Assimilation of Doppler weather radar data and their impacts on the simulation of squall events during pre-monsoon season

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Abstract The quantitative data from Doppler Weather Radar (DWR) such as the radial winds and reflectivity are useful for improving the numerical prediction of weather events like squalls. Mesoscale convective systems are responsible for majority of the squall and hail events and related natural hazards that occur over Bangladesh and surrounding region in pre-monsoon season. In this study, DWR observations (radial winds and reflectivity) of Bangladesh Meteorological Department are used for simulating the squall events during May 2011 with a view to update the initial and boundary conditions through three-dimensional variational assimilation technique within the Advanced Research Weather Research and Forecasting model. The simulated sea-level pressure, thermodynamic indices, wind fields at 850 hPa, and cloud hydrometeors from eight experiments are presented in this study for analyzing the observed and simulated features of the squall events which occurred in the month of May 2011. The model results are also compared with the Kalpana-1 satellite imagery and the observations of India Meteorological Department. Further, the intensity of the events generated from the simulations is also compared with the in situ meteorological observations in order to evaluate the model performance.

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1 Introduction

The severe thunderstorms that originate in the eastern and northeastern parts of India [i.e., Gangetic West Bengal (GWB), Jharkhand, Odisha, Bihar, and Assam] and Bangladesh during the pre-monsoon season (March–May) mostly travel from northwest to southeast direction (IMD 1944; Desai 1950; Kessler 1982; Das et al. 1994; Karmakar 2001; Yamane and Hayashi 2006; Tyagi 2000; Das et al. 2014a). They are locally called Nor'westers or 'Kalbaishakhi' in Bengali. These systems develop mainly due to merging of cold and dry northwesterly winds aloft and southerly low-level warm and moist winds coming from the Bay of Bengal (Das 2010; Das et al. 2014b). The pre-monsoon thunderstorms produce surface wind squalls, lightning, thunder, hailstorms, heavy rain showers, dust storms, and downbursts. Tornado cells are sometimes embedded in the mother thunder cloud. These storms hamper the socioeconomy of the region and cause loss of lives. The Nor'wester events are typical mesoscale systems dominated by intense convection. The understanding and prediction of these weather events are, therefore, the challenges to the atmospheric scientists.

Several studies have been made on the pre-monsoon thunderstorm events over Bangladesh with statistical analysis and numerical model but without data assimilation. The studies made by Karmakar (2001), Karmakar and Alam (2005, 2006, 2007), Islam et al. (2005), Prasad (2006), Litta and Mohanty (2008), Yamane and Hayashi (2006), Yamane et al. (2009, 2010a, b, 2012), Murata et al. (2011) may be mentioned in this respect. These studies showed that the frequency of pre-monsoon thunderstorm events in Bangladesh usually reaches its maximum in May. The frequency is maximum over the northeast and middle region and is relatively less over the southern parts of Bangladesh. Prasad (2006) made a detailed study on the thunderstorms over Bangladesh using the European Centre for Medium-Range Weather Forecasts (ECMWF) re-analysis (ERA-40) products. This study indicated that the conditions favorable for the occurrence of Nor'westers are (1) an elongated trough over the Gangetic plains from north India to Bangladesh, (2) low-level jet with a poleward meridional component, (3) a tongue of high moisture content of magnitude about 16–20 g kg^{-1} intruding from the head of the Bay of Bengal into Bangladesh, (4) presence of subtropical jet stream with strong vertical wind shear in the low-to-mid troposphere over Bangladesh, (5) a well-marked convergence line in the lower levels extending from the east coast of India to northeast India across Bangladesh, (6) a pocket of warm air advection at 850 hPa and cold advection at 300 hPa, and (7) intrusion of a plume of high Convective Available Potential Energy (CAPE) and low Convective Inhibition Energy (CINE) from the Bay of Bengal into Bangladesh.

The study of pre-monsoon thunderstorm systems over Bangladesh and the Indian region has shown that numerical weather prediction (NWP) models have modestly good capability to simulate high-impact convective events with some limitations (e.g., Das et al. 2009; Basnayake et al. 2010; Das et al. 2010; Litta et al. 2012; Akter and Ishikawa 2014). However, 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 (Das et al. 2012). One reason for this failure may be the lack of sufficient and qualitative observations at mesoscale resolution. These problems could be alleviated by assimilation of observations from Doppler Weather Radar (DWR).

Modern radars are important equipments for nowcasting Local Severe Storms. Radar observations from DWR provide useful information about the mesoscale structure of the event. It has been a challenging task to ingest radial wind and reflectivity observations of

DWR in the assimilation cycle of a numerical model. A few case studies have been reported with experiments involving assimilation of the Indian DWR data in order to simulate extreme weather events using mesoscale models (Abhilash et al. 2007; Routray et al. 2010, 2013; Sen Roy et al. 2010; Srivastava et al. 2011; Roy Bhowmik et al. 2011). Abhilash et al. (2007) established that assimilation of derived Doppler radar wind data in the MM5 model using three-dimensional variational assimilation (3DVAR) had a positive impact on the prediction of intensity, organization, and propagation of rainbands associated with pre-monsoon convective storms over northeast India. Sen Roy et al. (2010) investigated the impact of assimilation of Indian DWR data to capture nowcast features of land falling cycle. Srivastava et al. (2011) and Roy Bhowmik et al. (2011) showed that assimilating quality-controlled radar data in the advanced regional prediction system (ARPS) model showed a positive impact on model performance. Routray et al. (2010) assess the utilization of DWR radial velocity and reflectivity in Advanced Research Weather Research and Forecasting model (WRF ARW) to predict Bay of Bengal monsoon depressions (MDs). They found that assimilation of DWR data improved the prediction of location, propagation, and development of rainbands associated with the MDs. Very recently, Prasad et al. (2014) studied pre-monsoon thunderstorm with Kolkata DWR data. In their study, DWR observations improve the dynamic and thermodynamic features of the thunderstorm with the improvement of wind and moisture in the boundary layer. Despite the importance of DWR data for use in extreme weather event warnings, there have been limited efforts in utilizing the same in the assimilation cycle of weather prediction models used for operational purpose (Das et al. 2006). Recently, there is availability of DWRs data from Bangladesh Meteorological Department (BMD) through SAARC STORM (Das et al. 2014b) project. An attempt has been made to use DWR data of BMD in the WRF ARW (Skamarock et al. 2008) modeling system using the 3DVAR data assimilation technique (Xiao et al. 2005; Xiao and Sun 2007).

The 3DVAR data assimilation approach is one of the most promising techniques (Barker et al. 2004) available to directly assimilate heterogeneous mesoscale observations in order to improve the estimate of the model's initial state. Several episodes of Mesoscale Convective System (MCS) associated with squalls occurred during May 2011. Widespread outbreaks of intense thunderstorms occurred on the following days affecting Bangladesh and neighborhood region (east and northeastern parts of India) on (i) May 11, (ii) May 19, (iii) May 21, and (iv) May 23, 2011. In this study, DWR observations (radial winds and reflectivity) of BMD are used to study the 4-day episodes of squalls mentioned above. The DWR observations are used to update the initial and boundary conditions through 3DVAR technique within the WRF modeling system.

Assimilation of radar data for mesoscale applications is a new activity in the South Asian region. Using DWR data of BMD is one of the pioneer attempts to assimilate pre-monsoon squall events over this region to see the impacts of forecasting. In order to study the impact of the special observations on forecasts, two sets of experiments were conducted. The first set of experiments were the control experiments (CTRL) in which 24 h forecasts were made based on the initial conditions produced by the National Centers for Environmental Prediction (NCEP) Final (FNL) Operational Global Analysis data. The second set of experiments (3DVAR) was conducted based on the initial conditions produced by assimilating the special field observations including the DWR data. Results were analyzed and compared for the two experiments CTRL and 3DVAR.

The main objective of this study is to explore the impact of DWR radial velocity and reflectivity for the simulation of pre-monsoon squalls. This study is one of the pioneer

research works utilizing DWR data of BMD in an assimilation system to improve the forecast skill of squalls over Bangladesh.

This paper is organized as follows: Sect. 2 presents an overview of the WRF ARW and 3DVAR Data Assimilation System. Description of squall events, satellite image analyses, and common synoptic features are described in Sect. 3. The details of the numerical experiments, and data used are provided in Sect. 4. In Sect. 5, a brief description of the analyses of DWR reflectivity and radial wind of BMD are presented. Section 6 deals with results and discussion of the model simulations. Finally, Sect. 7 presents the conclusions from the study.

2 WRF ARW and 3DVAR data assimilation system

2.1 WRF ARW

The WRF modeling system version 3.4.1 has been used for the study domain Bangladesh and neighborhood region (Fig. 1). The WRF model is a new-generation mesoscale NWP system designed to serve both operational forecasting and atmospheric research needs
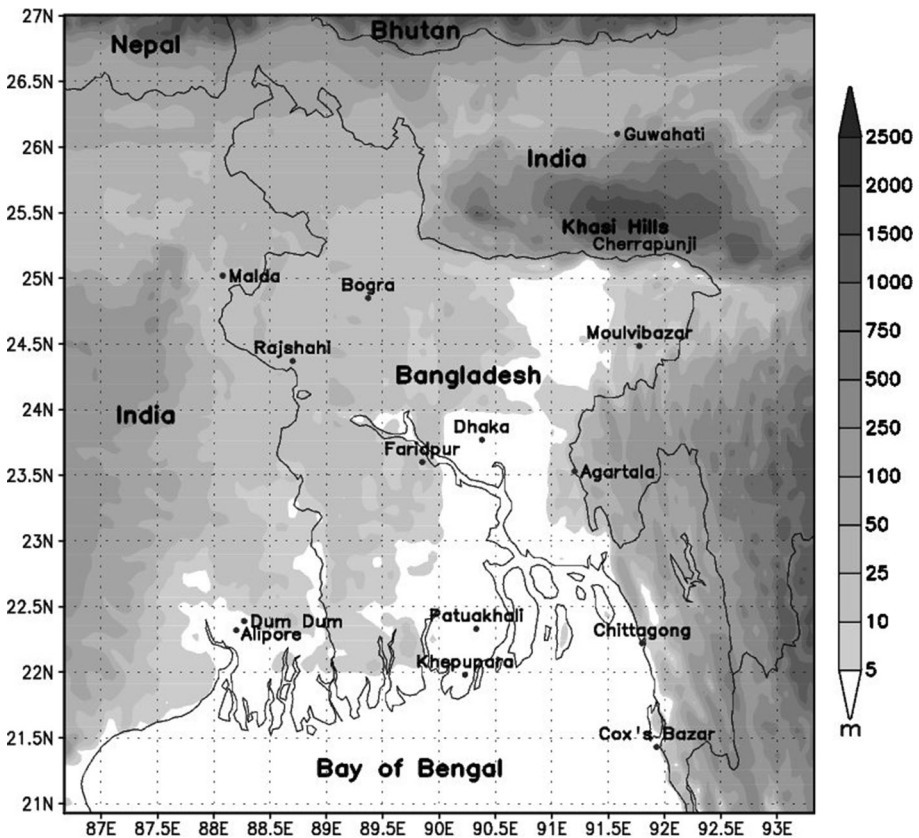

Fig. 1 WRF model domain under study and topography (*shaded*)

(Skamarock et al. 2008). It features multiple dynamical cores, a 3DVAR data assimilation system, and a software architecture allowing for computational parallelism and system extensibility. There are two dynamic solvers in the WRF system: the Advanced Research WRF (ARW) solver (originally referred to as the Eulerian mass or "em") developed primarily at National Center for Atmospheric Research (NCAR), and the NMM (Nonhydrostatic Mesoscale Model) solver developed at NCEP. The ARW system consists of the ARW dynamic solver with other components of the WRF system needed to produce a simulation. The model physics options and parameterization details are presented in Skamarock et al. (2008). 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 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, and baroclinic waves).

