outbreak of tornadic supercells in the United States using rawinsonde data. But STSs are one of the least predictable weather phenomena, especially if they are severe. They may cause damage to property and electric utilities, and endanger humans and livestock (Schemetis et al. 2008). Karmakar and Alam (2006) showed the statistics of convective parameters associated with nor'westers during the pre-monsoon season in Bangladesh using rawinsonde data at 0000 UTC in Dhaka. They provided critical values indicating the likelihood of occurrence of nor'westers for each parameter. However, the critical values provided in their study are subjectively determined.

According to Bangladesh Meteorological Department (BMD), a number of severe thunderstorms have occurred over Bangladesh and its surrounding areas in the pre-monsoon season (March–May) of 2013. They are associated with high winds and moderate to heavy rainfalls. But the events of 22 March, 16, 19 and 27 April, 4, 8, 13 and 16 May are significant and have considerable impact on the life and livelihood of the affected areas. The prediction process of the severe thunderstorms over SAARC region including Bangladesh is still inadequate and demands further study for its improvement. The present study comprehensively examines the environmental conditions of STS occuring during 19 April in Bangladesh. Simulated parameters are investigated. It is believed that the present study greatly contributes to the understanding and forecasting of the environmental conditions of STS in Bangladesh.

1.1 Observed Weather

On 19 April 2013, STSs were recorded at different places of western, southwestern regions and some parts of central region of Bangladesh with the maximum winds of 70 km/h at Ishurdi. Some of the information related to this is given in Table 1. Light to moderate rainfall was recorded at different places of Bangladesh in addition to the places where severe thunderstorms were recorded. Significant amounts of rainfall were recorded at Ishurdi (57 mm), Jessore (47 mm), Rangpur (39 mm), Srimongal (21 mm) and Chuadanga (20 mm). Spatial distribution depicts that the light to moderate rainfall was recorded over west-central and extreme northern parts and light rainfall over central and northern parts of Bangladesh (Fig. 1a). Similar signatures were found from TRMM (version 7) product (Fig. 1b).

Table 1 Recorded significant winds and rainfall on 19 April 2013 in Bangladesh

	Gusty/Squally wind			Significant weather	
Station	Direction (°)	Speed (km/h)	Time (UTC)	Rainfall (mm)	Hail
Chuadanga	NW'ly	67	1400–1430	20	–
Faridpur	W'ly	50	1630	7	–
Khulna	SW'ly	46	1330–1400	17	–
Ishurdi	NW'ly	70	1430–1440	57	–
Dhaka	W'ly	41	1500–1530	9	–

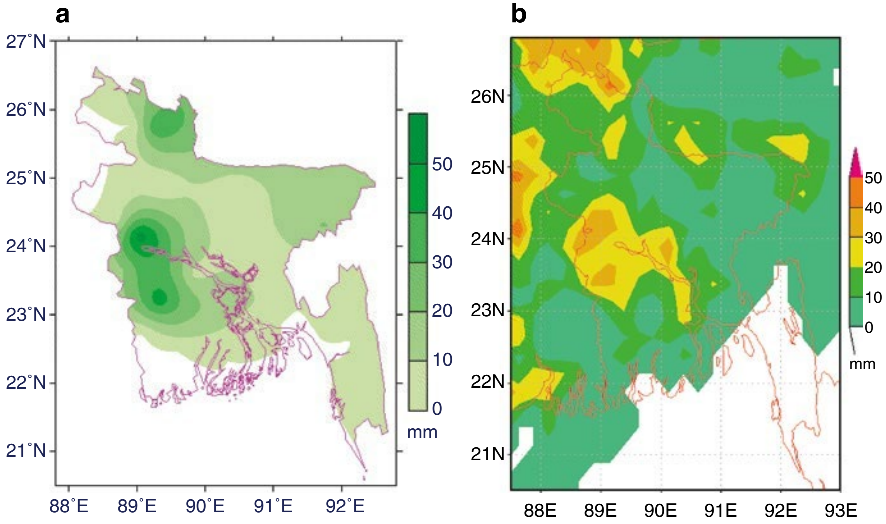

Fig. 1 Spatial distribution of rainfall for (**a**) observed and (**b**) TRMM over Bangladesh on 19 April 2013

1.2 Synoptic Condition on 19 April 2013 over Bangladesh and Adjoining Areas

NCEP reanalysis data set reveals a low pressure area lay over Bihar and adjoining area with its trough extending to West Bengal at 0000 UTC. Another part of the trough extended to Jharkhand, Chattisgarh and Orissa in India. At 0600 UTC, the distribution of MSLP was similar to the trough but it extended to central part of Bangladesh and covered some more parts over eastern ghat of India. At 1200 UTC, the low pressure system and its associated trough strengthened and covered Bangladesh and its adjoining areas including some more parts over India. At 1800 UTC, the low pressure system weakened (Fig. 2). The surface winds were southerly flowing from the Bay of Bengal and bringing moisture over central and eastern parts of India and Bangladesh. The positive vorticity field over this region at surface level was also established (Fig. 3). Accordingly, a strong CAPE field persisted over

