Assimilation of Doppler Weather Radar Data Through Rapid Intermittent Cyclic (RIC) for Simulation of Squall Line Event over India and Adjoining Bangladesh

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1 Introduction

A squall line is a cluster of severe thunderstorms or storm cells that have formed into a line. Squall lines are hundreds of kilometres in length and having a life span of several hours, which is considerably longer than embedded thunderstorms. Squall lines generate gusty winds, sudden changes in the wind direction with an abrupt increase in wind speed and heavy rains with thunder which are more intense and extensive than individual thunderstorms. The severe gust associated with squall lines can exceed 100 km per hour. Some of them even carry hails and tornadoes. Area under influence of squall lines is extremely unstable and severely turbulent. Over Indian subcontinent, squall lines are often observed during the late pre-monsoon and early summer southwest monsoon over north-eastern states of India and adjoining Bangladesh. Squall line in Doppler Weather Radar (DWR) image will have solid line of heavy rainfall followed by a large area of light rainfall.

Most of the radar data assimilation (DA) studies based on other 3DVAR systems used only one or a few analysis at longer intervals (Xiao et al. 2007; Lin et al. 2011). However, to take full advantage of the high frequency of radar observations, Zhao and Xue (2009) assimilated radar data over a 6 h period at 30 min intervals using the ARPS 3DVAR and cloud analysis package. The results show that the assimilation of radial velocity (Vr) data help to improve the track and intensity forecast more while reflectivity data help to improve precipitation structure forecast. Over Indian region, Srivastava and Bhardwaj (2013a, b) have assimilated DWR data for cyclone

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K. Ray et al. (eds.), *High-Impact Weather Events over the SAARC Region*,
DOI 10.1007/978-3-319-10217-7_2

and cloud burst events. These studies have demonstrated that nowcast of cloud burst event and very short-range forecast of cyclone is significantly improved with DWR data assimilation.

In the current study, ARPS3DVAR and cloud analysis package of ARPS model is used for radar data assimilation and WRF model for forecast of weather. Squall line event that occurred over India and Bangladesh on 09 May 2013 is considered to evaluate the impact of assimilation of DWR data through rapid intermittent assimilation cycle on squall-line structure and subsequent very short-range forecast, as compared to the one time assimilation. Doppler Weather Radar observation taken by Agartala DWR is assimilated in NWP model. Other aim of this study is to demonstrate successful coupling of ARPS3DVAR and WRF model to be used for real time operational implementation in near future.

In Sect. 2, assimilation procedure and forecast model are described. In Sect. 3, design of experiment is discussed. Squall line event occurred over India and Bangladesh on 09 May 2013 is described in Sect. 4. Result and discussion are presented in Sect. 5. Conclusions are summarized in Sect. 6.

2 Assimilation Procedure and WRF Model

Indian DWR data is assimilated into the coupled ARPS3DVAR-WRF model through ARPS3DVAR and cloud analysis. This coupled system is used to carry out various experiments and generate wind, pressure and precipitation forecast. WRF model and ARPS3DVAR assimilation system is briefly described here.

2.1 WRF Model

WRF model is a new generation meso scale numerical weather prediction system. It serves both operational forecasting and atmospheric research requirements. The WRF model has multiple dynamic cores. This study uses Advanced Research WRF model (ARW-WRF). ARW-WRF is based on an Eulerian solver for fully compressible non-hydrostatic equations, cast in flux conservation form and mass (hydrostatic pressure) vertical coordinates. It uses a third-order Runge–Kutta time integration coupled with split-explicit second-order time integration scheme for the acoustic and gravity wave modes. ARW-WRF carries multiple physical options for cumulus, microphysics, planetary boundary layer (PBL) and radiation physical processes. Details of the model are provided in Shamrock et al. (2005). Fifth-order upwind biased advection operations are used in the fully conservative flux divergence integration.

2.2 Data Assimilation System

2.2.1 Three-Dimensional Variational (3DVAR) Technique

ARPS3DVAR data assimilation technique is an advance technique of the ARPS model developed by CAPS, Oklahoma University, USA. This technique uses dynamic constraints appropriate for storm-scale analysis, as documented by Gao et al. (2004). The analysis variables in this procedure are three wind components (u, v and w), potential temperature (θ), pressure (p) and water vapour mixing ratio (q_v). In this system, the cross correlations between variables are not included in the background error covariance. The background error correlations for single control variables are modelled by a recursive spatial filter. The observation errors are assumed to be uncorrelated; hence, observation error covariance is a diagonal matrix, and its diagonal elements are specified according to the estimated observation errors.

