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Simulation of monsoon depression over India using high resolution WRF Model – Sensitivity to convective parameterization schemes

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सार – सितम्बर 2008 में बने मानसून अवदाब ने माह की 16 तारीख को उड़ीसा के समुद्री तट के निकट चंदाबाली को पार किया एवं इस सिस्टम के मार्ग में आने वाले उड़ीसा, छत्तीसगढ़ और उत्तरी भारत में भारी वर्षा हुई। इस मानसून अवदाब के पूर्वानुमान में मौसम अनुसंधान पूर्वानुमान (डब्ल्यू.आर.एफ.) उच्च विभेदन के अद्यतन वर्जन (3.0) का उपयोग करते हुए तीन क्यूम्यूलस पैरामिटराइजेशन स्कीम तथा – कैन फ्रिच (के.एफ.) स्कीम, ग्रेल डेवेनी (जी.डी.) स्कीम और बेट्स – मिलर जैन्जीक (बी. एम. जे.) स्कीम की संवेदनशीलता / सुग्राहिता का परीक्षण किया गया है।

इस अध्ययन के परिणामों से पता चला है कि इस सिस्टम के बनने की प्रक्रिया इस मॉडल में अच्छी तरह से बताई गई है जैसा कि इन तीनों संवहनीय प्राचलीकरण योजनाओं में 48 घंटों के पूर्वानुमान के लिए दर्शाया गया है। यह देखा गया है कि मानसून अवदाब का मार्ग मॉडल में बताए गए क्यूम्यूलस पैरामिटराइजेशन स्कीम के काफी समीप है और भिन्न– भिन्न प्रकार के तीनों क्यूम्यूलस योजनाओं के उपयोग से मार्ग का पूर्वानुमान देने में सुधार आया है, जब इस मॉडल की शुरूआती अवदाब के आरम्भिक अवस्था की तुलना निम्न दाब क्षेत्र की आरम्भिक अवस्था से की गई। यह भी देखा गया हे कि जब यह सिस्टम धरातल के ऊपर था उस समय सभी योजनाएँ के. एफ. और जी. डी. योजनाओं के साथ सही–सही कार्य कर रही थी और बी. एम. जे. स्कीम में बताए गए मार्ग के काफी निकट से गुजर रही थी। के. एफ. और जी. डी. योजनाओं के कार्य निष्पादन 72 घंटे तक लगभग सदृश रहे इनमें के. एफ. योजना में सिस्टम के धरातल से टकराने के मार्ग की त्रुटि अन्य दो योजनाओं की तुलना में सबसे कम थी जबकि बी. एम. जे. स्कीम में 48 घंटों के औसत पूर्वानुमान की त्रुटि सबसे कम थी और 72 घंटों के औसत पूर्वानुमान की त्रुटि सबसे अधिक थी। कुल मिलाकर मानसून अवदाब पर आधारित वर्षा पूर्वानुमान को भी डब्ल्यू. आर. एफ. मॉडल में के. एफ. स्कीम के साथ शामिल किया गया है क्योंकि के.एफ. योजना के तहत उड़ीसा, छत्तीसगढ़ और पश्चिमी हिमालय क्षेत्र में भारी वर्षा के पूर्वानुमान जी. डी. और बी. एम. जे. योजना के तहत दिए गए पुर्वानुमान से अधिक सही थे।

ABSTRACT. The monsoon depression of September 2008, which crossed Orissa coast near Chandbali on 16th had contributed heavy rainfall over Orissa, Chhattisgarh and northern India along the track of the system. The sensitivity of three cumulus parameterization schemes *viz*., Kain-Fritch (KF) scheme, Grell-Devenyi (GD) scheme and Betts-Miller-Janjic (BMJ) Scheme are tested using high resolution advanced version (3.0) Weather Research Forecasting (WRF) model in forecasting the monsoon depression.

The results of the present study shows that the genesis of the system was almost well captured in the model as indicated in 48hr forecast with all three convective parameterization schemes. It is seen that the track of monsoon depression is quite sensitive to the cumulus parameterization schemes used in the model and is found that the track forecast using three different cumulus schemes are improved when the model was started from the initial condition of a depression stage compared to that when it started from the initial condition of low pressure area. It is also seen that when the system was over land all the schemes performed reasonably well with KF and GD schemes closely followed the observed track compared to that of BMJ track. The performance of KF and GD schemes are almost similar till 72 hrs with lowest landfall error in KF scheme compared to other two schemes, whereas the BMJ scheme gives lowest mean forecast error upto 48 hr and largest mean forecast error at 72 hr. The overall rainfall forecast associated with the monsoon depression is also well captured in WRF model with KF scheme compared to that of GD scheme and BMJ scheme with observed heavy rainfall over Orissa, Chhattisgarh and western Himalayas is well captured in the model with KF scheme compared to that with GD scheme and BMJ scheme.

Key words – Monsoon depression, WRF model, Track forecast, Heavy rainfall, Forecast error.

1. Introduction

Monsoon depression (a low pressure system with maximum sustained surface wind speed between 17 to 33 knots) is one of the most important synoptic scale disturbances on the quasi-stationary planetary scale monsoon trough over the Indian region during the summer monsoon season from June to September (JJAS). The systems originate either *in situ* or is generated over the Bay of Bengal due to the redevelopment of westward-propagating residual lows that move across Indochina during the summer monsoon season over the Indian subcontinent. The monsoon depressions in the Bay of Bengal move predominantly along westerly/northwesterly direction and give heavy rainfall of the order of 10-20 cm in a day along their track. There have been many earlier observational studies with respect to the dynamical and thermal structure of monsoon depressions. However, with the development of advance meso-scale model, many authors have carried out the modeling study of high impact weather systems including the monsoon depression (Das 2005; Ratnam and Cox, 2006; Potty *et al*., 2000; Pattanaik and Rama Rao 2009).

One of the physical processes that play a key role in controlling the heat, moisture, and momentum distribution in the region of monsoon depression and the surrounding atmosphere is the parameterization of cumulus convection. An accurate parameterization of moist convection in numerical model is, therefore, essential to simulate properly the track of monsoon depression and hence the distribution of precipitation associated with the monsoon depression. Many studies have been performed to investigate the sensitivity of the prediction of a monsoon depression to the adjustment parameters in different convective parameterization schemes. Vaidya and Singh (1997) have shown that the track of the monsoon depression is sensitive to different adjustment parameters in the Betts-Miller scheme and found that the adjustment parameters are sensitive to the track of monsoon depression. Ratnam and Cox (2006) investigated the sensitivity of the simulation of the monsoon depressions to the cumulus parameterization schemes using MM5 model. Potty *et al*., (2000) have studied structure and track of monsoon depressions over India during the summer monsoon using a double-nested limited-area numerical weather prediction model and found that the location of the centres of the depressions and their track could be predicted satisfactorily.

In the present study, sensitivity of different convective parameterization schemes have been tested using Weather Research Forecasting (WRF) meso-scale model for a case of a monsoon depression that gave heavy rainfall over many parts of country along its track. The system considered here was seen initially as a low pressure area over northwest Bay of Bengal off Orissa-West Bengal coasts on 15th September, 2008. It moved west-northwestwards and further intensified into a deep depression on 16th morning over northwest Bay of Bengal about 130 kms southeast of Chandbali and crossed Orissa coast near Chandbali between 2130 and 2230 hours IST of 16th. The system also contributed heavy rainfall over Orissa and Chhattisgarh region after crossing the Orissa coast. The uniqueness of the system is that the system came under the influence of the mid latitude westerly trough and moved in north-northwesterly direction and also caused flood over Yamuna river basin affecting Haryana, Delhi and Uttar Pradesh associated with the heavy rainfall over the region. Several experiments are carried out with different initial conditions using high resolution Advanced Research WRF (ARW) model with different initial conditions with three well known convective parameterization schemes. A brief description about the WRF model used is given in section 2. Some brief introduction to three different convective parameterization schemes used in the model is discussed in section 3. The results of WRF model forecasts on real time basis are discussed in section 4 and all the results are summarized in section 5.

