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The effect of a surface data assimilation technique and the traditional four-dimensional data assimilation on the simulation of a monsoon depression over India using a mesoscale model

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Abstract The objective of this study is to investigate the impact of a surface data assimilation (SDA) technique, together with the traditional four-dimensional data assimilation (FDDA), on the simulation of a monsoon depression that formed over India during the field phase of the 1999 Bay of Bengal Monsoon Experiment (BOBMEX). The SDA uses the analyzed surface data to continuously assimilate the surface layer temperature as well as the water vapor mixing ratio in the mesoscale model. The depression for the greater part of this study was offshore and since successful application of the SDA would require surface information, a method of estimating surface temperature and surface humidity using NOAA-TOVS satellites was used. Three sets of numerical experiments were performed using a coupled mesoscale model. The first set, called CONTROL, uses the NCEP (National Center for Environmental Prediction) reanalysis for the initial and lateral boundary conditions in the MM5 simulation. The second and the third sets implemented the SDA of temperature and moisture together with the traditional FDDA scheme available in the MM5 model. The second set of MM5 simulation implemented the SDA scheme only over the land areas, and the third set extended the SDA technique over land as well as sea. Both the second and third sets of the MM5 simulation used the

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NOAA-TOVS and QuikSCAT satellite and conventional upper air and surface meteorological data to provide an improved analysis. The results of the three sets of MM5 simulations are compared with one another and with the analysis and the BOBMEX 1999 buoy, ship, and radiosonde observations. The predicted sea level pressure of both the model runs with assimilation resembles the analysis closely and also captures the large-scale structure of the monsoon depression well. The central sea level pressures of the depression for both the model runs with assimilation were 2–4 hPa lower than the CONTROL. The results of both the model runs with assimilation indicate a larger spatial area as well as increased rainfall amounts over the coastal regions after landfall compared with the CONTROL. The impact of FDDA and SDA, the latter over land, resulted in reduced errors of the following: 1.45 K in temperature, 0.39 m s^{-1} in wind speed, and 14° in wind direction compared with the BOBMEX buoy observation, and 1.43 m s^{-1} in wind speed, 43° in wind direction, and 0.75% in relative humidity compared with the CONTROL. The impact of SDA over land and sea compared with SDA over land only showed a further marginal reduction of errors: 0.23 K in air temperature (BOBMEX buoy) and 1.33 m s^{-1} in wind speed simulations.

Keywords SDA · FDDA · NOAA-TOVS · QuikSCAT · Bay of Bengal · Monsoon depression

1 Introduction

Data assimilation methods combine all available meteorological observations, both past and present, to improve the analysis. The utility and the benefits of the traditional nudging approach through the four-dimensional data assimilation (FDDA) have been extensively studied and reported in the literature (Stauffer and Seaman 1990). Large errors in atmospheric boundary layer (ABL) simulations can arise due to inaccurate surface parameters as well as simplification in the boundary layer formulations and other model deficiencies (Alapaty et al. 1997; Niyogi et al. 1999). One way of overcoming the large errors in ABL simulation is to assimilate surface observations. Alapaty et al. (2001) have proposed a new surface data assimilation (SDA) scheme that allows for the continuous assimilation of surface observations to improve surface layer prediction. In the new scheme, Alapaty et al. (2001) directly assimilated the surface layer temperature and the water vapor mixing ratio into the model's lowest atmospheric layer using analyzed surface data. The assimilated temperature and water vapor mixing ratio were then used to calculate the corrections in the surface sensible and latent heat fluxes as a difference between the model prediction and observation (of temperature and humidity). They used a simple surface energy budget equation to estimate the new ground/skin temperature and showed that this approach, when applied at every advective time step, can significantly reduce simulation errors in the ABL. Additionally, this approach takes care of the unrealistic changes in the sign of the surface buoyancy flux and hence improves on the Stauffer et al. (1991) technique. More details of the SDA scheme are available in Alapaty et al. (2001).

The chief objective of this study is to investigate the impact of FDDA and the SDA of temperature and humidity (the latter over land only and also over both land and sea) on the structure and spatial distribution of the precipitation of a monsoon depression that formed during the field phase of the Bay of Bengal Experiment (BOBMEX, Bhat and Ameenulla 2000). The satellite (QuikSCAT surface wind vector over seas and NOAA-TOVS temperature and humidity profiles, and estimated surface values of temperature and humidity from NOAA-TOVS) and the conventional upper air and surface meteorological observations from the India Meteorological Department (IMD) are used for assimilation. The SDA of temperature and humidity alone cannot contribute to an improved thermodynamic structure above the ABL. Hence, this study has endeavored to study the simultaneous impact of FDDA as well as SDA on the prediction of a monsoon depression where the SDA is restricted over land and also over land and sea. The next section provides an account of the case study, the data, and observations used, and the model experiments, followed by the results and discussions, and the conclusions of the study.

