Study of Two Pre-monsoon Thunderstorms that Affected Bangladesh, Bhutan, India and Nepal in 2009 by 3DVAR Data Assimilation in WRF-ARW Model

Sujit Kumar Debsarma

Visiting/ Adjunct Professor

Bangabandhu Sheikh Mujibur Rahman Maritime University (BSMRMU)

14/06-14/23, Pallabi, Mirpur-12, Dhaka-1216, Bangladesh

e-mail: sujit.debsarma@gmail.com, sujit.ocn@bsmrmu.edu.bd

Abstract

Wide spread thunderstorms or nor'westers (locally known as "Kalbaishakhi") occurred over Nepal, east and northeast India and Bangladesh on 03 May and 10 May 2009. These two cases were studied in this paper by Three-Dimensional Variational (3DVAR) Data Assimilation (DA) in Weather Research and Forecasting (WRF) – Advanced Research WRF (ARW) (i.e. WRF-ARW) Model. National Centers for Environmental Prediction - Final Analysis (NCEP-FNL) data is utilized as initial and boundary condition (IC/BC) at six-hour intervals. STORM Domain covering Bangladesh, Bhutan, Nepal, east and northeast India at 09 km horizontal resolution with 27 vertical terrain following eta levels, Kain-Fritch cumulus parameterization scheme WRF- Single Moment 3-Class (WSM3) microphysics, Monin-Obukhov Surface Layer with Carslon-Boland viscous sub-layer, Yonsei University Planetary Boundary Layer (PBL), Noah 4-layer Land Surface Model (LSM) and Rapid Radiative Transfer Model (RRTM) for Long and Short Wave (Dudhia Scheme) are used in running the Model. Synoptic, Automatic Weather Station (AWS) and upper-air sounding data collected during Coordinated Field Experiment-2009 under the SAARC STORM (Severe Thunderstorm Observation and Regional Modeling) Programme are assimilated with a view to improving the forecast. Grid Analysis and Display System (GrADS) is used for visualization of the Model outputs. The 3DVAR Data Assimilation (DA) into the WRF-ARW Model shows little improvement over normal model run without DA. However, little temporal as well as spatial shift of occurrence of the thunderstorms is observed.

Keywords: WRF-ARW Model, NCEP-FNL, Data Assimilation (DA), 3DVAR, SAARC-STORM, RRTM, LSM, PBL, AWS, Rawinsonde, LITTLE_R, First Guess and Kalbaishakhi.

1. Introduction

Wide spread thunderstorms or nor'westers (locally known as "Kalbaishakhi") occurred over Nepal, east and northeast India and Bangladesh on 03 May and 10 May 2009. These are pre-monsoon thunderstorms. These particular cases of nor'westers during the Coordinated PILOT Field Experiment - 2009 is studied in this paper by using Advanced Research WRF (ARW) Model. Three-Dimensional Variational (3DVAR) Data Assimilation (DA) technique of WRF-ARW Modeling System is employed with a view to assimilating synoptic, Automatic Weather Station (AWS) and upper-air sounding data collected during the STORM Field Experiment - 2009.

In this paper Advanced Research WRF (Weather Research and Forecasting) Model of NCAR-NCEP is used to study various features of the thunderstorms of 03 May and 10 May 2009. National Centers for Environmental Prediction (NCEP) - Final Analysis (FNL) data is utilized as initial and boundary condition (IC/BC) at six-hour intervals. STORM Domain covering Bangladesh, Bhutan, Nepal, east and northeast India at 09 km horizontal resolution with 27 vertical terrain following eta levels, Kain-Fritch cumulus parameterization scheme WRF- Single Moment 3-Class (WSM3) microphysics, Monin-Obukhov Surface Layer with Carslon-Boland viscous sub-layer, Yonsei University Planetary Boundary Layer (PBL), Noah 4-layer Land Surface Model (LSM) and Rapid Radiative Transfer Model (RRTM) for Long and Short Wave (Dudhia Scheme) are used in running the Model. Three-Dimensional Variational (3DVAR) Data Assimilation (DA) technique of WRF-ARW Modeling System is employed with a view to assimilating Synoptic, Automatic Weather Station (AWS) and upper-air sounding data collected during Coordinated Field Experiment-2009 under the SAARC STORM (Severe Thunderstorm Observation and Regional Modeling) Programme. Grid Analysis and Display System (GrADS) is used for visualization of the Model outputs. The 3DVAR Data Assimilation (DA) into the WRF-ARW Model shows little improvement over normal model run without DA. However, little temporal as well as spatial shift of occurrence of the thunderstorms is observed. If Global Forecast

System (GFS) data instead of FNL data are used and 3DVAR DA technique is employed then remarkable improvement over the normal run is expected. Good qualitative data is required for ensuring good forecast. It is to be noted that 'no data is better than wrong data' in case of assimilation and forecasting.

The SAARC - STORM Programme was one of the long-term programmes of SAARC Meteorological Research Centre (SMRC). It aimed at collecting intensive field observations of thunderstorms over the SAARC region for understanding their structure, dynamics, microphysics and improve predictability by using mesoscale model like Weather Research and Forecasting (WRF) Model. Debsarma, S.K. (2004) observed that if there is a sudden fall of pressure over a small area, then due to differential heating supported by deep layer of atmospheric instability, there are chances of formation of local thunderstorms [1]. The SAARC – STORM Programme was divided into three phases to cover the whole SAARC region in phases. In the first phase, India, Bangladesh, Bhutan and Nepal (Fig.1) have jointly conducted three well-coordinated Pilot Field Experiments during 2009 - 2011. In the second phase (during 2012-2014) of the experiment Afghanistan, Pakistan and Western part of India participated and in the third phase (during 2013-2015) southern peninsular India, the Maldives and Sri Lanka participated. Since 2013 all the eight Member States of SAARC took part in the SAARC - STORM Pilot Field Experiment.

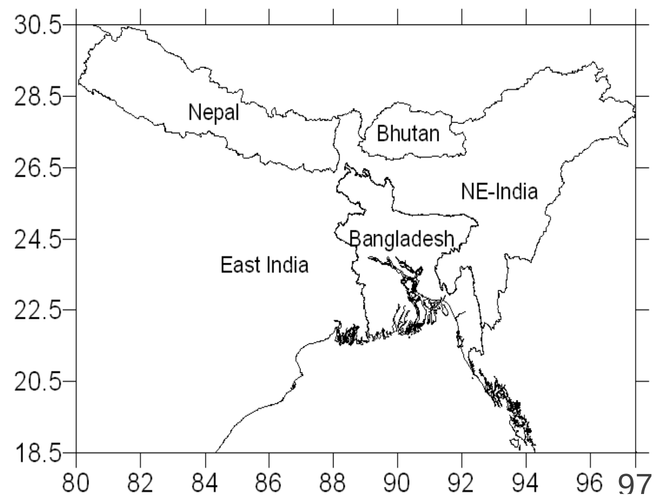

Fig 1: SAARC - STORM Project (Phase – I) Domain (Bangladesh, Bhutan, Nepal, east and northeast India).

A lot of simulation studies have so far been done over the SAARC Region by using WRF Model. Rao, G.V. and Bhaskar Rao, D.V. (2003) observed mesoscale characteristics of tropical cyclones and made some preliminary numerical simulations of their kinematics features [2]. Ahasan, M.N., Debsarma, S.K. made simulation of the thunderstorm of 11 May 2011 over Bangladesh by using WRF model with DA technique. It could capture the thunderstorm event of 11 May 2011 reasonably well though there are some spatial and temporal biases in the results [3]. Basnayake B.R.S.B., Das, M.K., Nessa, F,F,, Rahman, M.M. (2010) studied thunderstorms of 2010 over Bangladesh and neighbourhood during pre-monsoon season of 2009 by using WRF Model. Model simulated Convective Available Potential Energy (CAPE) and Convective Inhibition Energy (CINE) can be used to detect thunderstorms well [4]. Das, S. (2009) made an SMRC (SAARC Meteorological Research Centre) Scientific Report on composite characteristics of Nor'Westers observed by TRMM & simulated by WRF Model [5]. Das, S., Dutta, S.K., Debsarma, S.K., Ferdousi, N., Nessa, F.F. (2012) in their assimilation of STORM 2009 Field Observations in WRF Model and their impact on the simulations of thunderstorms (SMRC Report No. 43), mentioned that most of the models are unable to predict the precise time and location of occurrences of thunderstorms owing to lack of generation of convective instability at the right locations [6]. Ferdousi, N., Debsarma, S.K., Mannan, M.A., Sarker, M.M.A. (2014) studied the impact of Data Assimilation in simulation of thunderstorm event over Bangladesh using WRF Model [7]. Debsarma, S.K. (2011) studied thunderstorm of 03 May 2009 using WRF-ARW Model and mentioned that WRF-ARW Model could capture the thunderstorm to certain extent with some temporal and spatial shift [8].