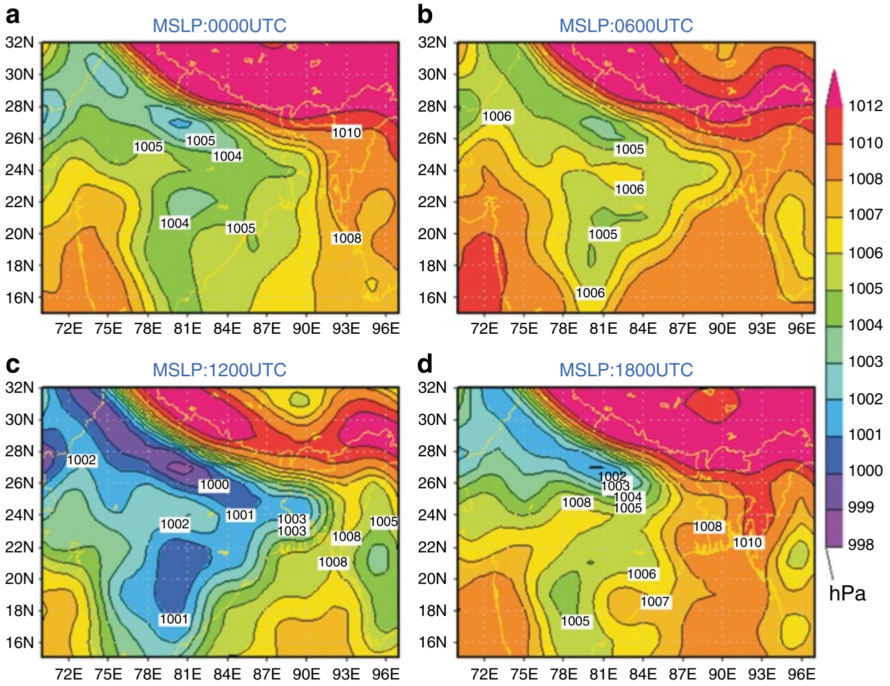

Fig. 2 MSLP distribution over Bangladesh and adjoining areas at (**a**) 0000, (**b**) 0600, (**c**) 1200 and (**d**) 1800 UTC on 19 April 2013 derived from NCEP data

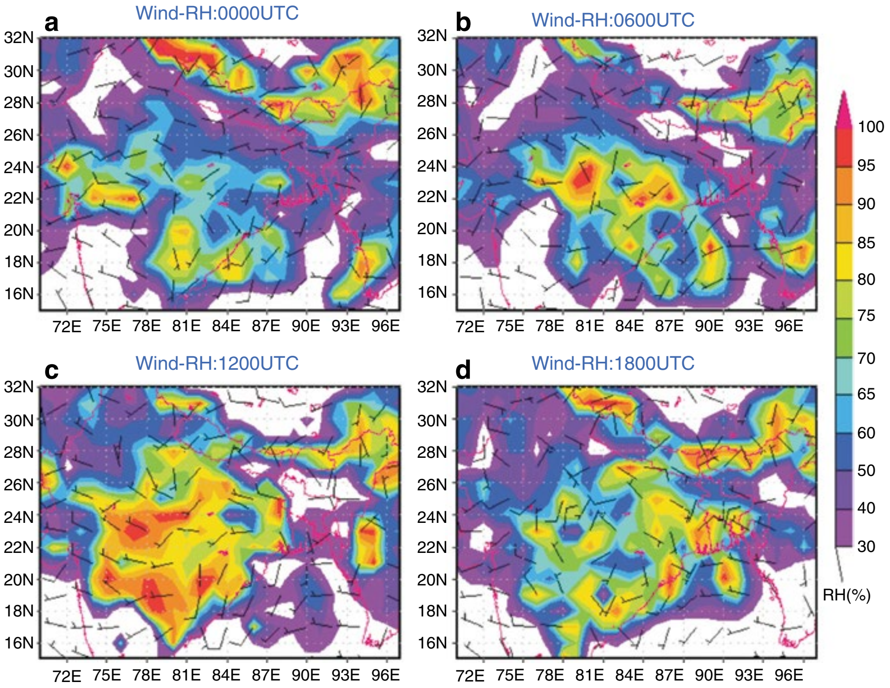

Fig. 3 RH distribution over Bangladesh and adjoining areas at (**a**) 0000, (**b**) 0600, (**c**) 1200 and (**d**) 1800 UTC on 19 April 2013 derived from NCEP data

