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The Impact of Assimilation of MODIS Observations Using WRF-VAR for the Prediction of a Monsoon Depression During September 2006

M. Govindankutty[1], A. Chandrasekar[*,1], A.K. Bohra[2], John P. George[2] and Munmun Das Gupta[2]

[1]*Department of Physics & Meteorology, Indian Institute of Technology, Kharagpur, India*

[2]*National Centre for Medium Range Weather Forecasting, Noida, India*

Abstract: Monsoon depressions form over the sea, which is a typical data-sparse region for conventional observations. The Moderate Resolution Imaging Spectroradiometer (MODIS) provides for very high-horizontal resolution temperature and humidity soundings. Such high-resolution satellite data can improve the poorly analyzed depressions. The objective of this study is to investigate the impact of ingesting and assimilating the MODIS temperature and humidity profiles on the prediction of a monsoon depression, which formed over the Bay of Bengal during September 2006 using three-dimensional variational data assimilation (3DVAR). The NCAR Weather Research and Forecast model (WRF) has been utilized in this study. The results of the study indicate that the simulated sea level pressure fields from the 3DVAR run is in better agreement with the sea level pressure field from the NCEP-FNL analysis as compared to the control run. Higher spatial correlation and the lower rms errors of the sea level pressure field are associated with the 3DVAR run. The simulated structure of the spatial precipitation pattern for the assimilation experiments (3DVAR) are closer to the TRMM observations with more rainfall simulated over the east coast regions in the assimilation experiments. The 3DVAR runs clearly shows lower number of false alarms, higher probability of detection and larger value of equitable threat score for the 48 hours accumulated precipitation as compared to the control run. The results also indicate that the 3DVAR has larger positive bias values for precipitation as compared to the control run. For the 3DVAR run, the results reveal lower rms errors for temperatures at all levels and dew point temperatures, except for the upper troposphere. However, the rms errors for the wind speeds are not lower for the 3DVAR run. Overall, the results of this study indicate a very positive impact of the 3DVAR assimilation of MODIS observations on the simulation of a monsoon depression over India.

1. INTRODUCTION

The Indian summer monsoon rainfall is very much dependent on the occurrence of monsoon disturbances (like low-pressure areas and monsoon depression) which form over the Bay of Bengal and Arabian Sea. In fact, the monsoon depression is the most important of the synoptic-scale disturbances on the monsoon trough. Hence the monsoon depression plays an important and vital role in the space and time distribution of the Indian summer monsoon rainfall and needs to be better understood and simulated. In the short-range, a good numerical prediction requires very accurate initial conditions. It is possible to obtain improved and accurate initial condition by ingesting and assimilating high-resolution meteorological observations to the initial analysis using Three-Dimensional Variational (3DVAR) data assimilation [1]. Since most of these monsoon depressions form over the data sparse oceanic regions, it is important to assimilate satellite observations into the numerical model to obtain improved analysis and improved forecasts. The main objective of this study is to investigate the impact of ingestion and assimilation of MODIS observation for the prediction of a monsoon depression over India using a mesoscale model. The basic objective of the 3DVAR system is to produce an optimal estimate of the true state of the atmosphere at any desired analysis time by the iterative solution of the prescribed cost function [2]. Additional details about the components of the 3DVAR system can be found in Barker *et al.,* (2004) [3]. In recent times, several studies have utilized the three-dimensional variational (3DVAR) assimilation methods to improve the prediction of weather systems [4-6]. The following section provides brief details of the synoptic features of the monsoon depression being studied while section 3 gives details of the model description and the numerical experiments performed. Section 4 provides the results and discussions while section 5 briefly mentions the broad overall conclusions of this study.

2. SYNOPTIC FEATURES OF MONSOON DEPRESSION

The system was first seen as a low-pressure area, which formed over the east central and adjoining northeast Bay off Arakan coast on 27th September 2006. The system intensified into a depression at 0900 UTC over east central Bay and lay centered near 18.0^{o} N 89.0^{o} E on 28 September 2006. At 0300 UTC of the next day, the depression was near 19.0^{o} N 86.0^{o} E. Moving in westerly direction; the depression crossed the Orissa coast close to Gopalpur in the afternoon of 29 September and lay near 19.0^{o} N 84.5^{o} E around 1200 UTC. Subsequently, the system weakened into a well-marked low-pressure area, moved westward and became less marked over Vidarbha on 1st October 2006.

*Address correspondence to this author at the Department of Physics & Meteorology, Indian Institute of Technology, Kharagpur, India;
E-mail: chand@phy.iitkgp.ernet.in

3. MODEL DESCRIPTION AND EXPERIMENTS

The present study utilized the National Center for Atmospheric Research (NCAR) Weather Research and Forecast (WRF) model version 2.2. The model was configured with twenty-eight vertical layers (centered at σ = 1.000, 0.990, 0.978, 0.964, 0.946, 0.922, 0.894, 0.860, 0.817, 0.766, 0.707, 0.644, 0.576, 0.507, 0.444, 0.380, 0.324, 0.273, 0.228, 0.188, 0.152, 0.121, 0.093, 0.069, 0.048, 0.029, 0.014, 0.000) and a single domain (36 km horizontal grid spacing with 129 x 119 grid cells in the east-west and north-south directions). The other model settings included: YSU scheme for Planetary Boundary Layer (PBL) scheme, the Kain-Fritsch (new Eta) scheme for cumulus parameterization, simple ice scheme, RRTM radiation scheme, and a multi-level soil model. The National Center for Environmental Prediction (NCEP) Final analysis (FNL) data available at a horizontal resolution of 1^{o} x 1^{o} latitude/longitude and a time resolution of 6 hours was used to develop the initial and lateral boundary conditions. The climatological background error statistics (BES), which is a key component of 3DVAR system, was calculated for the entire month of September 2006, using the NMC method (Parrish and Derber, 1992). The BES utilized forecast differences of WRF-ARW model using NCEP-FNL data in 12 hour and 24 hour forecasts in which the control variables are in eigenvector space. It is true that there is scope to improve the model resolution in both the horizontal and vertical from what is being used in this study. This could possibly provide for a relatively more robust impact on the assimilation of MODIS observation.

The impact of the MODIS satellite data on the simulation of the September 2006 Bay of Bengal monsoon depression development is evaluated through two numerical (control and 3DVAR) experiments. The present study utilized MODIS temperature and humidity profiles at 14 standard pressure levels (1000, 950, 920, 850, 780, 700, 600, 500, 400, 300, 250, 200,150, 100 –in hPa). The total number of MODIS profiles assimilated is 2248 in number. The control experiment employed the NCEP-FNL analysis for the initial and lateral boundary and the model simulations were performed from 27 September 2006 06 UTC to 30 September 2006 12 UTC. The 3DVAR run assimilated the MODIS temperature and humidity profiles to improve the NCEP FNL analysis on 27th September 2006 06 UTC. For all the model simulations a time step of 108 seconds was used. The WRF model was subsequently integrated from 27 September 2006 06 UTC to 30 September 2006 12 UTC in a free forecast mode without any further assimilation of observations for the 3DVAR run. The results of the WRF simulation corresponding to the above two experiments were then compared with one another as well as with observations and NCEP FNL analysis. The root mean square (RMS) error is calculated for wind speed, temperature and dew point temperature with respect to all radiosonde station data available over Indian domain.