2.2 The 3DVAR system

In recent years, efforts have been initiated toward the development of variational data assimilation systems to replace previously used schemes such as the Cressman, Newtonian nudging, optimum interpolation, and analysis algorithms. The 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).

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

where J^{b} and J^{o} represent the cost functions of the background and observations, respectively; 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. Error of representativeness is an estimate of inaccuracies introduced in the observation operator H, which is used to transform the gridded analysis x to observation space $y = Hx$.

The 3DVAR system consists of the four components (Barker et al. 2004, 2012): (1) background preprocessing, (2) observation preprocessing and quality control, (3) variational analysis, and (4) updation of boundary conditions. Details of these components are briefly described below.

2.2.1 Background preprocessing

Analysis for a particular initial condition can be done either in cold-start mode or in a cycling mode. In cold-start mode, standard WRF preprocessing programs may be used to reformat and interpolate forecast fields from a variety of sources to the target WRF domain. In cycling mode, background processing is not required as the background field x^{b} is supplied by short-range forecast of WRF model over the same domain. Before proceeding to the variational analysis, a background error field of the model is required. In the present study, the background error fields are calculated based on the National Meteorological Center (NMC) method (Parish and Derber 1992; Huang et al. 2009).

2.2.2 Background error (BE) computation

Background error covariances are vital input to any variational analysis scheme. They influence the analysis fit to observations and also define the analysis response away from the observations (Lorenc et al. 2000; Barker et al. 2004). Background error covariance statistics are used in WRF–3DVAR cost function to weight background field. The assimilation system filters those background structures that have high error relative to more accurately known background features and observations. In reality, error in the background field is synoptically dependent. As mentioned earlier, in the current implementation of 3DVAR, background errors have been calculated over the Indian region based on the operational configuration of WRF run at NCMRWF using NMC method (Dasgupta et al. 2005). In this method, background errors are approximated by averaged forecast difference (e.g., month-long series of 24 h–12 h forecasts valid at the same time). Thus, the BE covariance matrix (B) is approximated as

$$B \cong \overline{(T_{12} - T_{24})^T (T_{12} - T_{24})}$$

Cycling-mode application requires errors representative of a short-range forecast run from a previous 3DVAR analysis. Background errors will vary for each domain and so should ideally be tuned for each domain. For any new domain, the cycling application has to use background errors interpolated from another source of similar resolution/location. Once the new system runs for a sufficient period (~ 1 month), a better estimate of background error may be obtained using forecasts from this cycle. This is an iterative process, as the change in background error used in 3DVAR will again modify features of the resulting short-range forecast used as background. WRF–3DVAR includes a number of namelist variables that allow some control of re-specifying the background error statistics at runtime.

After generating the desired forecast differences, averaged forecast error statistics computation is mainly done through following three stages:

- Computation of eigenvectors and eigenvalues of vertical background errors,
- Calculation of balance regression statistics used to filter balance mass increments,
- Calculations of recursive filter characteristic length scales.

Using the WRF model 12 and 24 h forecast outputs, BE was computed by NMC method over Indian region. Generally, before making an attempt to run any assimilation cycle, it is essential to test the BE statistics. With this aim, the old BE (OLDBE) statistics was subjected to pseudo single observation test (PSOT). It involves the assimilation of a pseudo (or bogus) observation of one of the model variables (u, v, T, p, q) at a single point in the domain.

The response of BE is mainly observed in two ways. Firstly, the fit of any observation (O) with analysis (A) or the background (B) is dictated by the background (σ_b^2) and observation (σ_o^2) error variances according to

$$(O - A) = \frac{\sigma_o^2}{\sigma_o^2 + \sigma_b^2}(O - B), \quad (A - B) = \frac{\sigma_b^2}{\sigma_o^2 + \sigma_b^2}(O - B) \tag{2}$$

Secondly, in addition to setting the relative weight of observation and background in the analysis via Eq. (2), BE also defines the response of the analysis away from the observation location for other variables due to multivariate characteristics of WRF–3DVAR. This is very important especially, in the data sparse region. PSOT has been performed for different parameters over the Indian region at various vertical levels.

2.2.3 Observation preprocessing and quality control

The WRF–3DVAR has a module, "OBSPROC" for preprocessing and quality control of observations. It packs the observations in a suitable format for ingest into 3DVAR. The main functions of the observation preprocessor are as follows:

- It reads the decoded observations packed in the LITTLE_R format.
- Pack observations in 3DVAR format (American Standard Code for Information Interchange—ASCII).
- Performs spatial and temporal checks to select only observations located within the target domain and within a specified time-window.
- Calculates heights for observations whose vertical coordinate is pressure.
- Merges duplicate observations (same location, type) and chooses observation nearest to analysis time for stations with observations at several times.
- Estimates and assigns the error for each observation. Observation errors for different meteorological parameters (e.g., pressure, temperature, height, wind, and moisture), for various types of data sources (e.g., SHIP, radiosonde/rawinsonde etc.) at standard pressure levels are given in a file 'obserr.txt' These values are originally from NCEP, but have been modified at NCAR after comparisons against observation background (OB) statistics. These may also require proper tuning over the study region.
- Performs a variety of quality control checks (e.g., check for negative wind speed, spike in wind profile, spike in temperature profile, super adiabatic lapse rate, height above/below the model lid/surface.)
- Assigns proper quality control flag to each datum according to the result of quality control checks.
- Generates run-time diagnostics about the rejection statistics.

2.2.4 Variational analysis (VAR)

The VAR problem can be summarized as the iterative solution of Eq. (1) to find the analysis state x that minimizes the cost function $J(x)$. The two terms in J, namely J^b and J^o, are the contributions of background and observations, respectively, toward the total cost function J. Details of the variational analysis may be referred from the paper of Barker et al. (2004). The main features of WRF–3DVAR analysis system are summarized as follows:

- Incremental formulation of the model-space cost function given by Eq. (1).
- Quasi-Newton/conjugate gradient minimization algorithm.
- Analysis increments on unstaggered "Arakawa-A" grid.
- Analysis performed on the sigma-height levels of MM5.
- J^b preconditioning via a "control variable transform" U defined as $B = UU^T$.

Preconditioned control variables are chosen as stream function, velocity potential, unbalanced pressure, and specific/relative humidity. Linearized mass–wind balance (including both geostrophic and cyclostrophic terms) is used to define a balanced pressure. Representation of the horizontal component of background error has been made via isotropic recursive filters. The vertical component is applied through projection onto climatologically averaged eigenvectors of the vertical error (estimated via the NMC method). Horizontal/vertical errors are non-separable (horizontal scales vary with vertical eigenvector).

Although the variational analysis is frequently described as "optimal", it is so, subject to a number of assumptions. Firstly, given both imperfect observations and background information as inputs to the assimilation system, the quality of the output analysis depends crucially on the accuracy of prescribed errors. Secondly, although the variational method allows for the inclusion of linearized dynamical/physical processes, real errors in the NWP system may be highly nonlinear. This limits the usefulness of variational data assimilation in highly nonlinear regimes, e.g., the convective scale or in the tropics.

3 Squall events description, satellite image analysis, and common synoptic features

A squall is an event, when a sudden increase of wind speed by at least 8 m s^{-1} (16 knots), the speed rising to 11 m s^{-1} (22 knots) or more, and lasting for at least one minute (WMO 1962). According to the Beaufort scale, 'squall is a sudden increase of wind speed by at least three stages of the Beaufort scale, the speed rising to force 6 or more and lasting for at least one minute.' In 2011 edition (updated in 2014), WMO defined (WMO 2014) squall as an atmospheric phenomenon characterized by a very large variation of wind speed: It begins suddenly, has a duration of the order of minutes, and decreases rather suddenly in speed. It is often accompanied by a shower or thunderstorm.

In this study, four squalls and gusty events that occurred on May 2011 are considered. The reported weather phenomena over Bangladesh and surroundings during May 11, 19, 21, and 23, 2011, are shown in Table 1. The detailed synoptic situations for the four events are given below.

Table 1 Reported weather events on the dates of occurrence

Dates	Reported stations	Wind speed (m s^{-1})	Wind direction	Reported time (UTC)
May 11, 2011	Rajshahi	11.32	W	0300–0330
	Alipore	12.77	NW	0435
	Dum Dum	13.88	NW	0435
	Dhaka PBO	15.43	W	0542–0544
	Chittagong MMO	19.55	WNW	0932–0934
	Alipore	13.88	NW	1235
	Dum Dum	17.77	NW	1238
May 19, 2011	Chittagong MMO	15.43	NW	0100
	Chittagong PBO	12.35	NW	0530–0600
	Alipore	13.61	NW	1000
May 21, 2011	Malda	15.27	NW	0915
	Dhaka MMO	20.58	WNW	1209
	Dhaka PBO	18.52	W	1215
	Alipore	17.77	NW	1220
	Faridpur	15.43	NW	1230
	Patuakhali	16.46	NW	1400
	Chittagong MMO	22.12	N	1500–1530
May 23, 2011	Alipore	15.27	WSW	0051
	Bogra	12.35	NW	0130–0200
	Agartala	19.03	NW	0521

May 11, 2011 Squalls and gusty events were reported at many stations over Bangladesh and neighborhood region at 0300 to 1300 UTC over Rajshahi, Alipore, Dum Dum, Dhaka, Chittagong Main Meteorological Organization (MMO) and Pilot Balloon Observatory (PBO) stations (Fig. 2a–c).

Monitoring of the squall and gusty events is done by using half-hourly Kalpana-1 imageries. Moderate convection was seen over Belagunj of Bihar, India (cloud top temperature, CTT < -30 °C) at 2130 UTC of May 10, 2011, which moving southeastwards. It expanded into Bangladesh at 0300 UTC of May 11, 2011, and squall event was reported over Rajshahi (CTT < -30 °C). Due to this system, squall and gusty events were reported over Alipore, Dum Dum, Dhaka, and Chittagong regions from 0430 to 0945 UTC of May 11, 2011. Another system developed over Baroa of Jharkhand, India (CTT $= -30$ °C) at 1000 UTC of May 11, 2011, and moved southeastwards. For the second system, another squall and gusty events were reported over Alipore and Dum Dum (CTT $= -40$ °C) at 1235 and 1238 UTC. First system dissipated from land at 1500 UTC, and second system dissipated from land area after 2000 UTC of May 11, 2011.