One unique feature of the ARPS3DVAR is that multiple analysis passes can be used to analyze different data types with different filter scales to account for the variations in the observation spacing among different data sources. The main advantage of variational method (3DVAR) over classical data assimilation methods is the feasibility of assimilating directly the observed parameters (radial wind and reflectivity) at any given time and space location.

2.2.2 Cloud Analysis

The cloud analysis component of ADAS is derived from that of Local Analysis and Prediction System (LAPS) with a number of modifications (Bratseth 1986; Albers et al. 1996; Brewster 1996; Zhang et al. 1998). The radar reflectivity and thermodynamics are used to solve for the model's precipitating hydrometeors (rain, snow and hail). Because the radar reflectivity is generally a function of drop diameter raised to the sixth power and the water content is a function of diameter cubed, some assumptions must be made about drop size distribution (DSD). The present system uses relationships based on a Marshall-Palmer DSD. The analyzed temperature is used in the scheme in the diagnosis of precipitation species. Direct replacement of the background hydrometeors is done in areas where observed reflectivity is greater than a prescribed threshold (typically 10–20 dBZ). Precipitation is removed from the background in areas within the radar volume coverage and having reflectivity less than the precipitation threshold.

An important aspect of building and maintaining thunderstorm updrafts in a non-hydrostatic model is the inclusion of the effect of latent heat release due to condensation processes in the updraft regions. A moist adiabatic ascent from the analyzed cloud base with entrainment is calculated, and any excess in this temperature over the analyzed temperature is then added to the analyzed value.

3 Design of Experiment

Model domain for the squall line event on 09 May 2013 approximately covers the area between 21° to 27°N and 89° to 95°E with horizontal resolution of 9 km with 80 × 80 grid points in X and Y directions. This domain covers an area of 720 × 720 km with DWR Agartala at the centre of domain. The vertical grid stretched from surface to model top is located at about 20 km height at a vertical resolution of 500 m. IMD global forecast system (GFS) data at 1° × 1° resolution are used to provide initial and boundary conditions for both the data assimilation experiments (i.e. rapid intermittent cycles and only one time) for both the events.

Two sets of experiments are carried out using coupled ARPS3DVAR-WRF model to investigate the impact of radar data assimilation on simulation of squall line event. In the first experiment data is assimilated through rapid intermittent cycles (cyclic) and in other experiment only one time (non-cyclic) assimilation is done. Both the reflectivity and wind data have been assimilated simultaneously through ARPS3DVAR and cloud analysis procedure. For 09 May 2013 event, first experiment (RIC) assimilates Agartala DWR data through rapid intermittent cycles every 20 min within 1 h assimilation window from 0300 UTC to 0400 UTC and second experiment (NORIC) assimilates DWR data only one time at 0400 UTC (Table 1).

4 Squall Line Event on 09 May 2013

4.1 Description of Event

On 9 May 2013 squall line occurred over northeast Indian region. Figure 1 shows domain of study which covers northeast India and Bangladesh. This study focusses on northeast to southwest oriented squall line initiated around 0300 UTC 09 May 2013 over northeast Bangladesh. At 0500 UTC it was hook shaped. Hook of the squall line is enclosed by the dotted red circle in Fig. 1. At 0700 UTC squall line is well developed and is seen as bow shaped in reflectivity field. This caused flash flood and nearly 200 houses were damaged in Mizoram and Tripura states of India. Squall line moved southeast ward throughout its life span and dissipated after 0900 UTC.

