SAARC STORM Pilot Field Experiment 2011 and Mesoscale Data Assimilation Impacts

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1. Introduction

The SAARC STORM is a unique programme undertaken by SAARC Meteorological Research Centre (SMRC) for preparation of a well designed coordinated plan for monitoring life cycle of severe thunderstorms, formulate ideas on modeling mesoscale convection and validate available models with the data collected during the field experiments over the SAARC region. The STORM Pilot Field Experiment 2011 was conducted during 15 April - 31 May 2011 jointly with India, Bangladesh, Nepal and Bhutan to study the characteristics of severe thunderstorms (also known as Nor'westers) that affect these countries during the pre-monsoon season. SAARC is the South Asian Association for Regional Cooperation and STORM is an acronym for Severe Thunderstorm Observations and Regional Modeling. Intensive observations were collected in a coordinated manner for improving our understanding and prediction of Nor'westers.

Most of the models are unable to predict the precise time and location of occurrences of thunderstorms owing to the lack of generation of convective instability at the right locations, advective-dynamic forcing, or the triggering mechanism. One reason for this failure may be the lack of observations at mesoscale resolution, or deficiencies in the initial and boundary conditions. These problems could be alleviated by assimilation of special observations collected during the STORM Field Experiments. The variational data assimilation approach is one of the most promising techniques available to directly assimilate heterogeneous mesoscale observations in order to improve the estimate of the models initial state. In this study a 3DVAR data assimilation scheme has been used with the Weather Research & Forecasting (WRF) model to assimilate the special observations collected during the STORM Field Experiments.

Several episodes of thunderstorms occurred during 15 April - 31 May 2011. Widespread outbreaks of intense thunderstorms occurred on the following days affecting all the four countries (India, Bangladesh, Nepal and Bhutan) on (i) 24 April, (ii) 25 April, (iii) 19 May, and (iv) 23 May. In order to study the impact of the special observations on forecasts, 2 sets of experiments were conducted to study the 19 May 2011episode of thunderstorms mentioned earlier. The 1st set of experiments were the control experiments (CTRL) in which 24 hours forecasts were made based on the initial conditions produced by the T254 L64 global model of NCMRWF. The 2nd set of Data Assimilation experiments (DA) were conducted based on the initial conditions produced by assimilating the special field observations. Results were analyzed and compared for the 2 experiments CTRL and DA.

2. Data and Methodology

2.1 The Model

The WRF Model consists of multiple dynamical cores, a 3-dimensional variational (3DVAR) data assimilation system, and a software architecture allowing for computational parallelism and system extensibility. WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. Applications of WRF include research and operational numerical weather prediction (NWP), data assimilation and parameterized-physics research, downscaling climate simulations, driving air quality models, atmosphere-ocean coupling, and idealized simulations (i.e., boundary-layer eddies, convection, baroclinic waves). For the present study, the WRF-ARW (version 3.3.1) has been used over the SAARC STORM domain. The model is run at 9 km resolution with 27 vertical levels using initial and boundary conditions obtained from NCMRWF T382L64 global model.

2.2 The 3DVAR System

The three dimensional variational assimilation (3DVAR) is designed for a community data assimilation system flexible enough to allow a variety of research studies apart from its operational utilization. The basic goal of the 3DVAR system is to produce an "optimal" estimate of the true atmospheric state at any desired analysis time through iterative solution of a prescribed cost-function (Ide et al. 1997).

$$J(x) = J^b + J^0 = \frac{1}{2}(x-x^b)^T B^{-1}(x-x^b) + \frac{1}{2}(y-y^o)^T (E+F)^{-1}(y-y^o) \qquad \ldots\ldots\ (1)$$

where x is the analysis state, x^b is the background y^o is the observation, *B*, *E* and *F* are the background, observation (instrumental) and representivity error covariance matrices respectively. Representivity error is an estimate of inaccuracies introduced in the observation operator H used to transform the gridded analysis *x* to observation space $y=Hx$.

The 3DVAR system consists of the four components (Barker et al., 2003, 2004): (1) Background Pre-processing, (2) Observation Pre-processing and quality control, (3) Variational Analysis, (4) Updation of Boundary Conditions.