2. WRF modeling system & the details of the experiments

The version 3.0 of Advanced Research WRF model obtained from the National Centre for Atmospheric Research (NCAR) has been used in the present study. The model domain consists of 0 to 30° N and 65° E to 100° E with a horizontal resolution of 20 km and 28 vertical sigma levels. The WRF Preprocessing System (WPS) program is used to generates initial and lateral boundary conditions for the WRF ARW. The WPS consists of three independent programs: geogrid, ungrib, and metgrid. The purpose of geogrid is to define the domains of the model simulation and interpolate various terrestrial data sets to the model grids. The ungrib program reads GRIB files, degribs the data, and writes the data in a simple intermediate format. The grib files are the time-varying meteorological fields from the global models. The metgrid

TABLE 1

Details of the experimental design of WRF model

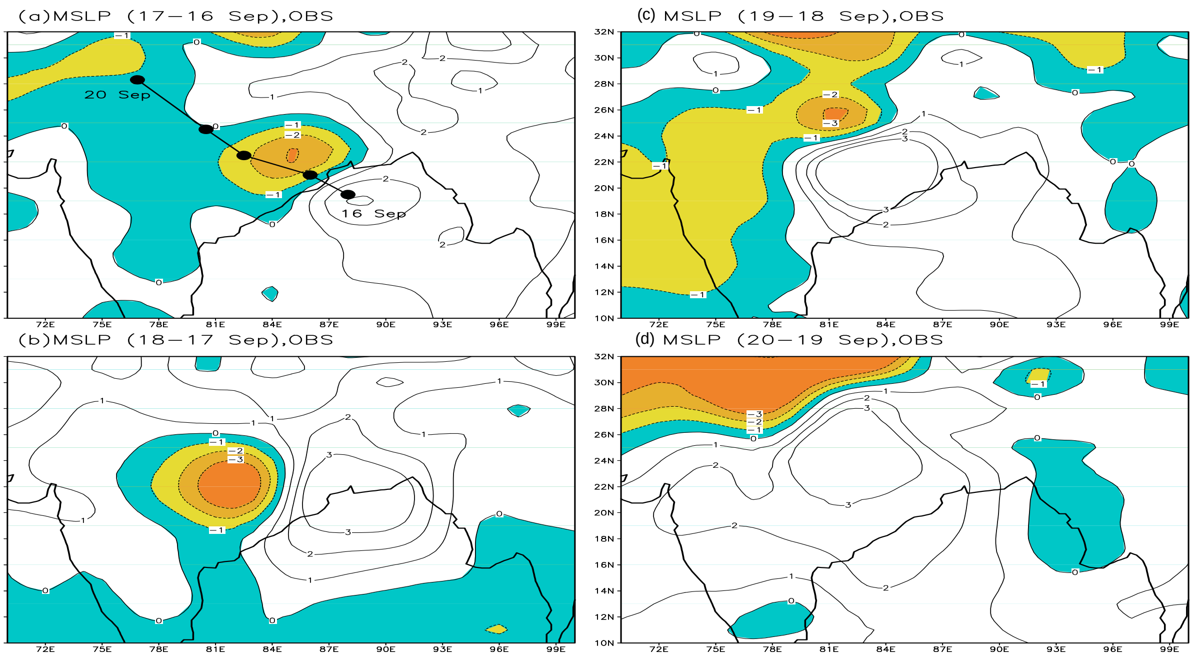
Expt.	Initial conditions from GFS 0000 UTC of	Forecast duration	Cumulus parameterization scheme used
EXP - 1	12^{th} , 13^{th}, 14^{th}, 15^{th}, 16^{th} and 17^{th} September, 2008	78 hr	Kain-Fritch (KF) scheme
EXP - 2	12^{th} , 13^{th}, 14^{th}, 15^{th}, 16^{th} and 17^{th} September, 2008	78 hr	Grell-Devenyi (GD) scheme
EXP - 3	12^{th} , 13^{th}, 14^{th}, 15^{th}, 16^{th} and 17^{th} September, 2008	78 hr	Betts-Miller-Janjic (BMJ) Scheme

program horizontally interpolates the intermediate-format meteorological data that are extracted by the ungrib program onto the simulation domains defined by the geogrid program and transforms them for input to ARW preprocessor program for real data cases.

Overview of the WRF (ARW) model used in the present study

Dynamics	Non hydrostatic
Model Domain	0-30°N, 65°E-100°E
Horizontal grid distance	20 km
Integration time step	60 sec
Map Projection	Mercator
Horizontal grid system	Arakawa-C grid
Vertical Coordinate Sigma coordinate system	28 σ levels
Time Integration scheme	third-order Runge-Kutta scheme
Spatial differencing scheme	2^{nd} to 6^{th} order schemes
Radiation parameterizations	RRTM, Dudhia scheme
Surface Layer Parameterizations	Monin – Obukhov scheme, Thermal diffusion scheme
PBL Parameterization	YSU scheme
Microphysics	WSM 3 simple Ice scheme

The cloud microphysics scheme is WRF Single-Moment (WSM) 3-class simple ice scheme, which is a simple efficient scheme with ice and snow processes suitable for mesoscale grid sizes (Hong *et al.* 1998, Hong *et al.* 2004). It replaces NCEP 3 scheme. The long-wave radiation parameterizations is the Rapid Radiative Transfer Model (RRTM) scheme, which is an accurate scheme using look-up tables for efficiency accounts for multiple bands, trace gases, and microphysics species (Mlawer *et al.* 1997). The short-wave radiation scheme is as per the Dudhia scheme, which allows simple downward integration for efficient cloud and clear-sky absorption and scattering (Dudhia 1989). The Planetary Boundary Layer (PBL) parameterisation is the Yonsei University scheme (YSU), which is the next generation MRF-PBL. It is non-local-K scheme with an explicit entrainment layer and parabolic K profile in unstable mixed layer (Skamarock *et al.*, 2005). The experiments in the operational mode are conducted for 78 hr by integrating the WRF model at a horizontal resolution of 20 km with the initial conditions of 12^{th} to 17^{th} September, 2008 with three convective schemes. The model experimental design is summarized in Table 1 with five different initial conditions and three convective parameterization schemes. In the present experiments the real time analysis field obtained from the Global Forecasting System (GFS), NCEP USA with one degree resolution is used as initial and 6 hourly forecast files as boundary conditions. Thus, the integrations carried out are truly operational in nature. Though, the sensitivity study can be performed by using the exact reanalysis as initial and boundary conditions (say FNL analysis from NCEP), the real time analysis and forecast available from GFS is used in the present study. It is an attempt to explain which scheme is to be used in operational run. For the diagnostic analysis of large-scale flow associated with the monsoon depression the NCEP FNL analysis data is used. However, the WRF model analysis at (initial condition t = 0) is used for the verification of model forecast variables. For the comparison of rainfall forecast the TRMM 3B42 data at 0.25° resolution, which is available both over the land and the Ocean region is used in the present study.



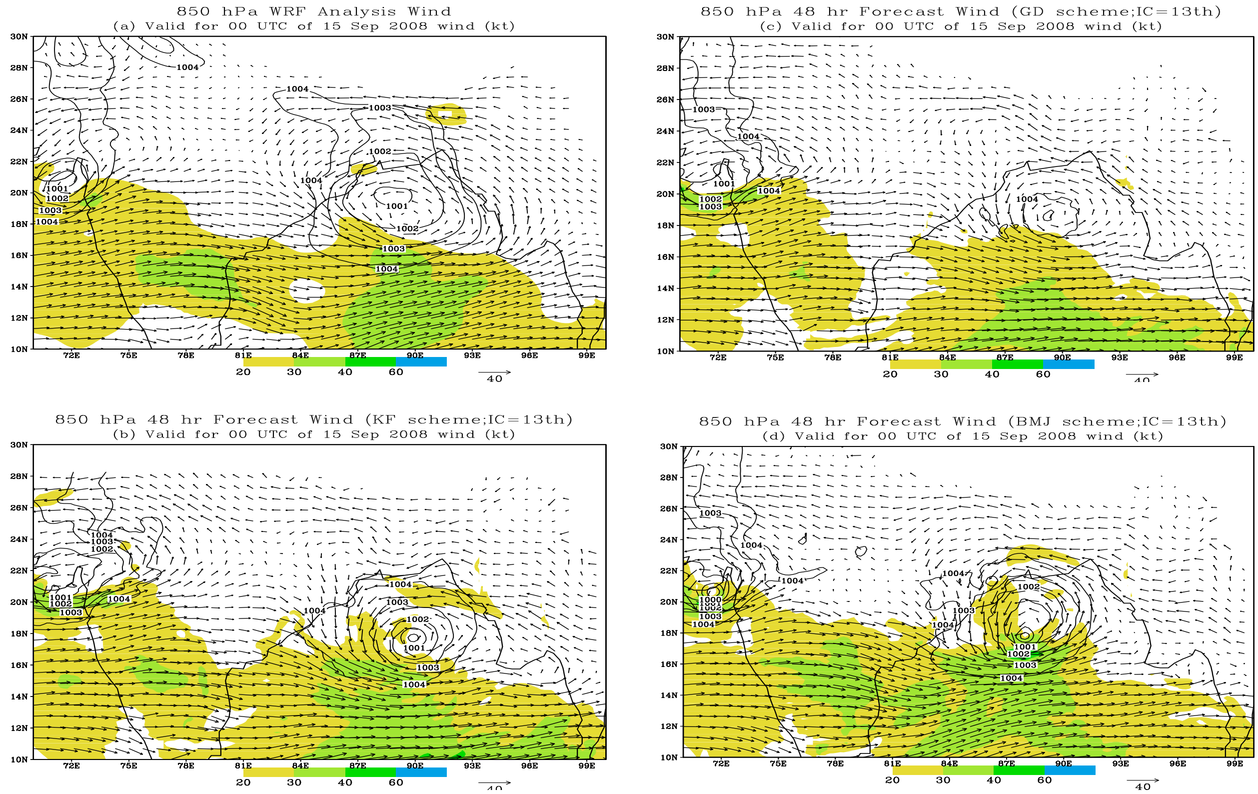
Figs. 1(a-d). The 24 hours observed mean sea level pressure change at 0000 UTC over Indian region from 17th September to 20th September 2008 (a) 17th -16th MSLP, and so on (d) 20th-19th MSLP. The 24hr'ly observed track from 16 to 20 September 2008 is shown in Fig. 1(a)