2 Numerical experiments

A low pressure system formed in the North Bay of Bengal on 25 July 1999. The system intensified to a depression on 27 July and further intensified into a deep depression on 28 July just before making landfall. The deep depression weakened into a low pressure system on 30 July over central India, northwest Madhya Pradesh, and continued to move west north-westward and weakened over Rajasthan on 3 August 1999. Das et al. (2003) obtained an enhanced analysis of the monsoon depression on 27 July 1999, 12 UTC by ingesting additional satellite, synoptic, and asynoptic data to the National Center for Environmental Prediction (NCEP) reanalysis data and found improvements due to the enhanced analysis. The Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) on board the National Oceanographic and Atmospheric Administration (NOAA) satellite provided 17 levels of temperature and six levels of humidity, with 80 km being the horizontal distance between any two retrievals. Off-shore surface wind vector from QuikSCAT with a swath of 1,800 km and a spatial resolution of 25 km $\times$ 25 km was also used. In addition to the above satellite observations, the assimilation employed IMD observations of conventional upper air (radiosonde/rawinsonde [RS/RW], pilot balloon [PB]), and surface observations. Besides the operational data sets, this case also corresponded to a special field program called BOBMEX. The BOBMEX data are used as additional data to evaluate model performance. The availability of surface temperature and surface humidity over the sea is restricted to ship/buoy data since satellites, including the NOAA-TOVS, do not provide them. In order to obtain surface temperature and surface humidity from the NOAA/TOVS satellite, a procedure to estimate them was taken from the work of Simon and Desai (1986).

A number of recent studies have employed mesoscale models to study monsoon depressions and low pressure systems over India (Roy Bhowmik 2003; Potty et al. 2000; Vaidya et al. 2004; Mukhopadhyay et al. 2005; Xavier et al. 2006). The present study used MM5 version 3.5 (Grell et al. 1994). The model was configured with 23 vertical layers (centered s = 0.995, 0.985, 0.97, 0.945, 0.91, 0.87, 0.825, 0.775, 0.725, 0.675, 0.625, 0.575, 0.525, 0.475, 0.425, 0.375, 0.325, 0.275, 0.225, 0.175, 0.125, 0.075, 0.025) and two nested domains (Outer Domain: 90 km grid spacing with 85 $\times$ 75 grid cells in east–west and north–south directions; Inner Domain: 30 km grid spacing with

129×119 grid cells in the east–west and north–south directions). The other model settings included: MRF PBL scheme, Grell cumulus scheme, Dudhia's simple ice scheme, a simple radiation scheme, and a multi-level soil model. The NCEP reanalysis data available at a horizontal resolution of $2.5° \times 2.5°$ and a time resolution of 6 h were used to develop the initial and lateral boundary conditions. A one-way nesting was employed. Three numerical experiments were designed to study the simultaneous impact of FDDA along with the SDA of temperature and humidity. The first experiment (called CONTROL simulation) used the NCEP reanalysis for the initial and lateral boundary conditions, and the model integrations were performed from 25 July 1999, 00 UTC to 29 July 1999, 00 UTC. The second numerical experiment (FDDA and SDA of temperature and humidity, the latter over land only, known henceforth as SDAL simulation) incorporated the NOAA-TOVS temperature and humidity profiles, QuikSCAT wind speed and wind direction, and IMD RS/RW, PB, and surface data, and also the surface temperature and humidity estimated from NOAA-TOVS over India to improve the NCEP reanalysis between 25 July 1999, 00 UTC and 26 July 1999, 00 UTC. The nudging coefficients used in this study are the following: 2.5×10^{-4} s^{-1} for temperature and wind, and 1×10^{-5} s^{-1} for the mixing ratio for 3-D analysis, and 2.5×10^{-4} s^{-1} for surface wind, and 5×10^{-4} s^{-1} for surface temperature and surface mixing ratio. In addition to the SDA scheme of temperature and mixing ratio (Alapaty et al. 2001) using the larger values of the nudging coefficients (response time to the order of 30 min) and the analysis nudging of the temperature, winds, and mixing ratio in the 3-D analysis, the surface winds were also assimilated using the nudging technique (Stauffer and Seaman 1990). The MM5 model was integrated into the free forecast mode from 26 July 1999, 00 UTC to 29 July 1999, 00 UTC. The third numerical experiment (FDDA and SDA of temperature and humidity, the latter over land and sea, known henceforth as SDALS simulation) was similar to the second experiment except that the SDA of temperature and humidity were extended over both land and sea. The SDA and SDALS runs during the pre-forecast assimilation period were subjected to quality control checks as available in the little-rawins module of the MM5 model. The results of the MM5 simulations corresponding to the three numerical experiments were then compared with observations and NCEP reanalysis. All the results discussed in this study correspond to the 30-km domain.

3 Results and discussions

An important objective of this work is to study the structure of a monsoon depression and the impact of ingestion and assimilation of satellite data (NOAA-TOVS temperature and humidity profile and QuikSCAT) and conventional observations over India using a simultaneous application of FDDA and SDA (both SDAL and SDALS). Figures 1 and 2 show the sea level pressure (SLP) pattern for 26–29 July 1999, 00 UTC from NCEP reanalysis and MM5 simulations. The CONTROL simulation indicates a much weaker depression with the central SLP higher by 2–4 hPa compared with the SDAL and SDALS model runs. Figures 1 and 2 shows that the impact of the SDALS model run reveals an SLP pattern that has a better large scale structure compared with the SDAL run. For both the SDA and SDALS runs, in the initial analysis (00 UTC, 26 July 1999) there appears near the northern