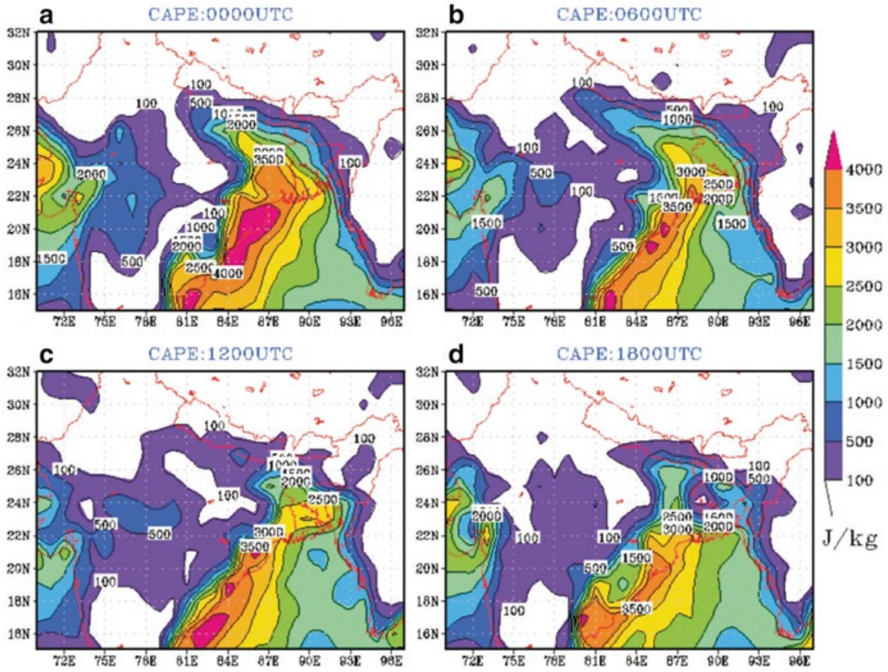

Fig. 4 CAPE distribution over Bangladesh and adjoining areas at (**a**) 0000, (**b**) 0600, (**c**) 1200 and (**d**) 1800 UTC on 19 April 2013 derived from NCEP data

eastern Ghat of India and adjoining Bay of Bengal which extended upto West Bengal of India, Bangladesh and adjoining areas and became strong with the progress of the day and weakened after the occurrence of severe thunderstorm over Bangladesh and adjoining areas (Fig. 4).

2 Methodology

WRF-ARW model (version 3.2.1) with the grid resolution of 9 km is used to diagnose the event using Ferrier (FR), Kessler (KS), Lin et al. (LN), WRF Single-Moment 5 Class (WSM5), WRF Single-Moment 6 Class (WSM6) and Thompson Graupel (TH) microphysics (MPs) schemes with the combination of Betts-Miller-Janjic (BMJ), Grell-Devenyi ensemble (GD), Kain-Fritsch (KF) and New Grell (NG) cumulus scheme (CPs) for extracting the physical processes. Therefore, the combination of MPs and CPs are: BMJFR, BMJKS, BMJLN, BMJTH, BMJWSM5, BMJWSM6, GDFR, GDKS, GDLN, GDTH, GDWSM5, GDWSM6, KFFR, KFKS, KFLN, KFTH, KFWSM5, KFWSM6, NGFR, NGKS, NGLN, NGTH, NGWSM5 and NGWSM6. The coverage area of the model domain is 12–30°N and 80–100°E.

The topography in the model is obtained from USGS land cover data set. NCEP data have been provided at every 6 h as initial and boundary conditions. The model has been run with 19 sigma levels in the vertical direction from the ground to the 100 hPa level to simulate and analyse the parameters of sea level pressure (SLP), relative humidity (RH), wind at 10 m, u and v-components of upper wind, vorticity, convergence and divergence, convective rain and non-convective rain etc. extracted by GrADS. Kringing method facilitated by Win Surfer (version 7.0) software has been used for preparation of all kinds of spatial distributions.

Convective parameters are essential to calculate/quantify the environmental conditions in the outbreak of STS. Commonly used convective parameters are K Index (KI), Lifted Index (LI), Total Totals Index (TTI), Showalter Index (SI), Precipitable Water (PW), Convective Available Potential Energy (CAPE), Convective Inhibition (CIN), Mean Shear (MS), Storm Relative Environmental Helicity (SREH), Vorticity Generation Parameter (VGP), Energy Helicity Index (EHI), and Bulk Richardson Number (BRN). MS, SHEAR and SREH are measures of vertical wind shear of the atmosphere. The vertical wind shear is important for organisation of convection like supercell and multicell (Weisman and Klemp 1982). Supercells and multicells have greater potential to produce severe weather such as tornadoes than ordinary cells (Houze 1993). Therefore, the vertical wind shear is an important ingredient for the outbreak of STS (Brooks et al. 2003). VGP, EHI and BRN are the combinations of the thermal instability and vertical wind shear parameters and common indicators of the formation of supercells and tornadoes. In this study KI, TTI, PW, equivalent potential temperature (θ_E), LI, CAPE, CIN, EHI and SREH are calculated and analysed as per the following definition:

(i) K Index is defined (George 1960) as:

$$\mathrm{KI} = T_{850\,\mathrm{hPa}} - T_{500\,\mathrm{hPa}} + Td_{850\,\mathrm{hPa}} - \left(T_{700\,\mathrm{hPa}} - Td_{700\,\mathrm{hPa}}\right)$$

where T is temperature and Td is dew point temperature. $T_{850\,\mathrm{hPa}}$–$T_{500\,\mathrm{hPa}}$ indicates the lapse rate of temperature between the lower layer and middle layer. $Td_{850\,\mathrm{hPa}}$ indicates the moisture content in the lower layer. $T_{700\,\mathrm{hPa}}$–$Td_{700\,\mathrm{hPa}}$ is a measure of the reduction of negative buoyancy through entrainment of dry air. The KI exceeding 28 K indicates the likelihood of convection (Fuelbarg and Biggar 1994).