3. Parameterization of convection schemes

Cumulus convection is responsible in releasing huge amount of latent heat to the atmosphere. The primary objective of the parameterization scheme is to ensure that the local vertical temperature and moisture structures, which in nature are strongly constrained by convection, be realistic in the model (Betts 1986). Several parameterization techniques are used in large-scale models to incorporate the effect of release of latent heat due to penetrative convection. Various popular parameterizations schemes exist for the treatment of sub-grid scale deep convection, which differ in closure assumptions and parametric descriptions of the interaction between the convection and ambient forcing. The differences in the parameterizations are a consequence of the uncertainties in the current understanding of the complicated physics and dynamics of convective clouds, particularly with respect to how to express the interaction between the large-scale flow and the convective clouds in parameterized terms. Three well known parameterization schemes *viz*., the Kain-Fritsch scheme, the Grell-Devenyi (GD) scheme and the Betts-Miller-Janjic (BMJ) scheme are used in the present study. Since the physical process involved in parameterizing the cumulus convections are different in these three schemes the track as well as the associated rainfall from the depression is likely to be different. The process of parameterization in the above mentioned three schemes are highlighted below.

Kain-Fritsch scheme

The original Fritsch-Chappel (1980) scheme is based on the hypothesis that the buoyant energy available to a parcel, in combination with a prescribed period of time for the convection to remove that energy, can be used to regulate the amount of convection in a mesoscale numerical model grid element. This scheme is based on relaxation to a profile due to an updraft, downdraft, and subsidence region properties of a single cloud. Individual clouds are represented as the entraining moist updraft and downdraft plumes. The influence of subsidence heating in a volume containing convection is computed explicitly by balancing the mass continuity equation. Kain and Fritsch (1990) modified the updraft model in the scheme and later introduced numerous other changes, so that it eventually became distinctly different from the Fritsch-Chappell scheme. As they have shown sophisticated cloud-mixing scheme modulates the two-way exchange of mass between cloud and environment (*i.e*., entrainment/detrainment) as a function of the buoyancy characteristics of various mixtures of clear and cloudy air.



Figs. 2(a-d). 850 hPa analysis winds along with MSLP valid for 15th September along with the 48 hr forecast winds and forecast MSLP valid for the same day based on the initial condition of 13th September with three convection schemes

Betts-Miller-Janjic (BMJ) scheme

The BMJ deep convective parametization scheme is based on the observation that deep convection is a thermodynamically driven process that transports heat and moisture upward in order to remove or reduce conditional instabilities (Betts and Miller 1986; Janjic 1994). In the BMJ scheme, the temperature and moisture profiles at a given grid point are relaxed simultaneously toward a profile type which has been observed in nature. The model first checks for deep convection, and then for shallow convection. By relaxing the profiles at a grid point simultaneously, the model always maintains a realistic vertical temperature and moisture structure in the presence of convection. By doing this simple adjustment, it is believed that the subgrid-scale cloud and mesoscale processes, which created these structures will be adequately represented.

The difference of the BMJ scheme from KF scheme is that the BMJ adjustment profiles are constrained to be close to specified shapes, based on a moist adiabat profiles, whereas the KF adjustment profiles are determined by mass rearrangement in a column, effected by 1-dimensional models of updrafts and downdrafts.

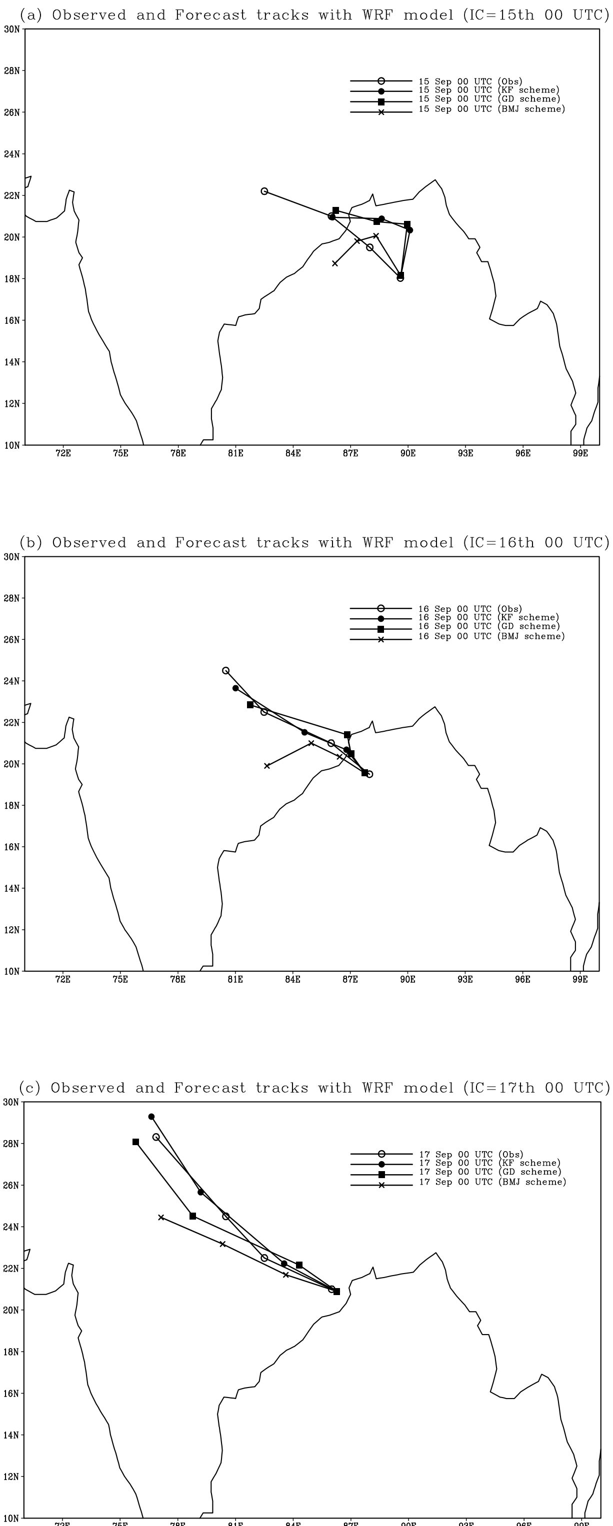
Grell-Devenyi (GD) scheme

The G-D scheme is an expansion from the Grell convective parameterization (Grell 1993) to include several alternative closure assumptions that are commonly used in convective parameterizations. The unique aspect of the G-D scheme is that it uses 16 ensemble members derived from 5 popular closure assumptions to obtain an ensemble-mean realization at a time and location. These ensemble members are chosen because statistically they give a large spread in terms of accumulated convective rainfall. The details of how to determine the ensemble mean can be found in Grell and Devenyi (2002).

4. Model Simulation of Monsoon Depression

4.1. *Genesis of the monsoon system*

As mentioned earlier the system initially was seen as an upper air cyclonic circulation extending upto mid-