2. Methodology and data used

WRF-ARW Model developed by NCAR/NCEP, USA has been used for Simulation of extreme weather events with Three-Dimensional Variational (3DVAR) Data Assimilation (DA). Six hourly NCEP-FNL datasets from 00Z of 02 May to 00Z of 04 May 2009 were used as initial and boundary condition in the model. Synoptic, AWS and upper air data (Pilot and Rawinsonde) of the STORM Domain (Phase-I) were used for 3DVAR Data Assimilation. World Meteorological Organization (WMO) format of those datasets were first converted into LITTLE_R Format. Then as usual practice observation file (obs_gts_datetime.3DVAR), Background Error file (BE) and First Guess (FG) file were created. Finally, 3DVARDA was run.

The SAARC STORM Domain (Phase-I) was taken to be of 9 km horizontal resolution with 27 vertical terrain following eta levels, WSM 3-class scheme, Hong, Dudhia and Chen (2004) micro-physics [9], Rapid Radiative Transfer Model (RRTM) (Mlawer *et al.*, 1997) [10], for long wave and shortwave (Dudhia, J., 1989) [11], YSU PBL scheme (Hong and Noh, 2006) [12], Kain-Fritch cumulus parameterization scheme [13] and WRF-single moment 3-class microphysics scheme (simple ice and snow scheme) were used in order to simulate the nor'wester events of 03 May 2009 and 10 May 2009.

3. Case studies

3.1 Thunderstorm of 03 May 2009

A Mesoscale Convective System (MCS) with cloud top temperature of -50°C was seen over Nepal that yielded thunderstorm in Nepal at 0030Z of 03 May 2009 (Fig. 2a). At the same time there was another strong convective cell with cloud top temperature of -60°C seen over Chittagong region of southeastern Bangladesh. Both the systems started moving southeastwards until 0430Z (Fig. 2b). At 0830Z, hook pattern MCS with cloud top temperature of -60°C was observed over northwestern part of Bangladesh (Fig. 2c) which resulted in thunderstorm over the region.

3.1.1 Kalpana-1 satellite imageries

At 1230Z of 03 May 2009, the previous MCS grew bigger and spread over southern part of Bangladesh. At the same time the prevailing small cloud cell west of the hook pattern also grew bigger and spread over Gangetic West Bengal (Fig. 2c-d).

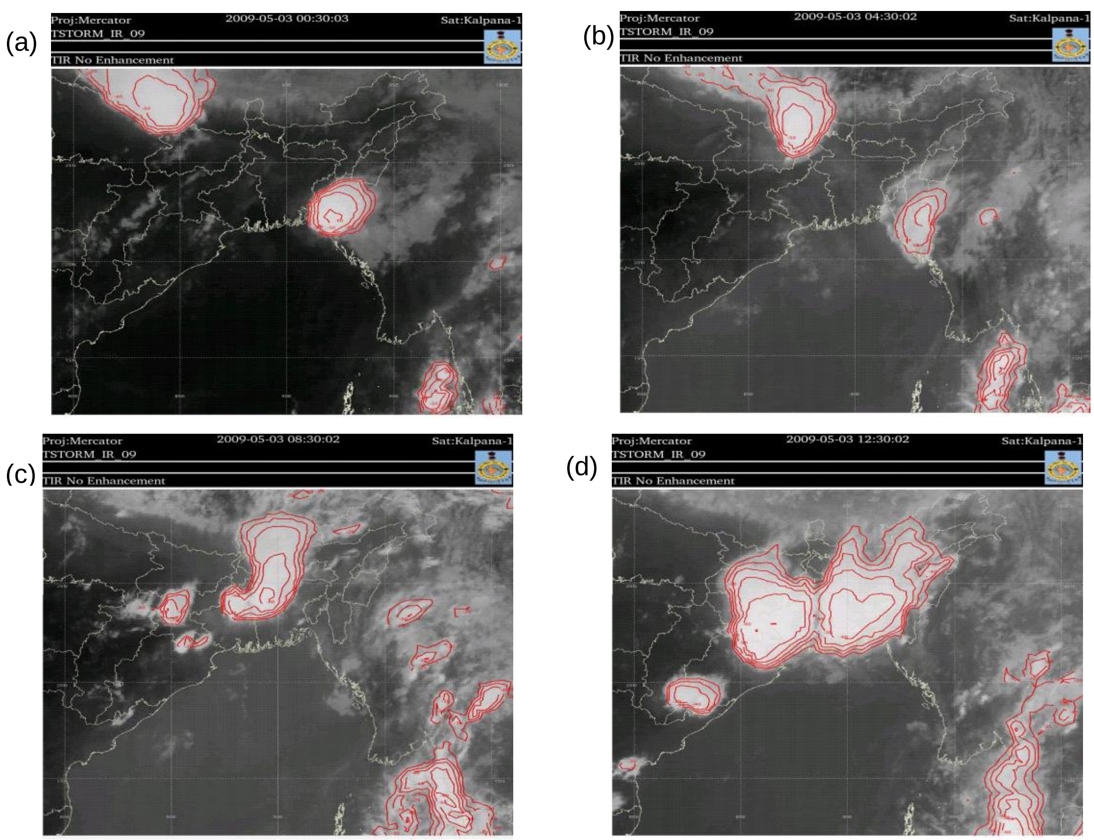

Fig 2: Kalpana-1 satellite imageries of 03 May 2009 at (a) 0030Z, (b) 0430Z, (c) 0830Z and (d) 1230Z

3.1.2 Kolkata Doppler Weather Radar (DWR)

In the Doppler Weather Radar (DWR) imageries of Kolkata a squall line was found over Rajshahi Division and adjoining area of West Bengal at 0610Z of 03 May 2009 (Fig. 3a). The squall line was found to accentuate and move southeastwards over Khulna Division and adjoining Gangetic West Bengal at 0810Z (Fig. 3b).

The squall line was found to move further southeastwards at 1010Z and a fresh squall line was found over east of Ranchi (Fig. 3c). The old squall line was found to move southeastwards and became weakened at 1210Z (Fig. 3d). At the same time the new squall line was found to accentuate and move east-southeastwards.