2.3 Updating boundary condition

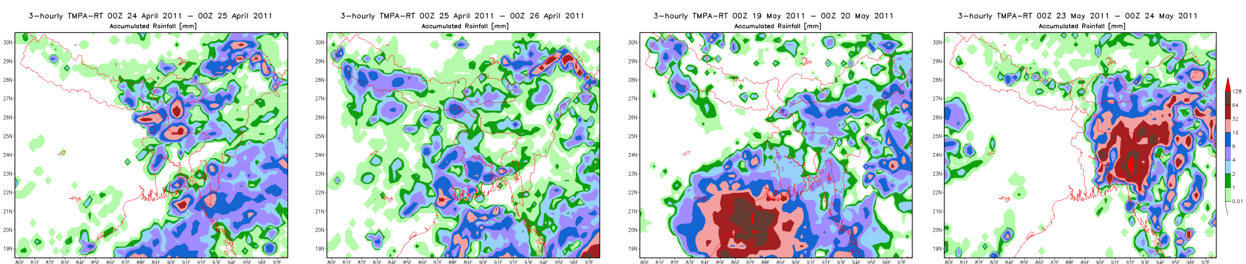
In order to run WRF forecast model using 3DVAR analysis as initial conditions, the lateral boundary conditions (originally computed from global model data) is updated to reflect the modified fields.

Three-dimensional observations are mainly centered on the main synoptic hours (0000, 0600, 1200, 1800 UTC) of observation. Keeping this in mind, the present assimilation system is designed as a 6-hrly intermittent assimilation scheme, where analysis is performed four times a day i.e. at 0000, 0600, 1200, 1800 UTC. The control analysis consists of the global data received through GTS / internet, which are ingested in the system at the analysis time with ±3 hours time window. Modules have been developed for reading the decoded observed data from NCMRWF's operational data sets and for packing in LITTLE-R format, required for ingesting in 3DVAR observation preprocessor.

In the present study, two experiments have been conducted. The first one is a control run (CTRL) in which the analysis produced by the NCMRWF global model (T254L64) is used for initial and boundary conditions to run the WRF model. In the second experiment (DA), continuous data assimilation (cyclic run) is carried out using the observations collected during the SAARC STORM Pilot Field Experiment of 2011 (mainly the AWS and SYNOP). In the cyclic run, the boundary conditions for WRF run are taken from global model analysis. However, the lateral boundary conditions are updated after each analysis. Subsequently, after each analysis, six-hour forecasts are made using WRF model. The 6-hour forecast of each run (valid for next analysis time) is used as the first guess for the next analysis (Parish et al. 1992). The assimilation started at 06Z of 19 May 2011 and completed at 06Z of 20 May 2011. Subsequently, 24 hours forecasts were made for 4 cases of widespread thunderstorms (discussed in the next section) based on the CTRL and DA run.

3. Thunderstorm events

Widespread outbreaks of intense thunderstorms occurred on the following days affecting four countries India, Bangladesh, Nepal and Bhutan in 2011; (a) 24 April, (b) 25 April, (c) 19 May, and (d) 23 May. The synoptic situations including inferences obtained from satellite and Doppler radars are summarized below for each case. Fig. 1 shows the TRMM rainfall accumulated for 24 hours. The observed rainfall ranged from traces to about 220 mm day^{-1}.



(a) (b) (c) (d)

Fig. 1 TRMM precipitation accumulated for 24 hours (a) 24 April, (b) 25 April, (c) 19 May, and (d) 23 May 2011.

Case-1: 24 April 2011

3.1.1 Synoptic main feature

i) A trough of westerly low lies over west Bengal and adjoining area.
ii) Seasonal low lies over south Bay.
iii) The upper air cyclonic circulation over Assam and neighbourhood in lower levels.
iv) Another upper air cyclonic circulation over West Madhya Pradesh and neighbourhood in lower levels with a trough extending from this system to southeast Arabian Sea across Maharashtra, Karnataka and North Kerala.

3.1.2 Realized Weather

Thunderstorm, shower and Rain were reported at Itanagar (Naharlagun), Silchar, Dhubri and CSO Shillong region on 24 April 2011. A gusty wind passed over Chittagong at 0028 UTC from northwesterly direction with max wind speed of 35 km hr^{-1}.

