The Impacts of Indirect Soil Moisture Assimilation and Direct Surface Temperature and Humidity Assimilation on a Mesoscale Model Simulation of an Indian Monsoon Depression

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ABSTRACT

This study investigates the impact of the Flux-Adjusting Surface Data Assimilation System (FASDAS) and the four-dimensional data assimilation (FDDA) using analysis nudging on the simulation of a monsoon depression that formed over India during the 1999 Bay of Bengal Monsoon Experiment (BOBMEX) field campaign. FASDAS allows for the indirect assimilation/adjustment of soil moisture and soil temperature together with continuous direct surface data assimilation of surface temperature and surface humidity. Two additional numerical experiments [control (CTRL) and FDDA] were conducted to assess the relative improvements to the simulation by FASDAS. To improve the initial analysis for the FDDA and the surface data assimilation (SDA) runs, the fifth-generation Pennsylvania State University–NCAR Mesoscale Model (MM5) simulation utilized the humidity and temperature profiles from the NOAA Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS), surface winds from the Quick Scatterometer (QuikSCAT), and the conventional meteorological upper-air (radiosonde/rawinsonde, pilot balloon) and surface data. The results from the three simulations are compared with each other as well as with NCEP–NCAR reanalysis, the Tropical Rainfall Measuring Mission (TRMM), and the special buoy, ship, and radiosonde observations available during BOBMEX. As compared with the CTRL, the FASDAS and the FDDA runs resulted in (i) a relatively better-developed cyclonic circulation and (ii) a larger spatial area as well as increased rainfall amounts over the coastal regions after landfall. The FASDAS run showed a consistently improved model simulation performance in terms of reduced rms errors of surface humidity and surface temperature as compared with the CTRL and the FDDA runs.

1. Introduction

The quality of an operational numerical weather prediction (NWP) model forecast depends significantly on the accuracy of the initial conditions specifications and also on the ability of the model to simulate well the atmospheric physical and dynamical processes. Data assimilation methods often provide for improved performance of these NWP models (Kalnay 2003). Data assimilation methods combine available past as well as current meteorological observations in order to improve the analysis fields. Much scientific literature on the uses of four-dimensional data assimilation (FDDA) already exists (Anthes 1974; Stauffer and Seaman 1990, 1994; Stauffer et al. 1991). The present study utilizes the continuous (every model time step) dynamical FDDA, using the analysis nudging approach, where forcing
functions are added to the model’s governing equations in order to “nudge” the model state toward the observations.

In recent years, several studies have attempted to improve the atmospheric boundary layer (ABL) simulations using improved surface boundary conditions in atmospheric models. The surface fluxes, and to some extent the entrainment fluxes at the top of the ABL, determine ABL structure and evolution. Improved surface fluxes over land require, in addition to surface observations of temperature and humidity, detailed observations of soil moisture and soil temperature. Soil moisture (and soil temperature) is not available from most routine meteorological observations, and the accuracy and availability of soil moisture observations from satellites are presently being improved (Njoku et al. 2003). Hence efforts have been undertaken to provide case-specific soil moisture profiles using multilevel soil models coupled with vegetative canopy submodels (e.g., Noilhan and Planton 1989; Chen and Dudhia 2001). Also, surface observations of temperature and mixing ratio have been utilized in continuous surface data assimilation (SDA) schemes to reduce the modeling errors and improve the ABL structure and simulation in atmospheric models.

The chief objectives of SDA techniques, in addition to error reduction, are to ensure consistency in the hydrological and the thermodynamical fields while assimilating soil moisture and soil temperature. Ruggiero et al. (1996) utilized an intermittent assimilation of analyzed surface observations and investigated the improvements in a mesoscale model. In an earlier study, Stauffer et al. (1991) performed a direct and continuous assimilation of surface temperature measurements and found that serious errors arose in the ABL structure because the sign of the surface buoyancy flux changed unrealistically as new data were assimilated, even in midday conditions. Among the indirect assimilation approaches, Mahfouf (1991) and Boudt et al. (1993) used the evolving surface layer temperature and humidity to estimate the soil moisture in numerical model predictions. Other notable indirect assimilation studies include the work of Pleim and Xiu (2003) and that of McNider et al. (1994).

Alapaty et al. (2001b) proposed and tested a modified technique that allowed for continuous assimilation of surface observations to improve surface layer prediction. In their technique, Alapaty et al. (2001b) directly assimilated the surface layer temperature and the water vapor mixing ratio into the model’s lowest atmospheric layer using analyzed surface data. They calculated the surface flux adjustments of sensible and latent heat from the difference between the model prediction and observation. Using a simple surface energy budget equation to estimate the new ground-skin temperature, Alapaty et al. (2001b) showed that this approach, when applied at every advective step, improves ABL simulations. This approach could also correct the unrealistic changes in the sign of the surface buoyancy flux and thus improve on the Stauffer et al. (1991) technique.