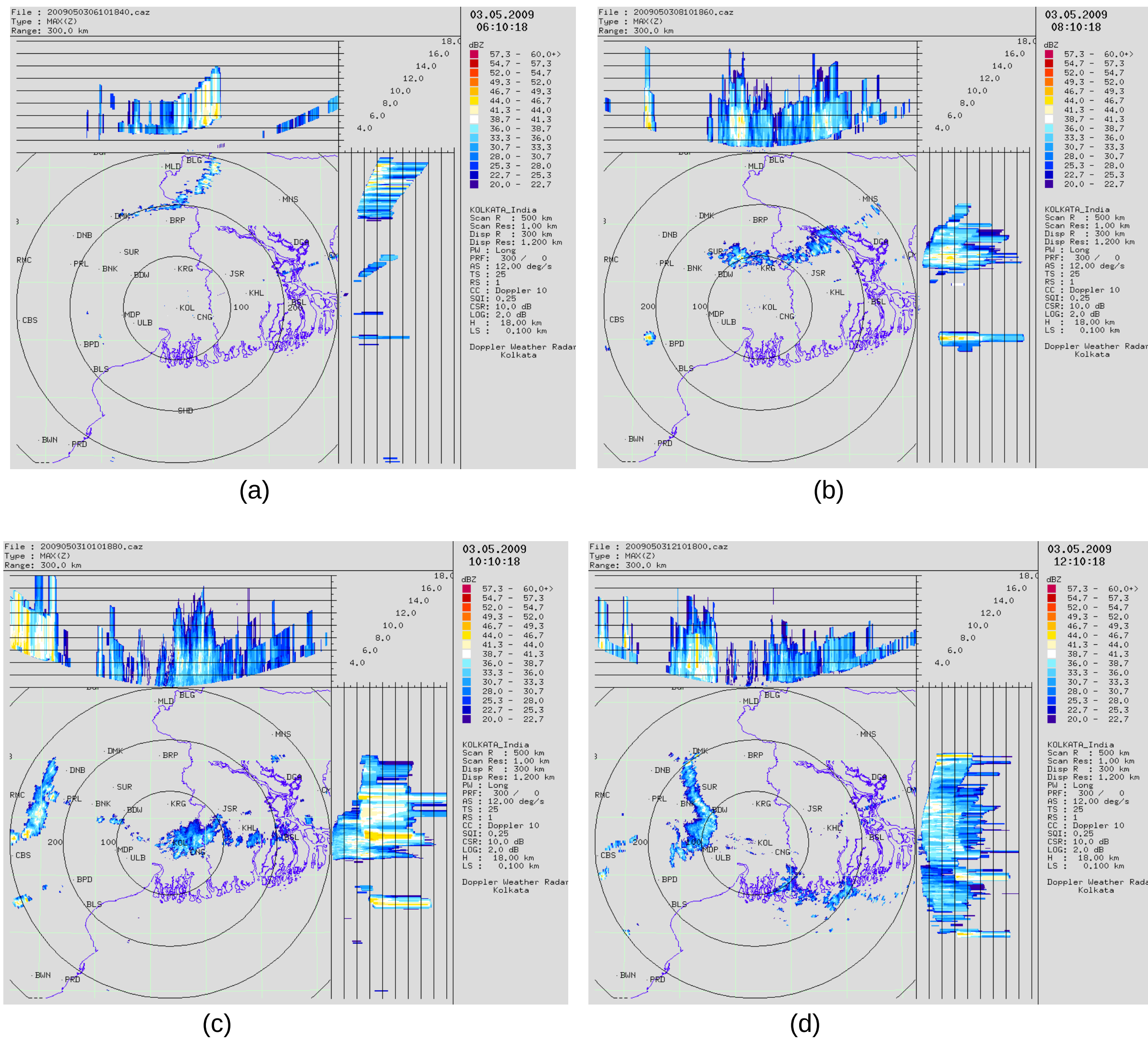

Fig 3: Doppler Weather Radar imageries of Kolkata at (a) 0610Z, (b) 0810Z, (c) 1010Z and (d) 1210Z.

3.1.3 TRMM V6 rainfall

TRMM V6 shows 08-16 mm/hr rainfall over east Nepal and adjoining Sub Himalayan West Bengal during 00-03Z of 03 May 2009. During same time another heavy rainfall area was over southeastern tip of Bangladesh (Fig. 4a). West Bhutan, northwestern part of Bangladesh and adjoining West Bengal received heavy rainfall (04-16 mm/hr) after three hours i.e. during 03-06Z. Ranchi received 04-08 mm/hr rainfall (Fig. 4b). During next three hours i.e. during 06-09 Z, the rainfall region shifted east-southeastwards (Fig. 4c). The main rainfall region was found to shift to southern coastal Bangladesh and the rainfall region over Ranchi grew bigger in area and moved east-southeastwards (Fig. 4d).

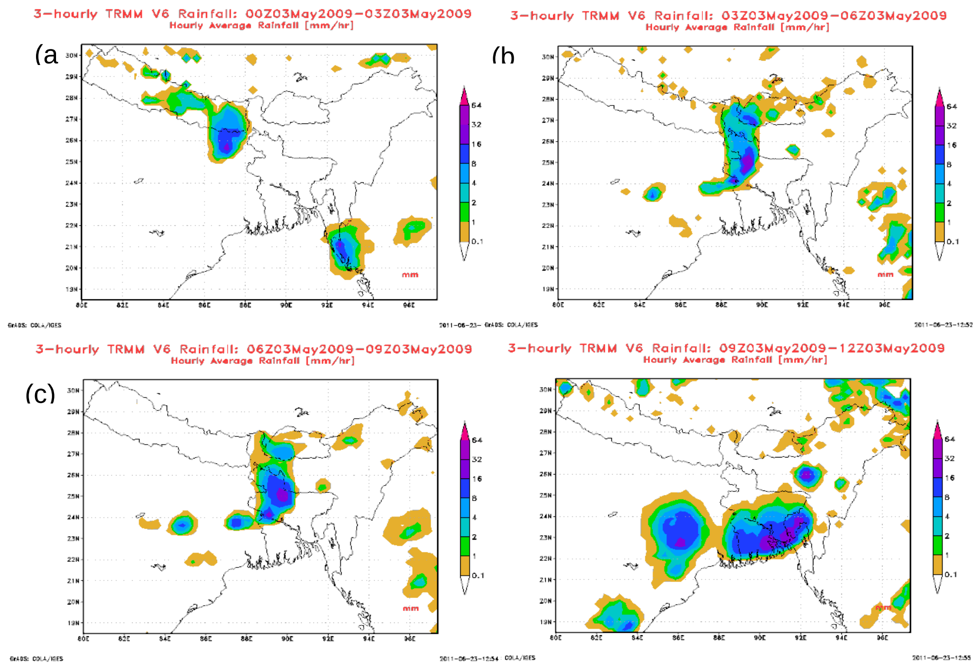

Fig 4: TRMM V6 rainfalls (mm/hr) over STORM Domain on 03 May 2009 during (a) 00-03Z, (b) 03-06Z, (c) 06-09Z and (d) 09-12Z.

3.1.4 Simulation of the thunderstorm event of 03 May 2009 by using WRF-ARW Model

3.1.4.1 Simulation of rainfall (mm)

3.1.4.1.1 WRF simulated rainfall (mm) without Data Assimilation

In the morning (03 - 06Z) of 03 May 2009 some rainfall (08-16 mm) was seen over eastern part of Bangladesh, northeast India, west Nepal and Bhutan (Fig. 5a-b). In the afternoon 09-12Z 08-16 mm rainfall was seen over many parts of east and northeast India, eastern and southern parts of Bangladesh, Nepal and Bhutan (Fig. 5c-d).

3.1.4.1.2 Rainfall (mm) with Data Assimilation

In the morning (03 - 06Z) of 03 May 2009 some rainfall (08-16 mm) was seen over eastern part of Bangladesh, northeast India, west Nepal and Bhutan (Fig. 6a-b). At 09 Z 08-16 mm rainfall was seen over many parts of east and

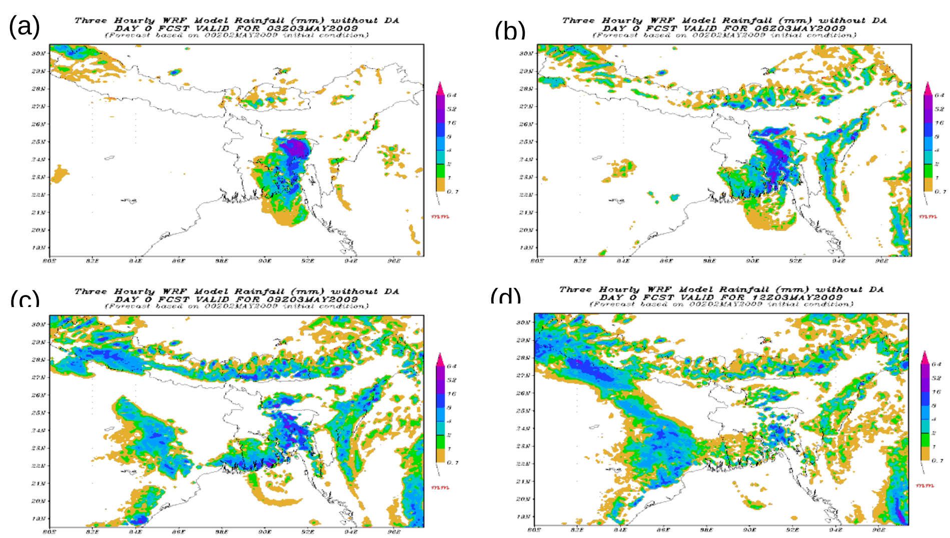

Fig 5: WRF Model rainfalls (mm) over STORM Domain without DA on 03 May 2009 at (a) 03Z, (b) 06Z, (c) 09Z and (d) 12Z.

northeast India, eastern and southern parts of Bangladesh, Nepal and Bhutan (Fig. 6c). At 12 Z rainfall increased over east India but decreased elsewhere over the STORM Domain (Fig. 6d).