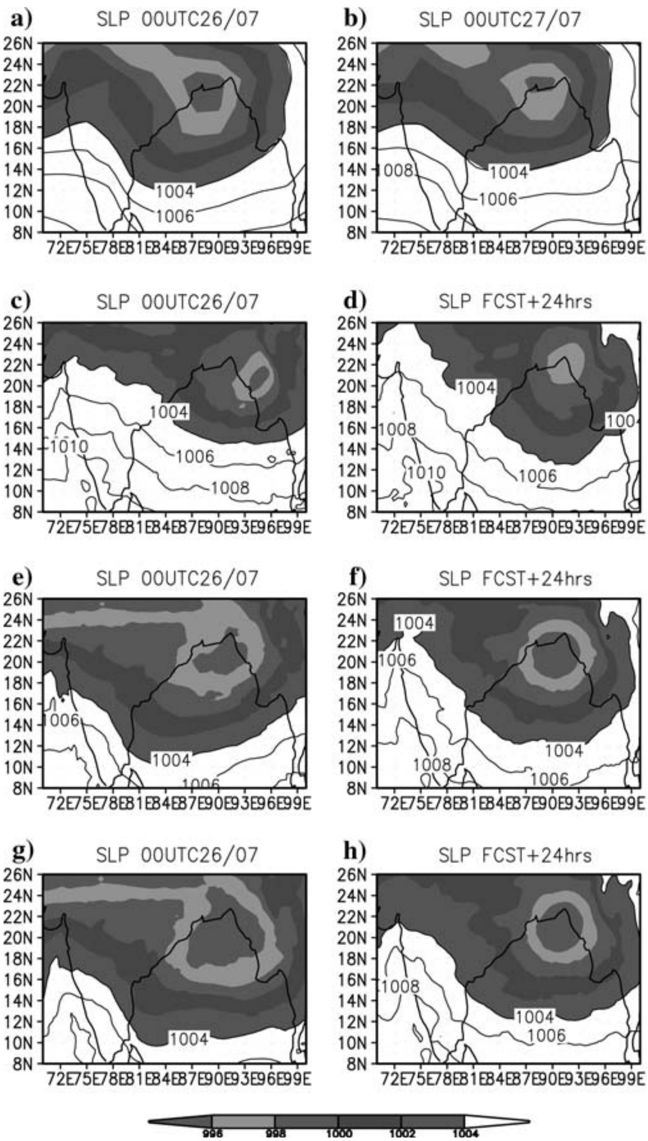


Fig. 1 Sea level pressure (hPa) for 26–27 July 1999, 00 UTC. (**a**, **b**) NCEP (National Center for Environmental Prediction) reanalysis, (**c**, **d**) CONTROL simulation, (**e**, **f**) SDAL (surface data assimilation, land only) simulation, and (**g**, **h**) SDALS (surface data assimilation, land and sea) simulation

boundary an east–west belt in the SLP pattern that is absent in the forecast. A low pressure trough called the monsoon trough is normally seen under active monsoon conditions oriented along the northwest–southeast direction from northwest India to the north Bay of Bengal region. The SLP field for the SDA and SDALS runs in the initial analysis shows that this monsoon trough is indeed very strong. Too strong an adjustment of the surface temperature and surface mixing ratio is possibly the reason for the above feature. It is possible that a smaller value of the radius of influence of