4. RESULT AND DISCUSSIONS

Fig. (**1**) depicts the model domain used in this study. Fig. (**2**) shows the analysis increment in potential temperature at the lowest σ level on 27 September 2006 06 UTC. It is clear

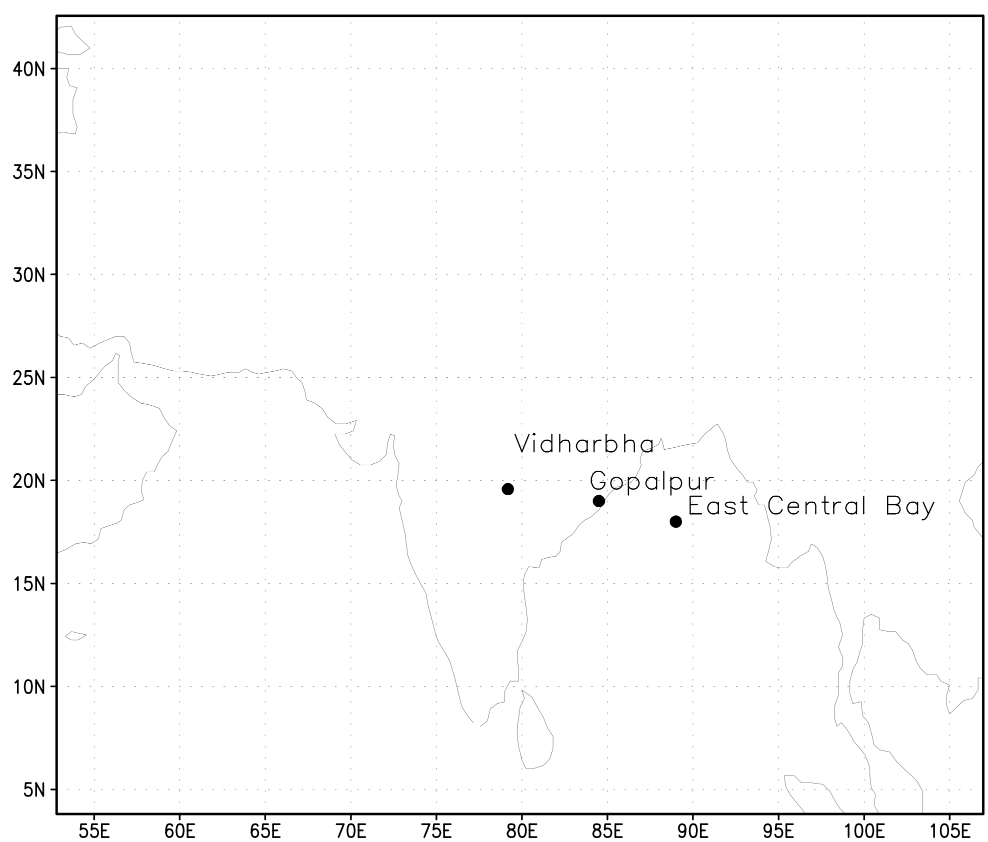

Fig. (1). Model domain.

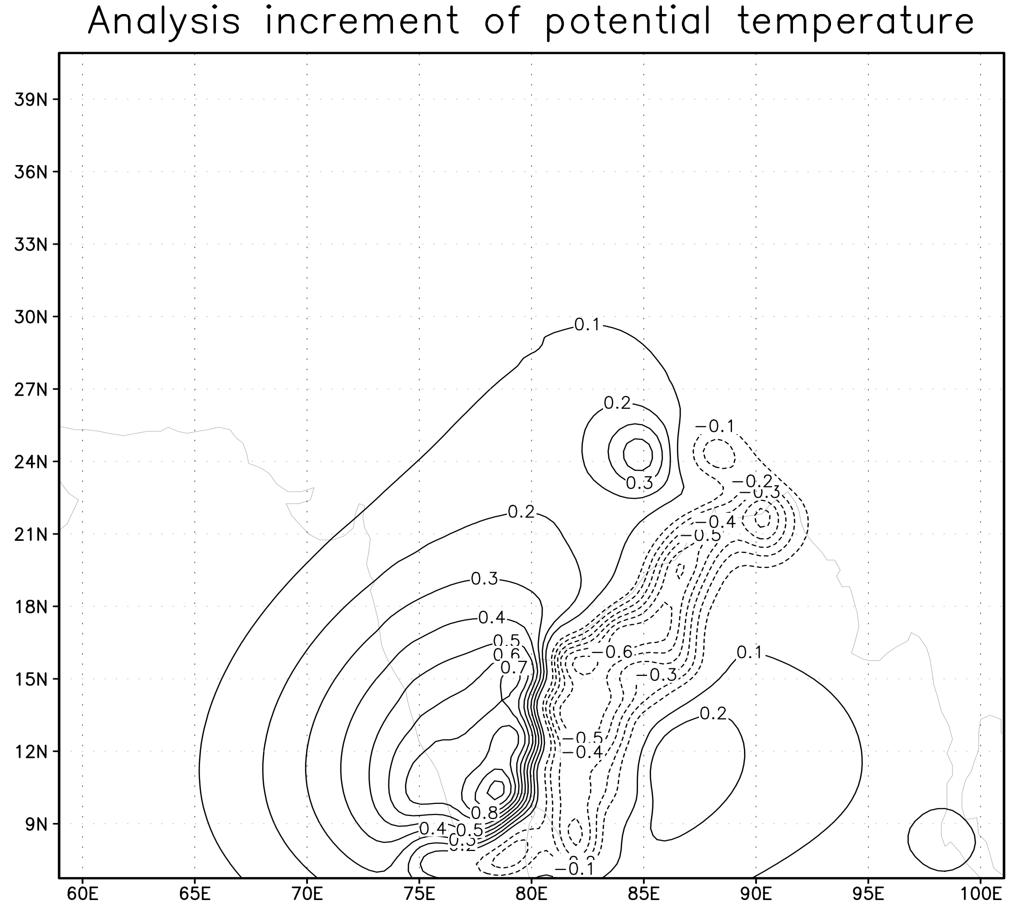

Fig. (2). Analysis increment in potential temperature at lowest sigma level on 27 September 2006 06 UTC.

from Fig. (**2**) that the assimilation of MODIS data has introduced moderate increments in potential temperature. Fig. (**3a-l**) depict the sea level pressure (SLP) fields valid on 29 September 2006 00 UTC, and after 12, 24 and 36 hours from the above time obtained from the NCEP FNL analysis (Fig. **3a-d**), the control (Fig. **3e-h**), 3DVAR (Fig. **3i-l**) runs. A very deep depression with SLP of the order of 998 hPa is manifested in the NCEP FNL analysis. Figs. (**3i-l**) reveal that the 3DVAR run simulates a relatively more active system as compared to the control run. The notable feature about the 3DVAR run is that it simulates the depression over the land on 30 September 12 UTC, while the control run fails to simulate the above feature. The SLP in the control run (Fig. **3e-h**), when compared to NCEP FNL analysis shows large errors in the location of the simulation of the center of the monsoon depression. The lower tropospheric winds (850 hPa) valid at 29 September 2006 00 UTC, and after 12, 24and 36 hours after the above time, from NCEP-FNL analysis, control and 3DVAR runs are shown in the Fig. (**4a-l**). The 3DVAR run could simulate a well-developed cyclonic circulation as seen in the NCEP-FNL analysis.