Alapaty et al. (2001a) extended their earlier work by developing a scheme for assimilating soil moisture (with soil temperature) using an inverse technique called Flux-Adjusting Surface Data Assimilation System (FASDAS). They sought to indirectly assimilate–adjust soil moisture and ground skin temperature together with the direct assimilation of surface data in the model’s lowest layer. Alapaty et al. (2001a) demonstrated that this approach ensures greater consistency between the soil temperature, soil moisture, and the surface layer mass-field variables. Also, FASDAS ensures soil moisture adjustment so that errors are reduced in the surface layer simulation. The inverse method also introduces observed temporal variability in the deep soil moisture on a weekly-to-monthly time scale.

Childs et al. (2006) numerically simulated the convective initiation over the southern Great Plains of the United States during the International H2O Project 2002 (IHOP_2002) using the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) Mesoscale Model (MMS) with FASDAS. The results indicated that the surface heat fluxes from the experimental simulation (with FASDAS) agreed more closely with the IHOP_2002 observations from Kansas and Oklahoma as compared with the control simulation with FDDA.

The impact of satellite sounder data assimilation in numerical weather prediction models has also been examined by many studies (Gal-Chen et al. 1986; Doyle and Warner 1988; Lipton and Vonder Harr 1990; Lipton et al. 1995; Ruggiero et al. 1999). Assimilating observed vertical profiles of temperature and humidity (in addition to producing an improved initial condition) enhances the model’s ability to correctly reproduce the processes associated with the structure and intensity of monsoon depression. A number of recent studies on assimilating satellite and special observations over India have shown positive results from the assimilation of such observations (Potty et al. 2000; Rajan et al. 2001; Das Gupta et al. 2003; Singh and Pal 2003; Roy Bhomik 2003; Vaidya et al. 2003; Mukhopadhyay et al. 2004; Sandeep et al. 2006; Xavier et al. 2006).

The chief objective of this study is to investigate the effect of assimilating surface data and atmospheric soundings from satellite datasets using FASDAS com-
bined with FDDA on the simulation of the structure and spatial distribution of the precipitation of a monsoon depression that formed during the 1999 Bay of Bengal Monsoon Experiment (BOBMEX) campaign field phase. Over the seas, the Quick Scatterometer (QuikSCAT) surface wind and the vertical profiles of the National Oceanic and Atmospheric Administration (NOAA) Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) temperature and humidity data were utilized. Over the land regions, conventional surface and upper-air observations from the India Meteorological Department (IMD), the vertical profiles of humidity and temperature from NOAA TOVS, along with the surface data estimated from NOAA TOVS, were used in the FDDA and FASDAS.

Figure 1 shows a schematic of the likely feedbacks and processes that have contributed to improved simulation through FASDAS and FDDA.

The following section provides a brief description of FDDA and FASDAS; section 3 outlines the case study, data and observations, the numerical model, and the design of the numerical experiments. Section 4 provides results and discussions, and section 5 describes the study conclusions.

2. A brief description of FDDA and FASDAS

a. FDDA

FDDA using Newtonian relaxation or nudging is a continuous data assimilation technique that relaxes the model state toward the observed state by augmenting some of the prognostic equations with tendency terms based on the difference between the observed and the model state. In this study, we have made use of the analysis nudging approach, that is nudging the model fields toward the gridded analysis based on synoptic observations and interpolated to the model’s current time step (Stauffer and Seaman 1990; Stauffer et al. 1991). Following Stauffer and Seaman (1990), the Newtonian relaxation technique for a variable \( \alpha(x, t) \) can be written as

\[
\frac{\partial p^* \alpha}{\partial t} = F(\alpha, x, t) + G_{\alpha} W(x, t) e(x) p^* (\hat{\alpha}-\alpha),
\]

where \( p^* = p_s - p_T \), the difference between the base state pressure at the surface and model top; \( F \) represents the physical forcing terms; \( x \) is the independent spatial variable; \( t \) is the time; and \( \alpha \) is the model-dependent variable. The second term on the right-hand side
side of Eq. (1) represents the analysis nudging term for \( \alpha \). Here \( G_\alpha \) is the nudging factor, \( W \) specifies the weighting as applied to the analysis, \( \varepsilon \) is the analysis quality factor with a value ranging from 0 to 1, and \( \hat{\alpha} \) is the estimate of the observation analyzed to the grid and interpolated linearly in time to \( t \). The nudging coefficients used for analysis nudging in this study are \( 2.5 \times 10^{-4} \) s\(^{-1}\) for temperature and wind, and \( 1 \times 10^{-5} \) s\(^{-1}\) for the mixing ratio of the 3D analysis, and \( 2.5 \times 10^{-4} \) s\(^{-1}\) for surface wind.