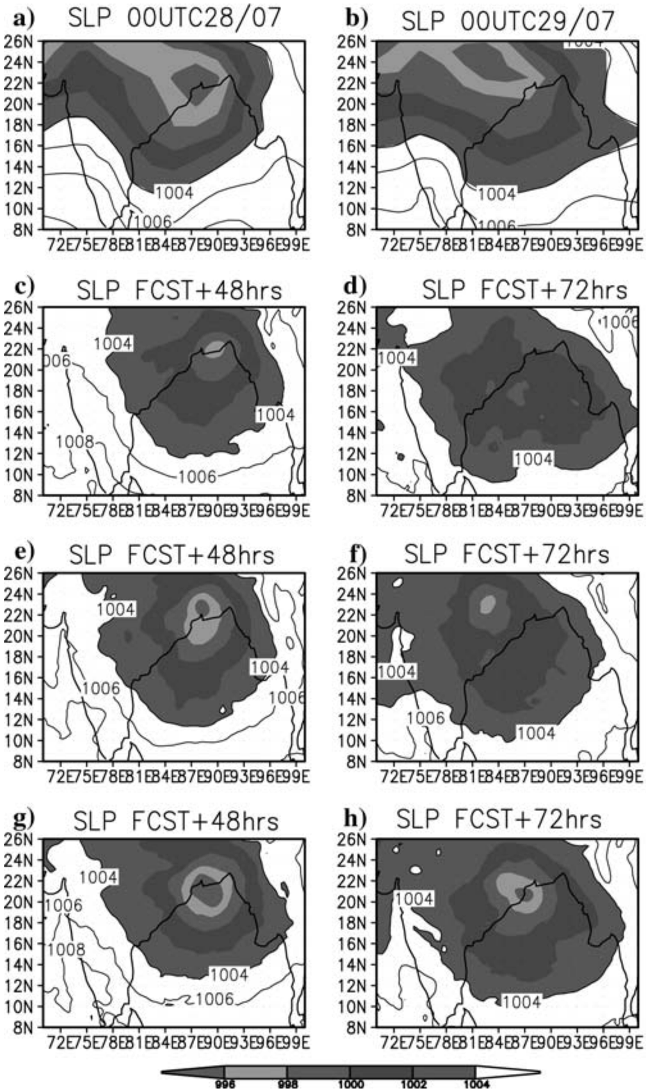


Fig. 2 Same as Fig. 1, for 28–29 July 1999, 00 UTC

the surface analysis than the one used in this study may help in reducing the too strong adjustment in the initial analysis. The fact that the east–west low-pressure belt is absent in the forecast indicates that the model without the SDA has smoothed out the east–west low-pressure belt during the forecast period. Observations indicate that the monsoon depression crossed land on 28 July 1999 and this feature is reproduced by the SDAL run. However, there is a delay in the depression crossing inland for the SDALS run (Fig. 2). Possible reasons for the above in the SDALS run are the larger number of estimates of surface temperature and surface mixing ratio data over both land and sea, obtained from NOAA-TOVS using the algorithm of Simon and Desai (1986) compared with the SDAL run where only the surface temperature and surface mixing ratio data over land were used in the SDA scheme. It is normally expected that a system will weaken slightly after it crosses inland due to frictional effects. The above observation generally holds for tropical cyclones, but may not always for monsoon depressions since the latter form in a moisture-rich environment of the Indian summer monsoon season. The SDAL run shows a weakening of the system after landfall. However, the SDALS run does not reveal a marked weakening of the depression after landfall, a feature also observed in the NCEP reanalysis. More surface temperature and mixing ratio data (estimated from NOAA-TOVS) over both land and sea ensured that the system did not weaken after landfall in the SDALS run. However, since the surface temperature and surface mixing ratio data over the sea in the SDALS run were estimates and not observed data, it is possible that the system was somewhat slower in the SDALS run. In order to obtain a quantitative measure of the impact of the improved analysis, the following strategy was conceived. A spatial box of $15° \times 15°$ domain was identified over the center of the depression. The space correlation as well as the root mean square errors (RMSE) of the SLP field for all three MM5 simulations (CONTROL, SDAL and SDALS) with regard to the NCEP reanalysis was calculated at different times and is shown in Table 1. The space correlations of the simulations with SDALS assimilations are higher by 0.22 and 0.25 compared with the SDAL simulations and the CONTROL simulations. The RMSE of the SLP for the SDALS run are consistently lower (except for the initial time) by 1.78 hPa and 3.61 hPa compared with the SDAL and CONTROL simulations.

Figures 3 and 4 depict the lower tropospheric winds for 26–29 July 1999, 00 UTC and the 24-h accumulated precipitation for 27–29 July 1999, 00 UTC. The figures show NCEP reanalysis and MM5 runs for CONTROL, SDAL, and SDALS simulations. The lower tropospheric winds from the NCEP reanalysis refer to a height of 1,829 m, and the winds from the MM5 model simulation correspond to the nearest s level (s = 0.775) with a height of 1,882 m. The assimilation of high-resolution QuikSCAT wind observation in the SDAL and SDALS runs have produced a well-developed cyclonic circulation (Figs. 3, 4). The impact of the SDALS run shows a cyclonic circulation, which is stronger north of the center of the monsoon depression compared with the SDAL run (Figs. 3, 4). All three MM5 simulations (CONTROL, SDAL, and SDALS) do not reveal marked inland penetration of the 24-h accumulated precipitation on 28 and 29 July 1999, 00 UTC. The slower response is

Table 1 Space correlation and root mean square errors (RMSE) of the sea level pressure (SLP) field for all three MM5 simulations

Date	Spatial correlation			RMS error		
	CONTROL	SDAL	SDALS	CONTROL	SDAL	SDALS
26/07/1999 00 UTC	0.385	0.695	0.593	3.582	2.112	2.393
26/07/1999 12 UTC	0.367	0.523	0.616	5.405	3.569	1.789
27/07/1999 00 U TC	0.467	0.296	0.493	2.755	2.803	2.590
27/07/1999 12 UTC	0.668	0.491	0.712	5.219	4.797	4.032
28/07/1999 00 UTC	0.534	0.505	0.599	3.363	3.301	2.704
28/07/1999 12 UTC	0.399	0.422	0.485	4.958	4.996	3.948
29/07/1999 00 UTC	–0.009	0.0276	0.194	4.618	4.465	3.908

CONTROL, SDAL (surface data assimilation, land only) and SDALS (surface data assimilation, land and sea) compared with NCEP reanalysis for a region $15° \times 15°$ around the depression center