3.1.3 T- Φ gram analysis

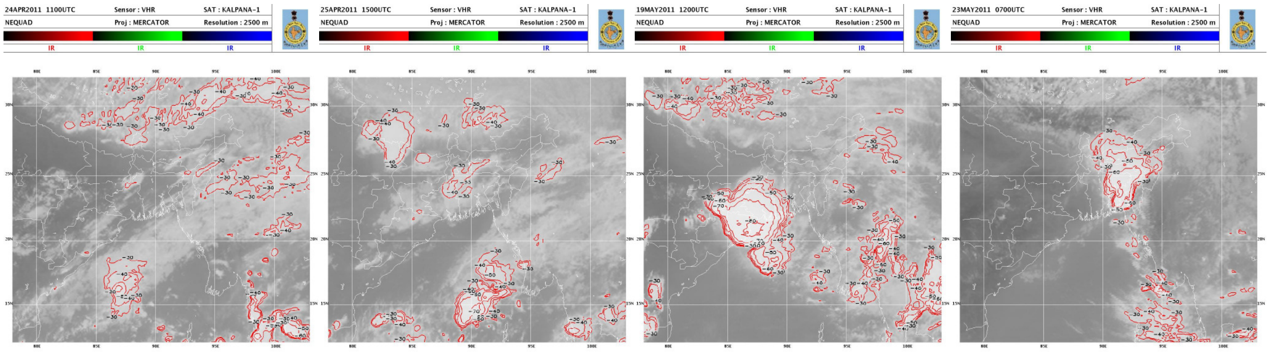
Kolkata T- Φ gram indicated a high CAPE (3027 J/kg) at 0000 UTC. The total precipitable water content stayed at 62.69 mm favouring convective activity.

Mohanbari T- Φ gram indicated a CAPE 1166 J/kg at 0000 UTC. The total precipitable water content indicated 57.40 mm over the day, which can be considered conducive for convective activity.

Patna T- Φ gram indicated a high CAPE 2790 J/kg and Total Totals Index 49.60 at 0000 UTC. The total precipitable water content stayed at 39.65 mm which can be considered conducive for convective activity.

3.1.4 Kalpana-1 satellite

Kalpana-1 satellite imagery (Fig. 2a) showed moderate convection over western and northeastern Bangladesh (CTT = -40^{0}C). Convection persisted over North Bay.

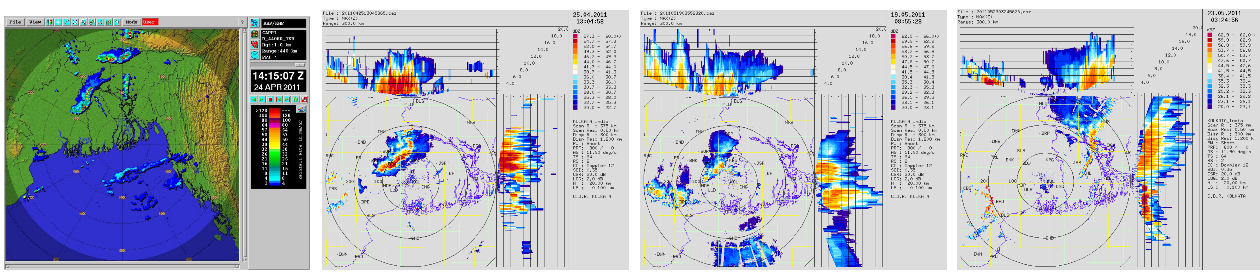


(a) (b) (c) (d)

Fig. 2: Cloud imageries with contours of the cloud top temperature (CTT) obtained from Kalpana-1 satellite on (a) 24 April, (b) 25 April, (c) 19 May, and (d) 23 May 2011.

3.1.5 Khepupara DWR

The Doppler Radar of Khepupara (Fig. 3a) showed an echo to the west and north of Bangladesh at 1415 UTC, which intensified into a NW-NE oriented squall line of 150 km length by 1530 UTC.



(a) (b) (c) (d)

Fig. 3: Maximum Reflectivity of thunderstorm evolution observed by Khepupara and Kolkata DWR on (a) 24 April, (b) 25 April, (c) 19 May, and (d) 23 May 2011.