Also from Fig. (**4a-l**), it is clear that the 3DVAR run simulates a cyclonic circulation at 24 hour and 36 hours which is seen over larger land areas as compared to the control run and is in better agreement with the NCEP FNL analysis indicating the reduction in the errors of the wind field due to assimilation of observations.

Fig. (**5a-f**) depict the 24 hour accumulated precipitation with Fig. (**5a,b**) showing the Tropical Rainfall Measurement Mission (TRMM) precipitation observations valid at 29 September 2006 00 UTC and 30 September 2006 00 UTC, respectively. Fig. (**5c-f**) depict the 24 hour accumulated precipitation from the two model runs (control and 3DVAR) valid at 29 September 2006 12 UTC and 30 September 2006 12 UTC. It is clear from the observed TRMM data (Fig. **5a,b**) that the depression has provided copious rainfall to the coastal state of Orissa on 29 September 2006.

Furthermore, the TRMM rainfall data shows maxima in the rainfall pattern along the west coast of India. Also, the 24-hour accumulated rainfall in the 3DVAR run, shows maximum rainfall around 14cms, a value closer to the TRMM rainfall. It is to be noted that there are some positional errors associated with the maximum precipitation simulated by the 3DVAR run. However, the control run could neither simulate the intensity nor the location of maximum rainfall precisely.

4.1. Quantitative Validation

In order to get a quantitative measure of the effect of assimilation of the MODIS temperature and humidity profiles on the prediction of the monsoon depression with respect to NCEP-FNL, a box with a 10^0 x 10^0 domain was identified over the center of the depression. The space correlation as well as the rms errors of the SLP field for the control and

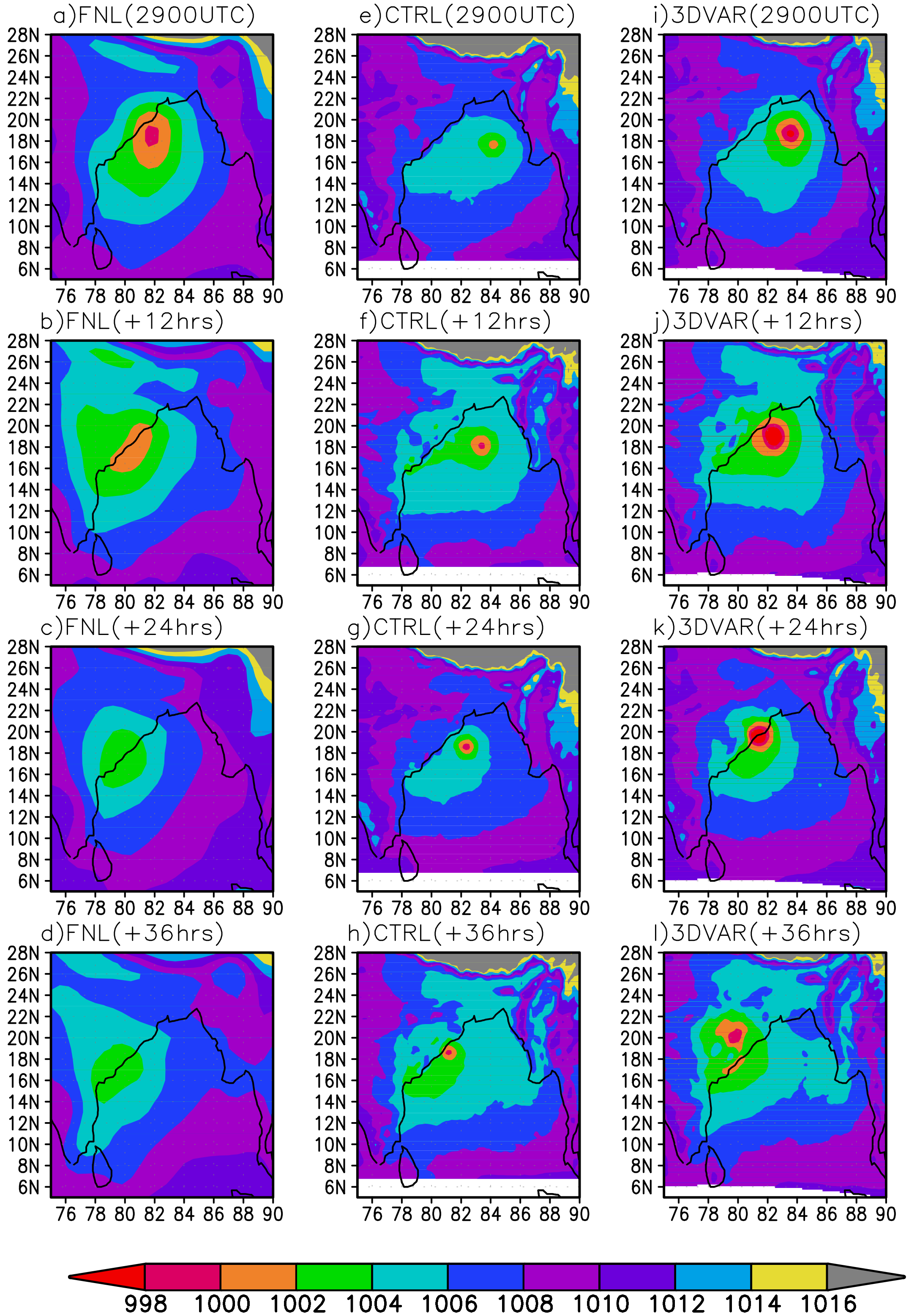

Fig. (3a-l). Mean sea level pressure of NCEP-FNL, CTRL and 3DVAR.

3DVAR runs were calculated at different times, with respect to the NCEP FNL analysis and are shown in Fig. (**6a**,**b**).