(ii) Total Total Index (TTI) is defined (Sadowski and Rieck 1977) as:

$$\mathrm{TT} = \left(T_{850\,\mathrm{hPa}} + Td_{850\,\mathrm{hPa}}\right) - 2\,T_{500\,\mathrm{hPa}}$$

where T is the dry bulb temperature and Td is the dew point temperature.

(iii) Lifted Index (LI) is defined (Galway 1956) as:

$$\mathrm{LI} = T_{500\,\mathrm{hPa}} - Tp^{*}{}_{500\,\mathrm{hPa}}$$

where $Tp^*_{500\,\mathrm{hPa}}$ is the temperature of a parcel with the mean temperature and dew point temperature in the lowest 100 hPa lifted adiabatically until saturated, and then moist adiabatically to 500 hPa. $T_{500\,\mathrm{hPa}}$ is the temperature at 500 hPa. Negative LI indicates the likelihood of convective activity. The LI explicitly reflects the condition in the boundary layer compared with the SSI.

(iv) Precipitable Water (PW) is defined (Huschke 1959) as:

$$\mathrm{PW} = \int_{Ps}^{0} q dp = \int_{Ps}^{100hPa} q dp$$

where Ps is the surface pressure and q is the specific humidity. In this study, the top pressure is defined as 100 hPa because of the scarce amount of water vapour above 100 hPa.

(v) Convective Available Potential Energy (CAPE) is defined (Moncrieff and Miller 1976) as:

$$\mathrm{CAPE} = g \int z\, LFC\; z\, EL \left(T_{vp} - T_v\right) / T_v dz$$

where g is the gravitational acceleration, z_{LFC} is the level of LFC (level of free convection), and z_{EL} is the equilibrium level, where the temperature excess of a parcel lifted from the LFC first becomes zero above the LFC, and T_{vp} and T_v are the virtual temperatures of the air parcel and the environment, respectively. The CAPE is referred as the net work of the environment on a parcel per unit mass lifted from z_{LFC} to z_{EL} and the measurement of the development of convection.

(vi) Convective Inhibition (CIN) is defined (Colby 1984) as:

$$\mathrm{CIN} = g \int z_i z LFC \left(T_{vp} - T_v\right) / T_v dz$$

where z_i is the initial level of the parcel lifted for calculating the CAPE, and T_vp and T_v are the virtual temperatures of the air parcel and the environment, respectively. The CIN is referred as the required net work to lift a negatively buoyant parcel per unit mass to the LFC. In general, the CIN is used for the measurement of stability of the atmosphere.

(vii) Storm Relative Environmental Helicity (SREH) index is defined (Davies-Johnes 1984) as:

$$\mathrm{SREH} = -\int_{0}^{h} \kappa . \left(V - C\right) \times \left(\partial V / \partial z\right) dz$$

where V is the horizontal velocity vector, C is the storm motion vector, k is the unit vector in the vertical and h is the depth over which the integration is performed (3 km herein).

(viii) Energy Helicity Index (EHI) is defined (Hart and Korotky 1991; Davies 1993) as:

$$\mathrm{EHI} = \left(\mathrm{SREH} \times \mathrm{CAPE}\right) / 1.6 \times 10^5$$

The EHI is the combination of the SREH and CAPE, and a measure of tornadic supercell. Rasmussen and Blanchard (1998) showed the EHI as highly correlated with the generation of supercells in the United States of America.

(ix) Equivalent potential temperature (θ_E) is characterised (Davies-Jones 2009) as:

$$\theta e = \theta \exp\left(L_0^* r / C_{pd} T_L\right)$$

where $L_0^* = 2.690 \times 10^6$ J kg^{-1}.

L_0 is the latent heat of condensation at temp T_L, θ is partial potential temperature, C_{pd} is specific heat of dry air, and r is mixing ratio in gram of water vapour per gram of dry air.

3 Results and Discussion

Simulated mean sea level pressure, surface and upper air relative humidity, wind at 10 m and upper levels vorticity ($\times 10^{-5}$ s^{-1}), divergence, vorticity, wind at 10 m for different MPs with CPs, recorded maximum wind at 10 m and rainfall of BMD on 19 April 2013 are plotted, presented and discussed in the following sub-sections.

3.1 *Surface Pressure, Wind and Relative Humidity*

Simulation depicted that a low pressure area formed over West Bengal of India and adjoining western part of Bangladesh at 0600 UTC which then became marked over the same area during next successive hours and extended to Bangladesh and its surrounding areas (Fig. 5). In response to this situation, the surface pressure of Bangladesh reduced and reached to its lowest level during 0900–1100 UTC and the lowest simulated minimum pressure of 1003.0 hPa was found at 0900 UTC for NGFR. Similar situation was observed at Chuadanga, Ishurdi, Khulna and Faridpur where STSs with rainfall were recorded (Fig. 6a). But in support of this situation, temperature at 2 m increased sharply over Bangladesh from morning to 0700 UTC (Fig. 6b). Due to decrease in SLP and increase in temperature, the RH decreases in surface levels but with the advection of moisture from the Bay of Bengal, the RH increases in the layer of 850–750 hPa. It decreases again in the layer of 700–500 hPa but increases in the layer above it due to the presence of positive vorticity and convergence. The vertical profile of area average RH for all combinations of MPs with CPs had similar pattern (Fig. 7). This feature was observed at all the places where STSs were recorded (Fig. 8).