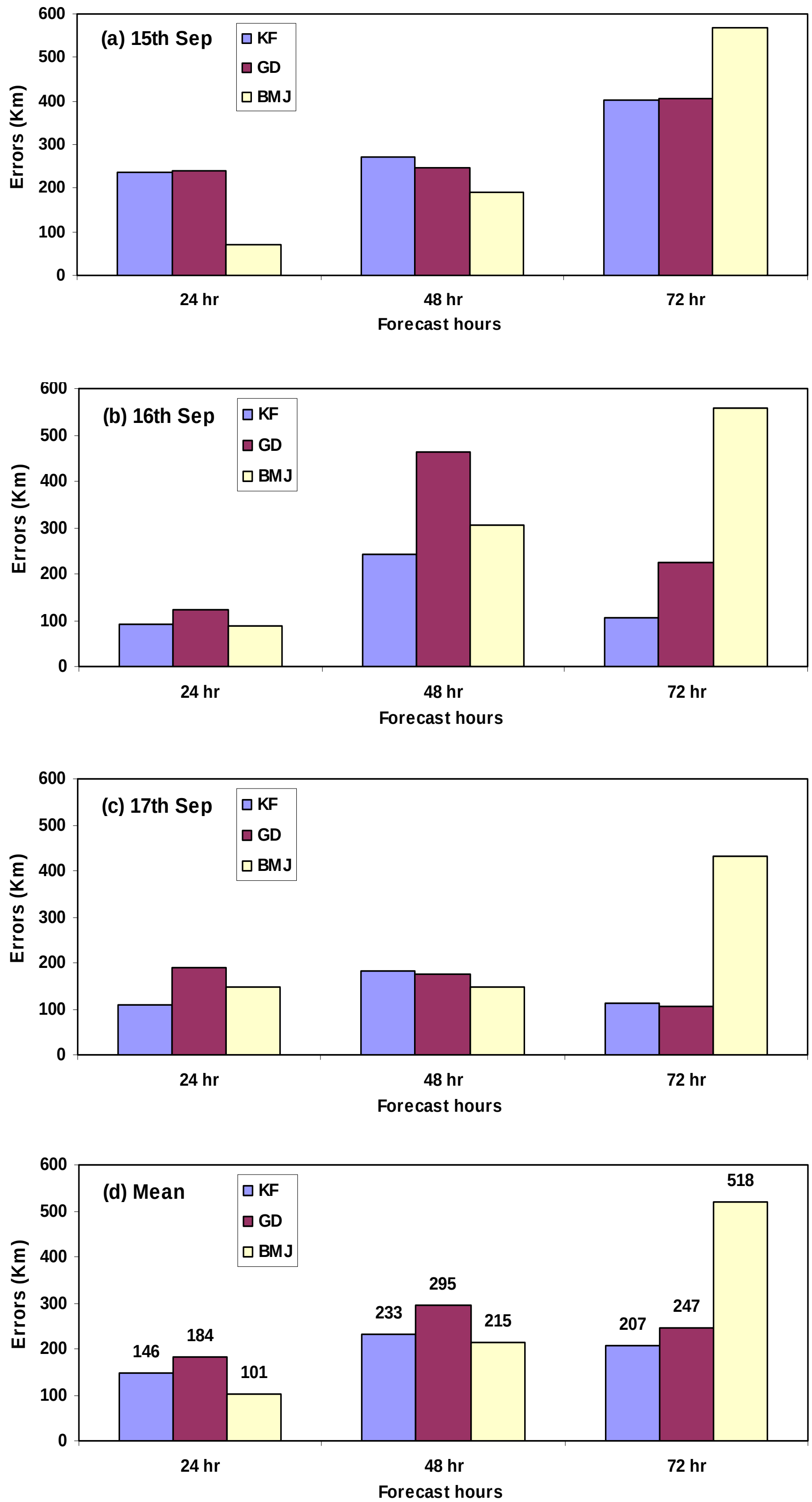
Figs. 3(a-c). The observed and WRF model forecast tracks of the system with three convective schemes based on the initial condition of (a) 15^{th}, (b) 16^{th} and (c) 17^{th} September, 2008. The track is plotted for 3 days in each Figure

TABLE 2

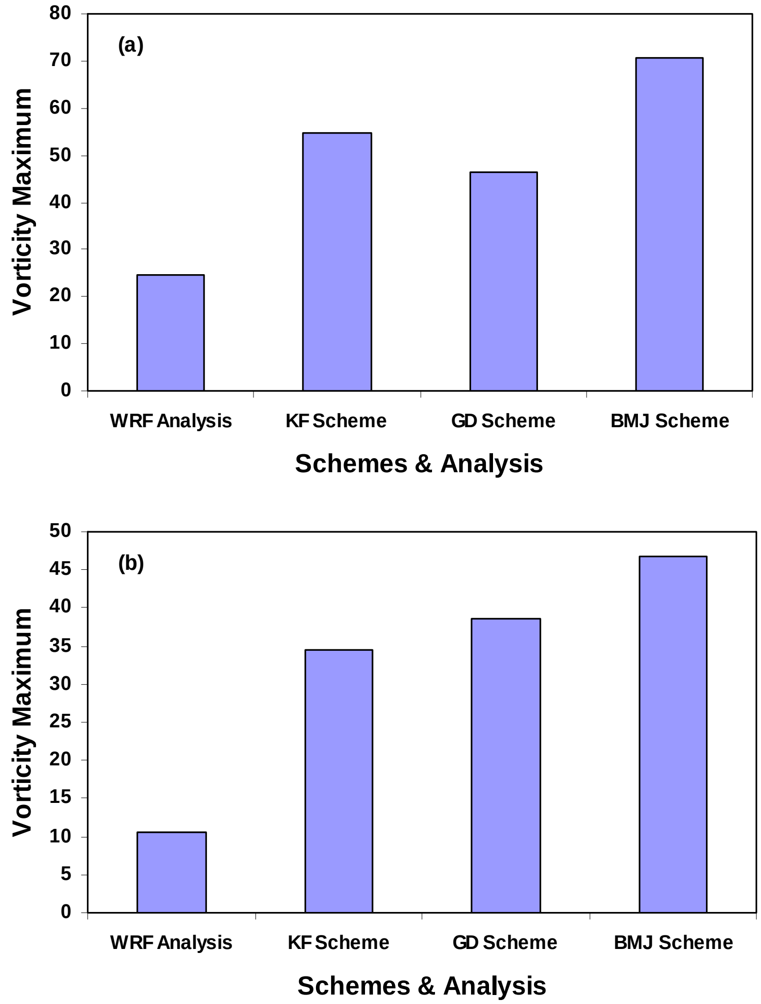
Forecast landfall errors with three convective schemes for the monsoon depression

Initial Cond. → Scheme used ↓	15^{th} 0000 UTC Landfall Errors	16^{th} 0000 UTC Landfall Errors
Kain-Fritch (KF)	60 km	22 km
Grell-Devenyi (GD)	78 km	60 km
Betts-Miller-Janjic (BMJ) Scheme	No landfall	30 km

tropospheric levels on 14^{th} and became a low pressure area on 15^{th} morning over northwest Bay of Bengal off Orissa-West Bengal coasts. In order to see the genesis of the system in the WRF model forecast, the 850 hPa WRF analysis wind on 15^{th} September, 2008 along with the contour of mean sea level pressure (MSLP) as shown in Fig. 2(a) clearly shows the circulation associated with a closed low in the surface of 1001 hPa over central Bay of Bengal. In order to see the genesis of the system in the WRF model the 48 hr forecast wind at 850 hPa level and forecast MSLP based on the initial condition of 13^{th} September, 2008 is shown in Figs. 2(b-d) with all three convection schemes. Genesis of the system is considered by taking both MSLP and 850 hPa wind together in the form of a closed isobar on the MSLP chart associated with a low-level cyclonic circulation at 850 hPa. It is seen that the 48 hr forecast based on the initial condition of 13^{th} September had clearly indicated formation of a low pressure area (in the form of a closed cyclonic circulation at lower level and closed contour of MSLP) on 15^{th} morning with the forecast genesis position with all three convection schemes matching almost well with the analysis position. The BMJ scheme shows a slightly stronger system with the lowest MSLP contour of about 999 hPa [Fig. 2(d)] and the GD scheme shows a relatively weaker system associated with lowest MSLP contour of 1004 hPa [Fig. 2(c)]. The KF scheme [Fig. 2(b)] on the other hand showed the system with the lowest closed isobar of 1000 hPa, which is much closer to the observed pattern shown in Fig. 2(a). Even the 72 hr forecast wind based on the initial condition of 12^{th} September also clearly indicated formation of a low pressure are although, the position is slightly to the southeast of actual position in the KF scheme and GD scheme and to the southwest of actual position in case of BMJ scheme (Fig. not shown). Thus, the WRF model could able to capture the genesis of the system reasonably well at least 48 hr to 72 hr in advance.



Figs. 4(a-d). The forecast errors of monsoon depression based on initial conditions of (a) 15th September, (b) 16th September, (c) 17th September (d) Mean forecast error



Figs. 5(a&b). The observed and WRF model forecast 850 hPa vorticity maximum with three convective schemes (a) based on the initial condition of 16th September and valid for 18th September 2008 (48hr forecast). (b) same as 'a' but for vorticity maximum of 20th September, based on the initial condition of 17th (72hr forecast)

4.2. *Model simulated track of monsoon depression*

The real time track forecast of the monsoon depression using WRF (ARW) model at 20 km resolution for 3 days starting from the initial conditions of 0000 UTC of 15th, 16th and 17th September, 2008 with three different convective parameterization schemes are shown in Figs. 3(a-c). The observed track and corresponding forecast track for three days is also plotted in these three figures. The observed track is plotted based on the best track position from IMD. It is seen from Fig. 3(a) that the forecast track of the system was almost in northerly direction for 24 hr in KF and GD schemes and moved in west-north-westerly (WNW) direction during subsequent 48 hr, whereas the observed track was in northwesterly direction till 48 hr (till 17th September) and in WNW direction during subsequent 24 hr valid till 18th 0000 UTC. In case of BMJ scheme although the forecast movement indicated northwesterly direction during 24 hr like that of observed track the system did not cross the coast for subsequent 48 hrs. Thus, with the initial condition of 15th when the system was very weak (only a low pressure area) the KF scheme and GD scheme gives almost identical results with landfall error of 60 km and 78 km respectively (Table 2) and in the BMJ scheme the system did not cross the coast. With the initial condition of 16th September (when the system was intensified as a depression and was close to the coast of Orissa) the performance of WRF model in forecasting the track is improved a lot with all three convection schemes