Fig. (**6a**) clearly shows that the 3DVAR run has higher spatial correlation of SLP (time averaged SLP is 0.65) as compared to the control run (time averaged SLP is 0.51). This shows clear improvement in the space correlation of the SLP field due to the assimilation of the MODIS temperature and humidity profiles. Consistent with the above observation, there is a marked reduction (time averaged rms value reduced from 1.76 hPa to 1.47 hPa) in the value of the rms

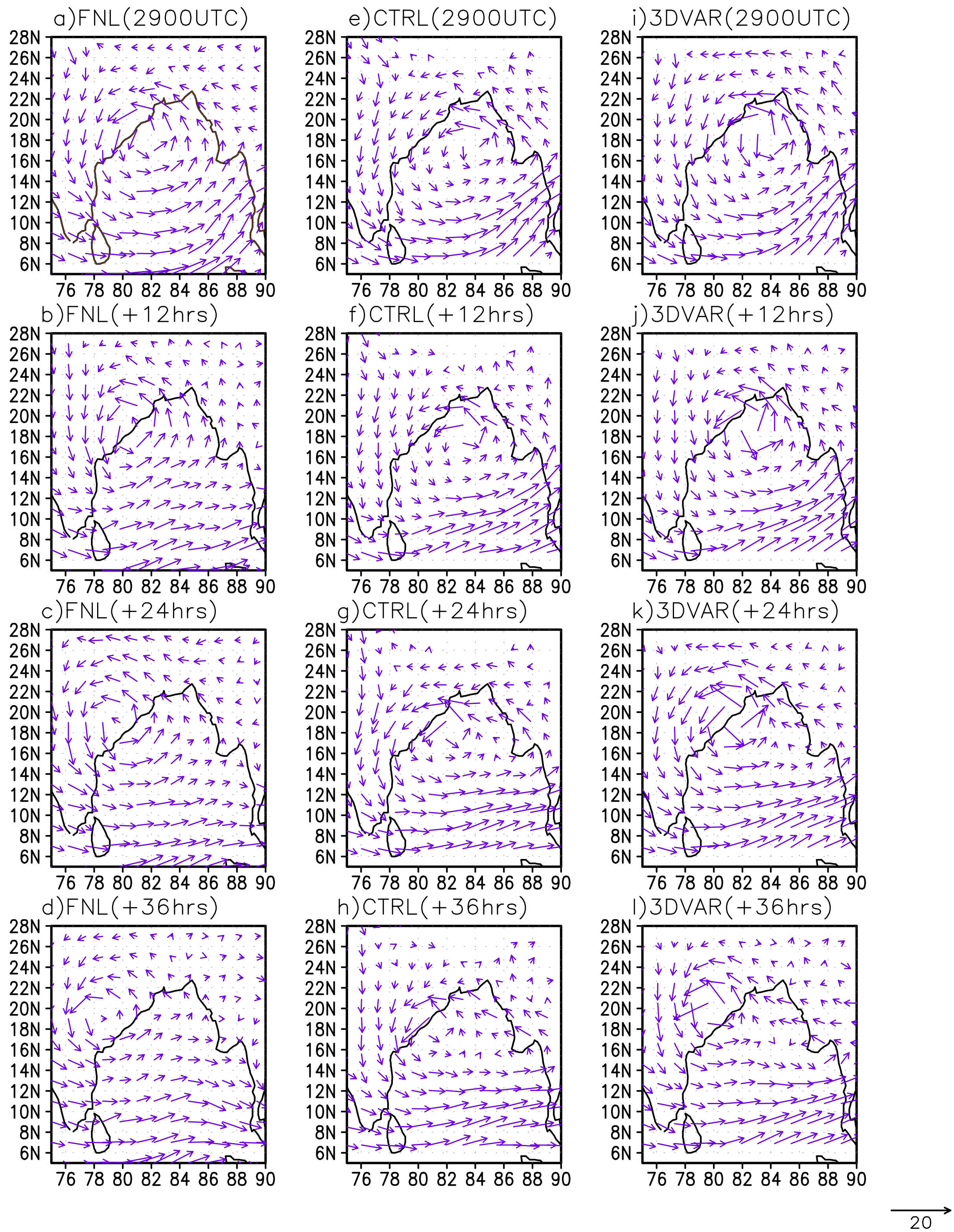

Fig. (4a-l). Lower tropospheric wind (ms^{-1}) at 850 hPa of NCEP-FNL, CTRL and 3DVAR.

errors of the SLP field due to the assimilation of the MODIS observations (refer Fig. (**6b**)).

4.1.1. Equitable Threat Score and Bias

A further quantitative measure of the impact of the assimilation of MODIS observations on 48-hour accumulated precipitation is calculated using the equitable threat score (ETS) and bias scores. From Fig. (**7b**) it is clear that the ETS values generated by 3DVAR are much greater than that of control run.