Table 1 Design of experiments

Experiments	Type of radar data assimilation	Time of data assimilation
RIC (Rapid intermittent cycle)	Reflectivity and radial velocity	0300, 0320, 0340 and 0400 UTC 09 May 2013
NORIC (No cycle, one time assimilation)	Reflectivity and radial velocity	0400 UTC 09 May 2013

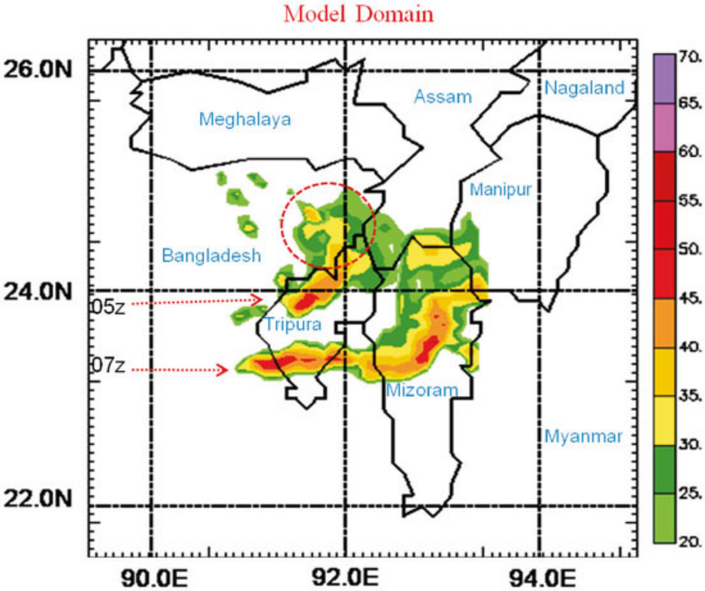

Fig. 1 Model domain and composite radar reflectivity observations (*colour*) at 0500 UTC 09 May and 0700 UTC on 09 May 2013

4.1.1 Radar Observation

Figure 2 shows hourly movement of squall line. The squall line from its initiation (around 0300 UTC on 9 May 2013) to dissipation (around 10 UTC 09 May 2013) was well observed by Agartala radar. Quality control of radial velocity and reflectivity data during assimilation cycle (03–04 UTC) is done by using WDSSII software. The method of DWR data quality control is same as described by Roy Bhowmik et al. (2011). Data assimilation experiments are performed using quality control data from Agartala to compare the relative importance of cyclic verses no cyclic data assimilation.

Figure 2 also shows that squall line formed around 03 UTC over northeast Bangladesh. It started moving southeast ward and lay over north Tripura and adjoining Bangladesh at 0500 UTC. At this time comma (hook) shaped echo was seen over northern end of squall line. Throughout its life period squall line moved southeast ward. At 0600 UTC it was well developed, bow shaped and lay over central part of Tripura and northwest part of Mizoram. During 0600–0800 UTC squall line was very intense, bow shaped and covered remaining southern parts of Tripura and northern parts of Mizoram. During 0800–1100 UTC system continued to move southeast ward and covered southern parts of Mizoram. The squall line started weakening after 1100 UTC and dissipated thereafter.

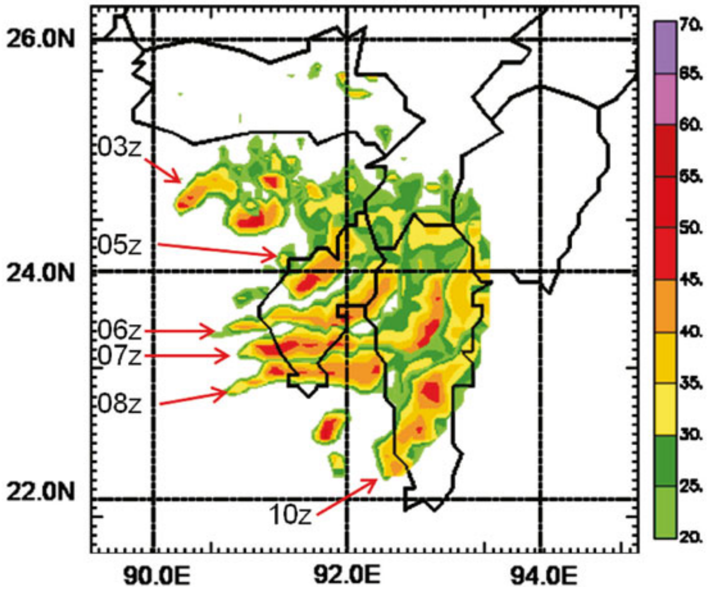

Fig. 2 Movement of squall line as observed by the Agartala radar during 03 UTC to 10 UTC on 09 May 2013

4.1.2 Observed Rainfall

In Fig. 3, shaded area shows the 24 h accumulated rainfall (in mm) during 03 UTC of 09 May 2013 to 03 UTC of 10 May 2013 estimated by the TRMM satellite. Figure 3 shows that the rainfall due to the squall line was mainly confined over northeast Bangladesh, Tripura and Mizoram and was in the range of 6–9 cm. This rainfall area is covered by the squall line during its southeast movement. Numbers shown in the figure are the amount of 24 h accumulated rainfall (in cm) observed by the synoptic observatories (Kailashahr – 8, Lengpui – 7, Silchar – 4, Cherrapunji – 6) located over the area covered by the squall line.