Case-2: 25 April 2011

3.2.1 Synoptic main feature

i) A trough of westerly low lies over west Bengal and adjoining area.
ii) Seasonal low lies over south Bay.
iii) The upper air cyclonic circulation over Assam and neighbourhood in lower levels persists.
iv) The upper air cyclonic circulation over southeast Rajasthan and adjoining northwest Madhya Pradesh in lower levels. A trough from this system extends up to south Tamilnadu where an upper air cyclonic circulation extending up to 4.5 km above sea level lies.
v) An east-west trough extends from east Rajasthan to Assam at 0.9 km above mean sea level across south Uttar Pradesh , Bihar and GWB .

3.2.2 Realized Weather

Lightning, thunderstorm, shower and Rain were reported over some parts of Nepal and Bhutan. A squall passed over Gaya at 2106 UTC from westerly direction with max wind speed of 80 km hr^{-1}.

3.2.3 T- Φ gram analysis

Dhaka T- Φ gram indicated a CAPE of 1988 J/kg at 0000 UTC. The total precipitable water content indicated 67.47 mm over the day, which can be considered to be conducive for convective activity.

Patna T- Φ gram indicated Total Totals Index 43.80. The total precipitable water content stayed at 41.47 mm.

Kolkata T- Φ gram indicated a very high CAPE (6776 J/kg) at 0000 UTC. The total precipitable water content stayed at 90.09 mm favouring convective activity.

Mohanbari T- Φ gram indicated a low CAPE of 679.1 J/kg at 0000 UTC. The total precipitable water content indicated 61.12 mm.

Bhubaneshwar T- Φ gram indicated a very high CAPE (6023 J/kg) and low CINE (-209 J/kg) at 0000 UTC. The total precipitable water content stayed at 57.53 mm favouring convective activity.

3.2.4 Kalpana-1 Satellite

Kalpana-1 satellite imagery (Fig. 2b) showed moderate convection over northwest of Bangladesh (CTT = -40^0C), moving southeastwards. Convection persisted over south Bay.

3.2.5 Kolkata DWR

The Doppler Radar of Kolkata (Fig. 3b) showed an echo to the northwest of Bangladesh at 1304 UTC, which intensified into a SE-SW oriented squall line of 250 km length by 1600 UTC.

Case-3: 19 May 2011

3.3.1 Synoptic main feature

i) Trough of low lies over North Bay.
ii) Seasonal low lies over south Bay.
iii) The upper air cyclonic circulation over Punjab and neighbourhood in lower levels persists. A trough from this system extends up to Gangetic West Bengal across Haryana, south Uttar Pradesh, north Madhya Pradesh, Chhattisgarh and Jharkhand.
iv) The upper air cyclonic circulation lies over Assam and neighbourhood in lower levels.

3.3.2 Realized Weather

Thunderstorm, shower and rain were reported at Tezpur, Silchar, Lengpuri region on 19 May 2011. A gusty wind passed over Chittagong at 0100 UTC from northwesterly direction with max speed of 56 km hr^{-1}. Squally wind passed over Ranchi at 1655 UTC from northwesterly direction with max speed of 44 km hr^{-1}. Alipore reported squally event at 2100 UTC from westerly direction with max wind speed of 49 km hr^{-1}. Six persons died due to lightning strike in Orrissa at night.

3.3.3 T- Φ gram analysis

Dhaka T- Φ gram indicated K index 42.7 and Total Totals Index 47.8 at 0000 UTC. The total precipitable water content stayed at 71.87 mm favouring convective activity.

Kolkata T- Φ gram indicated K index 37 and Total Totals Index 46.3 at 0000 UTC. The total precipitable water content stayed at 58.37 mm favouring convective activity.

Mohanbari T- Φ gram indicated K index 38.2 and Total Totals Index 48.3 at 0000 UTC. The total precipitable water content stayed at 57.53 mm favouring convective activity.

Agartala T- Φ gram indicated K index 38 and Total Totals Index 46.80 at 0000 UTC. The total precipitable water content stayed at 54.82 mm favouring convective activity.

Patna T- Φ gram indicated a low CAPE (636.96 J/kg) at 0000 UTC. The total precipitable water content stayed at 58.94 mm favouring convective activity.

Guwahati T- Φ gram indicated K index 35.30 and Total Totals Index 52.20 at 0000 UTC. The total precipitable water content stayed at 43.28 mm favouring convective activity.

Bhubaneshwar T- Φ gram indicated a very high CAPE (4036 J/kg) and low CINE (-151 J/kg) at 0000 UTC. The total precipitable water content stayed at 50.02 mm favouring convective activity.