This squall event accompanied by light-to-moderate-to-rather heavy rain (24 h accumulated) as recorded was at Rajshahi (7.20 mm), Alipore (12.60 mm), Dum Dum (42.40 mm), Dhaka (24.60 mm), and Chittagong (19.80 mm).

May 19, 2011 Squalls and gusty events were reported at many stations over Bangladesh and neighborhood region at 0100 to 1000 UTC over Chittagong MMO and PBO, and Alipore stations (Fig. 2d–f).

Convection started over the region of Bigara Bag, Uttarakhand, India, and western part of Nepal (CTT $= -30$ °C) at 0600 UTC of May 18, 2011, which continuously moved southeastwards. Another system developed over the area of Dhangara, Jharkhand, India (CTT $= -30$ °C) at 0900 UTC of May 18, 2011. Both the systems merged near Sushunia, West Bengal, India (CTT $= -70$ °C) at 1800 UTC of May 18, 2011, and moved eastwards. Due to this system, squall reported over the region of Chittagong MMO and Chittagong PBO at 0100 and 0530 UTC of May 19, 2011, respectively. Another convection generated over the region of Yarke, Uttar Pradesh (CTT $= -30$ °C) at 0030 UTC of May 19, 2011, and moved south southeasterly. The system merged with some small local convective systems near Banasandi, Jharkhand, India (CTT $= -30$ °C). Due to this system and partly of previous system, a squall reported over Alipore at 1000 UTC of May 19, 2011. The convection persisted over southwestern parts of Bangladesh on May 20, 2011, up to 0100 UTC.

These squall events accompanied by light rains (24 h accumulated) as recorded were 7.40 mm over Chittagong and 7.30 mm over Alipore.

May 21, 2011 Squalls and gusty events were reported at many stations over Bangladesh and neighborhood region at 0900 to 1530 UTC over Malda, Dhaka MMO and PBO, Alipore, Faridpur, Patuakhali, and Chittagong MMO stations (Fig. 2g–i).

In this day, three different systems were developed at three places of India. First system developed over Chhapia Sukhrampur, Uttar Pradesh, India (CTT $= -40$ °C) at 0300 UTC of May 21, 2011, and moved southeastwards. Malda, Dhaka MMO and PBO, Alipore, and Faridpur stations reported squall between 0900 and 1230 UTC of May 21, 2011, due to this system. Second system developed over the region of Mymensingh and Tangail of Bangladesh (CTT $= -30$ °C) at 0730 UTC of same day moved eastwards. The third system developed over the area of Kurara Rural, Uttar Pradesh, India, at 1030 UTC of same day and moved southeasterly. All three systems merged and organized a big squall system at 1300 UTC. After merging of all three systems, Patuakhali and Chittagong MMO reported squalls between 1400 and 1530 UTC. Moderate convection persisted over the area of Chittagong on next day (May 22, 2011) up to 2100 UTC.
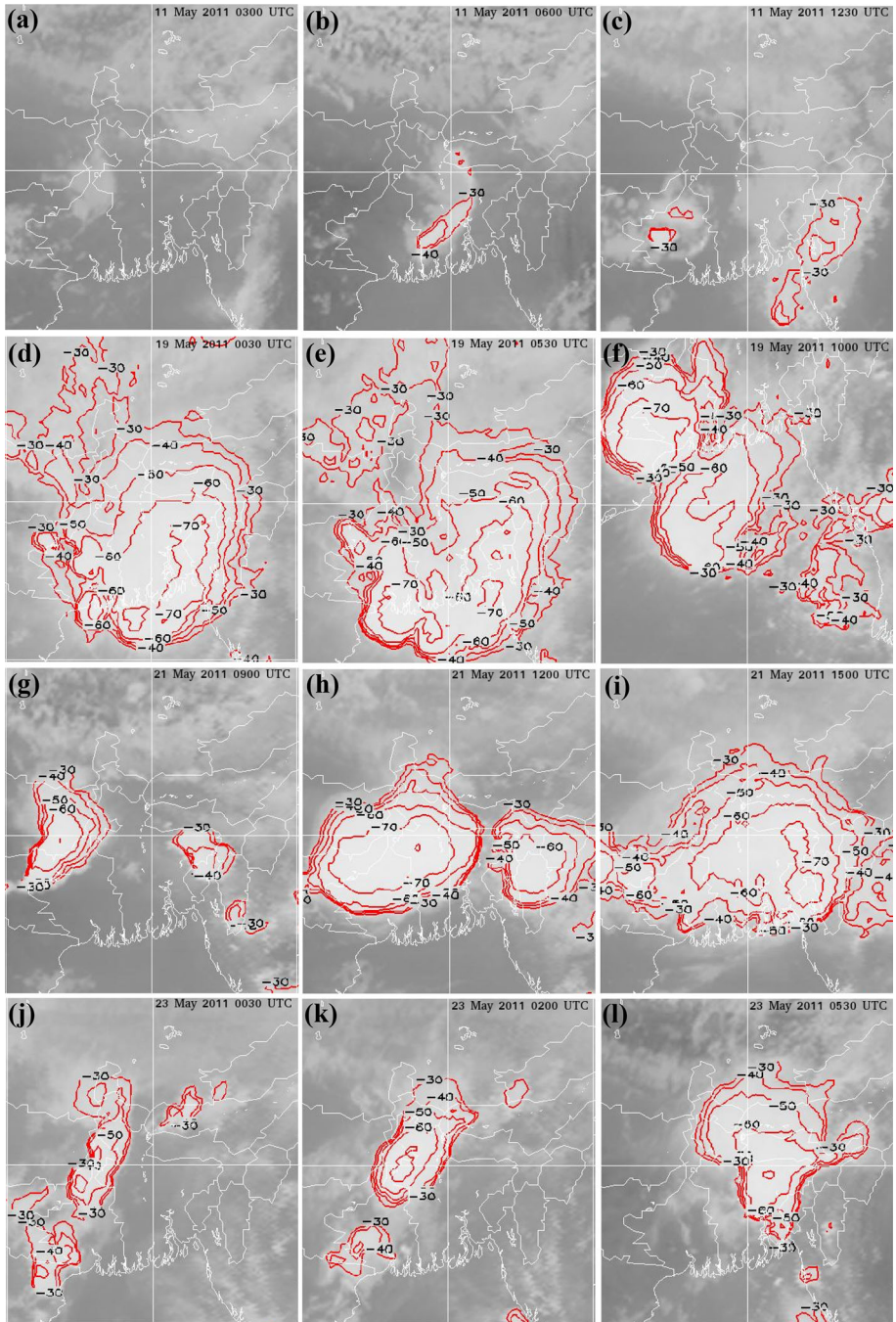
Fig. 2 Kalpana-1 satellite derived cloud top temperature (CTT) (°C) imageries on May 11, 2011 (**a–c**), May 19, 2011 (**d–f**), May 21, 2011 (**g–i**), and May 23, 2011 (**j–l**)

This squall event was accompanied by light-to-moderate-to-heavy rain (24 h accumulated) as recorded at Malda (11.20 mm), Dhaka (23.80 mm), Alipore (2.20 mm), Faridpur (13.60 mm), Patuakhali (5.60 mm), and Chittagong (64.60 mm).

May 23, 2011 Squalls and gusty events were reported at many stations over Bangladesh and neighborhood region at 0030 to 0530 UTC over Alipore, Bogra, and Agartala stations (Fig. 2j–l).

On May 22, 2011, at 1330 UTC, moderate convection started over the region of Gausganj, Uttar Pradesh, India (CTT = −50 °C), which moved eastwards. Another system of May 22, 2011, at 1930 UTC over Tikra, Jharkhand, India (CTT = −40 °C) moved northeastwards. Both systems are merged at 0000 UTC of May 23, 2011 and moved northeastwards. Alipore station reported squalls at 0051 UTC of May 23, 2011. Moderate-to-strong convection persisted over Bogra, Bangladesh (CTT = −70 °C) and reported squall at 0130 UTC of May 23, 2011. Agartala station reported squall at 0521 UTC of May 23, 2011, where moderate convection (CTT = −60 °C) was persisted.

Very light-to-moderate-to-rather heavy rain (24 h accumulated) occurred at a few places with 0.4 mm rainfall over Alipore, 29.00 mm over Bogra, and 59.00 mm over Agartala.

The common synoptic features of the squall events are given below:

i.   Trough of low persisted over the North Bay of Bengal.
ii.   There were strong southerly and southwesterly wind flows in the lower levels over the region of squall events.
iii. The upper air cyclonic circulation was over north Chhattisgarh, Assam, and nearby regions in lower levels.
iv.   A north–south-oriented trough persisted from Sub-Himalayan West Bengal (SHWB) to the North Bay of Bengal in the middle of troposphere.

4 Numerical model setup and data used

The WRF model is run at 4 km resolution with 28 vertical levels by using 6-hourly NCEP-FNL Data as initial and boundary conditions. Every 20 min, model output is taken for analyzing the events. Global Telecommunication System (GTS) and non-GTS data (automatic weather station—AWS), radial wind, and reflectivity data derived from DWR of BMD at Khepupara and Cox's Bazar are utilized in the experiments. YSU PBL scheme and WSM6 microphysics scheme (Hong and Lim 2006) have been used for simulation by the model. The main features of the WRF ARW model employed for this study are summarized in Table 2. The model has been integrated for 24 h for each episode; the starting time of integration is 0000 UTC of same day.

5 BMD DWR reflectivity and radial wind analysis

BMD has three DWRs at Cox's Bazar (21°27′0″N, 91°58′0″E), Khepupara (21°59′0″N, 90°14′0″E), and Moulvibazar (24°29′8″N, 91°46′30″E). These DWRs are S-Band, 10 centimeter radar, and beam width of 1.7° manufactured by Mitsubishi Company of Japan. Japan Meteorological Agency (JMA) and Meteorological Research Institute (MRI)'s draft 1.12.1 package is used to convert the BMD's DWR raw (binary) data into ASCII format (radial distance, r; angle, θ; elevation, α; reflectivity, Ze; and radial velocity, Ve). Due to

Table 2 WRF ARW model configurations

Model feature	Configurations
Horizontal spatial resolution	4 km
Grid points	171×171
Vertical levels	28
Topography	USGS
Dynamics	
Time integration	Semi-implicit
Time steps	20 s
Vertical differencing	Arakawa's Energy Conserving Scheme
Horizontal diffusion	Second order over quasi-pressure, surface, scale selective
Physics	
Cumulus	No cumulus
PBL	Yonsei University scheme
Surface layer	Monin–Obukhov (Janjic Eta) scheme
Cloud microphysics	WRF Single–moment 6–class Scheme
Radiation	RRTM (LW), Dudhia (SW)
Land surface process	Unified Noah Land Surface Model

curvature of the earth, height correction is made (Doviak and Zrnic 1993). BMD DWR raw data converted into ASCII file is then written into another file into radial distance and angle (r and θ) by using a FORTRAN 90 program. This r–θ file is converted into x distance and y distance file by using Perl script. From this file, another file is created as WMO FM-128 format file for assimilation by using Perl script and FORTRAN program. A few lines of this file are provided in Table 3. Since DWR data are very high resolution in the order of 10 m. To match with the model resolution, thinning of DWR data is done during data assimilation. Among the four of the three cases, 21,600 super observations of DWR data have been ingested where length of the squalls was found between 200 and 400 km. In the case of May 23, 2011, the number of super observations is 1,600. The number of super observation is less because of the event is strong but length was about 40–50 km.