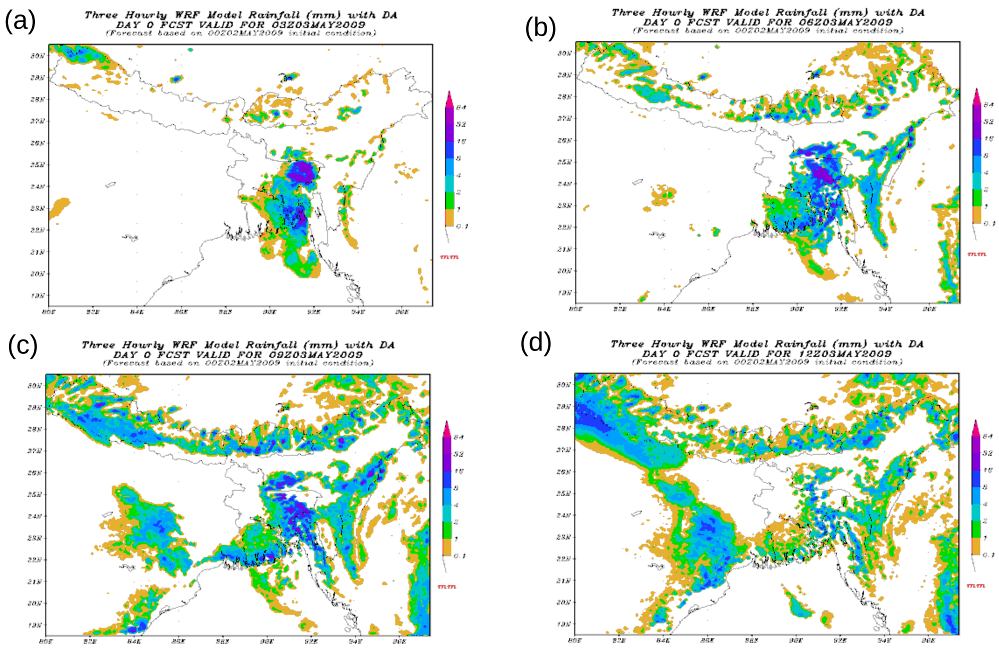

Fig 6: WRF Model rainfalls (mm) over STORM Domain with DA on 03 May 2009 at (a) 03Z, (b) 06Z, (c) 09Z and d) 12Z.

3.1.4.1.3 WRF simulated vertical wind w (m/s) along 23.5°N

3.1.4.1.3.1 WRF simulated vertical wind w (m/s) without DA

Maximum vertical wind w (0.2-0.3 m/s) was found between 625-450 hPa along 91.7°E at 00Z of 03 May 2009 (Fig. 7a) and that (0.3-0.5 m/s) between 875-625 hPa, 875-760 hPa, 900-760 hPa, 950-780 hPa, 700-340 hPa and 550-200 hPa along 80.5°E, 83°E, 83.8°E, 84.2°E, 86.3°E and 87°E respectively was found at 12Z (Fig. 7b) where convective clouds were likely.

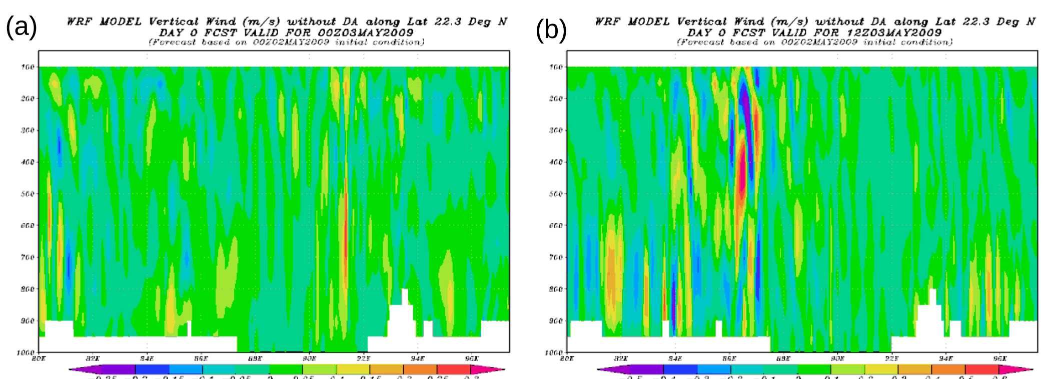

Fig 7: WRF simulated vertical wind w (m/s) of 03 May 2009 without DA at (a) 00Z and (b) 12Z, along lat 23.5°N.

3.1.4.1.3.2 WRF simulated vertical wind w (m/s) with DA

Maximum vertical wind w (0.1-0.2 m/s) was found between 800-500 hPa and 900-450 hPa along 80.7°E and 91.5°E at 00Z of 03 May 2009 (Fig. 8a) and that (0.4-0.6 m/s) between 850-425 hPa, 530-330 hPa, 850-650 hPa, 400-220 hPa and 950-650 hPa along 81.7°E, 86°E, 86.5°E, 86.5°E and 94.6°E respectively at 12Z (Fig. 8b) where convective c louds were likely.

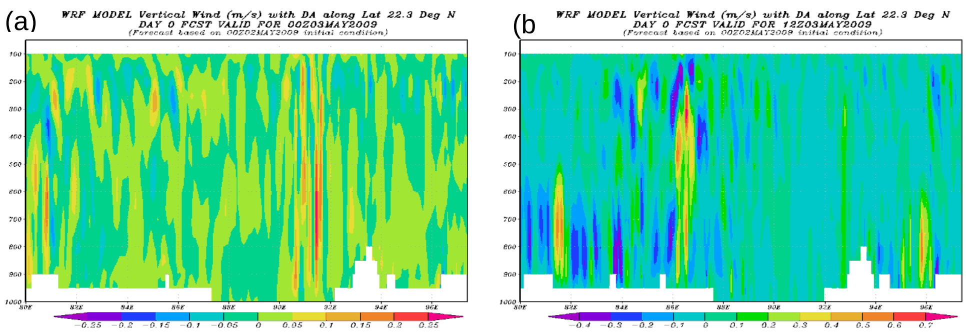

Fig 8: WRF simulated vertical wind w (m/s) of 03 May 2009 with DA at (a) 00Z and (b) 12Z, along lat 23.5°N.

3.1.4.1.4 WRF simulated Convective Available Potential Energy (CAPE) & Convective Inhibition Energy (CINE)

3.1.4.1.4.1 WRF simulated CAPE without DA

In the morning (00Z) of 03 May 2009, there was Convective Available Potential Energy (CAPE) of 1000-4000 J/kg over east India and Bangladesh except for north Bengal (Fig. 9a). But in the evening (12Z), CAPE value decreased over the region except for northeast India, Bhutan, northern and eastern Bangladesh where CAPE value increased (Fig. 9b). Higher CAPE value indicated possibility of thunderstorm development.