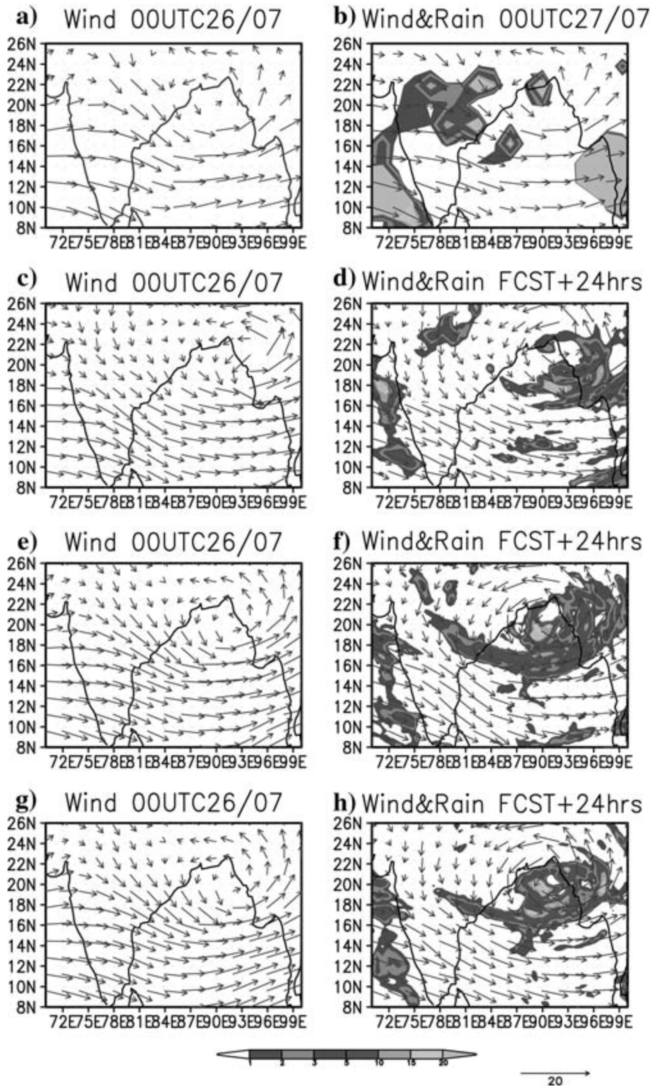


Fig. 3 Lower tropospheric winds (m s^{-1}; 1,829 m for NCEP reanalysis and s = 0.775 with an average height of 1,882 m for MM5 simulations) for 26–27 July 1999, 00 UTC and 24-h precipitation for 27 July 1999, 00 UTC. (**a**, **b**) NCEP reanalysis, (**c**, **d**) CONTROL simulation, (**e**, **f**) SDAL simulation, and (**g**, **h**) SDALS simulation

potentially due to additional errors in the upper air data, and larger scale forcings were not properly captured by the limited area model. It is possible that the assimilation