### b. FASDAS

Following Alapaty et al. (2001a), the temperature and mixing ratio equations for the surface data assimilation scheme for the model’s lowest atmospheric layer are obtained from Eq. (1) as follows, where the quantities have the same meaning as in Eq. (1):

\[
\frac{\partial p^*T_a}{\partial t} = F(T_L, x, y, t) + G_T W_1 r_T p^*(\hat{T} - T_a) \quad \text{and} \quad (2)
\]

\[
\frac{\partial p^*q_a}{\partial t} = F(q_L, x, y, t) + G_q W_1 r_q p^*(\hat{q} - q_a). \quad (3)
\]

The nudging factor \( G_q \) is chosen to be larger by a factor of 2 over typical values for upper-air sounding data. The larger nudging factors are chosen to account for the rapid adjustment rate of the surface fluxes to changes in surface forcings. The second term on the right-hand side of Eq. (2) can be written as \( (\partial T_a/\partial t) \), that is, as the rate of change of the surface layer temperature due to direct nudging (after excluding \( p^* \)). When all of the effects due to data assimilation are allowed to occur at the surface only, the adjustment turbulent sensible heat flux \( H_{TF}^c \) can be written as

\[
H_{TF}^c = \rho c_p \left( \frac{\partial T_a^c}{\partial t} \right) \Delta z, \quad (4)
\]

where \( \Delta z \) is the thickness of the lowest model layer, and \( \rho \) and \( c_p \) refer to density and specific heat at a constant air pressure, respectively. In the same way, if \( (\partial q_a^c/\partial t) \) represents the rate of change of the surface layer mixing ratio to direct nudging, by the same argument the adjustment turbulent latent heat flux \( H_{TL}^c \) can be written as

\[
H_{TL}^c = \rho L \left( \frac{\partial q_a^c}{\partial t} \right) \Delta z. \quad (5)
\]

In this study, the FASDAS technique is employed using the Noah land surface model (LSM). The Noah LSM has prognostic equations for four soil layers along with an equation for canopy storage. In the FASDAS technique, the adjustment turbulent latent heat flux \( H_{TL}^c \) is scaled in such a way as to account for errors in the specification of soil moisture. The normalized weighting function \( \psi_q \) for soil moisture is defined as

\[
\psi_q = \frac{\Delta q}{q_a},
\]

where \( q_a \) is the mixing ratio at the lowest model atmospheric layer, and \( \Delta q \) is the change in \( q_a \) due to the surface turbulent fluxes and boundary layer mixing processes.

The total kinematic evaporation flux \( E \) in the Noah LSM has five components representing the contributions from the direct evaporation flux from the ground surface: evaporation fluxes via roots from the three below-surface soil layers and evaporation fluxes from the precipitation intercepted by vegetation as well as dew formed on the canopy. These five evaporation fluxes are adjusted using the normalized weighting factor \( \psi_q \) and \( H_{TF}^c \) and are given in Alapaty et al. (2001a). The previously adjusted five evaporation fluxes are incorporated in the modified prognostic equations for the volumetric soil moisture of the four soil layers as well as in the equation for canopy storage. The final adjusted ground skin temperature is obtained from the following:

\[
T_g^c = T_g + \frac{(H_{TF}^c - \psi_q H_{TL}^c)}{C_g} \Delta t, \quad (6)
\]

where \( T_g \) is the predicted ground skin temperature, \( C_g \) is the thermal capacity of the uppermost soil slab per unit area, \( T_g^c \) is the updated–adjusted ground skin temperature, and \( \Delta t \) is the time step.

### 3. Experimental

The main objective of this study is to test the performance of FASDAS combined with the FDDA on the simulation of the structure and spatial distribution of monsoon depression precipitation that formed during the 1999 BOBMEX campaign field phase. In this section, we describe the case study to be simulated. The observations and the model configuration are also discussed.