3.2 *Zonal and Meridional Winds*

Area average zonal winds at 950 hPa over Bangladesh and its adjoining areas are negative in the morning but in the afternoon they become positive and strong (Fig. 9a). At 850 hPa it is positive in the night but decreases during morning and

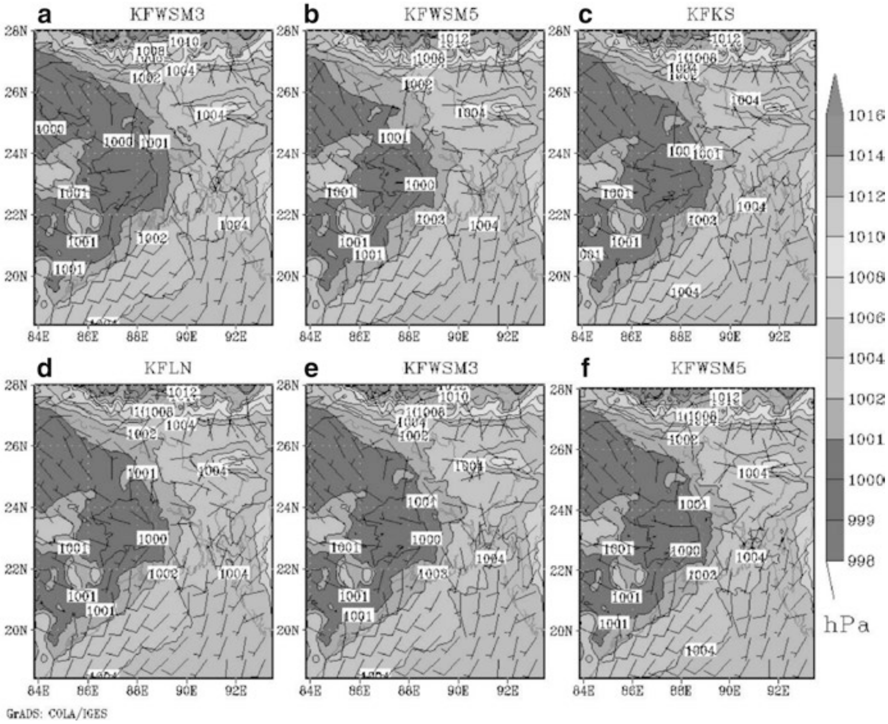

Fig. 5 Simulated MSLP and with (10 m) distribution for (**a**) KFFR, (**b**) KFKS, (**c**) KFLN, (**d**) KFTH, (**e**) KFWSM3 and (**f**) KFWSM6 over Bangladesh and adjoining areas at 1100 UTC of 19 April 2013

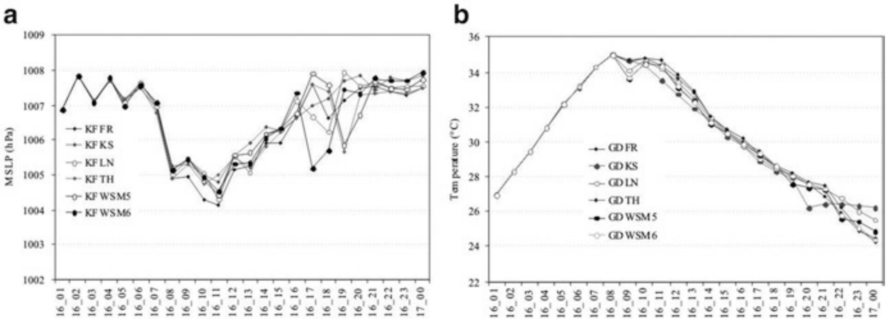

Fig. 6 Temporal variation of (**a**) SLP and (**b**) temperature (2 m) at Ishwardi for different combination of MPs and CPs on 19 April 2013

becomes negative temporarily in the early afternoon and then positive and increases till midnight (Fig. 9b). Above this layer, zonal wind components are absolutely positive but decrease in the afternoon. Similar situation was observed for different