of cloud vector motion winds derived from satellites may help to reduce uncertainties in the upper level winds and thus improve inland penetration. The 24-h accumulated precipitation from the MM5 simulations with assimilation (SDAL and SDALS) reveals an improved large-scale structure of the spatial precipitation pattern on 27 July 1999, 00 UTC compared with in the CONTROL simulations. The MM5 simulations with assimilation (Fig. 4) exhibit greater amounts of rainfall over

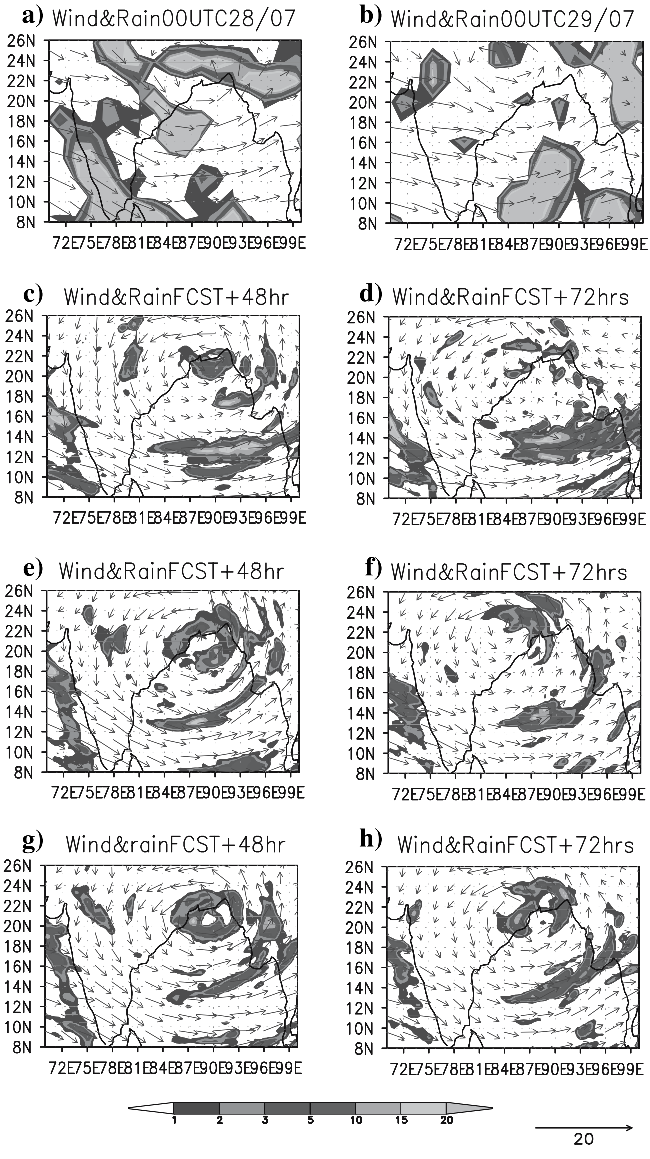
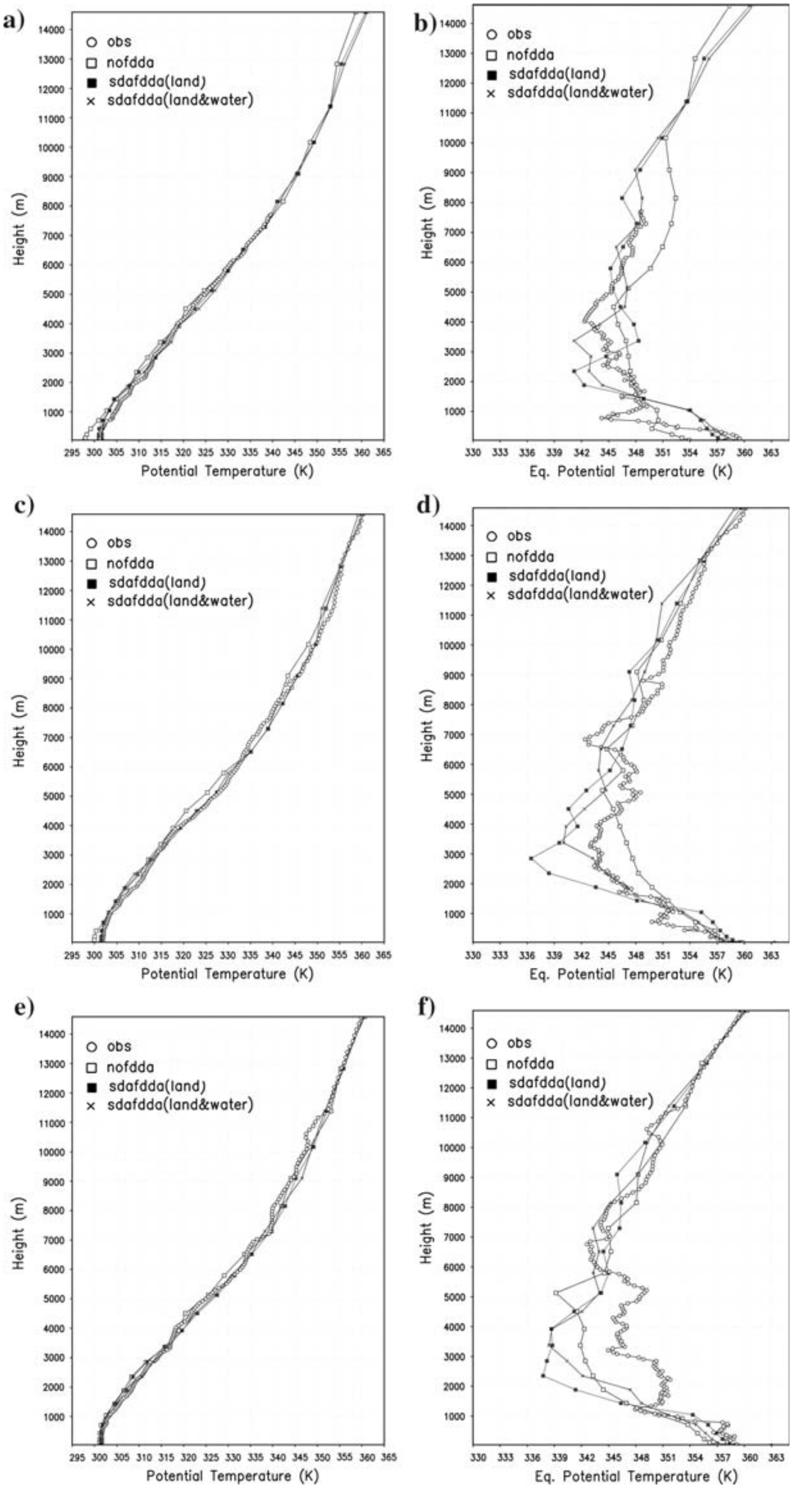