4.1.3 Synoptic Conditions

Figure 4 shows the wind pattern at 850, 500 and 200 hPa levels. Figure 4a shows that northsouth trough runs from north Bihar to Orissa coast through West Bengal at 850 hPa level. At the same level cyclonic circulation lies over Assam, Meghalaya and adjoining area. Figure 4a also shows that there is southwesterly wind flow over Bangladesh and Tripura in lower levels. Strong southwesterly wind flow of the order of 20–25 knots lead to the moisture incursion over the region, necessary for the development of thunderstorm/squall line. Upper level divergence at 200 hPa was also favourable for the development of TS/squall line.

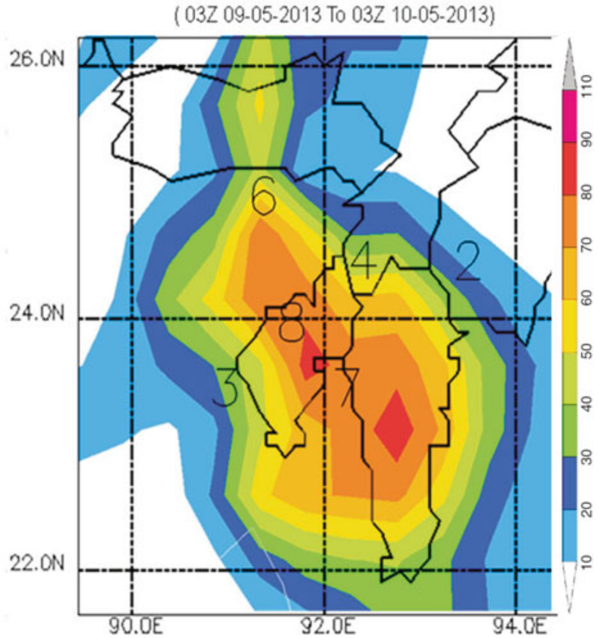

Fig. 3 24-h accumulated rainfall in cm (*shaded*) estimated by the TRMM satellite (*Number*) observed by the synoptic observatories

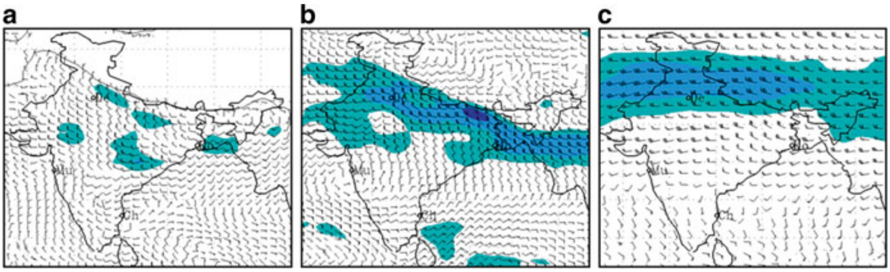

Fig. 4 Wind pattern at (**a**) 850 hPa, (**b**) 500 hPa and (**c**) 200 hPa levels at 00 UTC on 09 May 2013

5 Result and Discussion

5.1 Impact on Reflectivity Forecast

In this section we will evaluate whether the initialization through rapid intermittent assimilation cycle results in a better squall line structure in analysis and the subsequent very short range forecast, as compared to the one time assimilation. For this result from RIC experiment is analyzed and compared with NORIC experiment