#### a. Case study

A low pressure system formed in the north Bay of Bengal on 25 July 1999 intensified to a depression on 27 July, and further intensified into a deep depression on 28 July just before making landfall. Observations indicated an outgoing longwave radiation (OLR) with
strong convection—a minimum of 135 W m$^{-2}$ to the west of the depression center—and high values of OLR were also observed from the south and central bay. The deep depression weakened into a low pressure system on 30 July over central India (northwest Madhya Pradesh) and continued to move west-northwest to further weaken over the desert region of Rajasthan on 3 August 1999 (Kalsi 2000). The Indian National Satellite (INSAT) infrared (IR) imagery over the Bay of Bengal on 0900 UTC 27 July 1999 is shown in Fig. 2. Extensive cloud masses resulting from the monsoon depression over the northwest Bay of Bengal and adjacent regions is seen in Fig. 3. In a time span of 24 h, that is, by 0900 UTC 28 July 1999, the INSAT IR imagery (Fig. 3) indicated the cloud mass had organized into a deep depression as the system crossed over the east coast of India.

b. Data and observations

The TOVS on board the NOAA satellite has three infrared channels—8.3, 7.3, and 6.7 μm—and can provide precipitable water vapor data for the following three layers: 1000–700, 700–500, and 500–300 hPa. The method used in Rajan et al. (2002) is adopted to obtain vertical humidity profiles at standard levels of 1000, 850, 700, 500, 400, and 300 hPa from the precipitable water vapor. The temperature sounding data are from the High Resolution Infrared Radiation Sounder (HIRS)/2 instrument on board TOVS, which provides data on 15 vertical levels. The NOAA Advanced TOVS (ATOVS) satellite makes a morning and an evening pass (around 0730 and 1930 Indian standard time). Hence, the ATOVS temperature and humidity profiles are ingested at 0000 and 1200 UTC. The QuikSCAT passes 2 times per day and the MM5 model ingests its data at 0000 and 1200 UTC. The QuikSCAT provides the surface wind vector over the ocean with a swath of 1800 km and a spatial resolution of 25 km × 25 km.

In addition to the satellite observations, the assimilation in FASDAS and FDDA employed conventional IMD observations of 33 upper-air radiosonde–rawinsonde (RS/RW), 18 pilot balloons (PB), and 106 IMD surface observations. The satellite and other conventional observations were ingested using the Little_Rawins module of the MM5 model to modify the initial analysis at each analysis time (0000, 0600, 1200, 1800 UTC 25 July 1999 and 0000 UTC 26 July 1999). The Little_Rawins module had an inbuilt quality-control check of the observations ingested. Furthermore, the FDDA technique using analysis nudging was performed for the entire 24-h preforecast period for both the FDDA and the FASDAS runs. The temperature and humidity were not nudged in the ABL for the FDDA run. For the FASDAS run, only the surface temperature and surface humidity together with winds, temperature, and humidity above the ABL were nudged.
This case study occurred during a special intensive field campaign as part of BOBMEX (Sikka and Sanjeeva Rao 2000). The BOBMEX program sought to address the role of the Bay of Bengal in monsoon variability. Research ships, buoys, INSAT, coastal radar, and other conventional observation systems monitored air temperature, wind speed, wind direction, and relative humidity. These data together with radiosonde observations are used in this study to evaluate model performance.

Surface temperature and surface humidity data over the data-sparse sea regions are available from ship/buoy data, and over land from the conventional IMD network. The impact of FASDAS (or any other SDA scheme) depends on the density as well as the accuracy of the analyzed surface data used. To increase the quantity of surface data over the land, a procedure was used that Simon and Desai (1986) developed to estimate these values using the NOAA TOVS satellite. For estimating the atmospheric-specific humidity over land and sea using NOAA TOVS satellite data, an iterative exponential density method was employed (Simon and Desai 1986; also appendix). The surface, sounding, and satellite-based observations or measurement points available for this case, along with model domain and ship track, are shown in Fig. 4.

c. Model description and numerical experiments

The MM5 version 3.6 (Grell et al. 1994) model was configured with 23 vertical layers (centered at \( \sigma = 0.995, 0.985, 0.97, 0.945, 0.91, 0.87, 0.825, 0.775, 0.725, 0.675, 0.625, 0.575, 0.525, 0.475, 0.425, 0.375, 0.325, 0.275, 0.225, 0.175, 0.125, 0.075, 0.025 \)) and a time resolution of 6 h were used to develop the initial and lateral boundary conditions. A one-way nesting option was employed.