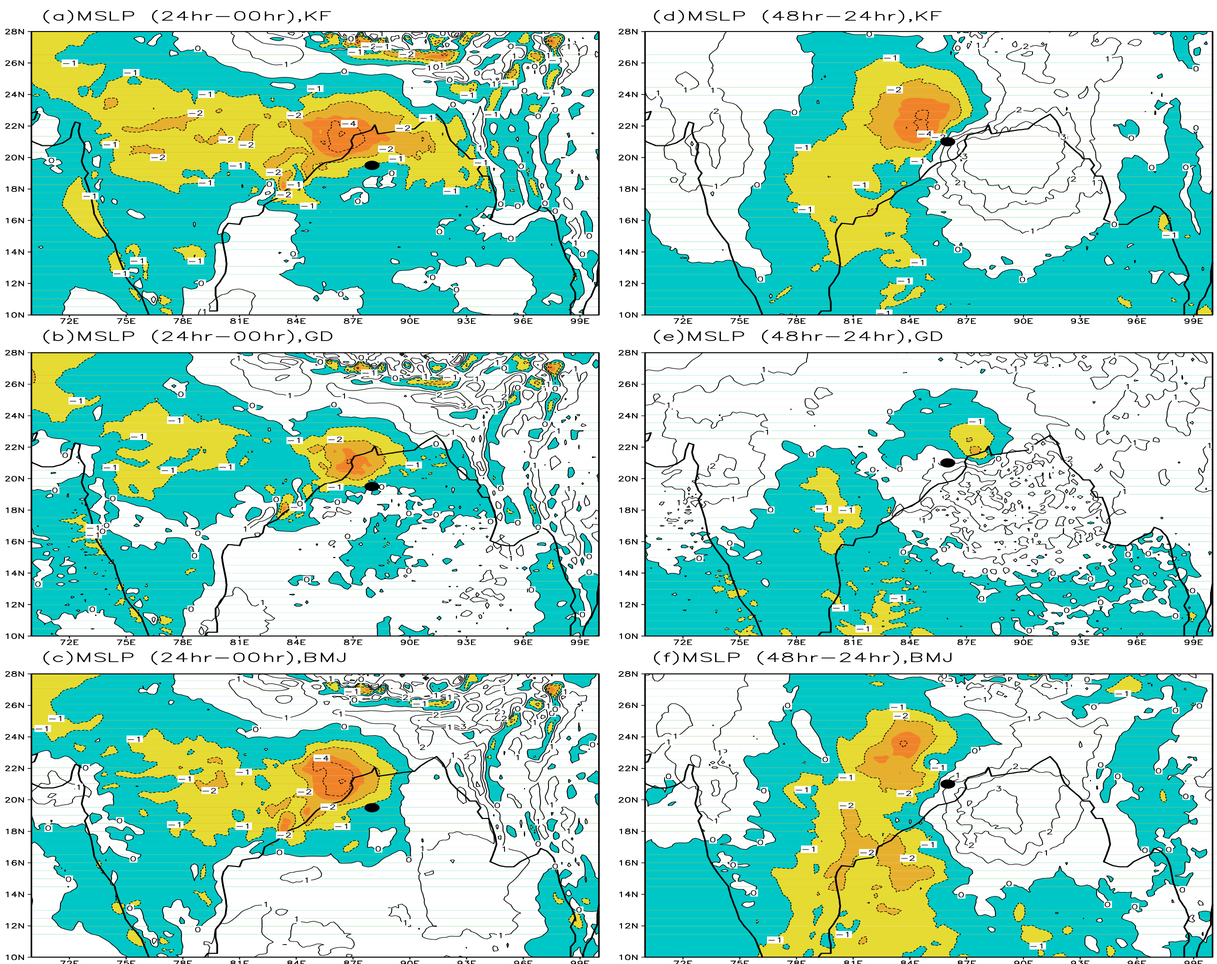
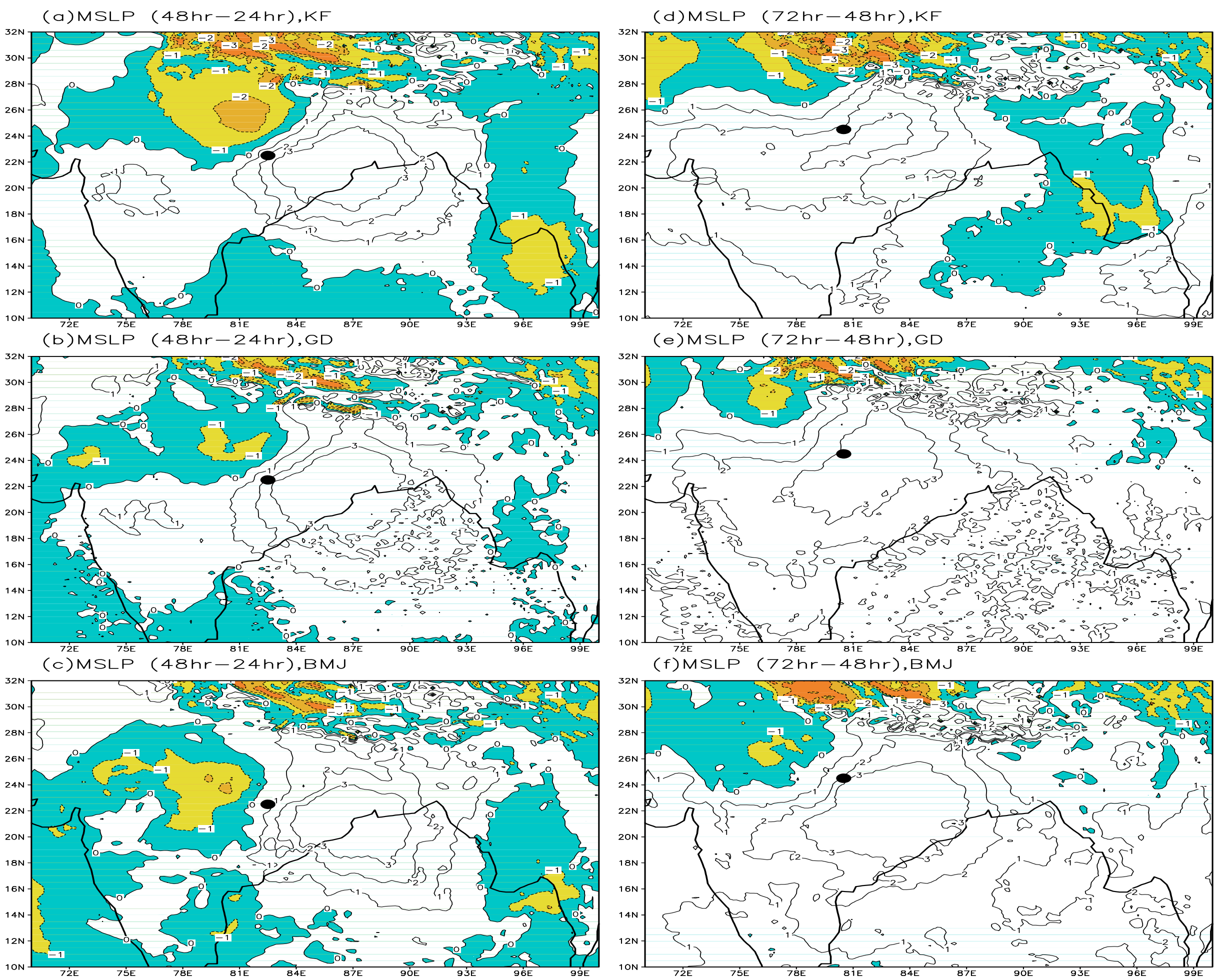


Fig. 6(a-f). The 24 hours mean sea level pressure change over Indian region from WRF model with initial condition of 16th September, 2008 (a) forecast 24 hr pressure change (24 hr – 00 hr) valid for 17th with KF scheme (b) same as 'a' but with GD scheme, (c) same as 'a' but for BMJ scheme, (d) forecast 48hr pressure change (48hr-24hr) valid for 18th with KF scheme, (e) same as 'd' but with GD scheme, (f) same as 'd' but for BMJ scheme. The black dot indicate the observed position on previous day or for 16th in fig 'a' and so on

[Fig. 3(b)]. The observed track is very close to the forecast track particularly with KF scheme and GD scheme till 72 hrs, whereas the BMJ scheme was close to the observed track till 48 hrs as it also followed the observed track. However, during the 72 hr forecast the track showed southwards movement in the BMJ scheme, which is some- what unrealistic compared to the NNW observed track during this period. The BMJ scheme also showed very slow movement of the system. The landfall error with KF, GD and BMJ schemes are found to be 22 km, 60 km and 30 km respectively (Table 2).