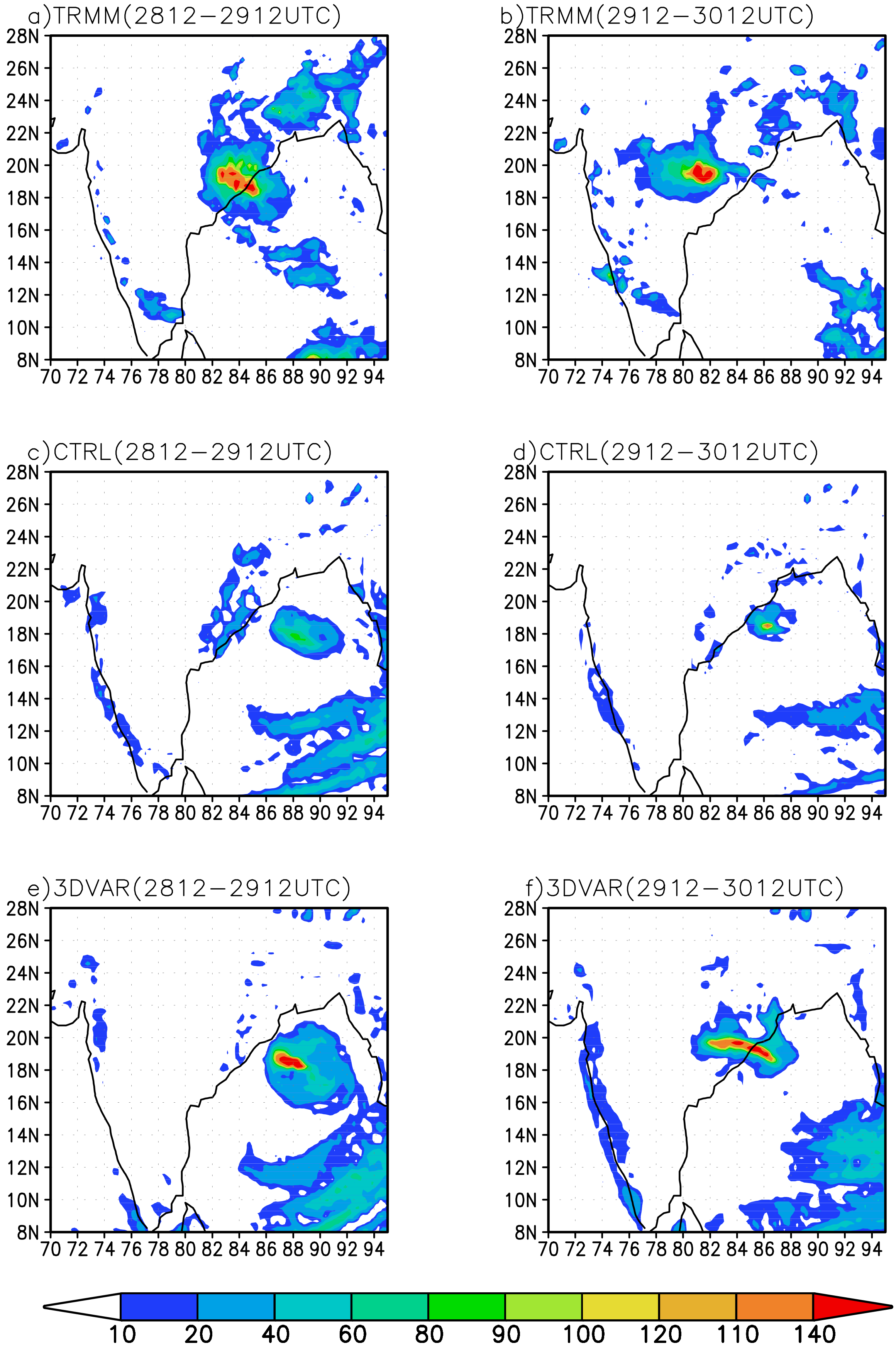

Fig. (5a-f). 24hr accumulated precipitation patterns (mm) from TRMM, CTRL and 3DVAR.

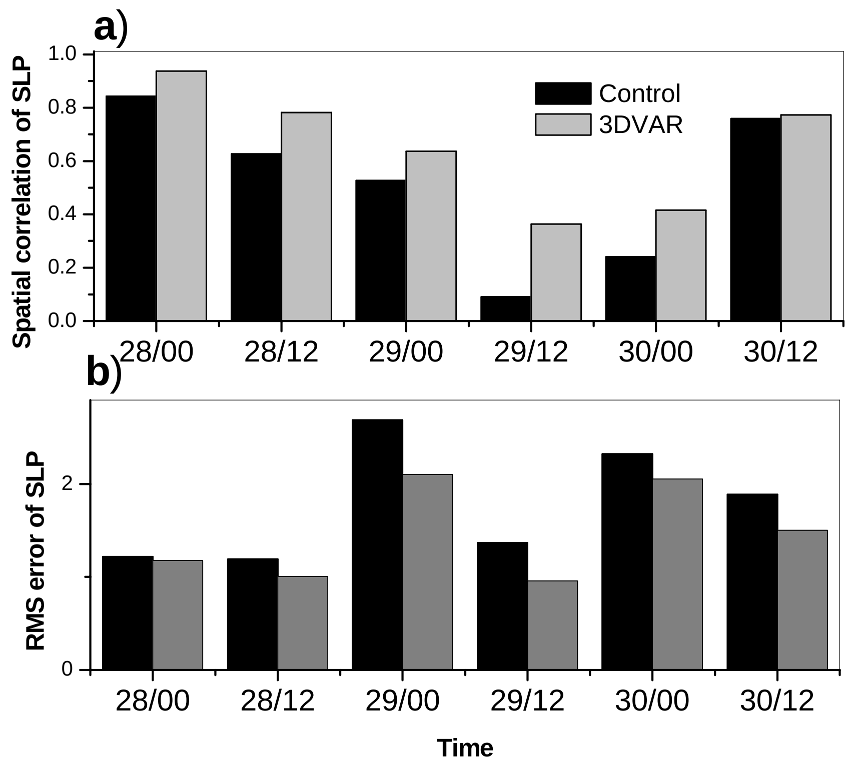

Fig. (6a-b). Time series of spatial correlation and rms error sea level pressure in hPa.

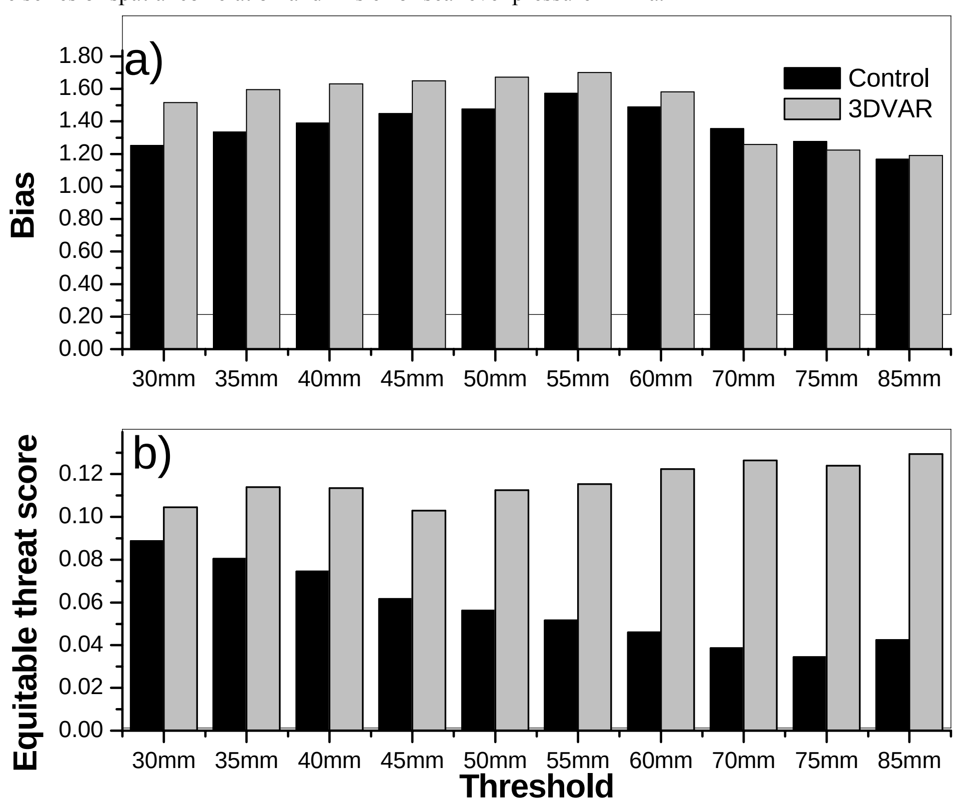

Fig. (7a-b). Bias and Equitable threat score of 48hour accumulated precipitation.

This is clear evidence of improvement in the forecasting ability of the model precipitation due to 3DVAR MODIS assimilation. Fig. (**7a**) shows the bias values for both control and the 3DVAR runs. A bias value of 1.0 indicates that the model forecast values of precipitation have the same frequency (or areal coverage) as that of the observation. The bias values associated with the 3DVAR run are higher than that of the control run, indicating that the 3DVAR run is overestimating the precipitation as compared to the control run.