DWR reflectivity correlated with rainfall and radial wind is correlated with horizontal wind. DWR Kolkata recorded the vertical extent of the system of about 16 km and the radar reflectivity of 45 dBZ. BMD DWR recorded reflectivity of 50 dBZ. Bow-type echoes of reflectivity are seen at 0503 UTC of May 11, 2011, at 0059 UTC of May 19, 2011, and at 1203 UTC of May 21, 2011 (Fig. 3a–c). In Fig. 3d, bow-type echo is not seen but comma-shaped echo is seen on May 23, 2011, at 0217 UTC. These are the indications of squall lines and severe thunderstorms.

Radial velocity between -40 and 50 m s^{-1} is seen during those times (Fig. 4a–d). Study of radar data showed that the squalls propagate in the form of parallel bow-shaped squall lines having horizontal length of more than 50–350 km at the time of the occurrence.

6 Results and discussion

The WRF model was run for 24 h to simulate the storms close to the time of their observations. The impact of modified initial conditions, when DWR data are assimilated to simulate squalls over Bangladesh region, is examined. We have investigated many

Table 3 WMO FM-128 format file of DWR Khepupara, Bangladesh

TOTAL RADAR = 1

RADAR BMD 21.980 90.230 38.0 2011-05-11-05:03:02 21660 100

FM-128 BMD 2011-05-11-05:03:02 22.161 90.230 38.0 1

    602.0 −888888.000 −88 1.000 −3.000 0 1.000

FM-128 BMD 2011-05-11-05:03:02 22.167 90.230 38.0 1

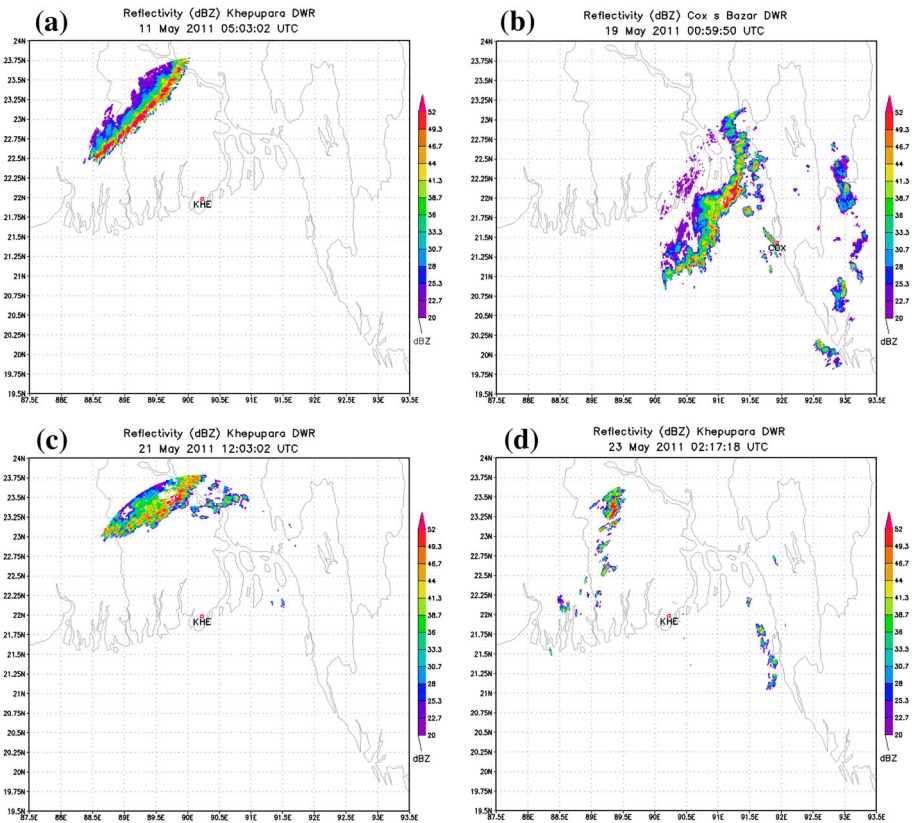   620.3 −888888.000 −88 1.000 −1.500 0 1.000

FM-128 BMD 2011-05-11-05:03:02 22.172 90.230 38.0 1

    638.6 −888888.000 −88 1.000 2.000 0 1.000

FM-128 BMD 2011-05-11-05:03:02 22.178 90.230 38.0 1

    657.0 −888888.000 −88 1.000 −0.500 0 1.000

FM-128 BMD 2011-05-11-05:03:02 22.184 90.230 38.0 1

    675.4 −888888.000 −88 1.000 −1.000 0 1.000

Fig. 3 DWR-derived reflectivity (dBZ) on **a** May 11, 2011 at 0503 UTC, **b** May 19, 2011 at 0059 UTC, **c** May 21, 2011 at 1203 UTC, and **d** May 23, 2011 at 0217 UTC
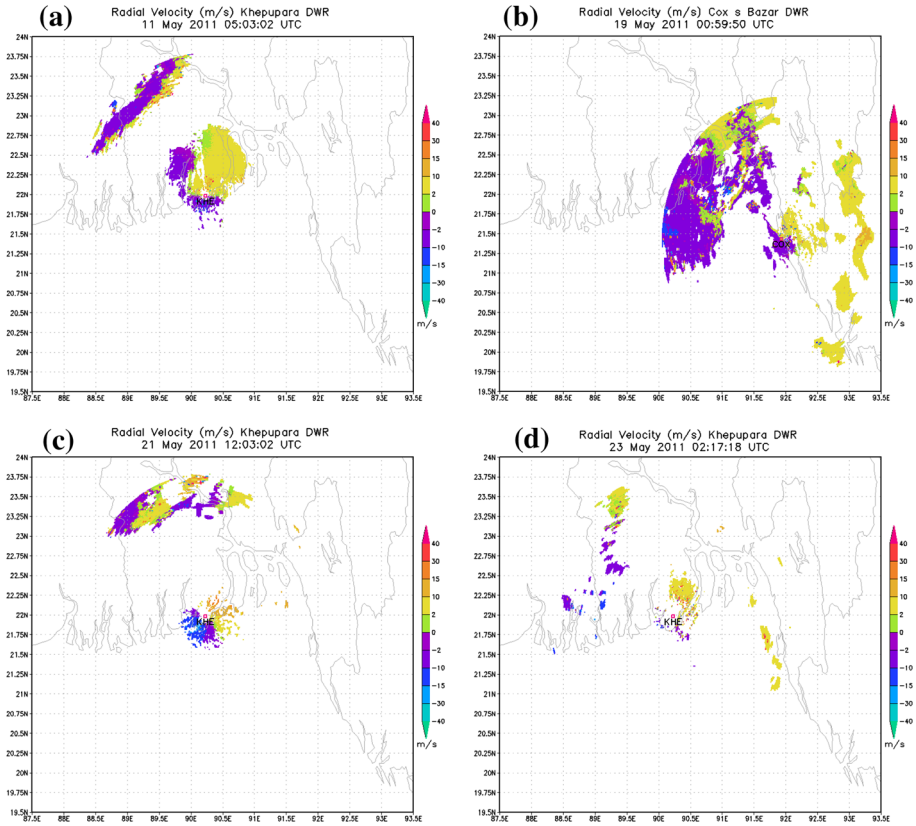
Fig. 4 DWR-derived radial wind (m s^{-1}) on **a** May 11, 2011 at 0503 UTC, **b** May 19, 2011 at 0059 UTC, **c** May 21, 2011 at 1203 UTC, and **d** May 23, 2011 at 0217 UTC

simulated characteristics of the four squall events such as thermodynamic indices from T–Φ gram, surface wind speed, flow patterns, rainfall, vorticity, and time–pressure cross section of cloud hydrometeors. Meteorological fields during the squall events are compared with available observations.

6.1 Impact on the model initial conditions

The assimilation of DWR data through 3DVAR modified the initial conditions. Figure 5a, b indicates the initial conditions of sea-level pressure (SLP) of CTRL and 3DVAR runs, which clearly demonstrate pressure changes at the location of northwest of Bangladesh. In the CTRL run (Fig. 5a), a trough persisted over the region of northwest Bangladesh. After data assimilation, a close contour is found over the region which demonstrated the event and the initial field is clearly modified (Fig. 5b). The assimilated data show proper occurrence of the event as the triggering is present with strong pressure gradient and the mixing of cold, dry, and warm moist air in the northeastern part of Bangladesh (Fig. 5b).

Table 4 shows improvement of initial conditions after data assimilation in the thermodynamic indices. The indices are compared with the available observations of Dhaka station radiosonde at 0000 UTC. The 3DVAR runs simulated slightly larger values of
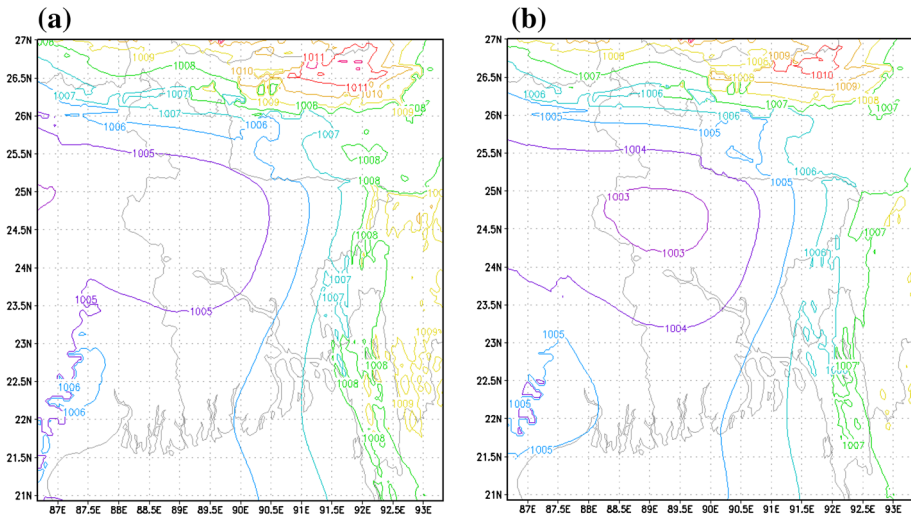
Fig. 5 Sea-level pressure (hPa) at 0000 UTC of May 19, 2011 **a** CTRL and **b** 3DVAR

Table 4 Comparison of observed and WRF ARW model-simulated (CTRL and 3DVAR) stability indices over Dhaka at 0000 UTC

Stability indices	Observation/ experiments	May 11, 2011	May 19, 2011	May 21, 2011	May 23, 2011
CAPE	Obs.	688.01	10.65	1837.68	1475.31
	CTRL	1088.00	70.00	839.00	1421.00
	3DVAR	1098.00	95.00	799.00	1535.00
Lifted Index (LI)	Obs.	−5.53	−0.34	−5.74	−3.75
	CTRL	−7.20	−0.50	−5.40	−3.50
	3DVAR	−7.20	−0.70	−4.90	−3.70
K Index (KI)	Obs.	44.00	42.70	43.40	34.40
	CTRL	36.00	33.00	40.00	35.00
	3DVAR	36.00	34.00	39.00	35.00
Total Totals Index (TTI)	Obs.	57.70	47.80	48.90	42.00
	CTRL	53.00	43.00	50.00	44.00
	3DVAR	52.00	44.00	49.00	44.00

CAPE compared to the CTRL runs in the May 11, 19, and 23, 2011. Lifted Index (LI) values around −3.50 to −7.20 at 0000 UTC indicate an unstable environment except May 19, 2011. K Index (KI) around 33.00 to 44.00 at 0000 UTC indicate unstable atmosphere for all the four events. Total Totals Index (TTI) around 42.00 to 57.70 also showed instability in the atmosphere.