Fig. 4 Same as Fig. 3, for 28–29 July 1999, 00 UTC

the eastern coastal areas with relatively more inland penetration compared with in the CONTROL simulation. The SDALS run shows a better large-scale structure of precipitation compared with in the SDAL run on 29 July 1999, 00 UTC (Fig. 4). The maximum precipitation near the western coasts of India as seen in the analysis is reproduced by all three MM5 simulations. However, the rainfall amounts of all three MM5 simulations are lower compared with the rainfall observations. A possible reason for this under-prediction would be due to uncertainties introduced by interaction between boundary layer dynamics through the PBL parameterization and the cumulus parameterization scheme in the model.

Fig. 5 *Left* and *right panels* indicate potential and equivalent potential temperature at times 06 (**a**, **b**), 12 (**c**, **d**), and 18 UTC (**e**, **f**) on 27 July 1999. *Circles* depict BOBMEX RS (17.5° N, 89.01° E) observations, *squares* CONTROL (NOFDDA) simulation, and *filled squares* and *crosses* depict SDAL and SDALS simulation respectively

Figure 5 depicts the potential temperature (θ) and the equivalent potential temperature (θ_e) for the 27 July 1999 at 06, 12, 18 UTC of MM5 simulations and BOBMEX observations. The θ and θ_e vertical profiles were obtained from the location of the grid cell in the 30-km MM5 domain closest to the radiosonde location at the same times. Figure 5 indicates that all three model runs compare very well with the BOBMEX radiosonde observation θ. However, at times 06 and 12 UTC on 27 July 1999, the θ of the CONTROL simulation underestimates the radiosonde observations compared with the SDAL and SDALS runs in the lower troposphere. For levels close to the surface, θ_e of both SDAL and SDALS simulations compare well with the BOBMEX observations on 27 July 1999 06 UTC. For θ_e profiles, the SDALS simulations are closer to the observations than the SDAL simulations, as seen in Fig. 5, and Fig. 6b depicts the temperature, wind speed, and wind direction from 26–29 July 1999, 00 UTC. The figure shows BOBMEX buoy observations and all three MM5 simulations. Tables 2 and 3 show the mean error, mean absolute error, and the standard deviation of the difference in the MM5 simulations with regard to the buoy and ship observations for the time period 26–29 July 1999. The model results are obtained from the location of the grid cell in the 30-km MM5 domain closest to the buoy and ship locations at various times. There is a marked reduction in the mean error corresponding to the temperature (1.45 K), wind direction (14°), and wind speed (0.39 m s^{-1}) for the simulations with SDAL assimilations compared with the CONTROL simulations. Table 2 reveals a further reduction in the mean errors for temperature (0.23 K) corresponding to the SDALS runs over the SDAL run. The model temperatures are underestimated in all three simulations with the CONTROL run having the largest underestimation (2.18 K). All three simulations exhibited a westerly bias in the wind direction, with the lowest bias (–6.18° and –7.78°) exhibited by the SDAL and SDALS simulations. Cox et al. (1998) have proposed a desired forecast accuracy of: 30° for wind direction, 2 K for temperature, 2.5 m s^{-1} for wind speeds greater than 10 m s^{-1} and 1 m s^{-1} for other wind speeds, 2 K for dew point depression, and 1.7 hPa for SLP. The above buoy results do meet the requirements for desired accuracy proposed by Cox et al. (1998). Figure 6b shows that the results of the MM5 simulations (SDAL and SDALS) compare favorably with the BOBMEX buoy observations compared with the CONTROL simulations. The marked drift seen in the temperature simulation (Fig. 6b) in the CONTROL run after 28 July 1999, 06 UTC is reduced in the SDAL simulation and is further reduced in the SDALS simulation. The marked departure in the MM5 temperature simulations in the CONTROL run seen on 28 July 1999, 06 UTC and thereafter is also reflected in the wind speed and wind directions and are not seen in the SDAL and SDALS simulations. Figure 6a depicts the temperature, wind speed, wind direction, and relative humidity of all three MM5 simulations with BOBMEX ship observations for the period 26–29 July 1999, 00 UTC. Table 3 shows that the model with the CONTROL run simulates a large westerly component with a mean error of –56.94° for the entire simulation period. The above value exceeds the desired accuracy as proposed by Cox et al. (1998); however, the simulations with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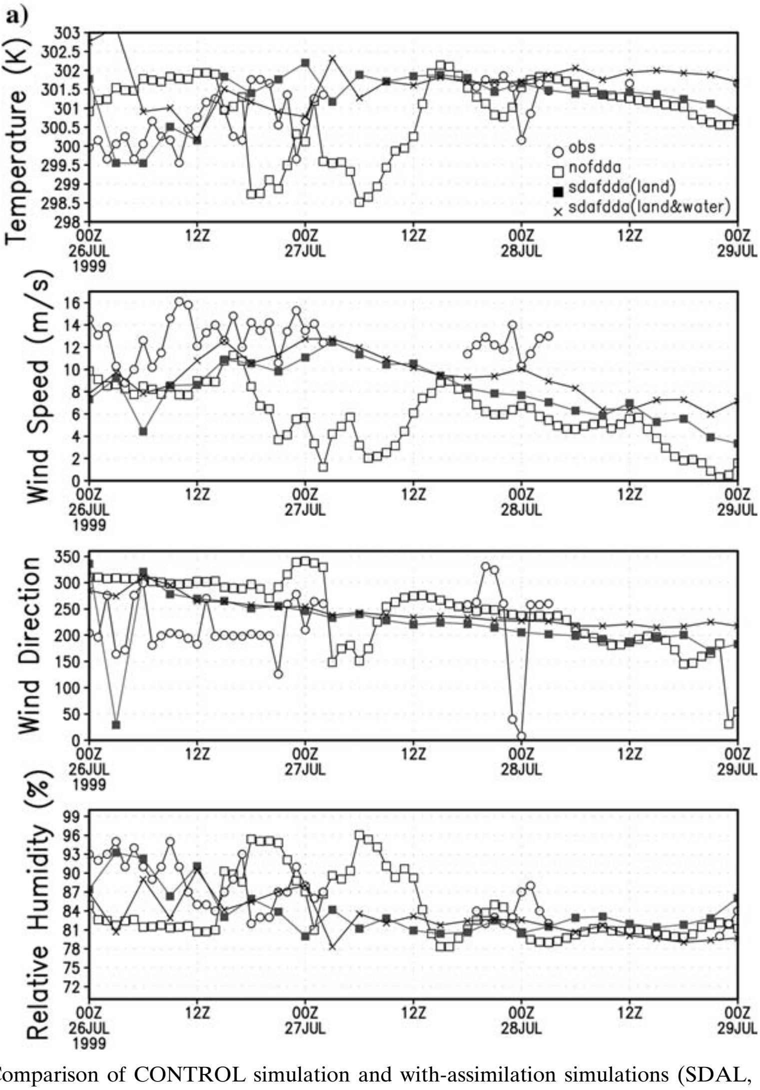

Fig. 6 Comparison of CONTROL simulation and with-assimilation simulations (SDAL, SDALS) with (**a**) the BOBMEX ship (varies from 19.4° N, 87.4° E on 26 July 1999, 00 UTC to 17.5° N, 89.01° E on 29 July 1999) temperature, wind speed, wind direction, and relative humidity, and with (**b**) the BOBMEX buoy (13° N, 87° E) temperature, wind speed, and wind direction

assimilation have reduced this westerly bias in the wind direction to –13.77° (for SDAL) and to –30.61° (for SDALS) and have ensured that the requirement of the forecast accuracy in the wind direction is satisfied. There is a considerable decrease in the mean error of wind speed due to assimilation for both SDAL and SDALS runs. Figure 6a reveals that both the simulations with assimilation show a departure in temperature at the initial time (26 July 1999, 00 UTC), but come closer to the observations as time increases. The wind speed simulations with assimilation show an initial offset (Fig. 6a), which is reduced at later times. The wind direction simulations (Fig. 6a) for all three cases reveal more westerly bias at the initial time (26 July 1999, 00 UTC), with the SDALS simulation showing the minimum bias.