4.1.2. Probability of Detection and False Alarm Ratio

The model simulated precipitation fields are further quantitatively analyzed using the False alarm ratio (FAR) and the probability of detection (POD) in Fig. (**8a**,**b**). False alarm ratio gives a measure of the false alarms (model simulating rainfall where none exists). From the Fig. (**8a**), it is clear that the false alarm ratio for control run is higher as compared to the 3DVAR run at all threshold values. However, the difference in the FAR of the control and 3DVAR runs with increase in threshold value shows an increase in magnitude, indicating that the number of false alarms for the control run increases at higher threshold values as compared to the 3DVAR run.

Fig. (**8b**) depicts the POD of rainfall for both the runs. It is clearly seen that the probability of detection of rainfall is greater for 3DVAR as compared to the control run at all times. Furthermore, the difference in POD of 3DVAR and the control run with increase in threshold values show an increase in magnitude, indicating that the probability of detection for the control run is decreasing at higher threshold values as compared to the 3DVAR run.

The model forecast soundings (vertical profiles of temperature, dew point temperature, and wind speed) were extracted at the grid cell (nearest to the India Meteorological Department (IMD) radiosonde/rawinsonde location) for both the model (control and 3DVAR) runs. The above-mentioned meteorological variables were then interpolated to the three standard pressure levels (850 hPa, 500 hPa and 200 hPa, representative of the lower, middle and upper troposphere) through log pressure interpolation. The rms errors were calculated at a given time by summing over all the radiosonde/rawinsonde stations for the two (control and 3DVAR) runs at that time. Subsequently, the above procedure was extended for all times.

4.1.3. Rms Error of Temperature

A clear reduction in the rms errors of temperature at 850 hPa (Fig. **9**), and at 500 hPa (Fig. **10**) in the 3DVAR run is noted for most of the times. However, the reduction in the rms error of temperature is not marked in the 3DVAR run at 200 hPa (Fig. **11**). The time-averaged value of the rms error for temperature at 850 hPa is 2.2 K for control run and 2.0 K for the 3DVAR. For 500 hPa, the time-averaged value of the rms error for the temperature is 3.3 K for both the control and the 3DVAR runs. Again, for 200 hPa, the time-averaged value of the rms error for the temperature is 5.0 K for control run and 4.9 K for the 3DVAR run.

4.1.4. Rms Error of Dew Point Temperature

The rms error of 3DVAR at 850 hPa (Fig. **12**) for dew point temperature shows higher values at 29 September 2006 00 UTC and 30 September 2006 12 UTC. For all other times there is significant reduction of root mean square error in 3DVAR as compared to control run. For 500 hPa, except for 28 September 2006 12 UTC, the 3DVAR run shows marked

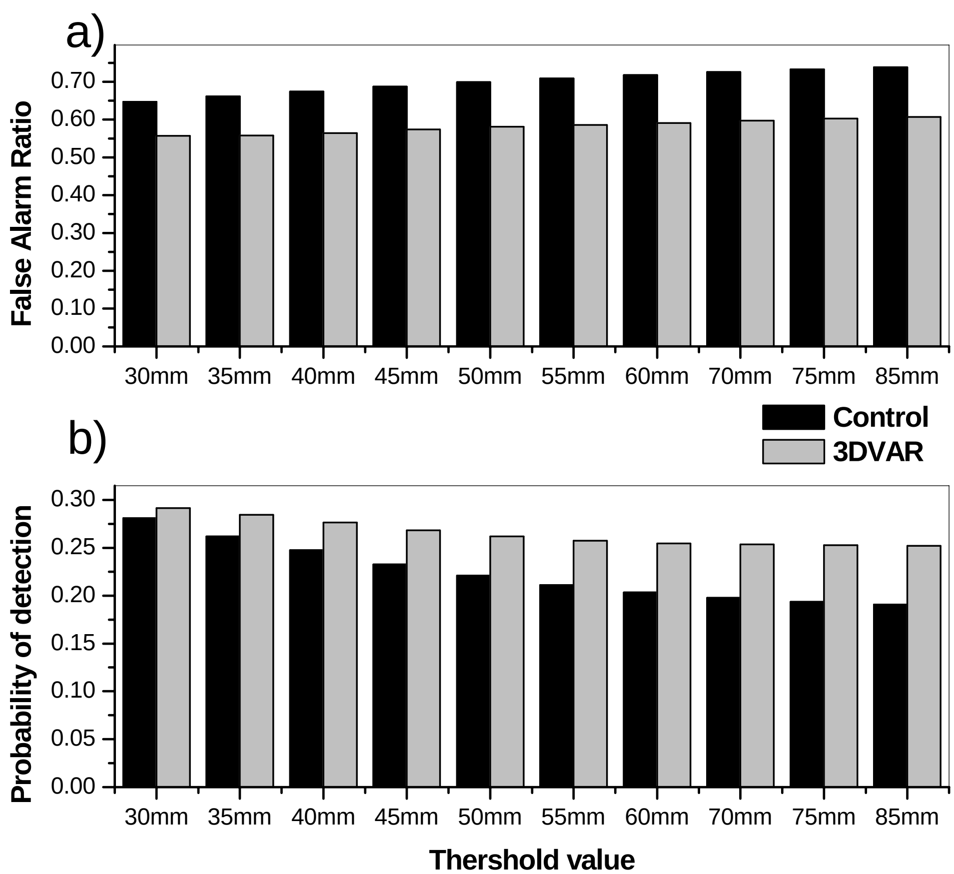

Fig. (8a-8b). False alarm ratio and probability of detection of precipitation.

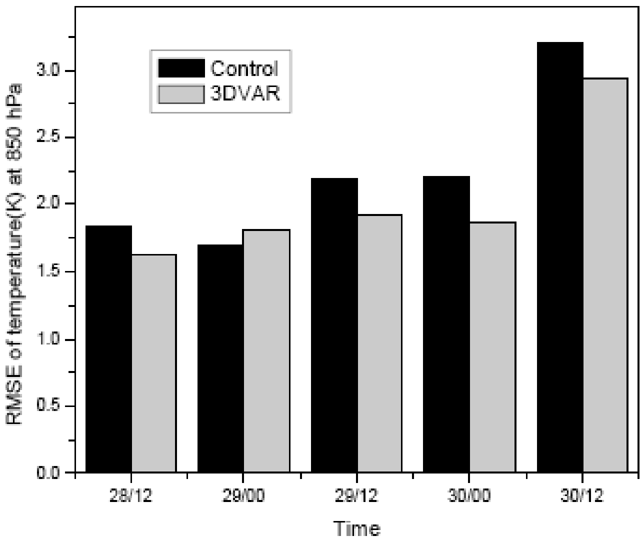

Fig. (9). Rmse of temperature(K) at 850 hPa.