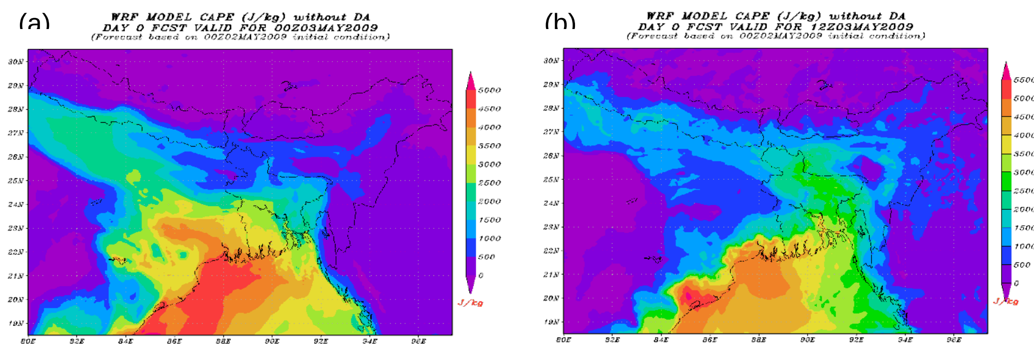

Fig 9: WRF simulated CAPE (J/kg) of 03 May 2009 without DA at (a) 00Z and (b) 12Z.

3.1.4.1.4.2 WRF simulated CINE without DA

In the morning (00Z) of 03 May 2009, there was Convective Inhibition Energy (CINE) of less than 400 J/kg over most of the region (Fig. 10a) and in the evening value of CINE decreased (Fig. 10b) which indicated possibility of thunderstorm development.

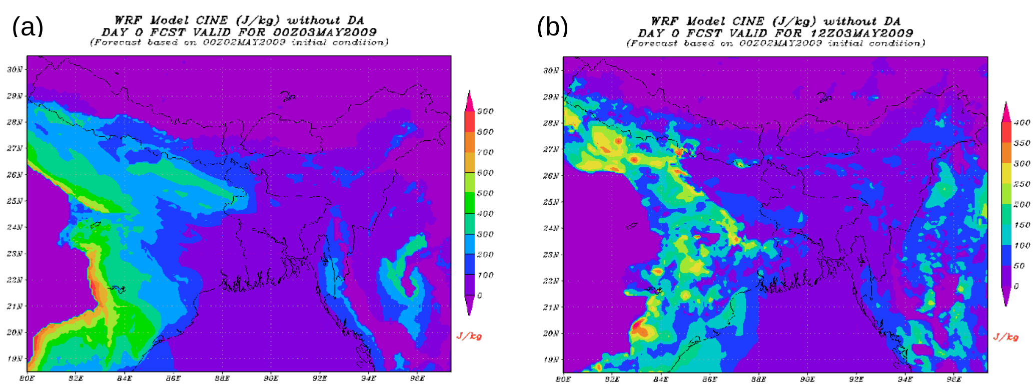

fig. 10: WRF simulated CINE (J/kg) of 03 May 2009 without DA at (a) 00Z and (b) 12Z

3.1.4.1.4.3 WRF simulated CAPE with DA

In the morning (00Z) of 03 May 2009, there was Convective Available Potential Energy (CAPE) of 1000-4000 J/kg over east India and Bangladesh except for north Bengal (Fig. 11a). But in the evening (12Z), CAPE value decreased over the region except for northeast India, Bhutan, northern and eastern Bangladesh where CAPE value increased (Fig. 11b). Higher CAPE value indicated possibility of thunderstorm development. 3DVARDA showed little improvement over non-DA.

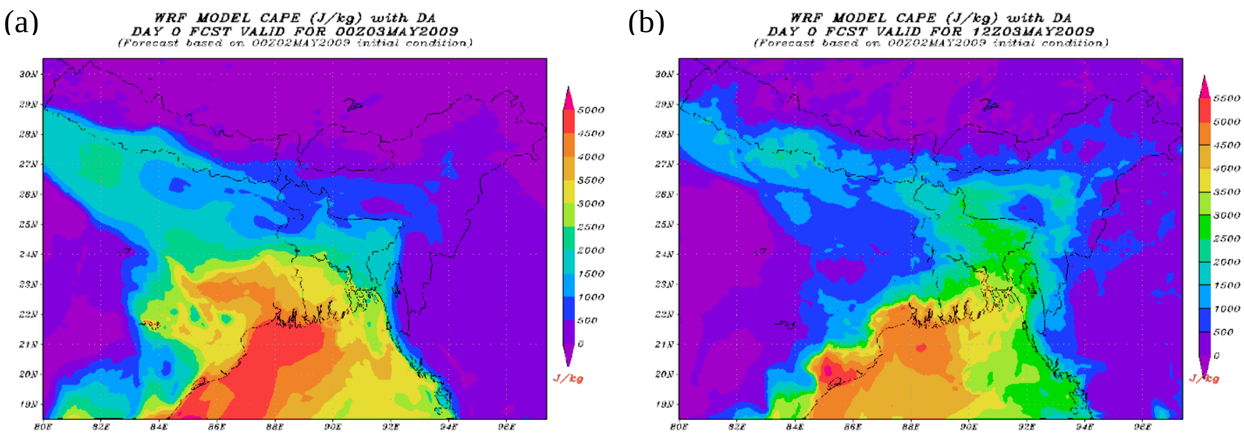

Fig 11: WRF simulated CAPE (J/kg) of 03 May 2009 with DA at (a) 00Z and (b) 12Z.

3.1.4.1.4.4 WRF simulated CINE with DA

In the morning (00Z) of 03 May 2009, there was Convective Inhibition Energy (CINE) of less than 400 J/kg over most of the region (Fig. 12a) and in the evening (12Z) value of CINE decreased (Fig. 12b) which indicated possibility of thunderstorm development. 3DVAR DA showed little improvement over non-DA.

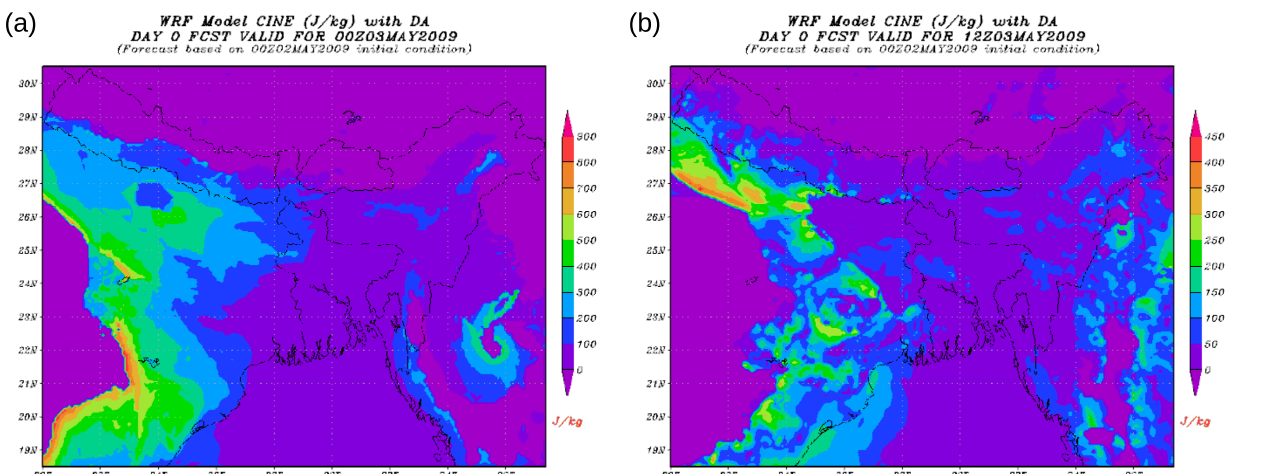

Fig 12: WRF simulated CINE (J/kg) of 03 May 2009 with DA at (a) 00Z and (b) 12Z.