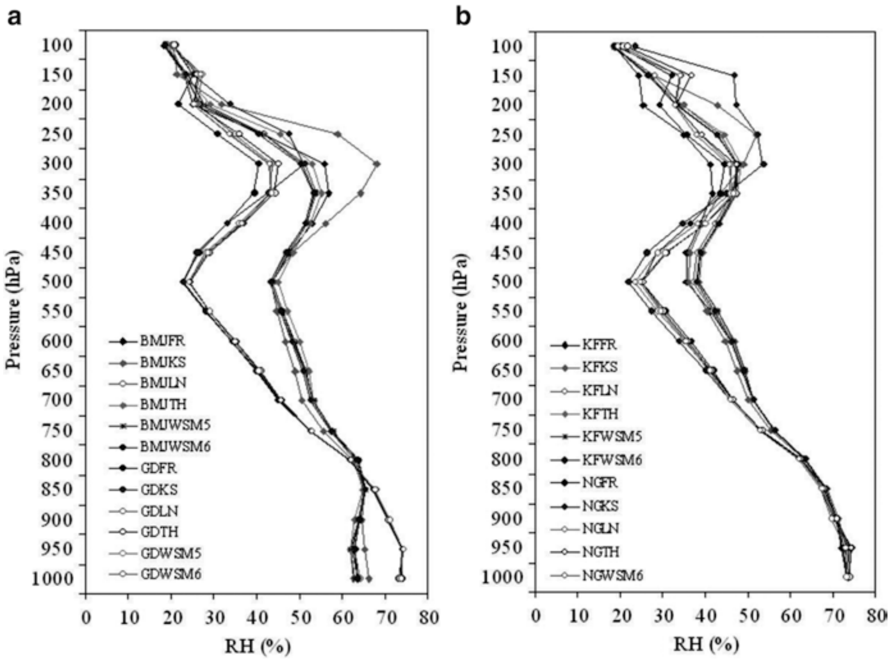

Fig. 7 Vertical profile area average RH: (**a**) for BMJFR, BMJKS, BMJLN, BMJTH, BMJWSM5, BMJWSM6, GDFR, GDKS, GDLN, GDTH, GDWSM5 and GDWSM6, and (**b**) for KFFR, KFKS, KFLN, KFTH, KFWSM5, KFWSM6, NGFR, NGKS, NGLN, NGTH, NGWSM5 and NGWSM6 over Bangladesh and adjoining areas on 19 April 2013

combinations of CPs and MPs at the places where the severe thunderstorms were recorded (Fig. 10).

Area average meridional winds over Bangladesh and its adjoining areas were absolutely positive in the layer 950–800 hPa but in the afternoon winds become strong (Fig. 11a). They were negative in the layer 750–500 hPa during morning but became positive and strong during the later period of the day (Fig. 11b). They were absolutely positive above this layer during the observed period. Accordingly, positive meridional winds in the afternoon period were stronger for different combinations of CPs and MPs at the places where the severe thunderstorms were recorded (Fig. 12).

3.3 Divergence and Vorticity

Following the surface wind field area, average divergence remained positive in the lower layer over Bangladesh during the early hours of the day and then convergence was established and became prominent as well as expanded to upper level.

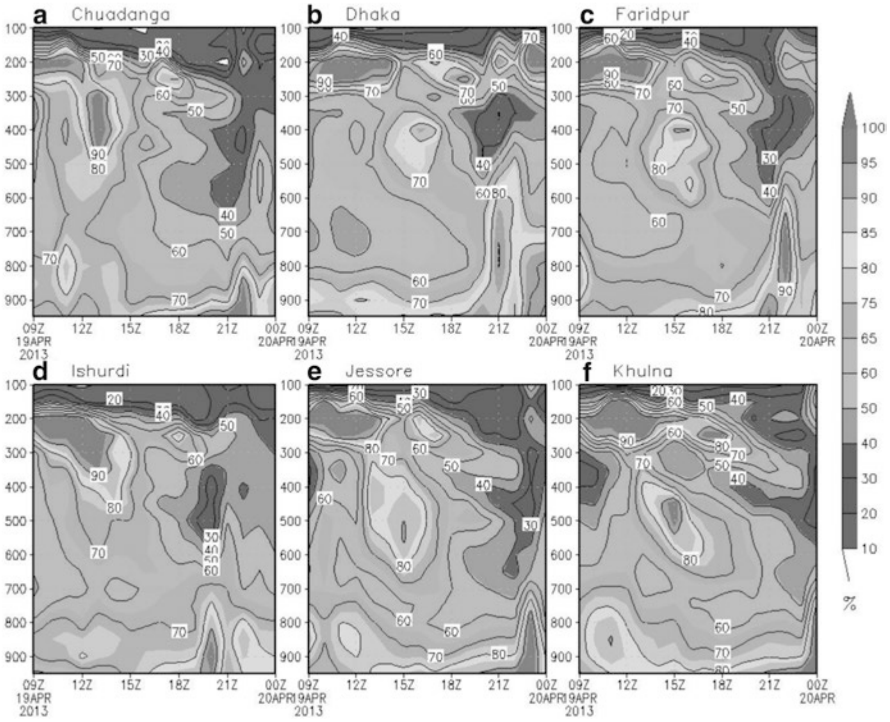

Fig. 8 Vertical profile RH for (**a**) Chuadanga, (**b**) Dhaka, (**c**) Faridpur, (**d**) Ishurdi, (**e**) Jessore, and (**f**) Khulna for KFWSM6 on 19 April 2013

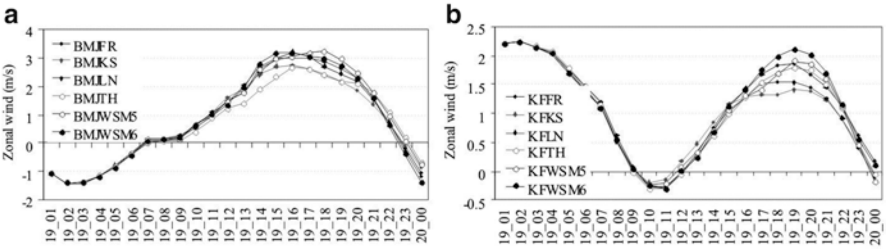

Fig. 9 Temporal variation of area average zonal wind for (**a**) 950 and (**b**) 850 hPa on 19 April 2013

Convergence persisted in the layer 400–150 hPa during the early hours of the day but it changed to divergence in the later period. Combination of this situation where convergence establishes in the lower layer and divergence in the upper layer during afternoon period and continues till the event happens was common over the places where the STS and rainfall occurred over Bangladesh and adjoining areas (Fig. 13).