6.2 $T–\Phi$ gram analysis

The $T–\Phi$ grams of all the four events showed instability in the atmosphere. Thermodynamic indices (LI, KI, and TTI) of all the events are examined at the station of where squall

reported. In all the four cases, the values are near the critical values which are studied by Tyagi et al. ([2011](#), [2013](#)) and Prasad et al. ([2014](#)).

All the four available RS observations (Agartala, Dhaka, Guwahati, and Kolkata) at 0000 UTC of May 19, 2011, show very low CAPE value (108.90, 10.65, 703.60, and 276.10 J kg^{-1}, respectively). That means the atmosphere was stable in the morning. Instability developed after 0300 UTC. But there was no RS observation at that time. Satellite, radar, and ground observations showed the instability in the atmosphere.

Model could simulate all the four events. CTRL and 3DVAR-simulated output times were selected by analyzing the best result near the time of occurrence. The model showed development of squall lines at 0540 UTC of May 11, 2011, at Dhaka, 0300 UTC of May 19, 2011, at Chittagong, 1120 UTC of May 21, 2011, at Dhaka, and 0200 UTC of May 23, 2011, at Bogra. 20 to 120 min time difference is found after diagnosing several parameters of those events.

Stability indices simulated by model show significant improvement after 3DVAR data assimilation (Table [5](#)). CAPE, LI, KI, and TTI are analyzed and presented in a tabular form for all the events. In the study of the event of May 19, the CAPE value showed 1110 J kg^{-1} at 0300 UTC at Chittagong in CTRL run but 3DVAR showed significant improvement and the value is 2847 J kg^{-1}. Highest LI values simulated after DWR data assimilation in the event May 11, 2011, at 0540 UTC (LI value −11). KI values significantly improve in the event May 21, 2011, at 1120 UTC after data assimilation (KI value 41). The study showed that the assimilation of DWR data has a notable positive impact on thermodynamic indices.

6.3 850 hPa wind vector and 10 m wind speed analysis

The CTRL and 3DVAR runs have simulated higher 10 m wind speed along the coastal belt of West Bengal. There are a strong trough at 850 hPa simulated by the 3DVAR in all the cases; this is absent in the CTRL runs (Fig. [6](#)a–d). The 850 hPa horizontal wind shows a trough and high wind velocity over the squall and gusty location. The phenomena are stronger in the 3DVAR runs (Dasgupta et al. [2005](#)) (Fig. [6](#)e–h). The 3DVAR run of May 19, 2011, showed a prominent cyclonic circulation closer to Dhaka and Chittagong region which are very feeble at CTRL run. In the study of May 21, 2011, 3DVAR run showed significant feature of southwesterly wind flow near Dhaka and east part of Bangladesh, which are chaotic in the CTRL run. Similar improvements are observed on May 11, 2011, at Dhaka and May 23, 2011, at Bogra station after DWR data assimilation.

It is examined that in the 3DVAR runs the wind speed at 10 m improved all the events. On May 11, 2011, wind speed increases at Dhaka and nearby area compared to CTRL run. Similarly on May 19, 2011, the 3DVAR run showed improvement near Chittagong area at 0300 UTC. It is seen that the 3DVAR run has simulated 10 m wind speed of about 14–15 m s^{-1} in small patches in the Dhaka station on May 21, 2011 (Fig. [6](#)g), whereas the CTRL run has produced 10 m wind speed 7–8 m s^{-1} at Dhaka (Fig. [6](#)c). On May 23, 2011, the simulated wind speed area expanded near Bogra area at 0200 UTC. The time and location are improved after 3DVAR study.

6.4 Time evolution of surface wind speed, wind direction, SLP, and relative humidity

Figures [7](#), [8](#), [9](#), and [10](#) show the time evolution of surface wind speed, wind direction, SLP, and relative humidity at the squall-reported stations for all the four events. The observed and 3DVAR values show fairly good correspondences in analysis of wind speed at 10 m,

Table 5 Comparison of CTRL and 3DVAR-simulated stability indices at the location where squalls were reported

Stability indices	Event date, time (UTC) and station	Experiments	Value
CAPE	May 11, 2011, 0540, Dhaka	CTRL	2,670
		3DVAR	2,703
	May 19, 2011, 0300, Chittagong	CTRL	1,110
		3DVAR	2,847
	May 21, 2011, 1120, Dhaka	CTRL	1,361
		3DVAR	830
	May 23, 2011, 0200, Bogra	CTRL	1,791
		3DVAR	1,865
Lifted Index (LI)	May 11, 2011, 0540, Dhaka	CTRL	−10
		3DVAR	−11
	May 19, 2011, 0300, Chittagong	CTRL	−4
		3DVAR	−6
	May 21, 2011, 1120, Dhaka	CTRL	−5
		3DVAR	−2
	May 23, 2011, 0200, Bogra	CTRL	−5
		3DVAR	−6
K Index (KI)	May 11, 2011, 0540, Dhaka	CTRL	33
		3DVAR	33
	May 19, 2011, 0300, Chittagong	CTRL	35
		3DVAR	28
	May 21, 2011, 1120, Dhaka	CTRL	37
		3DVAR	41
	May 23, 2011, 0200, Bogra	CTRL	38
		3DVAR	39
Total Totals Index (TTI)	May 11, 2011, 0540, Dhaka	CTRL	53
		3DVAR	53
	May 19, 2011, 0300, Chittagong	CTRL	44
		3DVAR	45
	May 21, 2011, 1120, Dhaka	CTRL	49
		3DVAR	44
	May 23, 2011, 0200, Bogra	CTRL	44
		3DVAR	45

wind direction, SLP, and relative humidity. The root-mean-square errors (RMSE) values are calculated based on BMD stations 3-hourly synoptic (0300, 0600, 0900, 1200, 1500, 1800, 2100, and 0000 UTC) observations (i.e., wind speed, wind direction, SLP, relative humidity, and rainfall). The model-simulated values are interpolated at the stations for calculating the RMSE.

The wind speeds are overestimated by 0.246 to 16.360 m s^{-1} in the CTRL simulations and 0.020 to 10.590 m s^{-1} in the 3DVAR runs for the three events of May 11, 21, and 23, 2011, in all the synoptic hours (Figs. 7a, 9a, 10a). But for the event of May 19, 2011, the results at 0300 and 0900 UTC showed underestimation of wind speed by 0.240 and
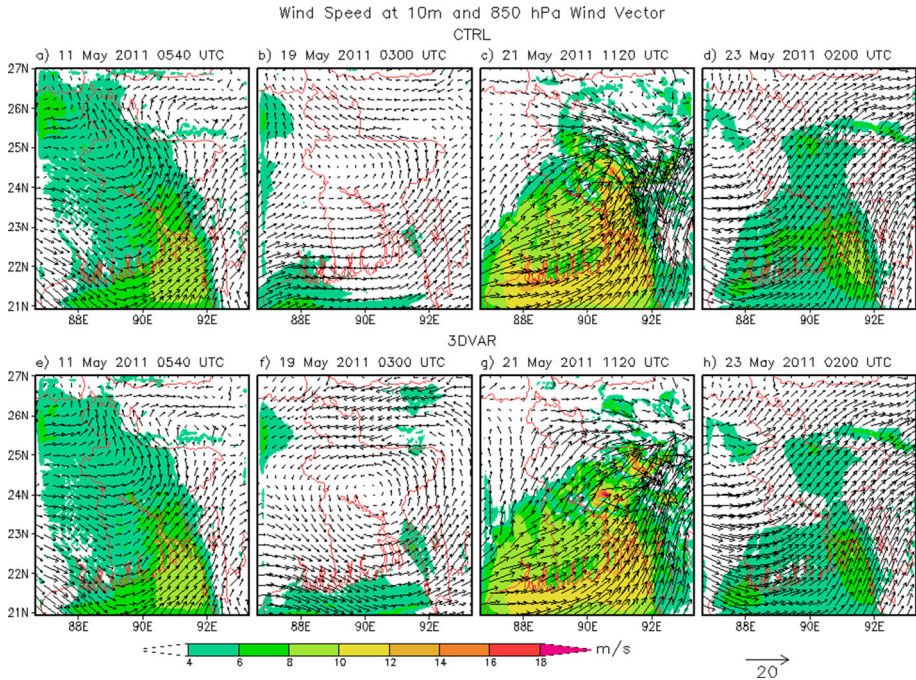
Fig. 6 Forecasted vector wind at 850 hPa and wind speed (m s^{-1}) at 10 m height (*shaded*) on the days of the squalls. CTRL (**a–d**) and 3DVAR (**e–h**) runs

1.990 m s^{-1}, respectively, in the CTRL simulation. 3DVAR run underestimated wind speed by 0.436 and 0.678 m s^{-1} at 0000 and 0900 UTC, respectively (Fig. 8a). Mixed trends between observed and simulated (CTRL and 3DVAR) values (overestimation/underestimation) are seen at surface. The 3DVAR runs showed some improvements compared to CTRL runs. On May 19, 2011, the RMSE of wind speed in 3DVAR and CTRL runs are 1.295 and 3.972, respectively. Improvements are also seen in the other events (Table 6).

In terms of time and location, wind directions are better simulated in 3DVAR runs than CTRL runs (Figs. 7b, 8b, 9b, 10b). The best improvement is observed in May 21, 2011 3DVAR run, and RMSE is 23.254, whereas the CTRL run RMSE is 138.230 (Table 6).