3.1.4.1.4.5 WRF Model simulated wind field at 850 hPa without & with DA

In the morning (00Z) of 03 May 2009, there was a cyclonic circulation over Orissa extending trough to northeastern part of Bangladesh (Fig. 13a without DA & Fig. 13c with DA). In the evening (12Z), there was a cyclonic circulation over north-central Bangladesh (Fig. 13b without DA & Fig. 13d with DA). However, 3DVAR DA showed better analysis than without DA.

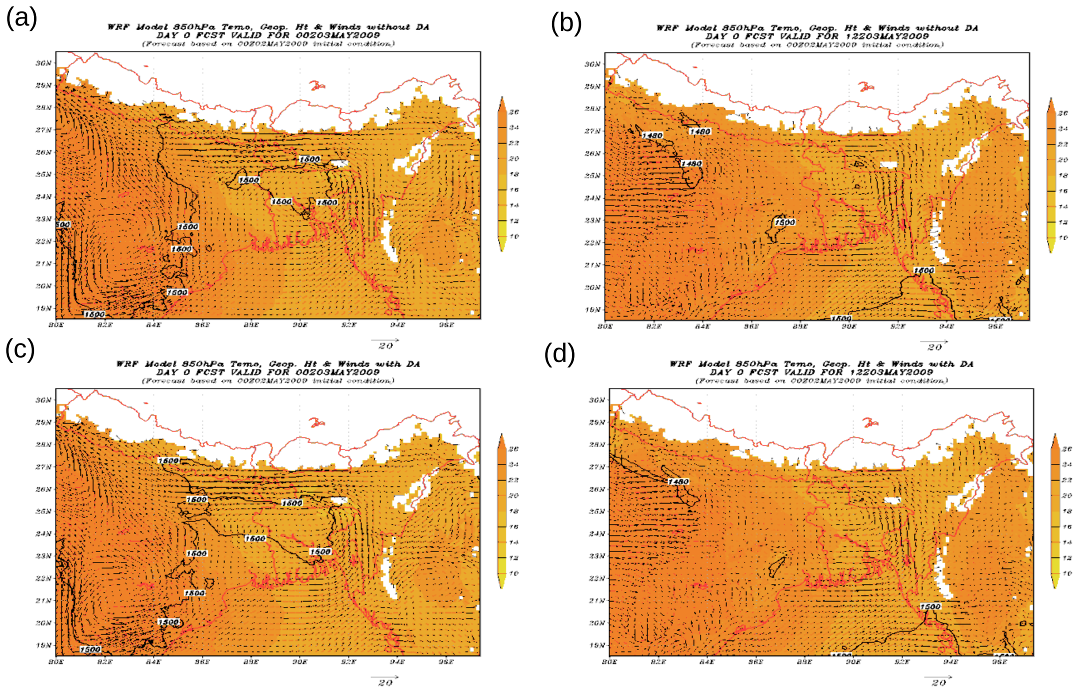

Fig 13: WRF Model simulated wind field at 850 hPa of 03 May 2009 (a) at 00 Z & (b) at 12 Z without DA, (c) 00 Z & (d) 12 Z with DA.

3.2 Case study – II: Thunderstorm of 10 May 2009

Well-coordinated SAARC STORM programme was undertaken by SMRC as a long term project with a view to monitoring life cycle of severe thunder storms and formulate ideas on mesoscale modeling. STORM Field Experiment – 2009 started on 15 April 2009 and ended on 31 May 2009. In this Experiment, Bangladesh, Bhutan, NE-India and Nepal took part. The Experiment domain is shown in Fig. 1. STORM Field Experiment – 2009 data is available in the National Meteorological and Hydrological Services (NMHSs) of SAARC Region, National Centre for Medium Range Weather Forecasting (NCMRWF, Noida, India), Indian Institute of Technology (IIT, Delhi) and SAARC Meteorological Research Centre (SMRC, Dhaka, now defunct). In this case study, eight Synoptic and one Rawin-Sonde data of Bangladesh Meteorological Department (BMD) has been assimilated in the WRF-ARW Model to get the better scenario by using 3DVAR technique.

3.2.1 Methodology

WRF-ARW Model developed by NCAR/NCEP, USA has been used for Simulation of nor'weter event of 10 May 2009 with Three-Dimensional Variational (3DVAR) Data Assimilation. Eight Synoptic and one Rawin-Sonde data of Bangladesh Meteorological Department (BMD) were used for assimilation. World Meteorological Organization (WMO) format of those datasets were first converted into LITTLE_R Format. Then as usual practice observation file (obs_gts_datetime.3DVAR), Background Error file (BE) and First Guess (FG) file were created. Finally, 3DVARDA was run. Up to this point, modeling work was done on IBM 575 Super Computer at NCMRWF, Noida, India as a part of Collaborative Research Programme (CRP) between SMRC and NCMRWF. The post processing was done at SMRC, Dhaka. WSM 3-class scheme, Hong, Dudhia and Chen (2004) micro-physics [9], Rapid Radiative Transfer Model (RRTM), Mlawer et al. (1997) for long wave [10] and Dudhia (1989) for shortwave [11], YSU PBL scheme (Hong and Noh) [12], and New Kain-Fritsch cumulous parameterization [13] were used.

3.2.2 Data used

Six hourly NCEP-Global Forecast System (GFS) data starting from 00Z of 10 May 2009 and ending at 00Z of 11 May 2009 were used as the initial and boundary condition (IC/BC) data. Eight Synoptic (Dhaka, Rangpur, Bogra, Mymensingh, Jessore, Comilla, Chittagong and Sylhet) and one Rawin-Sonde (Dhaka) data of Bangladesh

Meteorological Department (BMD) were used for Data Assimilation (DA). Tropical Rainfall Measuring Mission (TRMM) data (three hourly 3B42RT) was used for comparison of rainfall.

3.2.3 Results and discussions

The model was run for 24 hours at National Centre for Medium Range Weather Forecasting (NCMRWF), NOIDA, India with 100 Processors in 5 Nodes with South Asian Domain (with 9 km resolution). The result is quite encouraging which may be seen in the Fig. 14(a) - 14(b) below. In Fig. 14(a), Mean Sea Level Pressure (MSLP) at 1600 UTC of 10 May 2009 is shown without Data Assimilation (DA) and in Fig. 14(b), Mean Sea Level Pressure (MSLP) of the

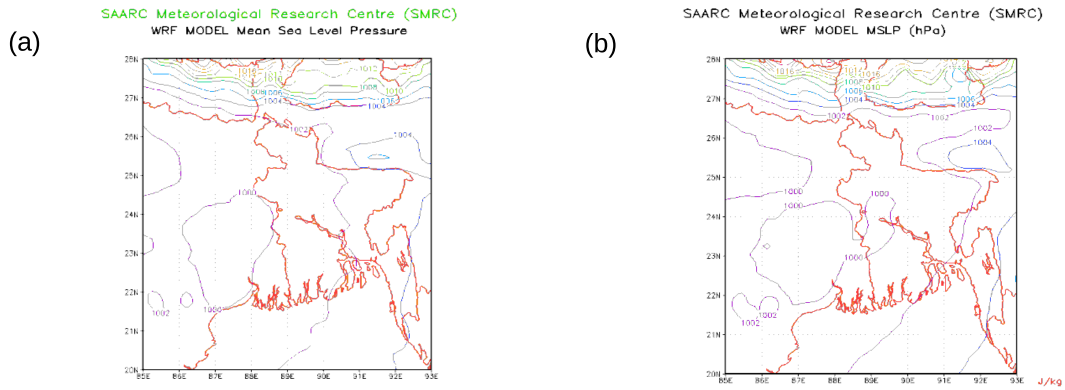

Fig 14: (a) MSLP at 1600 UTC of 10 May 2009 Without Data Assimilation, (b) MSLP at 1600 UTC of 10 May 2009 with Data Assimilation. A trough is seen to protrude from West Bengal to Western part of Bangladesh.