On 17th initial condition (when the system was over land and it was a deep depression) the WRF model forecasts shows almost very similar track with all the three schemes with KF scheme and GD scheme showed very close to the observed track. In case of BMJ scheme although the forecast track is very close to the observed track the forecast movement is slightly slower than that of actual movement [Fig. 3(c)]. The corresponding 24 hr'ly Direct Positional Errors (DPE) are calculated as the geographical distance between the observed and forecast point and the errors are plotted [Figs. 4(a-c)] with 15th,

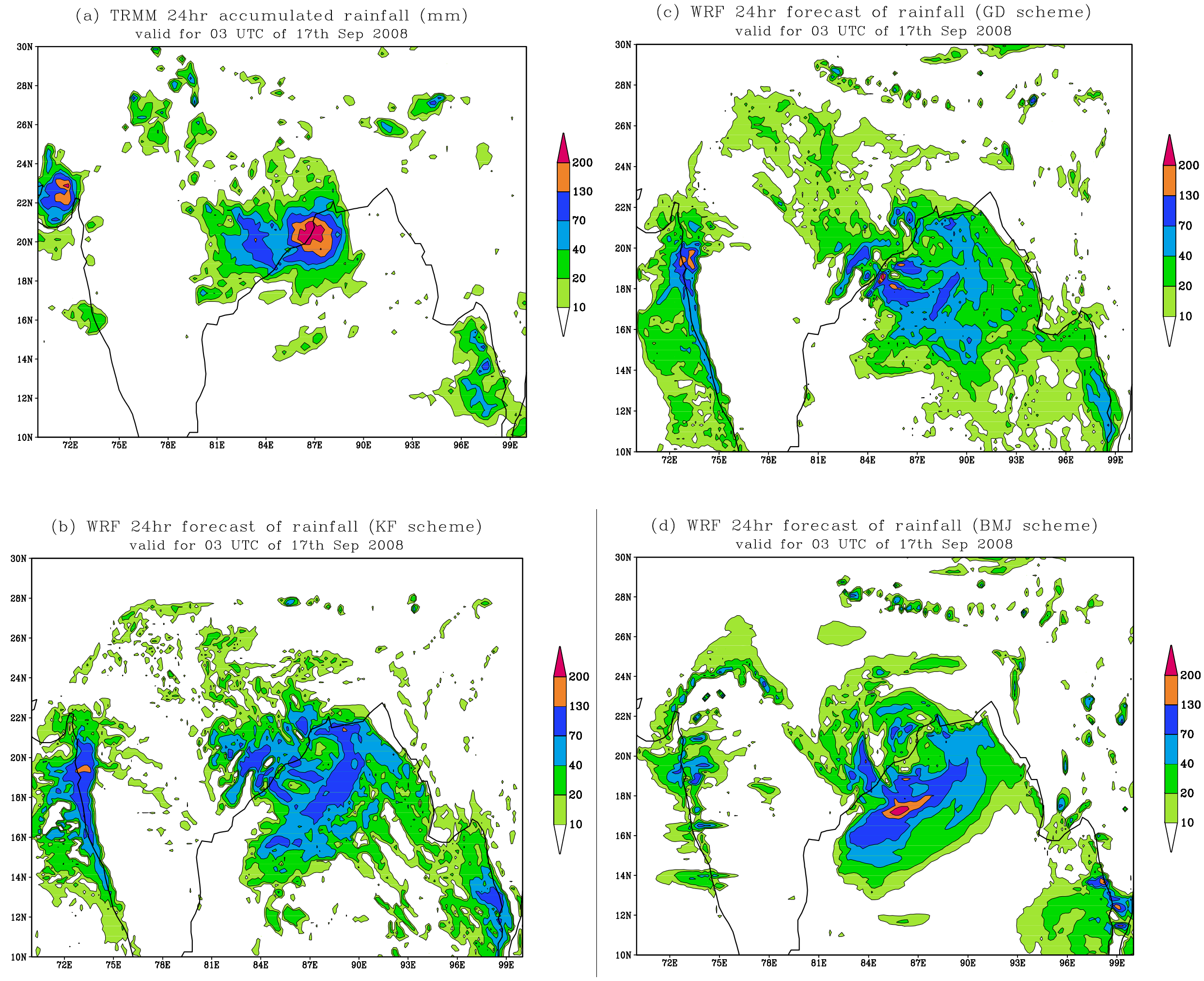


Figs. 7(a-f). The 24 hours mean sea level pressure change over Indian region from WRF model run for run with initial condition of 17th September, 2008 (a) forecast 24 hr pressure change (48 hr-24 hr) valid for 19th with KF scheme (b) same as 'a' but with GD scheme, (c) same as 'a' but for BMJ scheme, (d) forecast 72hr pressure change (72 hr – 48 hr) valid for 20th with KF scheme, (e) same as 'd' but with GD scheme, (f) same as 'd' but for BMJ scheme. The black dot indicates the observed position on previous day or for 18th in fig 'a' and so on

16th and 17th initial conditions along with the mean forecast errors of these three days. It is seen from Figs. 4(a-c) that the forecast error is slightly less for BMJ scheme particularly till 24 hour and the error is very high for longer forecast hour (72 hr). The performance of KF and GD schemes are almost similar with KF scheme doing good till 72 hour with least mean forecast error compared to other two schemes [Fig. 4(d)].

4.3. *Analysis of diagnostic fields from the WRF model forecast*

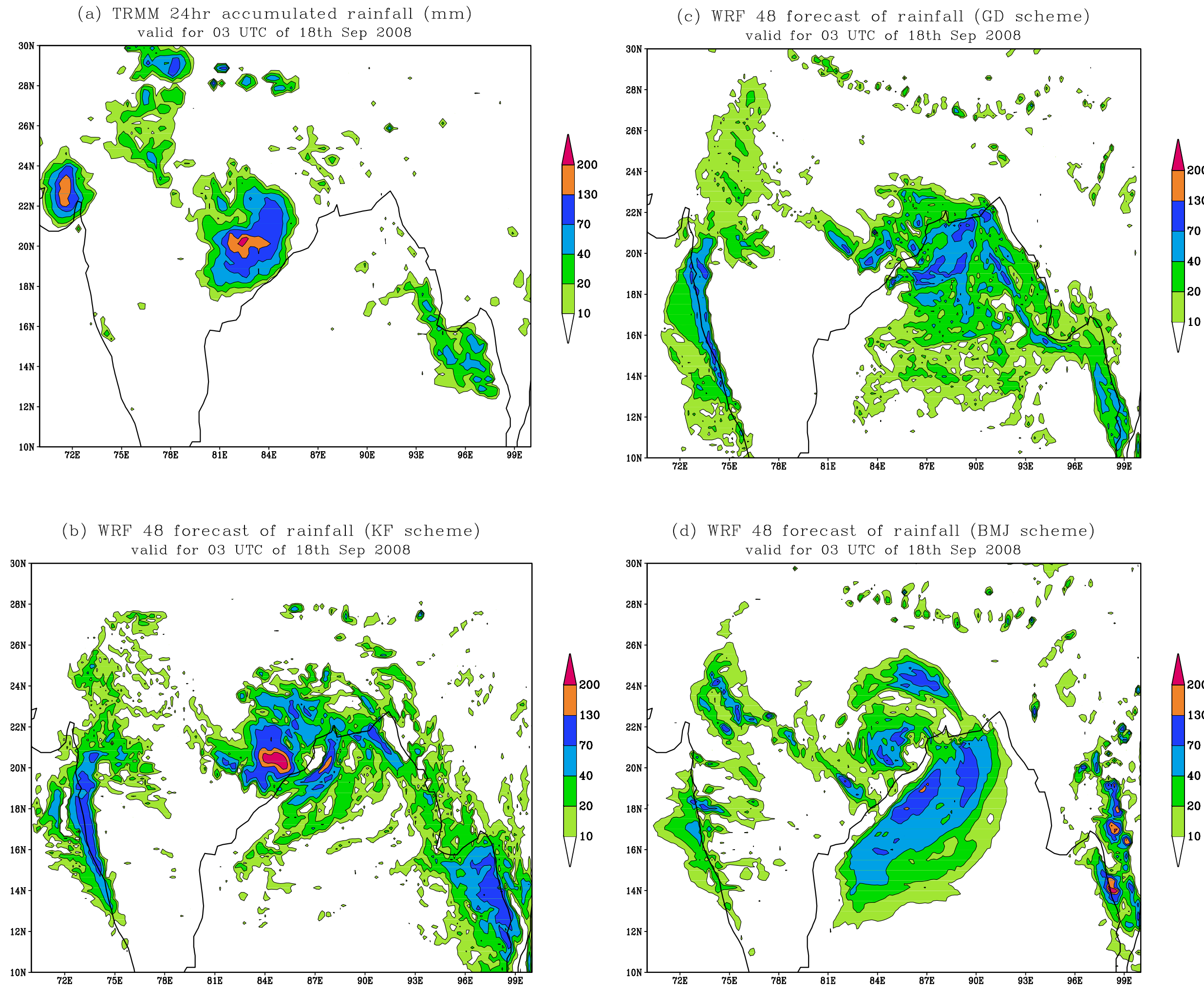
In order to see the skill of the WRF forecast circulation features associated with the depression the 48 hr forecast vorticity maximum near the system at 850 hPa level based on the initial condition of 16th September, 2008 and the corresponding 850 hPa level vorticity maximum from the WRF analysis field valid for 18th September 2008 is shown in Fig. 5(a). Similarly, the 72 hr forecast 850 vorticity maximum based on the initial condition of 17th September, 2008 and valid for 20th September, 2008 is also seen in Fig. 5(b) along with the corresponding analysis value of 850 hPa vorticity maximum valid for 20th September, 2008. It is seen from Fig. 5(a) that the 850 hPa forecast (48 hr) vorticity maximum valid for 18th September is on the higher side with all the three convections schemes compared to the analysed 850 hPa vorticity maximum valid for the same