Three numerical experiments were performed to study the impact of satellite data: 1) vertical profiles of NOAA TOVS temperature and humidity; 2) surface wind vectors from QuikSCAT; and 3) estimates of surface data from NOAA TOVS, along with conventional IMD observations including upper-air (RS/RW and PB) and surface observations on the simulated structure of a monsoon depression using FASDAS and FDDA. The first experiment, the control (CTRL) run, utilized the NCEP–NCAR reanalysis for the initial and lateral boundary conditions; the model integrations were performed from 0000 UTC 25 July 1999 to 0000 UTC 29 July 1999. The second numerical experiment, the FDDA run, incorporated the NOAA TOVS, QuikSCAT, IMD sounding and surface data, and surface temperature and humidity estimated from NOAA TOVS to potentially improve the NCEP–NCAR reanalysis between 0000 UTC 25 July 1999 and 0000 UTC 26 July 1999. The MM5 model was subsequently integrated in the free-forecast mode from 0000 UTC 26 July 1999 to 0000 UTC 29 July 1999. The third experiment, called the FASDAS run, was similar to the FDDA run except that the FASDAS scheme was also incorporated together with the FDDA for improving the initial analysis. For the CTRL run, the entire integration was in the free-forecast mode. The results of the MM5 simulation corresponding to the three numerical experiments were then compared with the TRMM, BOBMEX observations, and the NCEP–NCAR reanalysis.

4. Results and discussion

In this section we first compare the three experimental runs. The results are then compared with the TRMM rainfall observations, BOBMEX special observations, and the NCEP–NCAR reanalysis. The variables compared with those of the NCEP–NCAR reanalysis are the surface heat fluxes and mean sea level pressure fields, since no other reliable sources of observations were available over the region of interest.

a. Model evaluations of CTRL, FDDA, and FASDAS runs

The study’s objective is to investigate the impact of the ingestion and assimilation of various data sources on the simulation of a monsoon depression event. These data sources include satellite data, NOAA TOVS vertical profiles of temperature and humidity, QuikSCAT wind speed and wind direction, estimates of NOAA TOVS surface data, and conventional IMD upper-air and surface observations through a simultaneous application of FASDAS and FDDA. In consideration of the relevance of this research to operational forecasting, the ingestion and assimilation using FASDAS and FDDA is restricted to the first 24 h of preforecast model integration, and subsequently the model simulation is in the free-forecast mode. The model domain is shown in Fig. 4e. The NCEP–NCAR reanalysis has a relatively coarse resolution, therefore a
system of two nested domains with horizontal grid spacing of 90 km (D1) and 30 km (D2) was defined. All the model results discussed in this study correspond to the 30-km domain.

Figures 5a,b depict the time series of the sensible heat flux (SHF) values averaged over the area 7.5°–25°N and 70°–95°E. The sea regions were masked (Fig. 5a) and the land regions were masked (Fig. 5b) for the NCEP–NCAR reanalysis as well as the three model runs. The NCEP–NCAR reanalysis (Fig. 5a), averaged over the land only, shows the expected diurnal variation of the SHF values with negative values (−30 W m⁻²) at night, and positive values (50–100 W m⁻²) during day. All the three model runs (CTRL, FDDA, and FASDAS) simulate this diurnal variation in the SHF. It is to be noted that all the three model runs simulate values of area-averaged SHF over land, which are fairly close to one another. A possible reason for this is the

Fig. 4. Locations of all points directly below a typical pass of (a) QuikSCAT and (b) NOAA TOVS; locations of all IMD (c) surface and (d) upper-air stations (filled circles RS/RW and filled squares are PB). (e) The MM5 model domains (D1 and D2 are 90- and 30-km horizontal resolution) and (f) filled square depicts the BOBMEX buoy location and the gray line indicates the BOBMEX ship movement toward the southeast.
use of the same land surface model (Noah) in the three model runs. A time lag is apparent between the model results and the NCEP–NCAR reanalysis. One potential reason for this lag is that the NCEP–NCAR reanalysis is only available at each 6-h interval, while the model results are plotted for each 3-h interval. The NCEP–NCAR reanalysis, with SHF values averaged only over the sea (Fig. 5b), shows a smaller range of variation, as is to be expected with small negative SHF values (\(-3\) W m\(^{-2}\)) during 1800 and 0000 UTC, respectively. All three of the model runs simulate a smaller range of SHF values as seen in the NCEP–NCAR reanalysis.