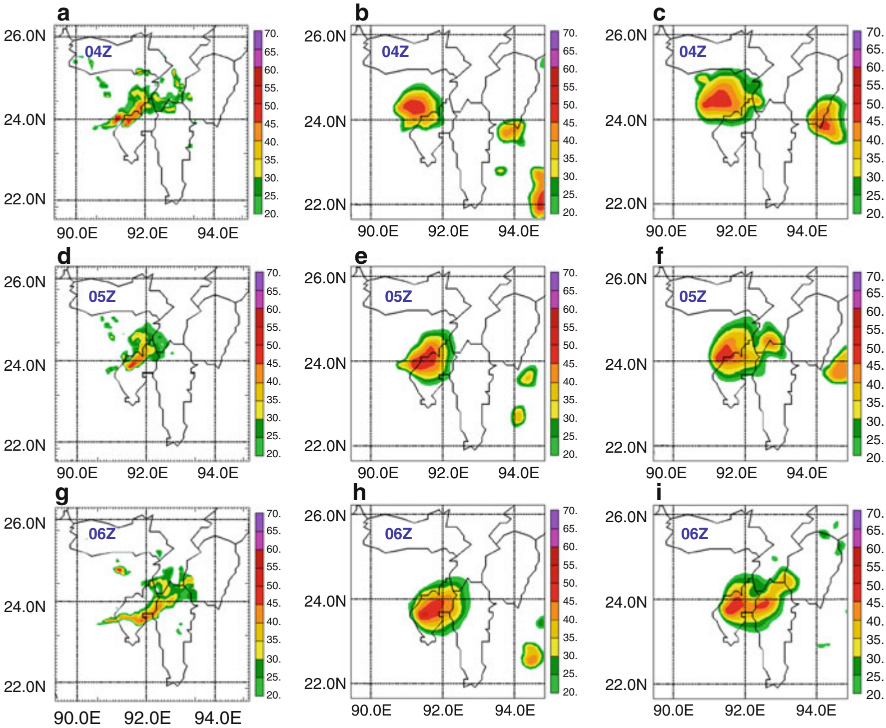

Fig. 5 Reflectivity fields at 0400, 0500 and 0600 UTC 09 May 2013: (**a**, **d**, **g**) observed by the Agartala radar, (**b**, **e**, **h**) simulated by NORIC experiment and (**c**, **f**, **i**) simulated by RIC experiment

(i.e. cycling versus no cycling). At the same time results from these experiments are compared with the radar observation. Figure 5 shows the simulated reflectivity patterns at 0400, 0500 and 0600 UTC 10 May from NORIC and RIC experiments, as well as the observations from the Agartala radar. Similarly Fig. 6 shows the reflectivity fields at 0700, 0800 and 0900 UTC.

It is noticed that throughout the life period of squall line (04–09 UTC), maximum reflectivity observed by DWR Agartala as well as simulated by both the experiments was of the order of 50 dBZ. Observed reflectivity plot at 0400 UTC depicts that squall line lies over northwest boundary of Tripura and have maximum value of 50 dBZ (Fig. 5a). Hook shaped echo is also seen at the northern end of squall line. Weak echoes are also seen over southern tip of Assam. NORIC experiment analyzes an oval shaped convective cell over the area (Fig. 5b). However, the location of reflectivity maxima (~50 dBZ) is slightly northwestward to the observed location. RIC experiment also analyzes an oval shaped convective cell but its horizontal extension is more than NORIC experiment and it has covered northeastern part of Bangladesh (Fig. 5c). In this experiment convective cell was slightly extended towards east and covered southern tip of Assam. Both the experiments also predict convective cell at the southern tip of Manipur, which moved eastward during subsequent forecast hours. Though both experiments analyze squall line as oval shaped convective cell, but RIC experiment analysis is better as it is extended eastward and covers southern tip of Assam. Reflectivity observation at 0500 UTC shows that squall line had moved slightly southeastward and covered northwest Tripura with maximum reflectivity of the order of 50 dBZ (Fig. 5d). Hook shaped echo at the northern end of squall line was slightly intensified. Echoes over Assam and Bangladesh at 0400 UTC had weakened. Figure 5e shows 1-h forecast by NORIC experiment; it depicts that simulated reflectivity pattern has shifted southeastward and covers north Tripura and adjoining Bangladesh. Similar to NORIC experiment, simulated reflectivity pattern by RIC experiment is also shifted southeastward and covers north Tripura and adjoining Bangladesh (Fig. 5f). Reflectivity field in this experiment is further extended eastward and eastern end is intensified.