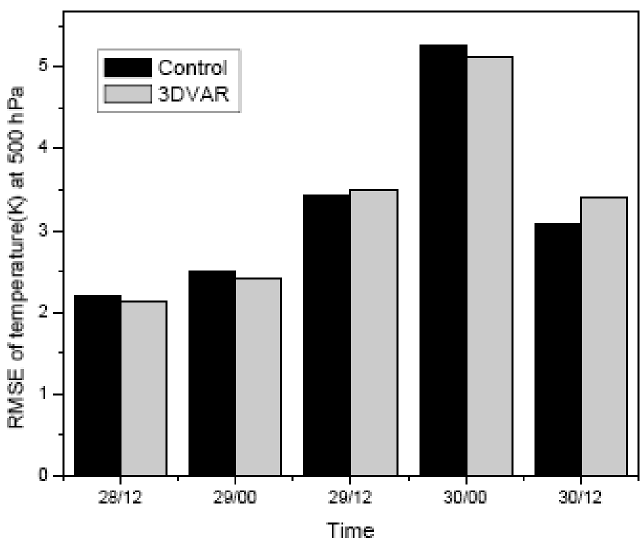

Fig. (10). Rmse of temperature(K) at 500 hPa.

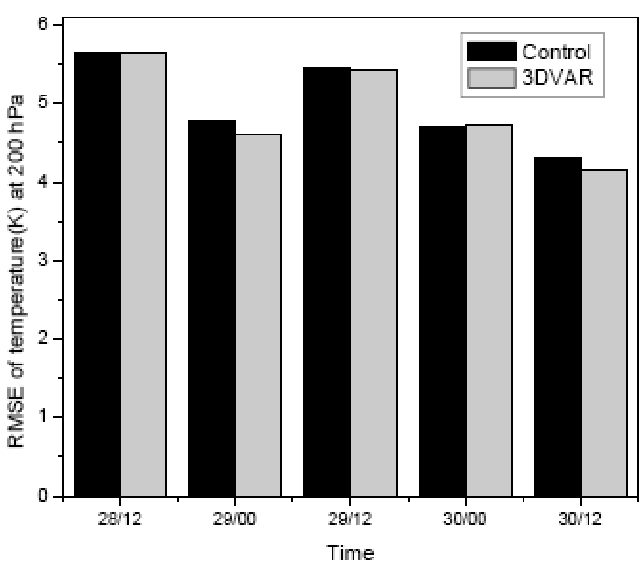

Fig. (11). Rmse of temperature (K) at 200 hPa.

drop in rms errors of dew point temperature (Fig. **13**). The improvement in the rms errors for dew point temperatures at 500 hPa on 30 September 2006 00 UTC are of the order of 6 K. The time-averaged value of the rms error for dew point temperature at 850 hPa is 4.5 K for control run and 4.3 K for the 3DVAR. For 500 hPa, the time-averaged value of the rms error for the dew point temperature is 11.0 K for control and 8.6 K for the 3DVAR run. At 200 hPa the time-averaged rms error for dew point temperature is 6.6 K for control and 7.7 K for the 3DVAR run. The rms errors of moisture for model runs usually show lower values in the lower troposphere since more moisture observations are available at 850 hPa. The results of this study generally agree with the above observation. Figs. (**12-14**) depicts the root mean square errors of dew point temperature at 850 hPa, 500 hPa and 200 hPa respectively.

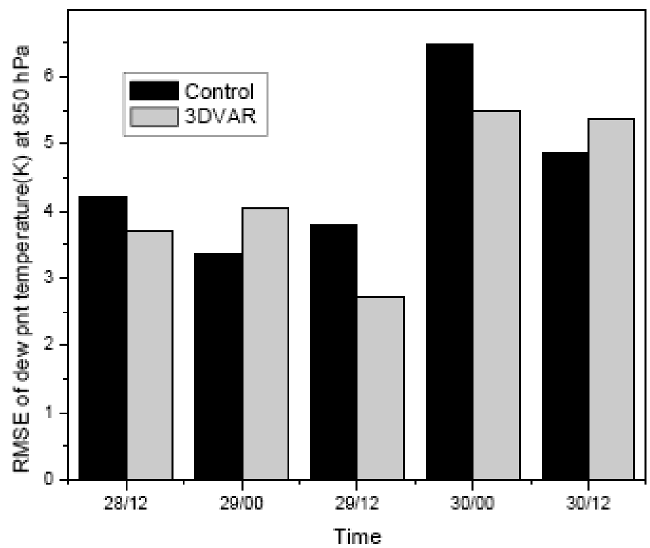

Fig. (12). Rmse of dew point temperature (K) at 850 hPa.

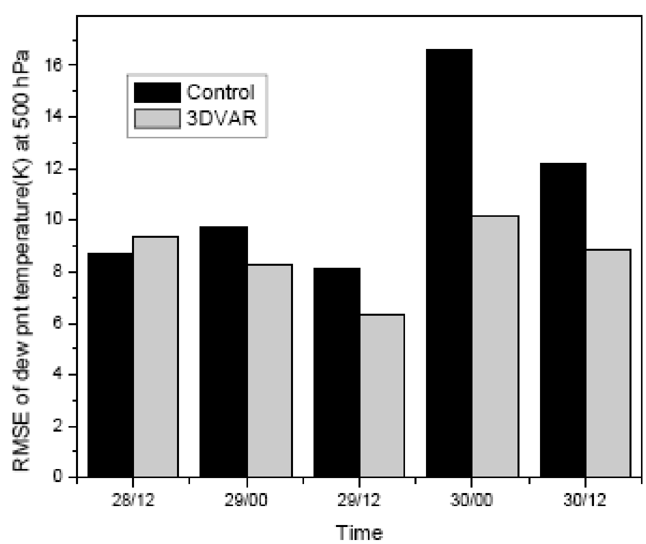

Fig. (13). Rmse of dew point temperature (K) at 500 hPa.

4.1.5. Rms Error of Wind Speed

The rms errors of the wind speed show maximum values over the upper troposphere with lower values in the lower

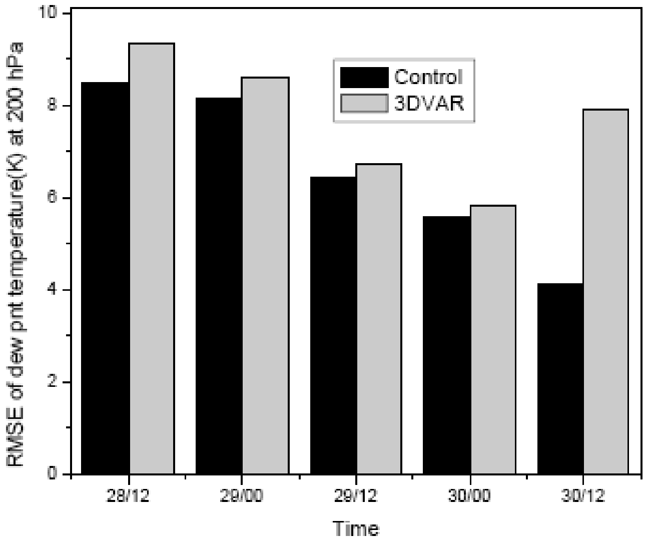

Fig. (14). Rmse of dew point temperature (K) at 200 hPa.