Strong surface heating due to solar insolation causes the formation of heat low at the surface. SLP seems to be less than 998 hPa (Fig. 9c) over Dhaka due to existence of heat low during the pre-monsoon season (Dalal et al. 2012). The 3DVAR shows pressure drop and increasing tendency due to convection which is helpful for forecasting. The SLPs obtained from CTRL and 3DVAR do not always follow the observed values but for some time 3DVAR is close to observed (Figs. 7c, 8c, 9c, 10c). Remarkable improvements are seen on May 19 and 23, 2011 3DVAR runs. The RMSE values are generally reduced by 37.709 to 59.600 % for SLP, wind speed, and wind direction (Table 6).

The relative humidity (Figs. 7d, 8d, 9d, 10d) simulated in both experiments is comparatively 8.85–22.15 % lower than that of the observations during the occurrence of squall hours except in 3DVAR simulation of May 21, 2011, when the relative humidity is 9.13 % above the observed value (Table 7). The pattern of diurnal variation of relative
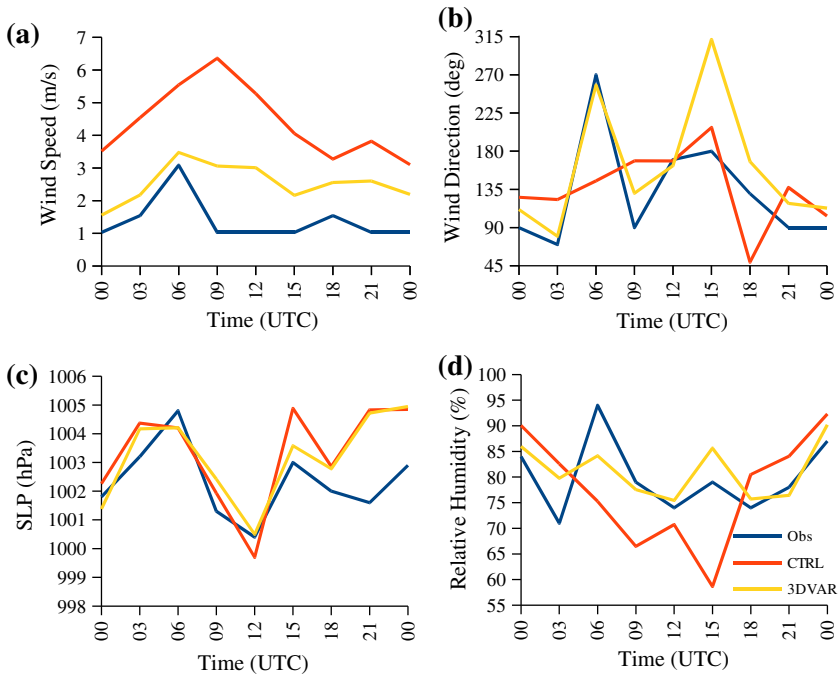
Fig. 7 Observed and model-simulated diurnal variation of **a** wind speed (m s⁻¹), **b** wind direction (°), **c** sea-level pressure (hPa), and **d** relative humidity (%) on May 11, 2011, at Dhaka
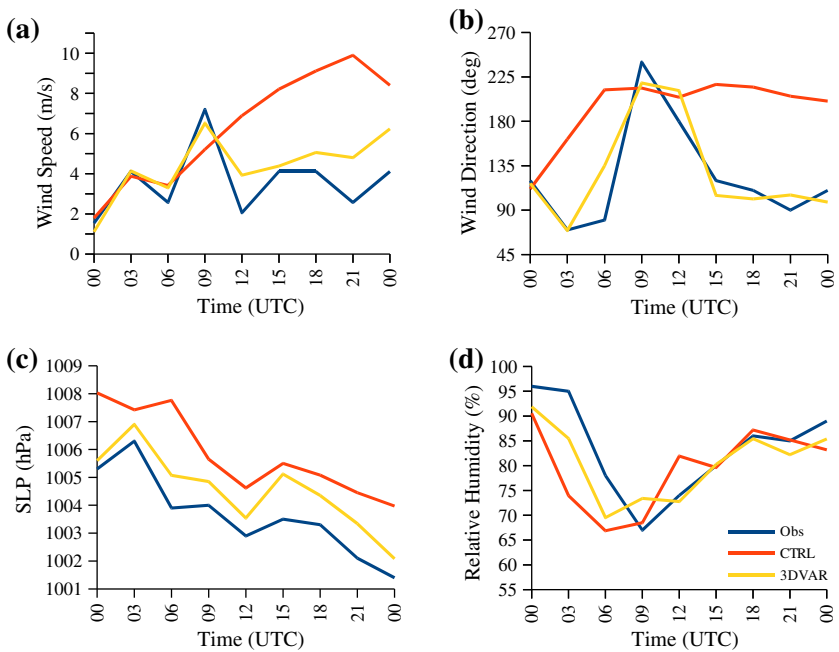

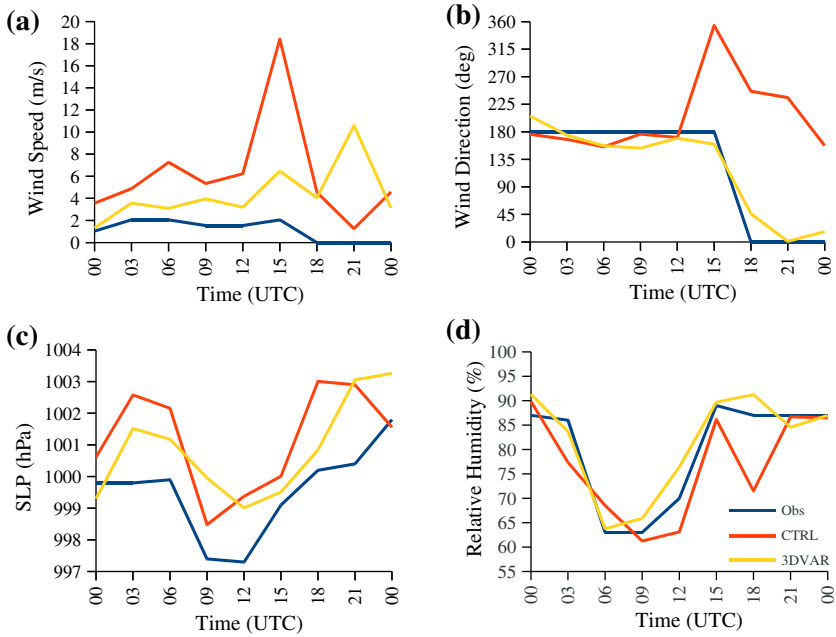**Fig. 8** Same as Fig. 7 but for May 19, 2011, at Chittagong

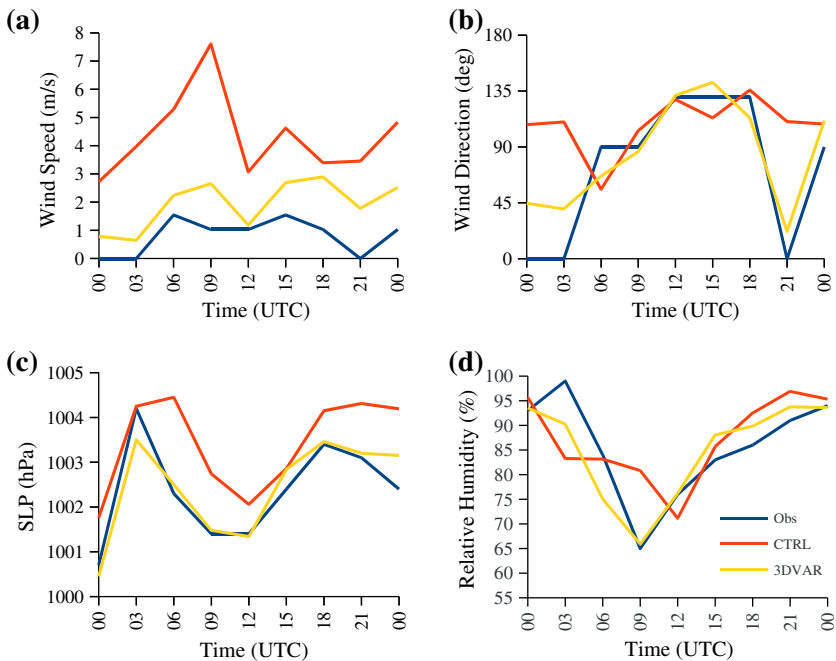**Fig. 9** Same as Fig. 7 but for May 21, 2011, at Dhaka

Fig. 10 Same as Fig. 7 but for May 23, 2011, at Bogra

Table 6 Root-mean-square errors (RMSE) and % reduction for wind speed, wind direction, SLP, relative humidity, and rainfall for the squall events

Parameters	Experiments and % reduction	May 11, 2011 and Dhaka	May 19, 2011 and Chittagong	May 21, 2011 and Dhaka	May 23, 2011 and Bogra	Average reduction %
Wind speed	CTRL	3.196	3.972	6.571	3.743	
	3DVAR	1.292	1.295	4.345	1.262	
	% Reduction	59.574	67.396	33.876	66.283	56.782
Wind dir.	CTRL	62.895	87.667	138.230	64.925	
	3DVAR	49.950	23.881	23.254	24.749	
	% Reduction	20.582	72.759	83.177	61.881	59.600
SLP	CTRL	1.539	2.323	1.944	1.221	
	3DVAR	1.398	0.981	1.636	0.390	
	% Reduction	9.162	57.770	15.843	68.059	37.709
Rel. humidity	CTRL	11.596	8.800	6.769	8.270	
	3DVAR	5.179	5.200	3.304	4.783	
	% Reduction	55.338	40.909	51.189	42.164	47.400
Rainfall	CTRL	15.144	7.214	13.208	23.941	
	3DVAR	8.029	3.109	7.076	3.158	
	% Reduction	46.982	56.903	46.426	86.809	59.280

Table 7 Percentage of change between observed and simulated values of relative humidity

Date, time (UTC) and station	Obs.	CTRL	3DVAR	% of change in case of CTRL run	% of change in case of 3DVAR run
May 11, 2011, 0600 and Dhaka	94.00	75.26	84.15	−19.94	−10.48
May 19, 2011, 0300 and Chittagong	95.00	73.95	85.47	−22.15	−10.03
May 21, 2011, 1200 and Dhaka	70.00	63.12	76.39	−9.83	+9.13
May 23, 2011, 0300 and Bogra	99.00	83.27	90.24	−15.89	−8.85

humidity in the 3DVAR runs is reasonably well matched with the observed pattern compared to CTRL runs. The RMSE value of 3DVAR indicates the best improvement in the event of May 11, 2011 (Table 6).

3DVAR runs show significant improvement of predictions of all the four squall events, i.e., RMSE values of 3DVAR runs are lower than CTRL runs for surface wind speed and direction, SLP, and relative humidity (Table 6).