3.3.4 Kalpana-1 Satellite

Kalpana-1 satellite imagery (Fig. 2c) showed strong convection over eastern India (CTT = -70^{0}C), moving southeastwards it expanded into Bangladesh and merged with convection over Jharkhand, Orissa and West Bengal (CTT = -80^{0}C). Moving south it dissipated over the sea after 2330 UTC. Convection persisted over northwest Bay.

3.3.5 Kolkata DWR

The Doppler Radar of Kolkata (Fig. 3c) showed an echo to the east of India at 0855 UTC, which intensified into a squall line of 300 km length by 1000 UTC.

Case-4: 23 May 2011

3.4.1 Synoptic main feature

i) The low over west Bengal and adjoining area persists extending its trough to North Bay.
ii) An upper air cyclonic circulation lies over Assam and neighbourhood in lower levels.
iii) A north-south trough extends from Sub Himalayan West Bengal to the North Bay of Bengal in the middle troposphere.

3.4.2 Realized Weather

Thunderstorm, shower and rain were reported at Passighat, Shillong, Cherapunjee and Lengpuri region on 23 May 2011. A squally wind passed over Bogra at 0130 UTC from northwesterly direction with max speed of 45 km hr^{-1}. Squally wind passed over Agartala at 1051 from northwesterly direction with max speed of 69 km hr^{-1}. Four persons died in Malda district due to lightning strike.

3.4.3 T- Φ gram analysis

Dhaka T- Φ gram indicated CAPE (1475 J/kg) and very low CINE (-8.08 J/kg) at 0000 UTC. The total precipitable water content stayed at 61.74 mm favouring convective activity.

Patna T- Φ gram indicated K index 29.3 and Total Totals Index 38.8 at 0000 UTC. The total precipitable water content stayed at 43.23 mm favouring convective activity.

Ranchi T- Φ gram indicated K index 31.5 and Total Totals Index 52.0 at 0000 UTC. The total precipitable water content stayed at 25.71 mm.

Kolkata T- Φ gram indicated a very high CAPE (6357.80 J/kg) at 0000 UTC. The total precipitable water content stayed at 61.02 mm which can be considered conducive for convective activity.

Bhubaneshwar T- Φ gram indicated a very high CAPE (6750.61 J/kg) at 0000 UTC. The total precipitable water content stayed at 62.52 mm favouring convective activity.

Agartala T- Φ gram indicated a high CAPE (3058.96 J/kg) at 0000 UTC. The total precipitable water content stayed at 48.03 mm favouring convective activity.

3.4.4 Kalpana-1 Satellite

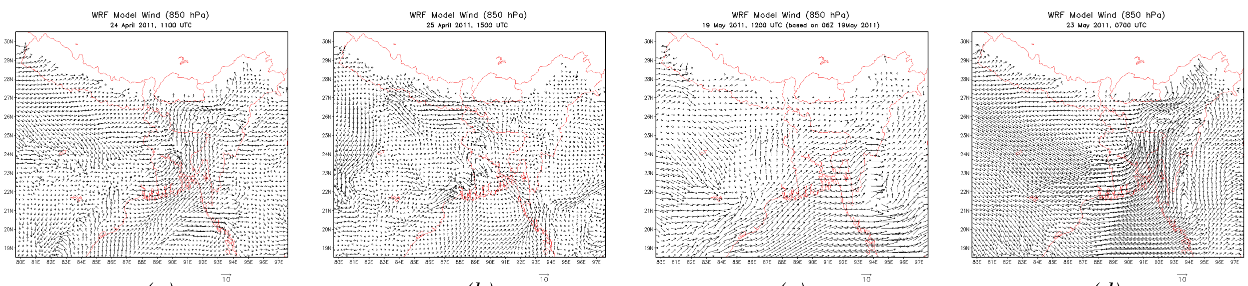
Kalpana-1 satellite imagery (Fig. 2d) showed moderate convection over Bhutan, NE India and E, NE and SE of Bangladesh (CTT = -60^0C) at 0700 UTC.

3.4.5 Kolkata DWR

The Doppler Radar of Khepupara (Fig. 3d) showed a NW-SE oriented squall line of 350 km length. At 0200 UTC a strong echo was noticed over Mymensingh, Dhaka and Khulna which intensified into a north-south oriented squall line by 0324 UTC, moving east-southeastwards, it dissipated by 1400 UTC over Bangladesh.