The NCEP–NCAR reanalysis (Fig. 5c) averaged only over the land shows excessive latent heat flux (LHF) values (\(>225\) W m\(^{-2}\)) for 1200 UTC. The three model simulations underestimate the LHF values with little differences between them. However, the trend of the temporal variation of LHF values seen in the NCEP–NCAR reanalysis (Fig. 5c) is reproduced in each of the three model integrations. As is expected, the NCEP–NCAR reanalysis with LHF values averaged only over the seas (Fig. 5d) shows a smaller temporal range of variation of values. The three model runs simulate larger LHF values when averaged over the seas only (Fig. 5d), and with the model simulations overestimating the LHF values as compared to the NCEP–NCAR reanalysis. Also, as in the NCEP–NCAR reanalysis, each of the model runs simulates a small diurnal range of LHF values when averaged over the seas only (Fig. 5d).

Figures 6a–p show the sea level pressure (SLP) pattern for the NCEP–NCAR reanalysis (Figs. 6a–d), the CTRL run (Figs. 6e–h), the FDDA run (Figs. 6i–l), and the FASDAS runs (Figs. 6m–p) at 0000 UTC 26 July 1999 and at 24, 48, and 72 h of forecast. A low pressure trough, known as a monsoon trough, is usually observed (under active monsoon conditions) along the northwest–southeast direction from northwest India to the north Bay of Bengal region. The monsoon trough is well delineated in the NCEP–NCAR reanalysis. It is true that the NCEP–NCAR reanalysis cannot replace actual observations and is itself not the complete truth. However, in the absence of observational data to validate the sea level pressure fields, a majority of the studies over the monsoon region (including the present study) have relied on the NCEP–NCAR reanalysis as
the best alternative source of comparison data. Resulting from the application of FDDA and FASDAS, wherein improvements and balanced adjustments are made to the initial analysis, both the FDDA and FASDAS runs simulate a strong monsoon trough at the initial time (0000 UTC 26 July 1999). The simulated SLP pattern from the CTRL run shows a weak system on the day 2 and day 3 forecasts, with the system’s
central pressure higher by 1 and 4 hPa at 48 and 72 h of forecast as compared with the FASDAS and the FDDA runs. However, the simulated SLP patterns of both the FDDA and FASDAS runs fail to simulate the monsoonal trough in the day 2 and day 3 forecasts as manifested in the NCEP–NCAR reanalysis. At 48 h of forecast, the FASDAS and the FDDA runs capture the large-scale horizontal structure of the monsoon depression (i.e., at an approximate 5° horizontal extent from the depression center; Godbole 1977). This large-scale horizontal structure, on day 2 of the forecast, however, has not been simulated well in the CTRL run.

Observations indicate that the monsoon depression crossed land on 28 July 1999, and is simulated by both the CTRL and FASDAS runs. Also, once such a system crosses land, it is expected to weaken and the CTRL and FASDAS runs do capture this feature. The central pressure of the system in the CTRL run has weakened by 4 hPa after landfall, and the FASDAS run shows a weakening of only 1 hPa after landfall. The observed weakening, as seen in the NCEP–NCAR reanalysis, is slight because of the existence of the moisture-rich monsoon environment reproduced in the FASDAS run. The FDDA run for the 48- and 72-h forecast indicates that the system did not cross land. Indirect assimilation of soil moisture, together with the continuous surface assimilation of surface temperature and humidity, are expected to contribute to an improved simulation of surface fluxes, and consequently to the improved ABL structure. Also, the performance of a numerical mesoscale model in the short range (2–3 days) is critically dependent on the accuracy of the initial conditions. Ingesting and assimilating high-resolution satellite and conventional upper-air and surface observations into the analysis can enhance the accuracy of the initial conditions. Based on this premise, simultaneous FASDAS and FDDA assimilation are expected to improve the ABL structure, and through the nudging procedure, provide for a better adjustment of the high-resolution observations. The results of the simulated sea level pressure from the FASDAS run (Figs. 6m–p) appear to support this view.

Figures 7a–p show the lower-tropospheric winds for 0000 UTC 26 July 1999 and at 24, 48, and 72 h of forecast, as well as the 24-h accumulated precipitation valid for 0000 UTC 27, 28, and 29 July 1999. The figures show the NCEP–NCAR reanalysis, and the three model (CTRL, FDDA, and FASDAS) runs. The lower-tropospheric winds from the NCEP–NCAR reanalysis refer to a height of 1829 m, and the winds from the MM5 model simulation correspond to the nearest \( \sigma \) level (\( \sigma = 0.775 \)) with a height of 1882 m. The FASDAS (Figs. 7m–p) and FDDA (Figs. 7i–l) runs result in a relatively better-developed cyclonic circulation associated with the monsoon depression. The assimilation of the high-resolution (25 km \( \times \) 25 km) QuikSCAT surface wind vector has contributed to the improved cyclonic circulation.