Figs. 8(a-d). The observed TRMM rainfall and 24 hr forecast rainfall based on 16th September valid for 17th September, 2008. (a) Observed rainfall (mm) valid for 17th, (b) 24 hr WRF forecast rainfall valid for 17th September with KF scheme, (c) same as 'b' but for GD scheme and (d) same as 'b' but for BMJ scheme

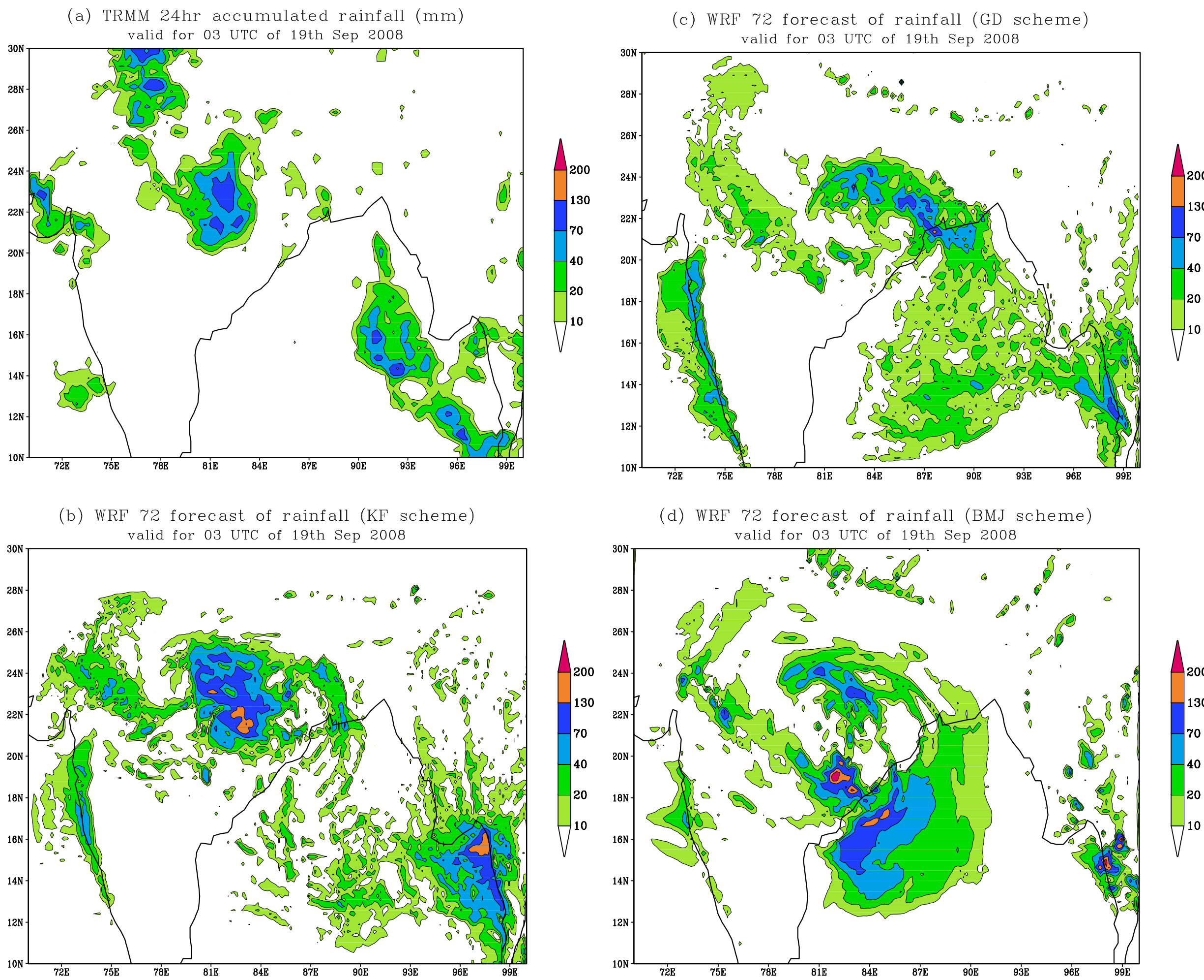
day. Similarly the 72 hr forecast vorticity maximum at 850 hPa level also shows higher values [Fig. 5(b)] with three convection schemes compared to that of analysis vorticity maximum value valid for 20th September 2008. There is not much difference in the forecast values (both 48hr forecast and 72 hr forecast) of vorticity maximum particularly with KF scheme and GD scheme, whereas the BMJ scheme shows much higher values compared to that of the corresponding analysis value of vorticity maximum, which was also reflected in the genesis of the system with lowest MSLP in BMJ scheme.

As shown above the WRF model has captured the observed track of monsoon depression reasonably well with all three convection schemes. As shown in Fig. 1 from the 24 hr MSLP change it is noticed that the system followed the direction of maximum negative isallobaric gradient (region of maximum pressure fall) and moved in the NW-WNW-NNW direction. Thus, it will be very interesting to see whether the diagnostic features observed in the reanalysis is also simulated well in the model. For that purpose the forecast MSLP change in 24 hr at different forecast hours run with the initial condition of 16th September (when the depression was over the ocean) with three different convection schemes is shown in Figs. 6(a-f). Similarly, the forecast MSLP change in 24 hr at different forecast hours run with the initial condition of 17th September (when the depression had already crossed



Figs. 9(a-d). The observed TRMM rainfall and 48 hr forecast rainfall based on 16th September, 2008 valid for 18th September, 2008. (a) Observed rainfall (mm) valid for 18th, (b) 48 hr WRF forecast rainfall valid for 18th September with KF scheme, (c) same as 'b' but for GD scheme and (d) same as 'b' but for BMJ scheme

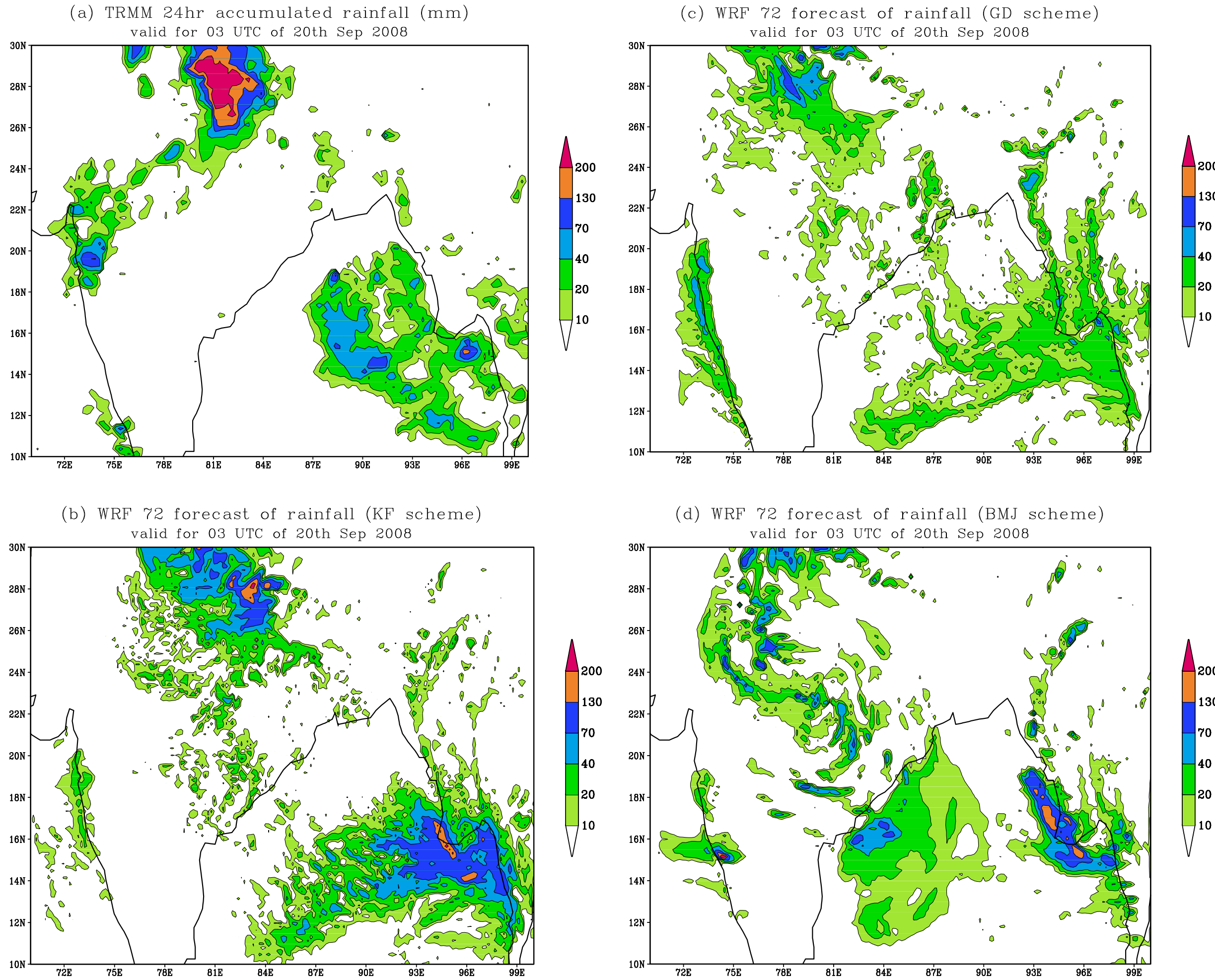
the coast) with three different convection schemes is shown in Figs. 7(a-f). As indicated in Fig. 6(d) the 24hr change of forecast MSLP (48 hr - 24 hr) based on the initial condition of 16th September with KF scheme indicated the difference of forecast MSLP of 48hr (18th September, 0000 UTC) and 24 hr (17th September, 0000 UTC) with black dot in the figure indicating observed position of the system on 24 hr forecast (17th September, 0000 UTC). The other figures in Figs. 6(a-f) and Figs. 7(a-f) have the similar descriptions. Fig. 6(a) indicates that the KF scheme gives maximum negative isallobaric gradient in northwest direction till 24 hr forecast and moved in northwest direction as indicated in case of observed isallobaric gradient [Fig. 1(a)]. Similarly, Fig. 6(d) indicates that the KF scheme gives maximum negative isallobaric gradient in WNW direction till 48 hr forecast and moved in WNW direction as indicated in case of observed isallobaric gradient [Fig. 1(b)]. Thus, as shown in the track forecast [Fig. 3(b)] with KF scheme the forecast upto 48 hrs is very consistent with the observed track. Fig. 6(b) and Fig. 6(e) with the GD scheme indicates consistent negative isallobaric gradient till 24 hr in the NW direction like that of observed case as shown in Fig. 1(a). However, the isallobaric gradient is very weak in case of 48 hr forecast [Fig. 6(e)] and the maximum negative isallobaric gradient with the GD scheme is in northerly direction in place of NW direction as in the case of observed track [Fig. 1(b)] and also compared to in the