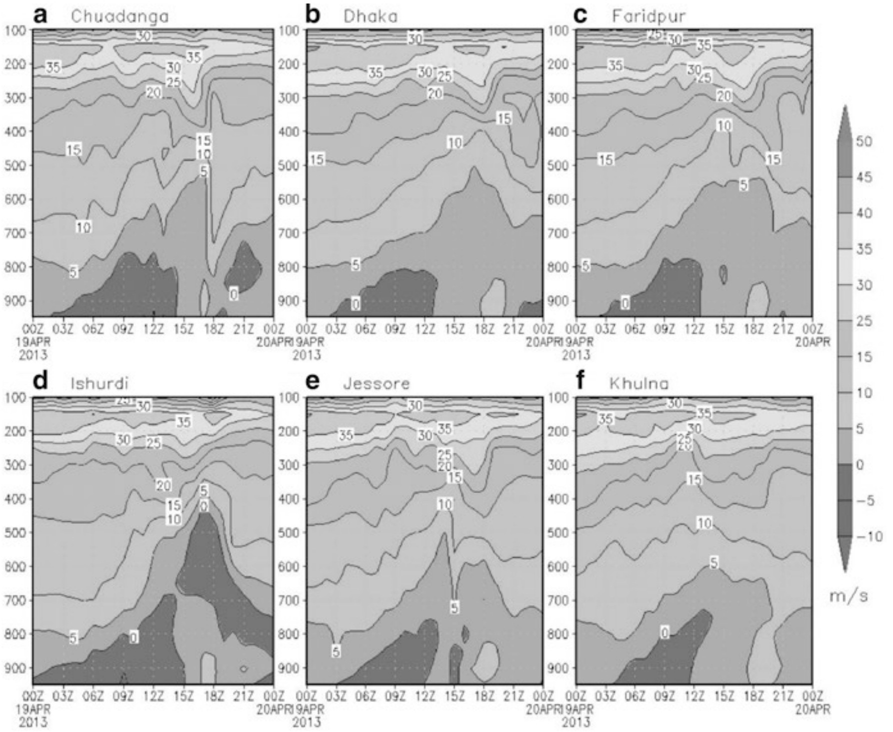

Fig. 10 Vertical profile zonal wind over (**a**) Chuadanga, (**b**) Dhaka, (**c**) Faridpur, (**d**) Ishurdi, (**e**) Jessore and (**f**) Khulna for KFTH on 19 April 2013

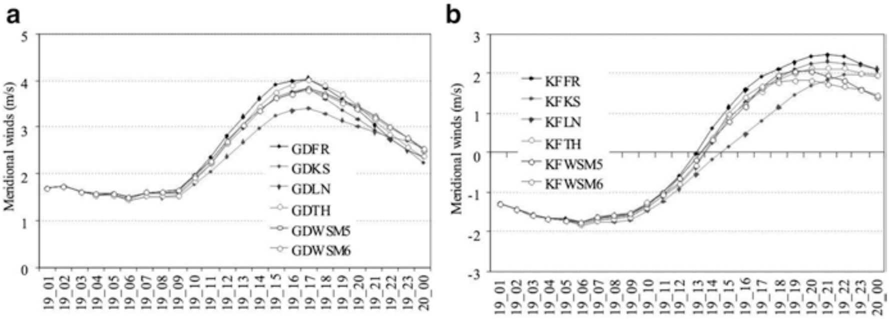

Fig. 11 Temporal variation of area average zonal wind for (**a**) 850 and (**b**) 700 hPa on 19 April 2013