Figure 5g shows that squall line continued to move southeastward and hook shaped echo lay over southern tip of Assam at 0600 UTC. At the same time squall line had covered central parts of Tripura, northwest part of Mizoram and southwest Manipur. Two-hour forecast by NORIC experiment at 0600 UTC depicted that simulated reflectivity pattern had shifted southeastward and covered almost entire Tripura and northwest boundary of Mizoram (Fig. 5h). Reflectivity field predicted by RIC experiment at 0600 UTC was east–west oriented and it further moved southeastward and covered north Tripura, northwest parts of Mizoram and southwest Manipur (Fig. 5i). At this time reflectivity pattern predicted by RIC experiment over Mizoram and Manipur is very close to the observation. Over Tripura, predicted reflectivity field has covered more area as compared to the observation.

Figure 6a shows that squall line continues to move southeastward and hook shaped echo is now disappeared at 0700 UTC. Squall line now (is now bow shaped echo) lies over southern parts of Tripura and extending up to northern part of Mizoram. Three-hour forecast by NORIC experiment at 0700 UTC depicts that simulated reflectivity pattern has further shifted southeastward and covers almost entire Tripura and also covers west-northwest area of Mizoram (Fig. 6b). East–west oriented reflectivity field predicted by RIC experiment at 0700 UTC is extended towards north; entire pattern has further moved southeastward and covers east Tripura and north Mizoram (Fig. 6c). At this time reflectivity pattern predicted by RIC experiment over Mizoram and Manipur is very close to the observation and reflectivity pattern also appears like bow shaped.

Figure 6d shows that squall line has further moved southeastward. Squall line now lies over extreme southern parts of Tripura, central Mizoram and extending up to eastern parts of Mizoram. Four-hour forecast by NORIC experiment at 0800 UTC depicts that simulated reflectivity pattern has further moved southeastward and covers western parts of Mizoram (Fig. 6e). Reflectivity field predicted by RIC experiment at 0800 UTC has further moved southeastward and covers central Mizoram (Fig. 6f). Reflectivity pattern predicted by RIC experiment over Mizoram is close to the observation. However reflectivity pattern is broader than observation.

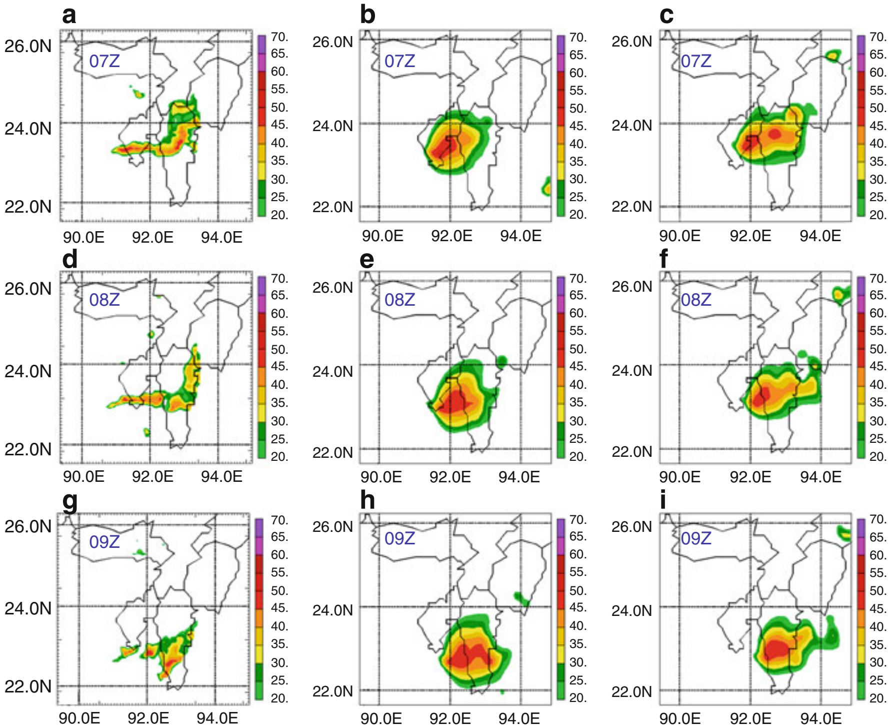

Fig. 6 Reflectivity fields at 0700, 0800 and 0900 UTC 09 May 2013: (**a**, **d**, **g**) observed by the Agartala radar, (**b**, **e**, **h**) simulated by NORIC experiment and (**c**, **f**, **i**) simulated by RIC experiment

0900 UTC radar observation in Fig. 6g depicts that squall line continues to move southeastward and now lies over southern parts of Mizoram. Five-hour forecast by NORIC experiment at 0900 UTC depicts that simulated reflectivity pattern has further moved southeastward and covers southern parts of Mizoram (Fig. 6h). Similar reflectivity field is predicted by RIC experiment at this time. However smaller area is covered in RIC experiment as compared to NORIC experiment. Location of predicted reflectivity field in both the experiments is very close to the observation. Above discussion indicates that RIC experiment demonstrates that squall line is much better simulated than NORIC experiment.