Figs. 10(a-d). The observed TRMM rainfall and 48 hr forecast rainfall based on 16th September, 2008 valid for 19th September, 2008. (a) Observed rainfall (mm) valid for 19th, (b) 72hr WRF forecast rainfall valid for 19th September with KF scheme, (c) same as 'b' but for GD scheme and (d) same as 'b' but for BMJ scheme

KF scheme [Fig. 6(d)]. Thus, the forecast movement in case of GD scheme is also in northerly direction till 48hr as shown in Fig. 3(b). In case of BMJ scheme [Figs. 6(c&f)] the isallobaric gradient is similar to that of KF scheme till 48 hours with maximum negative isallobaric gradient (pressure fall of the order of more than 4 hPa) is in the NW and West-North-West direction like that of observed case as shown in Figs. 1(a&b) and hence the forecast of monsoon depression also followed the observed track till 48 hours [Fig. 3(b)].

Considering the forecast isallobaric gradient based on the initial condition of 17th September it is seen from Figs. 7(a&d) that like the forecast of 16th initial condition the KF scheme could produce realistic patterns of MSLP change during 48 hr and 72 hr forecast like that of observed pattern shown in Figs. 1(c&d). Since the maximum pressure fall is in NNW direction in case of observation as well as the forecast with KF scheme the system had followed closely the observed track in case of KF scheme as shown in Fig. 3(c). In case of GD scheme [Figs. 7(b&e)] although the magnitude of pressure fall is slightly less than that of observation the direction is very much consistent with maximum pressure fall in the NNW direction. However, the BMJ scheme shows maximum pressure fall in west-northwest direction [Figs. 7(c&f)] and had more westerly component in the forecast track compared to that of observed track and also comparing with forecast tracks with KF scheme and GD scheme as shown in Fig. 3(c).



Figs. 11(a-d). The observed TRMM rainfall and 72 hr forecast rainfall based on 17th September, 2008 valid for 20th September, 2008. (a) Observed rainfall (mm) valid for 20th, (b) 72hr WRF forecast rainfall valid for 20th September with KF scheme, (c) same as ‘b’ but for GD scheme and (d) same as ‘b’ but for BMJ scheme

4.4. *Forecasting of heavy rainfall associated with the system*

As discussed earlier widespread rainfall with scattered heavy to very heavy falls and isolated extremely heavy fall was recorded over Orissa on 17th and 18th September, over Chhattisgarh on 19th September associated with the movement of the system. As a result, flood conditions prevailed over these regions. Associated with the NW and NNW movement of the system rainfall over western Himalayan region and adjoining plains had increased and consequently flood conditions over Yamuna river basin affecting Haryana, Delhi and Uttar Pradesh was reported.

In order to compare the observed rainfall with the forecast from the WRF model with three different convection schemes the forecast rainfall (24 hr, 48 hr and 72 hr) based on the initial condition of 16th September is compared with corresponding observed rainfall. The observed daily TRMM 3B42 rainfall data at 0.25° resolution reported on 17th September along with the 24hr forecast rainfall valid for the same day is shown in Figs. 8(a-d). The observed rainfall of 18th and 48 hr forecast rainfall valid for the same day is also seen in Figs. 9(a-d) and the 72 hr forecast rainfall valid for 19th September along with the observed rainfall of 19th is shown in Figs. 10(a-d). It is seen from Fig. 8(a) that on 17th September heavy rainfall reported over many parts of Orissa with rainfall belt extending in adjoining areas and also the Oceanic region. The 24hr forecast rainfall with three different schemes [Figs. 8(b-d)] valid for 17th September do not indicate significant difference of rainfall and are closer to observation, however the amount of forecast rainfall is slightly underestimated with all the three schemes. Similarly, the observed rainfall on 18th September as seen in Fig. 9(a) indicated heavy rainfall over Orissa and parts of Chhattisgarh. The 48hr forecast rainfall valid for the same day is well captured in KF scheme [Fig. 9(b)], whereas in the GD scheme and BMJ scheme the rainfall simulated is underestimated [Figs. 9(c&d)]. The heavy rainfall over Chhattisgarh reported on 19th September [Fig. 10(a)] is well captured even in 72hr forecast by the WRF model with KF scheme [Fig. 10(b)]. However, in case of GD scheme the rainfall amount is underestimated as is located slightly to the east of actual maximum [Fig. 10(c)] and the BMJ scheme also underestimates the rainfall amount and positioned southward [Fig. 10(d)] compared to the observed values shown in Fig. 10(a).

With the initial condition of 17th the forecast track of monsoon depression is almost close of observation [Figs. 3(a-c)] with KF scheme and GD scheme, whereas BMJ scheme shows more westerly track compared to that of observed track. The forecast rainfall on 20th September (72hr forecast) with three schemes along with that of observed rainfall is shown in Figs. 11(a-d). The observed rainfall [Fig. 11(a)] from TRMM indicates heavy rainfall over the western Himalayan region and as shown by Ananthakrishnan and Bhatia (1960), on occasions, the interaction of monsoon depression with mid-latitude westerlies leading to increase in rainfall over western Himalayan region and adjoining plains**.** This rainfall event in the model forecast is well captured in WRF forecast with KF scheme [Fig. 11(b)] with rainfall amount and position well captured in the forecast, whereas in the GD scheme [Fig. 11(c)] the rainfall amount is underestimated although it is properly located. With BMJ scheme [Fig. 11(d)] the forecast rainfall is diffuse and is to the much south of its actual location [Fig. 11(a)]. Thus, the overall forecast of rainfall associated with the monsoon depression is well captured in WRF model with KF scheme compared to that of GD scheme and BMJ scheme.

5. Conclusions

Based on the present case study the following broad conclusions can be drawn:

The WRF model had captured well the genesis of the system in the model in its 48 hr forecast with three convective parameterization schemes, although with slight difference in the genesis location from one scheme to other.

The study also shows that the track of monsoon depression is quite sensitive to the cumulus parameterization schemes used in the model. With the initial condition, when the system was very weak all the three schemes almost gave more northerly track initially and were slower than the actual movement, with KF and GD schemes giving relatively better forecast compared to that of BMJ scheme. The landfall error in this case was found to be 60 km with KF scheme and 78 km with GD scheme and there was no landfall till 72 hr forecast with the BMJ scheme. The track forecast improved a lot with all the three schemes with the initial conditions when the system was in depression stage with lowest landfall error of 22 km reported with the KF scheme.

Consistence with the observed track the WRF model forecast also indicates movement of the system towards the region of maximum pressure fall and was very prominent with KF scheme. The performance of KF and GD schemes are almost similar with KF scheme did better till 72 hour with least mean forecast error compared to other two schemes, whereas the BMJ scheme although performed well till 24 to 48 hrs it witnessed large error in 72 hr forecast. The overall rainfall forecast associated with the monsoon depression is well captured in WRF model with KF scheme compared to that of GD scheme and BMJ scheme. Thus, based on this study it can be concluded that KF scheme performed better both in terms of track and rainfall forecast associated with a monsoon depression compared to GD scheme and BMJ scheme, although more number of cases are to be investigated to substantiate the results.

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