6.5 Simulated cloud top temperature (CTT) (°C)

CTT derived from mesoscale model output has been used to demonstrate the advanced capabilities of the models for prediction of severe weather (Otkin and Greenwald 2008). In this section, we have examined the ability of DWR data assimilation implemented to realistically simulate the CTT over Bangladesh and neighborhood region.

Moderate-to-strong convection was seen over the area of squall locations on all the four days. The convections were moving southeastwards and expanded over Bangladesh which was observed from Kalpana-1 satellite imagery (CTT = −30 to −70 °C). Model-simulated result showed some spatial shift of CTT. 3DVAR CTT is found to be better matched than CTRL runs (Figs. 11, 12, 13, 14).

Simulation of convection in time and specific location is absent in the CTRL runs. On May 11, 2011, convection showed near Dhaka region at 0540 UTC after data assimilation (Fig. 11b). Similar modifications are seen on May 19, 2011, at 0300 UTC over Chittagong and Kolkata regions (Fig. 12b). Figure 13b shows the significant improvement of CTT
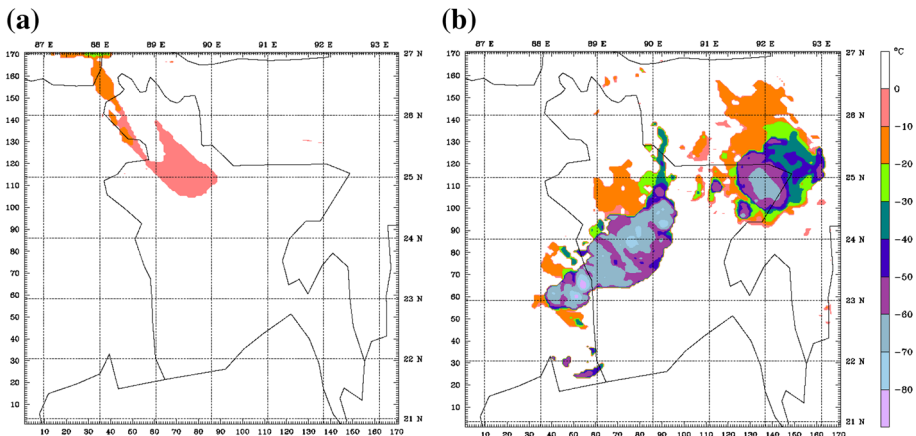

Fig. 11 Cloud top temperature (CTT) (°C) on May 11, 2011, at 0540 UTC **a** CTRL and **b** 3DVAR
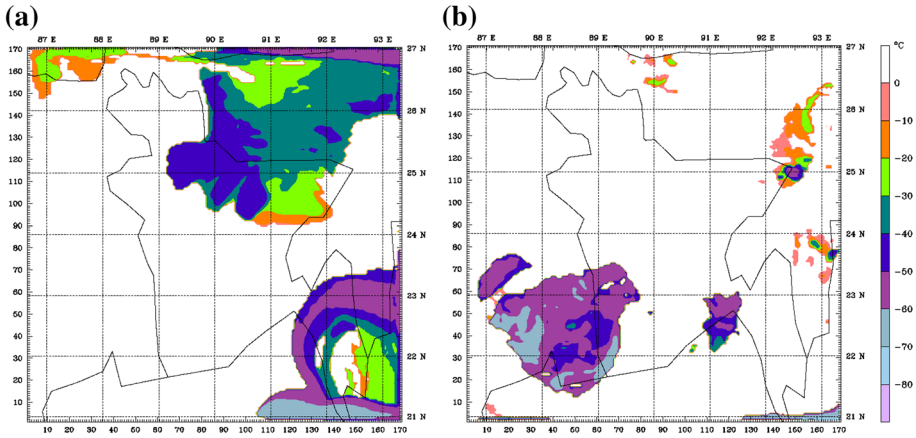
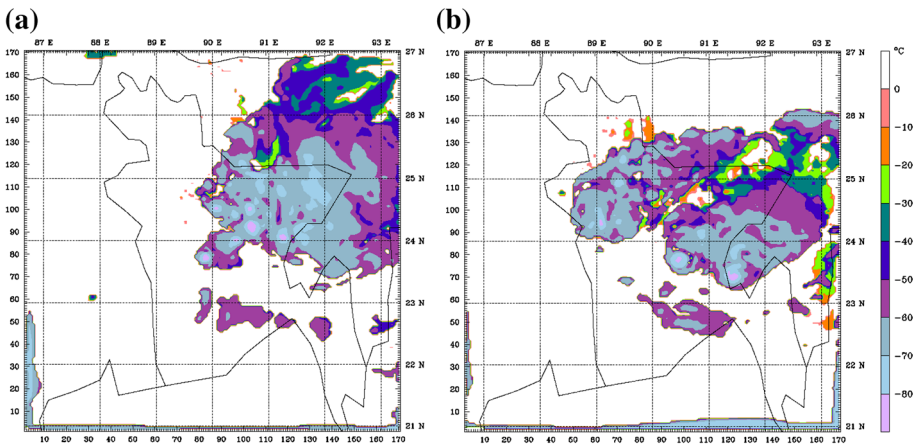**Fig. 12** Same as Fig. 11 but for May 19, 2011, at 0300 UTC **a** CTRL and **b** 3DVAR

Fig. 13 Same as Fig. 11 but for May 21, 2011, at 1120 UTC **a** CTRL and **b** 3DVAR

after 3DVAR run and indicates merging of two cloud cells on May 21, 2011, at 1120 UTC. On May 23, 2011, at 0200 UTC, convection was observed closer to the Bogra station (Fig. 14b).

The model-simulated CTT reached up to −80 °C during this cloud formation and movement in the 3DVAR runs. The convection diagnosed by the CTT appears to be fairly representative of the structure and intensity observed in Kalpana-1 satellite imageries (Fig. 2b, d, h, k).

6.6 Time evolution of rainfall

The observed and simulated precipitation differs from each other both in time and spatial distribution as earlier studies (Das et al. 2009). However, the model did simulate the precipitation on all the days of the squalls. The simulated precipitation also differs in intensity (Table 8) compared to the rain gauge observations of the BMD stations (Fig. 15a–d). The notable feature is the presence of squall line type of echoes in the 3DVAR-simulated

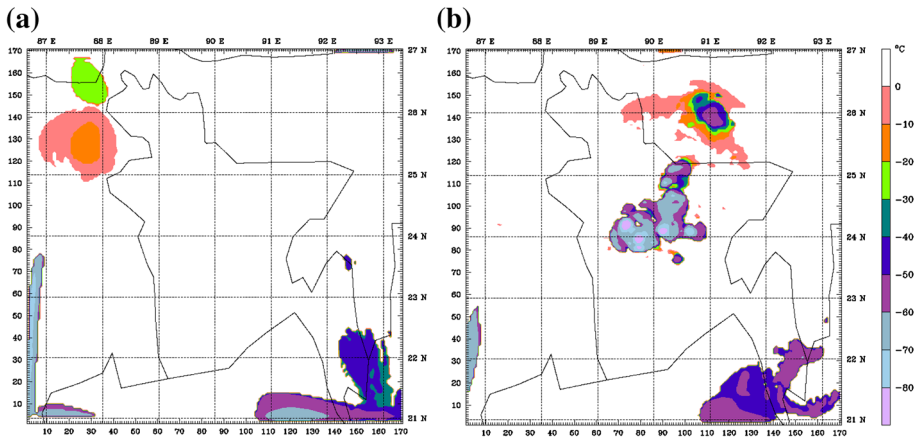**(a)**   **(b)**

Fig. 14 Same as Fig. 11 but for May 23, 2011, at 0200 UTC **a** CTRL and **b** 3DVAR

Table 8 Comparison of 24 h rainfall of observed (rain gauge), CTRL, and 3DVAR

Date	Reported station	24 h rainfall (mm)		
		Obs.	CTRL	3DVAR
May 11, 2011	Rajshahi	7.20	18.00	11.00
	Alipore	12.60	14.00	11.00
	Dum Dum	42.40	30.00	32.00
	Dhaka	24.60	32.00	17.00
	Chittagong	19.80	43.00	36.00
May 19, 2011	Chittagong	7.40	16.00	4.50
	Alipore	7.30	36.00	9.00
May 21, 2011	Malda	11.20	20.00	6.50
	Dhaka	23.80	41.00	30.00
	Alipore	2.20	1.00	2.40
	Faridpur	13.60	67.00	10.00
	Patuakhali	5.60	6.00	1.50
	Chittagong	64.60	87.00	70.00
May 23, 2011	Alipore	0.40	2.00	0.30
	Bogra	29.00	8.00	32.63
	Agartala	59.00	56.85	52.00

precipitation, particularly on May 19 and 23, 2011. The CTRL runs overestimated the intensity of precipitation on an average but 3DVAR runs show improvement in the predication of 3-hourly accumulated rainfall (Fig. 15a–d) as compared to observed rainfall time.

Figure 15a–d comparing the model-simulated rainfall with the observed rainfall indicates that May 11 and 19, 2011 3DVAR runs underestimated 3-hourly accumulated rain where CTRL runs overestimated with 6–9 h temporal shift. The time lag is reduced by about 3–6 h in the 3DVAR runs. For the event May 21, 2011, CTRL and 3DVAR both runs overestimated rainfall amount. For the event May 23, 2011, CTRL run underestimated
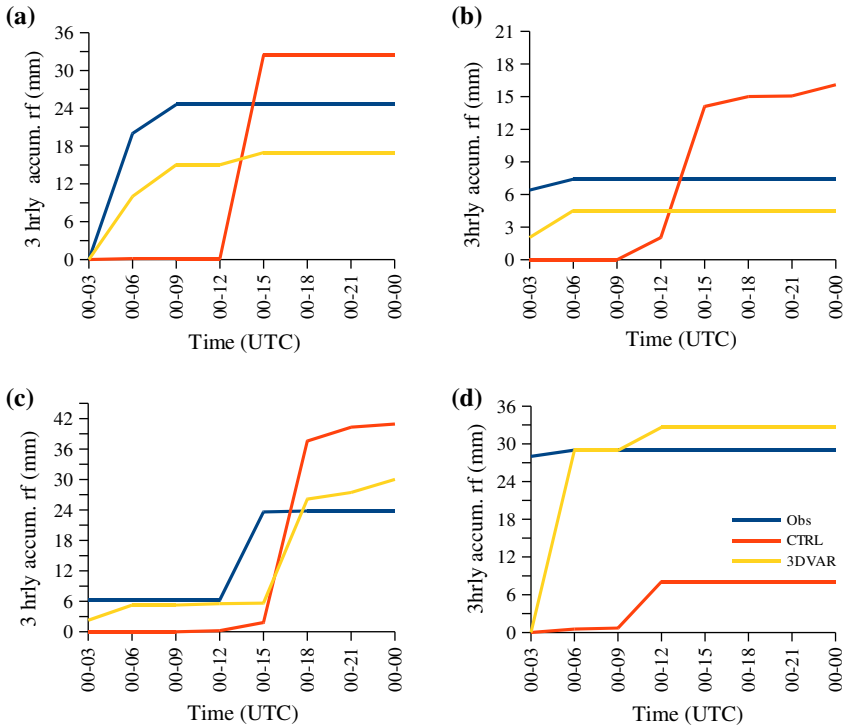
Fig. 15 Observed and model-simulated diurnal variation of 3-hourly accumulated rainfall (mm) on **a** May 11, 2011 at Dhaka, **b** May 19, 2011 at Chittagong, **c** May 21, 2011 at Dhaka and **d** May 23, 2011 at Bogra

21 mm and 3DVAR run overestimated 3.60 mm rainfall amount. The improvement in the 3DVAR run is reduced time lag, and rainfall spells simulated closer to the observations. The RMSE of the rainfall is comparatively less in the 3DVAR runs as compared to CTRL runs (Table 6). Significant improvements are shown on May 23, 2011, 3DVAR run, where RMSE value is 3.158 but in CTRL run the value is 23.941.