4 Simulated Characteristic

The large-scale synoptic conditions at 850 hPa during the days of thunderstorms events are shown in the Fig. 4(a-d). It is seen from the diagrams that during most of the storm events, the flow was southerly or south-westerly feeding moisture from the Bay of Bengal over Bangladesh at 850 hPa. The low level moisture incursion in the zone of convergence coupled with upper level trough made conditions conducive for development of severe thunderstorms over the region. However, the large scale flow pattern over Bangladesh on 23 May 2011 was anomalous. The flow was easterly/ northeasterly at 850 hPa, which was caused by shifting of the western branch of the subtropical high towards Bangladesh. The storms were embedded in the northeastern side, and moved roughly from east to west.



(a) *(b)* *(c)* *(d)*

Fig. 4. Wind vectors at 850 hPa by the model for (a) 24 April, (b) 25 April, (c) 19 May, and (d) 23 May 2011.

4.1 Assimilation of STORM Field Observations

Pilot experiment 2011 was carried out based on the existing networks in the four countries. Being the first experiment of this type, some of the countries experienced practical difficulties in collecting hourly observations during the Intensive Observation Period (IOPs). For example, Bhutan could collect the observations only during 12 noon to 9 PM and Nepal could collect the observations only 3 hourly. Bangladesh could not collect the Radiosonde observations as per the IOPs due to scarcity of consumables, but it collected 3 hourly surface data from all its stations. During the IOP days, extra surface observations (hourly) and an additional RS/RW sounding at 09 UTC were collected in India. Further, AWS installed at several places in India (West Bengal and northeastern states) collected observations at 3 minutes intervals, which were transmitted hourly (Das et al. 2009). Data collected during STORM Field Experiment-2011 were assimilated in the WRF Model in the case of 19 May 20122.

4.2 Impact of assimilated data on the forecast fields

The 19 May 2011 episode of thunderstorms was simulated using both CTRL and DA analyses. The model was integrated for 24 hours for the case. Results of simulations and the impact of data assimilation on the case are described below.

4.2.1 Case: 19 May 2011

Fig. 5 presents the 10 m wind speed and vector wind at 950 hPa, for CTRL and DA valid at 12 UTC of 19 May, 2011. It is seen that in the region 18.5^0 - 22.5^0N and 83^0 - 88^0E, the DA runs have simulated more than 22 m/s of 10 m wind speed. The value simulated by the control run is quiet less (about 14-16 m/s) and in the region $18^{\,0}$ - 22.5^0N and $84^{0\,-}$ 88^0E. The control and DA run has also simulated high 10m wind speed along the coastal belt of West Bengal.

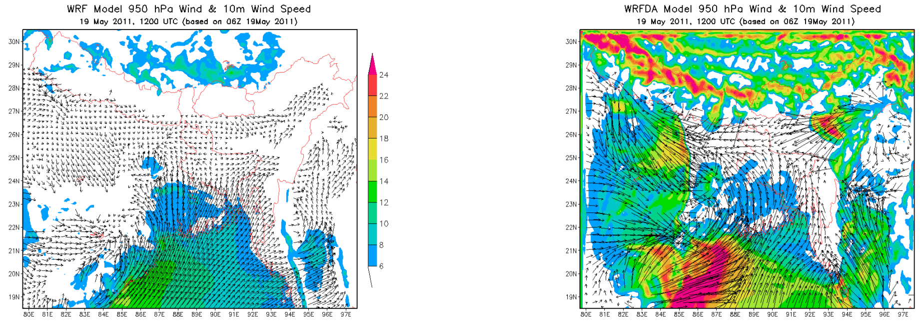


Fig. 5: Vector Wind at 950 hPa and 10 m wind speed (m/s) forecasts valid at 12 UTC of 19 May, 2011.