5.2 Impact on Precipitation

Figure 7 shows three-hourly rainfall estimated by TRMM satellite and simulated by NORIC and RIC experiment during 03–06 UTC and 06–09 UTC on 09 May 2013. Comparison of Fig. 7a–c shows that rainfall during 03–06 UTC in RIC experiment

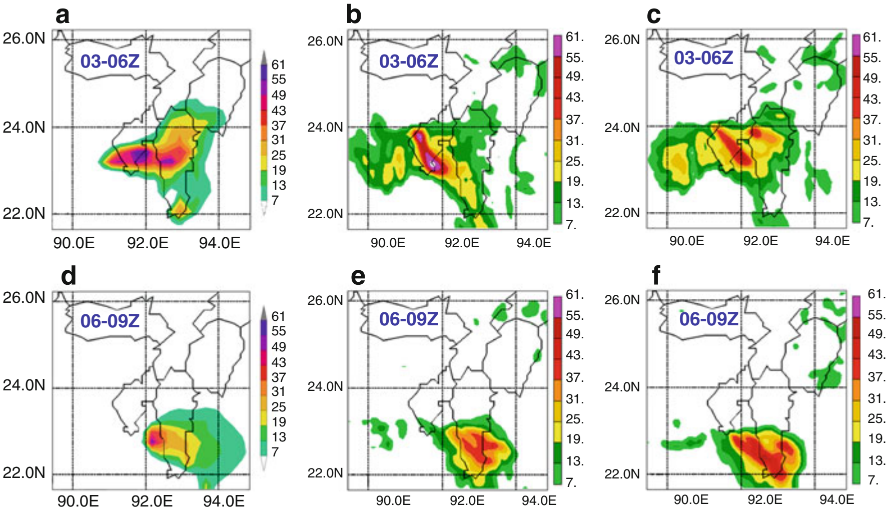

Fig. 7 Three-hourly precipitation during 03–06 UTC and 06–09 UTC on 09 May 2013: (**a**, **d**) Estimated by TRMM satellite, (**b**, **e**) simulated by NORIC experiment and (**c**, **f**) simulated by RIC experiment

is better predicted than the NORIC experiment as rainfall over north Mizoram is well captured when data is assimilated through rapid intermittent cycle. However rainfall pattern during 06–09 UTC in both the experiments is similar and close to the observation.

Conclusions

Squall line event occurred over India and Bangladesh on 09 May 2013 is investigated to see the impact of assimilation of DWR data through rapid intermittent assimilation cycle on squall-line structure and subsequent very short range forecast, as compared to the one time assimilation. Based on the experiments carried out, following conclusions can be drawn:

- Coupling of data assimilation package ARPS3DVAR and cloud analysis with WRF model has been successfully accomplished for Indian DWR data.
- Horizontal extension, merger of cells, intensity and direction of movement of squall line are better predicted when data is assimilated through rapid intermittent cycles (RIC).
- Amount and precipitation structure are significantly improved in cyclic assimilation.

Acknowledgement Authors are thankful to Guru Gobind Singh Indraprastha University, New Delhi for their support to carry out this study. The authors are also grateful to the Director General of Meteorology, IMD, New Delhi for encouraging to do present work. Authors also thankfully acknowledge the support of DWR Delhi; NWP Division, IMD, New Delhi; NWP system (ARPS) of CAPS, University of Oklahoma, USA and HPCS system for this study.

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High-Impact Weather Events over the SAARC Region
Ray, K.; Mohapatra, M.; Bandyopadhyay, B.K.; Rathore, L.S. (Eds.)
2015, XIV, 414 p. 235 illus., 101 illus. in color., Hardcover
ISBN: 978-3-319-10216-0