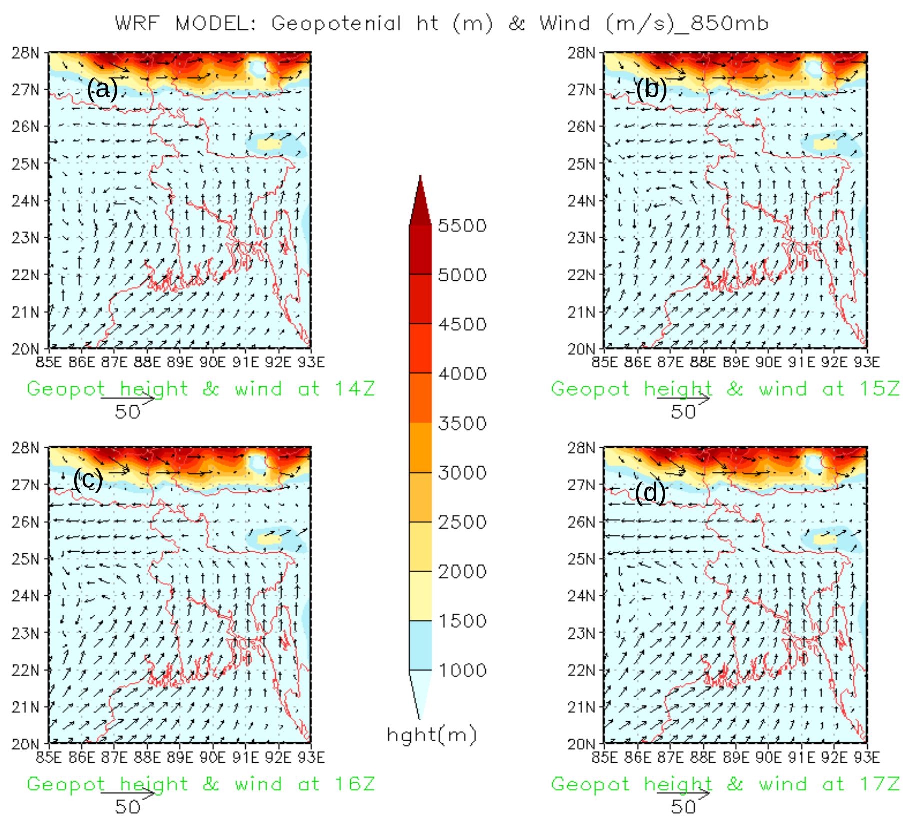

Fig 15: An area of convergence is seen over West Bengal at 850 hPa level after DA, (a) 14Z, (b) 15Z, (c) 16Z and (d) 17Z.

same date and time is shown with DA. A protruding trough of low is seen after DA which indicates some severe weather is going to take place over north-western part of Bangladesh. And a thunder storm occurred over Rangpur region at around 1600 UTC of 10 May 2009 as per STORM Field Experiment – 2009 dataset.

In case of wind field at 850 hPa, an area of convergence is shown after DA (Fig. 15(a)-(d)) but there is no such convergence in the analyses without DA (Fig. 16(a)-(d)). The area of convergence is the indication of possible thunder storm development.

Comparing with TRMM image (Fig. 17c), the predicted rainfall with Data Assimilation (Fig. 17a) is better representative than the predicted rainfall without Data Assimilation (Fig. 17b). So, forecasts are likely to be better if local or regional data are assimilated in WRF-ARW Model. Of course, there should not be any compromise with the quality of data.

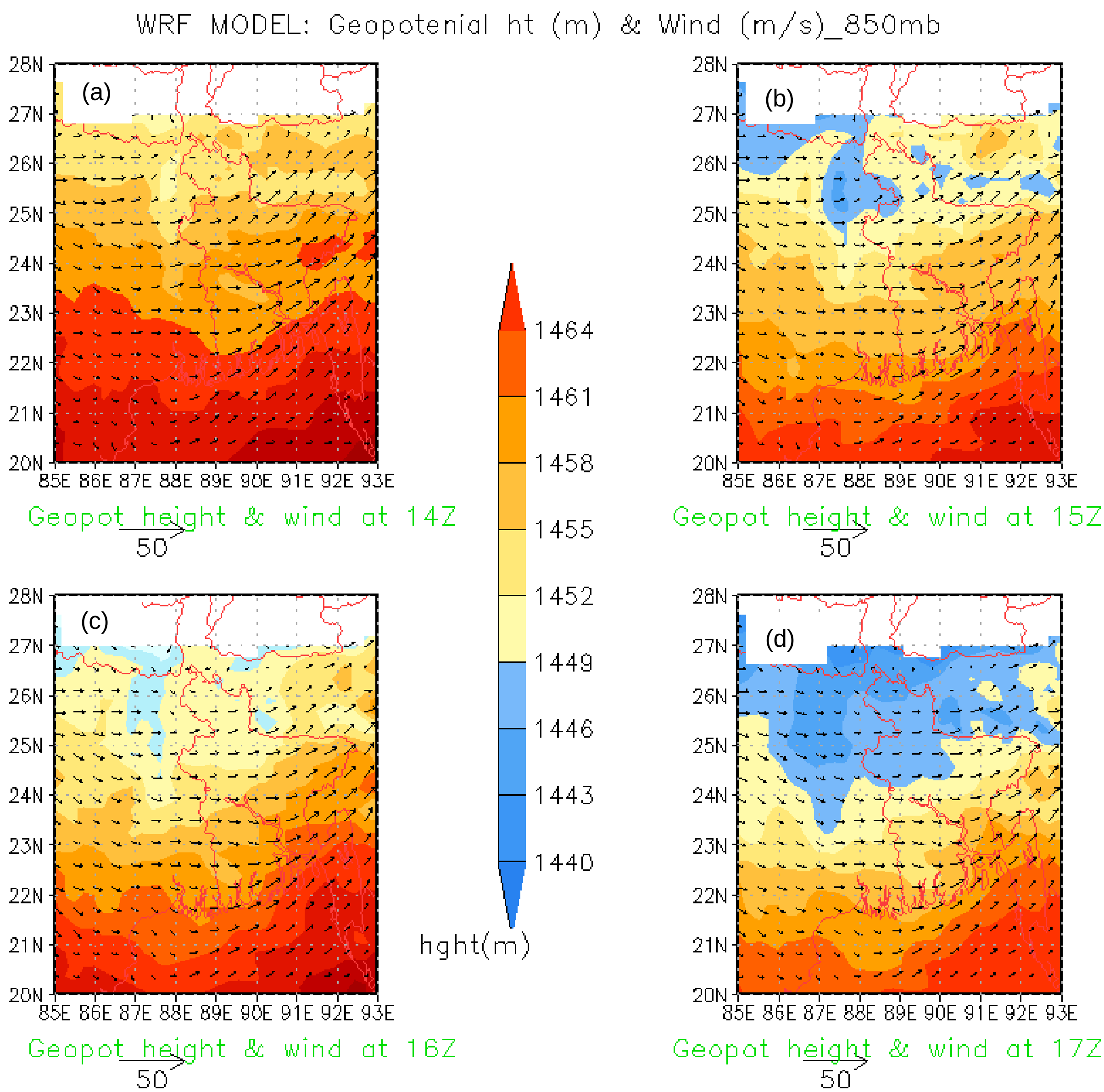

Fig 16: No area of convergence is seen at 850 hPa level before DA, (a) 14Z, (b) 15Z, (c) 16Z and (d) 17Z.