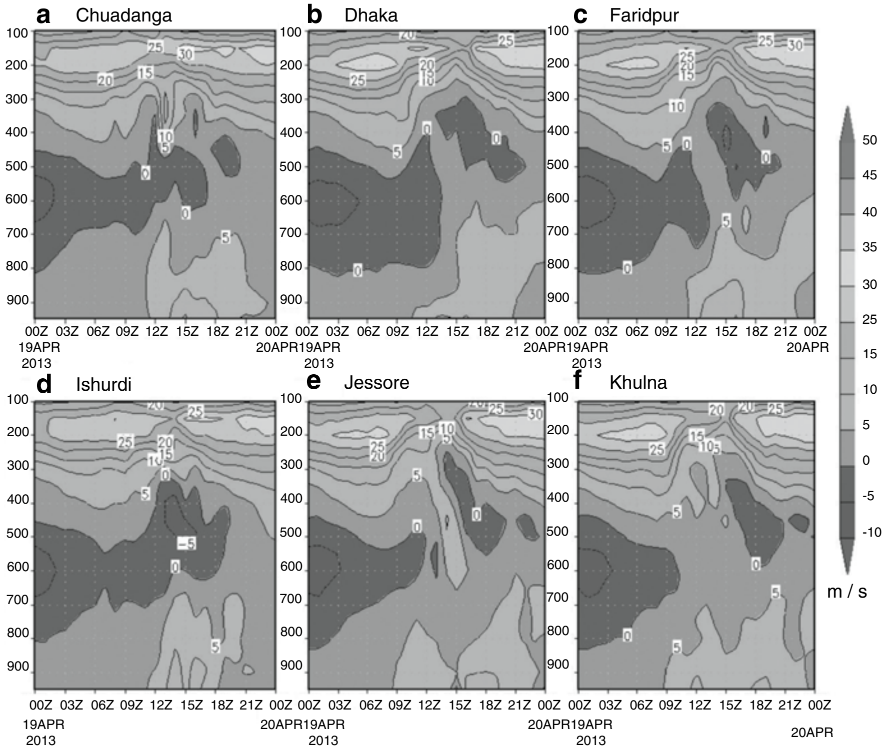

Fig. 12 Vertical profile meridional wind over (**a**) Chuadanga, (**b**) Dhaka, (**c**) Faridpur, (**d**) Ishurdi, (**e**) Jessore and (**f**) Khulna for NGFR on 19 April 2013

Area average vorticity remained positive during the early hours of the day and expanded to higher levels, but it changed to negative value during the later period of the day. It remained positive in the layer 600–200 hPa throughout the day. Accordingly, negative vorticity was established in the lower levels and positive vorticity in the upper levels. In other words, positive vorticity continued in the upper levels with extension in the lower levels. But the short-lived positive vorticity spikes were observed just before the event, at the places where STS was recorded (Fig. 14).

3.4 Convective Parameters

On the basis of the simulated lowest pressure for different MPs with CPs, the instability indices of K, TT, PW, $\theta_{E,}$ LI, CAPE, CIN, EHI and SREH were calculated. It was found that the convective thresholds were sufficiently strong and were found at

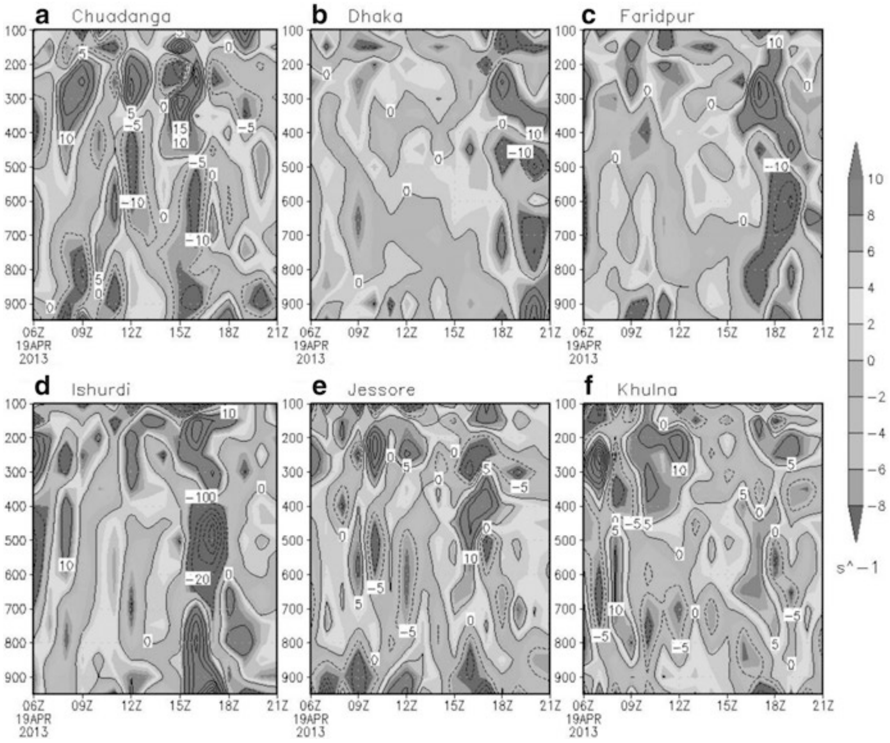

Fig. 13 Vertical profile divergence over (**a**) Chuadanga, (**b**) Dhaka, (**c**) Faridpur, (**d**) Ishurdi, (**e**) Jessore and (**f**) Khulna for KFWSM6 on 19 April 2013

Chuadanga, Ishurdi, Rajshahi and Satkhira where STSs were recorded. The brief description is summarized in Table 2.

The mean and median values for KI index on the day of STS over Bangladesh are 27.6 and 29.0 K (Yamane et al. 2010). The simulated KI indices at the places where STS was recorded were higher than these indices, indicating most unstable atmosphere. Simulated θ_E was much higher than its minimum thresholds of 320 K for severe thunderstorm. The mean and median values for LI are −0.2 and 0.1 K (Yamane et al. 2010) but simulated LI were within the range of −9 to −2 K. The mean and median values for the PW on STS are 38.2 and 38.5 g kg^{-1} (Yamane et al. 2010) but the simulated values were much higher than the minimum thresholds.

The mean and median values of CAPE for STS over Bangladesh are 1,363 and 1,170 J kg^{-1} (Yamane et al. 2010) but simulated CAPE was much higher than that. The mean and median values for CIN for STS over Bangladesh are 322 and 300 J kg^{-1} (Yamane et al. 2010) but the simulated CIN were much lower than that. The mean and median values of EHI for STS over Bangladesh are