Signal of severe thunderstorm activity over the observed region is present in the model simulated Mean CAPE (J/kg) and Mean CINE (J/kg) for forecasts valid at 11 Z of 19 May, 2011. Fig. 6 presents the wind shear between 500 and 950 hPa pressure levels for forecasts valid at 12 UTC of 19 May, 2011. Regions having the shear values above 10m/s have been shaded. Both the simulations are able to produce maxima in shear (> 10 m/s) in the region of the max. dBZ as simulated by the model. High shear regions are wide spread in the West Bengal, Bihar and northwest of Bangladesh region in the CTRL and DA run. There is a feeble trough at 850 hPa simulated by the DA; this is absent in the CTRL run. The 700 hPa horizontal wind shows a trough and high wind velocity over the thunderstorm location. The phenomena are stronger in the DA run (Dasgupta et al. 2005).

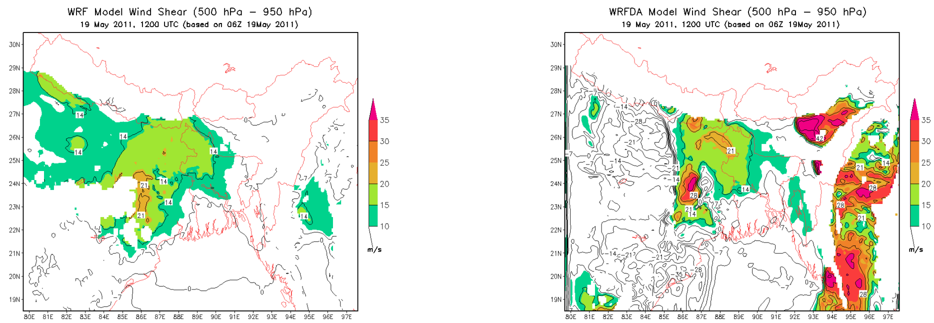


Fig. 6: Wind Shear of [500 – 950 hPa] (m/s) forecasts valid at 12 UTC of 19 May, 2011.

5. Conclusion

From the thunderstorm cases described above, it is found that out of four severe thunderstorm events, the model was able to simulate three cases close to the observations. The impact of data assimilation is very clearly highlighted as the experimental simulations from the WRF-3DVAR are able to capture the thunderstorm closer to the observations compared to the control runs. The position and intensity of the simulated thunderstorms in the experimental runs is close to the observed values, as compared to the DWR images.

The thunderstorm event from the model simulation is best highlighted from the spatial distribution of 10 m wind speed and maximum reflectivity. They are in turn supported by the wind shear within 500 to 950 hPa pressure level. It is observed that the signature of the thunderstorm activity is well represented in the model generated CAPE and CINE distribution.

The model is still not able to accurately produce the exact location and time of occurrences of the thunderstorms. The genesis and growth of cells, their horizontal distribution, vertical structure, the direction and speed of their movement and time of dissipation are still some of the challenges unresolved by the model. The skill scores of the forecasts have to be examined. Further studies are required to improve the simulation by assimilating Doppler Radar and satellite observations. Investigations have to be carried out to examine whether there are deficiencies in the generation of convective and advective forcings, generation of convective instabilities, or if there is inadequacy in the triggering mechanism for the formation of cells. Forecasting accurate location and time of occurrence of thunderstorms is still a challenge for the modelers.

Acknowledgment

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References

Barker D. M., W. Huang, Y.-R. Guo and Al Bourgeois, 2003: A Three Dimensional Variational (3DVAR) Data Assimilation System For Use With MM5, *NACR Technical Note, NCAR/TN-453+STR,* February 2003, pp 68.

Barker D. M., W. Huang, Y.-R. Guo and Q. N. Xio, 2004: A three dimensional Variational (3DVAR) Data Assimilation Syatem with MM5: Implementation and Initial results. *Mon. Wea. Rev*., **132**, 897-914.

Das Someshwar and the SAARC STORM team, 2009: SAARC STORM Pilot Field Experiment 2009. SMRC No. **32**, ISSN NO. 2074-9260, 72 pp.

Dasgupta, M., J. P. George and S. Das, 2005: Performance of MM5-3DVAR system over Indian Sub-continent. *International Conf. on MONEX and its legacy*, 3-7 Feb 2005, Delhi.

Ide, K., P. Courtier, M. Ghil and A. C. Lorenc, 1997: Unified notation for data assimilation: Operational, sequential and variational. *J. Meteor. Soc. Japan*, **75**, 181-189.

Parish, D. F. and J.C. Derber, 1992: The National Meteorological Centre's Spectral Statistical Interpolation analysis system. *Mon. Wea. Rev.,***120**, 1747-1763