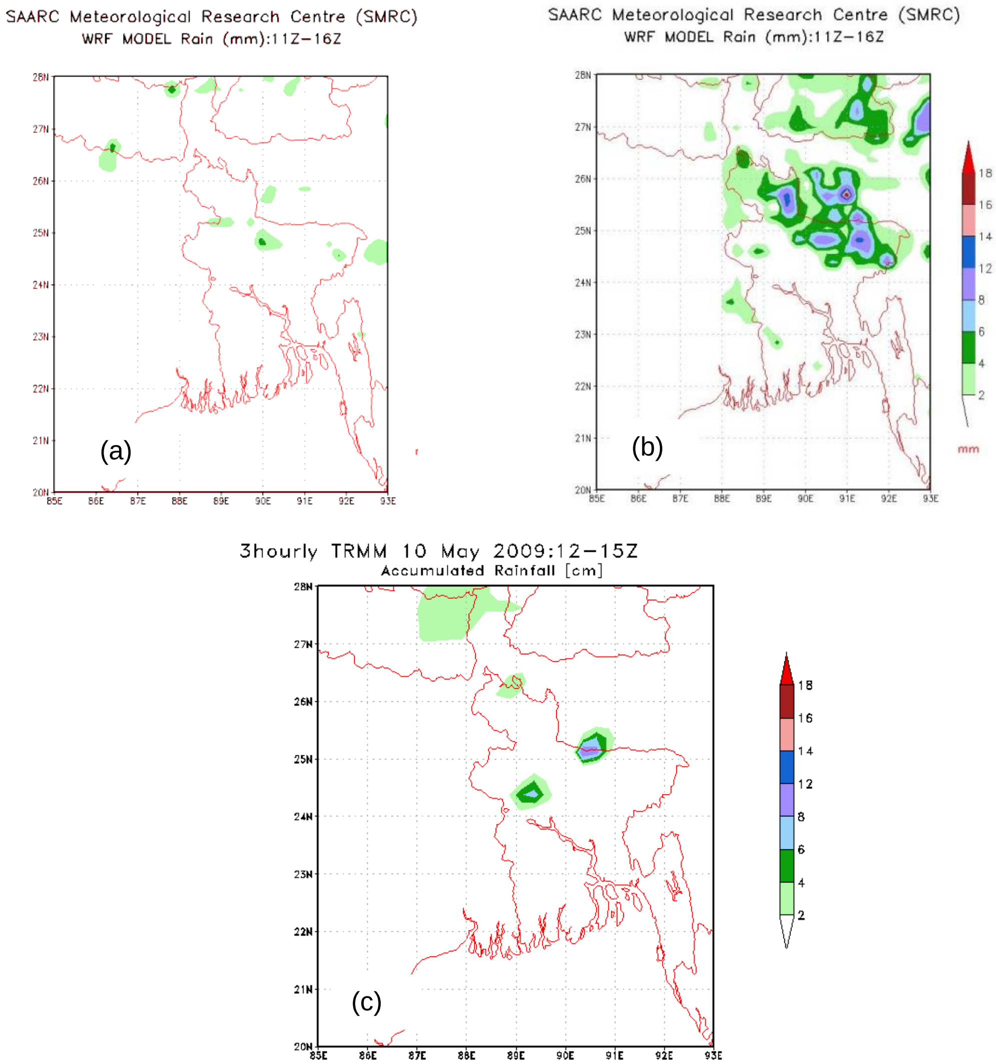

Fig 17: (a) Rainfall distribution with DA, (b) Rainfall distribution without DA, (c): Three hourly Rainfall during 12-15 UTC of 10 May 2009 as seen from TRMM (3B42RT).

4. Conclusion

If WRF-ARW Model of considerably higher resolution is run with 3DVAR data assimilation having ingestion of local and/or regional qualitative data then forecasts are expected to be better. There were three mesoscale convective cells (MCS) on 03 May 2009 over the SAARC-STORM (Phase-I) Domain. WRF-ARW Model could capture the thunderstorms of 03 May 2009 and 10 May 2009 to certain extent with some temporal and spatial shifts. 3DVAR Data Assimilation of the synoptic, Automatic Weather Station (AWS) and upper air observations data collected during STORM Field Experiment – 2009 in the WRF Model improved the forecasts a little bit. Change of microphysics and cumulous parameterization schemes may improve forecasts further. Rigorous study with high resolution 3DVAR Data Assimilation is needed to improve the quality of mesoscale weather forecasts. Forecast of rainfall tendency is alright but quantitative precipitation forecast is still difficult. Forecast of actual time and location of the occurrence of thunderstorms is still a challenge to the modelers.

Acknowledgement

For making WRF-ARW Model freely available to the scientific/ research community, the National Center for Atmospheric Research (NCAR), USA is gratefully acknowledged. The National Center for Environmental Prediction (NCEP) is thanked for providing NCEP-FNL Data free of cost. Profound gratitude and thanks are due to India Meteorological Department (IMD), Bangladesh Meteorological Department (BMD), Department of Hydrology & Meteorology (DHM), Nepal, Department of Hydro-Meteorological Services (DHMS), Bhutan, the National Centre for Medium Range Weather Forecasting (NCMRWF), NOIDA, India, Indian Institute of Technology (IIT), Delhi, India and their Data Assimilation Teams and all International Programme Committee (IPC) Members for their contribution to the SAARC STORM Field Experiments and amazing Collaborative Research facilities provided to the author.

References

[1] Debsarma, S.K. (2004). Post mortem (analysis) of the nor'wester that hit Dhaka on 14 April 2003. SAARC Meteorological research Centre (SMRC), Dhaka, Bangladesh.

[2] Rao, G.V. and Bhaskar Rao, D.V. (2003). A review of some observed mesoscale characteristics of tropical cyclones and some preliminary numerical simulations of their kinematic features. Proc Ind Nat Sci Acad, 69: 523-541.

[3] Ahasan, M.N., Debsarma, S.K. (2015). Impact of data assimilation in simulation of thunderstorm (squall line) event over Bangladesh using WRF model, during SAARC–STORM Pilot Field Experiment 2011. Nat Hazards 75, 1009–1022 (2015). https://doi.org/10.1007/s11069-014-1369-z.

[4] Basnayake B.R.S.B., Das, M.K., Nessa, F,F,, Rahman, M.M. (2010). Nor'westers over Bangladesh and neighbourhood during pre-monsoon season of 2009: Observations and WRF model simulation. SMRC Scientific Report No. 36: 61 pp.

[5] Das, S. (2009). Composite characteristics of Nor'Westers observed by TRMM & simulated by WRF Model, SAARC Meteorological Research Centre (SMRC). SMRC Scientific Report No. 25: 47 pp.

[6] Das, S., Dutta, S.K., Debsarma, S.K., Ferdousi, N., Nessa, F.F. (2012). Assimilation of STORM 2009 Field Observations in WRF Model and Their Impact on the Simulations of Thunderstorms. SMRC Report No. 43.

[7] Ferdousi, N., Debsarma, S.K., Mannan, M.A., Sarker, M.M.A. (2014). Impact of Data Assimilation in Simulation of Thunderstorm Event over Bangladesh Using WRF Model in Book "High Impact Weather Events over the SAARC Region" Edited by Kamaljit Ray, M. Mahapatra, B.K. Bandyopadhyay, L.S. Rathore, Capital Publishing Co., co-published by Springer, New Delhi, India (2014): 35-50 pp.

[8] Debsarma. S.K. (2011). Study of the Thunderstorm of 03 May 2009 by using WRF-ARW Model in the Proceedings: National Seminar on Space Technology Application for Monitoring Earth Resources, Disasters and Climate Change Impacts for Ensuring Human Security and Sustainable Development, Bangladesh Space Research and Remote Sensing Organization (SPARRSO), 28-29 June, 2011: 31-43 pp.

[9] Hong, S.Y., Dudhia, J. and Chen, S.H. (2004). A Revised Approach to Ice Microphysical Processes for the Bulk Parameterization of Cloud and Precipitations. Monthly Weather Review, 132, 103-120. http://dx.doi.org/10.1175/1520-0493(2004)132<0103:ARATIM>2.0.CO;2

[10] Mlawer, E. J., S. J. Taubman, P. D. Brown, M. J. Iacono, and S. A. Clough, (1997). Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. J. Geophys. Res., 102, 16663-16682.

[11] Dudhia, J., 1989: Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. J. Atmos. Sci., 46, 3077-3107.

[12] Hong, S., Y. Noh, and J. Dudhia, 2006: A new vertical diffusion package with explicit treatment of entrainment processes. Mon. Wea. Rev., 134, 2318–2341.

[13] Kain, J. S. and J. M. Fritsch. 1993. Convective parameterization for mesoscale models: The Kain–Fritsch scheme. The Representation of Cumulus Convection in Numerical Models, Meteor. Monogr., No. 24, Amer. Meteor. Soc., 165–170.