and middle troposphere. The results reveal that there is no marked reduction in the rms errors wind speed due to the assimilation of MODIS observations at 850 and 500 hPa. However, at the initial times, rms errors of wind speed for 3DVAR run at 200 hPa shows lower values as compared to the control run. The time-averaged value of the rms error for wind speed at 850 hPa is 5.2 m s^{-1} for control run and 5.6 m s^{-1} for the 3DVAR. For 500 hPa, the time-averaged value of the rms error for the wind speed is 3.7 m s^{-1} for the control and 4.2 m s^{-1} for the 3DVAR run. Again, for the 200 hPa, the time-averaged value of the rms error for the wind speed is 10.1 m s^{-1} for the control and 9.5 m s^{-1} for the 3DVAR run

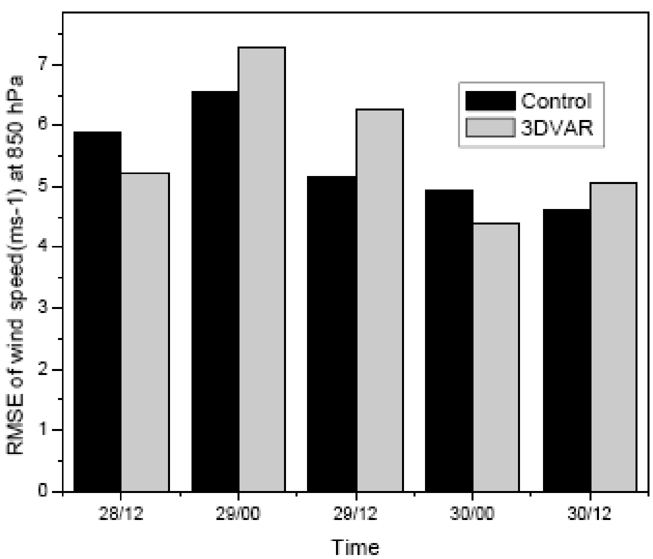

Fig. (15). Rmse of wind speed (ms^{-1}) at 850 hPa.

5. CONCLUSIONS

This study has explored the impacts of assimilation of the MODIS observations (temperature and humidity profiles) on the structure and associated precipitation pattern of a monsoon depression, which formed over the Bay of Bengal during September 27-30 using a mesoscale model. The only

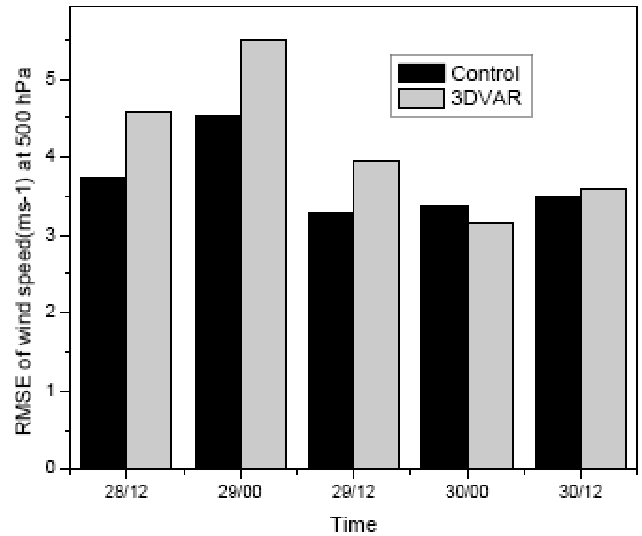

Fig. (16). Rmse of wind speed (ms^{-1}) at500 hPa.

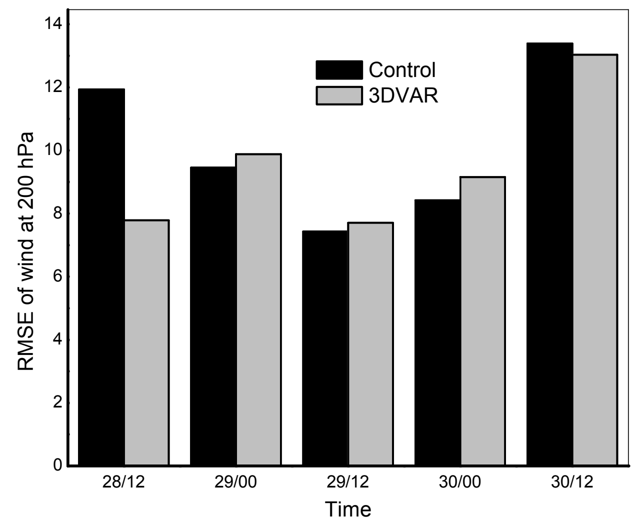

Fig. (17). Rmse of wind speed (ms^{-1}) at 200 hPa.

source of information of the upper temperature and humidity profiles over the tropical oceanic regions is the satellites. It is true that performing simulations for a single depression cannot yield broad conclusions on the impact of MODIS assimilation. However, there have not been many studies, which have addressed the impact of ingestion and assimilation of MODIS observation on the prediction of tropical systems over the Indian region using WRF-VAR. With the availability of the MODIS data, it was thought that there is a real need to undertake such a study as this, even if the study is restricted to a single depression. The model output has been analyzed both qualitatively and quantitatively. The results of this study provide direct and good evidence of the impact of the assimilation of the MODIS using 3DVAR on the structure and spatial pattern of the precipitation associated with a monsoon depression. The monsoon depression is showing landfall at 30 September 12 UTC for 3DVAR run. Equitable threat score for precipitation shows higher values for the run with MODIS assimilation. The probability of detection of precipitation also increases in 3DVAR run. The sea level pressure field for the 3DVAR experiment shows higher spatial correlation and lower rms errors with respect to the

NCEP FNL analysis as compared to the control run. However, it is true that the rms error of the dew point temperature at 500 hPa at 12 UTC on 28 September 2006 and for most of the times at 200 hPa have larger magnitudes for the 3DVAR run as compared to the control run. Most models have difficulty in accurately simulating the moisture content especially in the upper troposphere. Furthermore, the moisture content in the upper troposphere is very low and any inaccuracies in the upper tropospheric moisture observations can lead to inadequate predictions of the moisture content in the upper troposphere. Except for 200 hPa, there are no marked improvements in the rms errors of the wind speed due to assimilation of MODIS observations. The model experiment with the assimilation of MODIS observation (3DVAR) also shows increased rainfall over a larger land area on the eastern coast of India as compared to the control run. Intense cyclonic circulation can be seen over land region for the 3DVAR run from the wind fields at 850 hPa. Also, there is some discernable reduction in the rms errors of temperature and dew point temperature due to the assimilation of MODIS observations. It is true that there is scope to improve the model resolution in both the horizontal and vertical and this possibly can provide a better and more robust impact on the assimilation of MODIS observation. Furthermore, assimilating the MODIS data over several analysis cycles, could also possibly improve the impact of assimilating MODIS observations.

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