Figures 7b–d show the Tropical Rainfall Measurement Mission (TRMM) 24-h accumulated rainfall for 0000 UTC 27–29 July 1999. The maximum accumulated precipitation is seen over the east coast of India as well as the adjacent Bay of Bengal regions on 0000 UTC 27 July 1999, and the rainfall pattern has moved inland for the next two days. None of the 24-h accumulated precipitation MM5 simulations (CTRL, FDDA, and FASDAS) reveal marked inland penetration of the rainfall pattern on 0000 UTC 28 and 29 July 1999 as seen in the TRMM data. Since most mesoscale processes evolve very rapidly, these time and/or phase errors are not unusual. The slower movement of the simulated depression is possibly due to the existence of phase errors and synoptic boundary conditions in the mesoscale model. The FASDAS run (Fig. 7n) and the FDDA run (Fig. 7j) on 0000 UTC 27 July 1999 show an extensive region of precipitation over the north Bay of Bengal and adjacent coastal regions which compare favorably with the TRMM observations. However, the CTRL run does not compare favorably with the TRMM rainfall on the day 1 forecast. The FASDAS and FDDA runs reproduce the precipitation maxima (>250 mm) observed around 19°N and 86°E in TRMM data on the day 1 forecast, and the three model runs reproduce the large amount of orographic rainfall observed near the west coast of India seen in the TRMM data (Figs. 7b–7d). This could be attributed to the MM5 model’s relatively finer horizontal resolution (30 km) used in this study. Over land, the simulated rainfall amounts of the three model runs seem to be underestimated as compared to the TRMM rainfall results. Possible reasons for this under prediction could be the uncertainties in the model lateral and surface boundary conditions as well as the cumulus and the land–surface–PBL interactions (Holt et al. 2006).

b. Model evaluations with BOBMEX special observations

Figures 8a–d depict the equivalent potential temperature (\( \theta_e \)) profiles for 0600, 1200, and 1800 UTC 27 July 1999, and 0000 UTC 28 July 1999. The figures show the BOBMEX radiosonde observations (17.5°N, 89°E), the CTRL, the FDDA, and the FASDAS runs. The \( \theta_e \) vertical profiles are obtained at the grid cell in the 30-km MM5 domain closest to the radiosonde location. The \( \theta_e \) profile of the FASDAS run for 0600 UTC 27 July 1999 (Fig. 8b) shows good agreement with
Fig. 7. Similar to Fig. 6, but for the lower-tropospheric winds (m s\(^{-1}\); at 1829 m for NCEP–NCAR reanalysis and at \(\sigma = 0.775\) with an average height of 1882 m for MM5 simulations) for 0000 UTC 26 Jul 1999 and for 24, 48, and 72 h of forecast. The 24-h accumulated precipitation (cm) is also shown valid at 0000 UTC 27, 28, and 29 Jul 1999; (b)–(d) TRMM precipitation data; (f)–(h), (j)–(l), and (n)–(p) the precipitation refers to the respective model runs.
the BOBMEX observations close to the surface, while the CTRL and the FDDA runs are underestimated by about 12 and 7 K, respectively. At other times also, the FASDAS run does agree with the trend of the observed \(\theta_e\) profiles. Since we are comparing point measurements with grid-averaged model results, some departure from the observations is expected. Figures 9a,b are similar to Figs. 8a–d except that the former correspond to 28 July 1999 1200 and 1800 UTC. Again, in Figs. 9a,b, the FASDAS \(\theta_e\) profiles are in good agreement with the observed profiles. Figure 9c is the time series plot of the area-averaged (25° × 25° box) 3-h accumulated precipitation from 0300 UTC 26 July 1999 to 0000 UTC 29 July 1999 obtained from TRMM and the three model simulations. All three model results show an overestimation of the precipitation values most of the time, and the

Fig. 8. Equivalent potential temperature profiles at (a) 0600, (b) 1200 and (c) 1800 UTC 27 Jul 1999, and (d) 0000 UTC 28 Jul 1999. Squares depict BOBMEX RS observations, circles depict CTRL, triangles depict FDDA runs, and diamonds depicts the FASDAS runs.
FASDAS and the FDDA runs simulate more rainfall than the CTRL run.