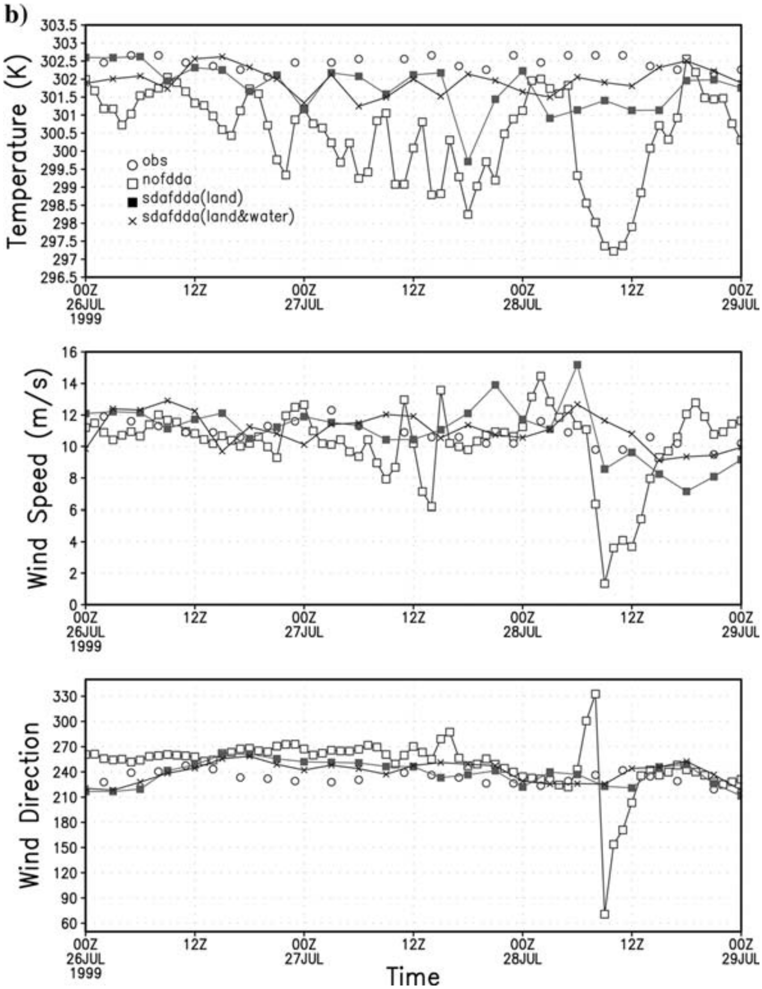

Fig. 6 continued

Table 2 Mean error, absolute error, and the standard deviation of difference between the BOBMEX buoy observations and the MM5 model simulations for 26–29 July 1999

	Mean error			Absolute error			Standard deviation of difference		
	CONTROL	SDAL	SDALS	CONTROL	SDAL	SDALS	CONTROL	SDAL	SDALS
Temperature (K)	2.18	0.73	0.5	2.18	0.74	0.56	2.5	0.9	0.65
Wind speed (m s^{-1})	0.6	–0.21	–0.27	1.7	1.06	0.81	2.17	1.4	0.96
Wind direction (°)	–20.42	–6.18	–7.78	27.51	12.7	12.43	34.35	15.16	13.92

Table 3 Mean error, absolute error, and the standard deviation of difference between the BOBMEX ship observations and the MM5 model simulations for 26–29 July 1999

	Mean error			Absolute error			Standard deviation of difference		
	CONTROL	SDAL	SDALS	CONTROL	SDAL	SDALS	CONTROL	SDAL	SDALS
Temperature (K)	–0.2	–0.31	0.64	1.14	0.59	0.85	1.38	0.82	1.23
Wind speed (m s^{-1})	5.28	3.85	2.52	5.28	3.85	2.59	6	4.37	3.2
Wind direction (°)	–56.94	–13.77	–30.61	70.71	63.4	52.82	84.11	76.67	65.58
Relative humidity (%)	2.74	1.97	2.55	5.95	3.34	3.81	7.3	4.21	5.17

4 Conclusions

This study investigated the impact of the simultaneous use of FDDA and SDA (the latter over land only and also over land and sea) on the structure and the spatial distribution of the precipitation of a monsoon depression formed during the field phase of the 1999 BOBMEX. The results are indeed favorable in terms of simulating the large-scale structure of the sea level pressure field as well as the spatial distribution of the precipitation. The results of the comparison with the BOBMEX observations indicate that use of SDA and FDDA have contributed to reduced errors in the simulation of surface fields and improved model performance overall. The impact of the SDALS model run over the SDAL run shows in the overall higher spatial correlations as well as lower RMSE of the sea level pressure field. The CONTROL simulation indicates a very weak system with a central pressure higher by about 2–4 hPa compared with the SDAL and SDALS runs. A comparison of the model results with the BOBMEX 1999 observations indicates a better agreement of the simulations with FDDA and SDA compared with the CONTROL simulation. The monsoon depression investigated in this study was chosen because it happened to form during the 1999 BOBMEX field campaign and provided additional data for model evaluation.

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