6.7 Vorticity at 950 hPa

The low-level relative vorticity field at 950 hPa is depicted in Fig. 16a–h. Positive values are shaded. The vorticity is positive in the lower level over Bangladesh and adjoining head Bay of Bengal. Pockets of positive vorticity of magnitude greater than 5×10^{-5} s^{-1} are seen in most of the cases. The vorticity field is generated due to horizontal shear in the wind field and provides spin in the flow. The strong low-level heating and a cooperative positive vorticity in the wind field act as a triggering mechanism for the initial rise and growth of the thermals (Trapp and Weisman 2003). 3DVAR runs show some improvement near the locations of squall events. The 3DVAR simulations exhibit strong cyclonic vorticity structures, which are not found in the CTRL simulations near the region where squalls reported. The positive vorticities increased near the location of Dhaka on May 11 and 21, 2011 (Fig. 16e, g), at Chittagong region on May 19, 2011 (Fig. 16f), and at Bogra region on May 23, 2011 (Fig. 16h).
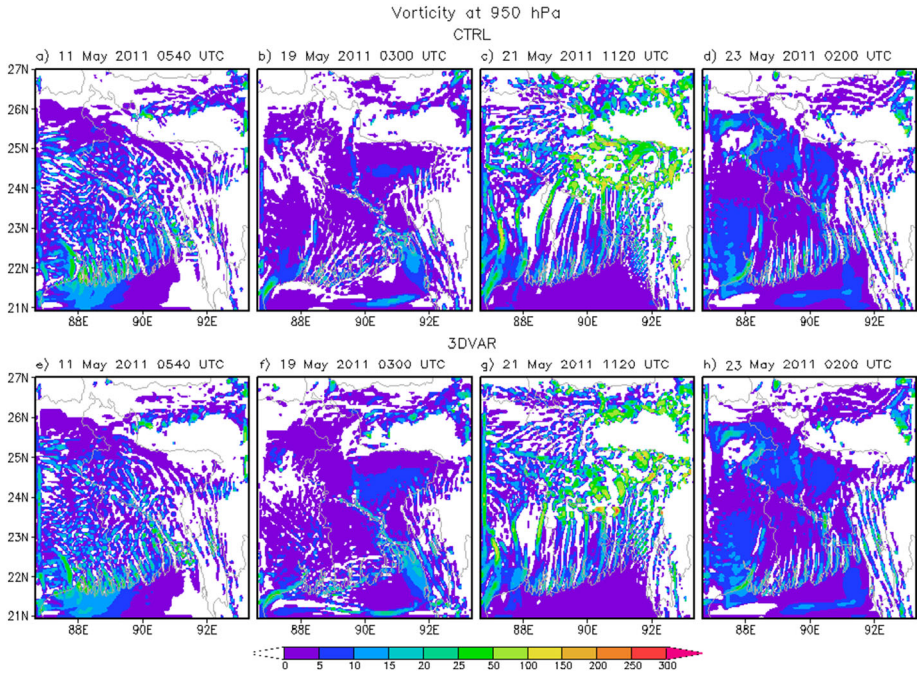
Fig. 16 Relative vorticity ($\times 10^{-5}$ s^{-1}) at 950 hPa simulated by the WRF model on the days of the squalls. **a–d** CTRL and **e–h** 3DVAR runs. Positive values are *shaded*

6.8 Cloud hydrometeor

Hydrometeors play an important role at different stages of convective activities (Mohanty et al. 2012). Therefore, the time evolution of cloud hydrometeor structures over the station where squall reported is analyzed in this section. The vertical profiles of total cloud hydrometeors (Liquid Water + Snow + Ice) obtained by the WRF model on the days of squalls are shown in Fig. 17a–h. The profiles are drawn across the regions where squalls were reported. The time–pressure cross section of hydrometeors such as cloud water mixing ratios obtained from the CTRL and 3DVAR simulations for all the four events are illustrated in Fig. 17a–h. The cloud hydrometeors present below the freezing level (about 4 km) may be interpreted as liquid, while those above the freezing level may be considered to be ice or super-cooled liquid (Das et al. 2009). Maximum concentrations of the hydrometeors are present at around 10–12 km altitude. The maximum amounts of hydrometeors simulated inside the regions are about 1.81 g m^{-3} on the day of May 19, 2011, over Chittagong. The vertical extensions of the cloud water mixing ratios are greater in the 3DVAR simulations (Fig. 17e–h) and are not observed in the CTRL simulations (Fig. 17a–d). It is clearly found that the cloud hydrometeors are relatively stronger in the 3DVAR runs after ingestion of DWR observations. Seven- to nine-hour temporal advancement is seen in Chittagong area on May 19, 2011, in the 3DVAR run (Fig. 17f) compared to CTRL simulation (Fig. 17b).
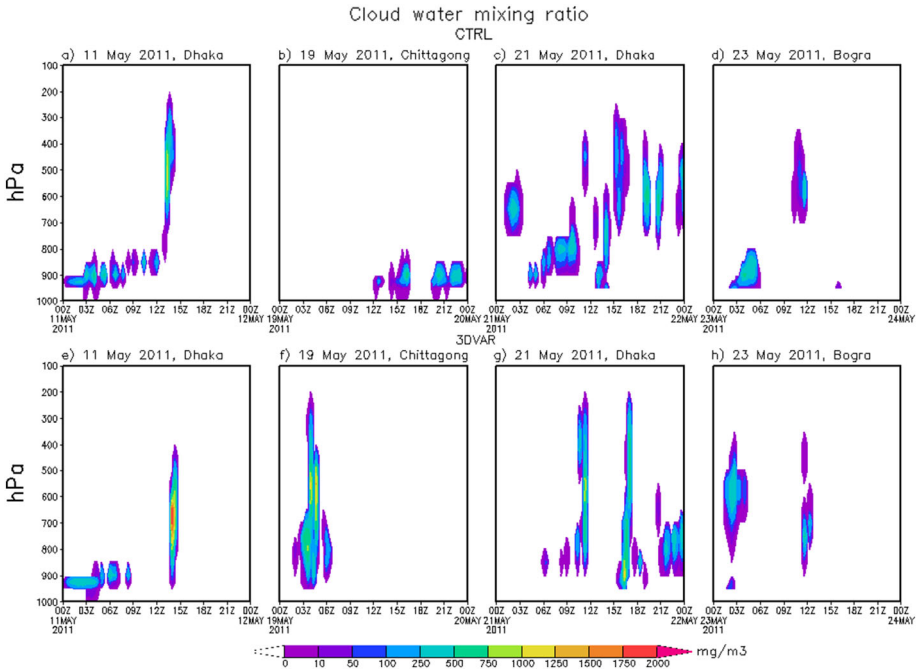
Fig. 17 Time–pressure cross section of cloud water mixing ratio (mg m^{-3}) on the days of the squalls. **a–d** CTRL and **e–h** 3DVAR runs

7 Conclusions

An attempt was made to simulate the 4 days of squalls using mesoscale model WRF ARW and 3DVAR data assimilation system that occurred on May 2011 over Bangladesh and neighborhood region. The model was run with a single domain of 4 km horizontal resolution. For this purpose, eight numerical experiments (CTRL without assimilation, and 3DVAR with assimilation of DWR data) are conducted to evaluate the impact of DWR observations on squall simulations.

From the above results and discussion, the following broad conclusions can be put forward. The impact of data assimilation is clearly visible as the experimental simulations from the WRF–3DVAR runs are able to capture the squalls closer to the observations as compared to the CTRL runs. The study reveals that the 3DVAR runs improved the dynamic and thermodynamic features of the squall events as compared to the CTRL runs. The position and intensity of the simulated squalls in the experimental runs is close to the observed values as compared to the DWR derived products and observations.

The instability indices from $T-\Phi$ gram analysis are well captured by the 3DVAR runs in comparison with that in the CTRL runs. The larger CAPE values in the 3DVAR runs for three events out of four events could be attributed to higher moisture convergence aided by stronger moisture-laden winds in the lower atmosphere. The 3DVAR runs have well represented the different stages of squall evolution as compared to the CTRL runs.

The 3DVAR runs could simulate the bow-type squall lines, which are also observed by the radar. The model estimated the strength of the squall lines in general. The squall events from the model simulations are clearly seen from the spatial distribution of 10 m wind

speed. It is observed that the signature of the squall activity is well represented in the model generated wind speed at 10 m level. The 850 hPa wind fields also reflect the system captured by the 3DVAR runs. The simulated wind speed at surface was more than 14 m s^{-1} on May 21, 2011, at 1120 UTC at Dhaka station in the 3DVAR run which showed distinct improvement compared to CTRL run.

The diurnal variation of surface wind speed and direction, SLP, relative humidity, and rainfall are also well produced in the 3DVAR runs, and the statistical skill scores have significantly advanced. Model-simulated CTT was well captured in terms of time and location. Spatial distribution of vorticity field at 950 hPa and time variation of cloud hydrometeor showed improvement in 3DVAR runs.

Results have provided many interesting findings, but also indicated many weaknesses in our present understanding and capability to forecast the squall storms with sufficient lead time and accuracy. 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 that remain unresolved. There is a severe scarcity of data to understand the observational characteristics of the squalls in this region. Such data will have to be supplemented by intensive field observations. The modeling studies will have to be carried out at much higher resolution (few hundred meters) considering the scale of such storms (Dowell and Wicker 2009; Dowell et al. 2011). Many sensitivity studies with the physical processes need to be carried out to unravel the dynamical and physical mechanisms of the genesis of squalls and intensification of the updraft vortex in this region. In addition to this, further improvement could be obtained with the use of extensive quality-controlled multi-radar radial velocity and reflectivity through advanced data assimilation techniques such as the ensemble Kalman filter (EnKF) and 4DVAR with flow-dependent background error covariance (Zhang et al. 2011; Zhang et al. 2013). Assimilation of satellite and dense network of surface observations in the mesoscale model may improve the accuracy of the forecasts.

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