Figures 10a–c depict the temperature, wind speed, and wind direction as a time series for 0000 UTC 26–29 July 1999. The figures show the three model runs (CTRL, FDDA, and FASDAS) and the BOBMEX buoy observation located at 13°N, 87°E. The mean error, mean absolute error, and the standard deviation of differences are shown in Table 1. Consistent with the dynamical results, the mean error, absolute error, and standard deviation of temperature are lowest for the FASDAS run, while the errors in temperature for the CTRL run are largest (Table 1). The above result is supplemented by Fig. 10a. Cox et al. (1998) have proposed a desired forecast accuracy of 30° for wind direction, 2.5 m s\(^{-1}\) for wind speeds greater than 10 m s\(^{-1}\), 1 m s\(^{-1}\) for other wind speeds, 2 K for temperature, 2 K for dewpoint temperature, and 1.7 hPa for SLP. Table 1 indicates that the FASDAS run meets the Cox et al. (1998) accuracy requirement except for wind direction. Figures 10a–c clearly show that the FASDAS run compares favorably with the BOBMEX buoy observations as compared to the CTRL and FDDA runs.

Data from a sonic anemometer and fast response humidity sensor were available on board the ORV Sagar Kanya at a height of 11.5 m during BOBMEX in 1999 (Bhat and Ameenulla 2000). These data (10-Hz sample averaged over 360 s) form part of the slow data and are
compared with the MM5 model results. Figures 11a–d compare the model simulations for CTRL, FDDA, and FASDAS runs for air temperature, wind speed, wind direction, and relative humidity with the BOBMEX ship observations for the period 26–29 July 1999. The mean error, mean absolute error, and the standard deviation of difference for all the three model runs, with respect to the above BOBMEX ship observations are

<table>
<thead>
<tr>
<th></th>
<th>CTRL</th>
<th>FDDA</th>
<th>FASDAS</th>
<th>Mean error</th>
<th>CTRL</th>
<th>FDDA</th>
<th>FASDAS</th>
<th>Absolute error</th>
<th>CTRL</th>
<th>FDDA</th>
<th>FASDAS</th>
<th>Std dev of difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (K)</td>
<td>1.31</td>
<td>1.14</td>
<td>0.91</td>
<td>1.31</td>
<td>1.14</td>
<td>0.91</td>
<td>1.52</td>
<td>1.19</td>
<td>0.93</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind speed (m s(^{-1}))</td>
<td>-0.20</td>
<td>-1.49</td>
<td>-0.37</td>
<td>0.82</td>
<td>1.49</td>
<td>0.58</td>
<td>0.93</td>
<td>1.51</td>
<td>0.66</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind direction (°)</td>
<td>-17.04</td>
<td>-53.91</td>
<td>-50.23</td>
<td>17.04</td>
<td>53.91</td>
<td>50.23</td>
<td>37.03</td>
<td>53.99</td>
<td>50.45</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
shown in Table 2. These statistical measures are calculated for wind direction only for those times in which the differences between the model predictions and the observations are within 180° (Buckley et al. 2004). Table 2 indicates that a considerable decrease in the errors of temperature, wind speed, wind direction, and relative humidity is observed in the FASDAS run. Figure 11a shows that despite some departure at the initial time, the FASDAS run simulates temperature close to the observations. Also, Fig. 11b shows that the wind speed simulations with the FASDAS and the FDDA runs compare favorably with the observed wind speed. The predicted wind direction (Fig. 11c) for all three simulations shows a westerly bias most of the time. Neither simulation reproduces the marked veering seen in the observations near 0000 UTC 28 July 1999. Again, the relative humidity results (Fig. 11d) from the FASDAS run show better agreement with the observations. Thus, the FASDAS run has the best overall performance as was anticipated at the design of this study.

The statistical significance of the differences between
the FASDAS and the FDDA results as well as the FASDAS and the CTRL results (in Tables 1 and 2) for the BOBMEX buoy and ship observations, have been calculated using the two-tailed Student’s t statistics. For buoy results, the differences between FASDAS and the FDDA and the FASDAS and the CTRL runs are also statistically significant. Similar results are obtained for the comparison of the model differences with respect to the sonic anemometer observations. Generally the most statistically significant differences between FASDAS and the other two model runs are for wind speed, wind direction, and humidity (at 99% confidence). The statistical significance of the temperature differences between the FASDAS and the other two model runs, however, were somewhat lower at 85%.

c. Space correlations and RMSE of SLP of the MM5 simulations with NCEP–NCAR reanalysis

The space correlation and the root-mean-square errors (RMSE) of the SLP field, over a spatial box of $15^\circ \times 15^\circ$ around the center of the depression, identified as the minimum SLP in the NCEP–NCAR reanalysis, were calculated for the three model runs (CTRL, FDDA, and FASDAS) with respect to NCEP–NCAR reanalysis at different times (Table 3). The FASDAS-based space correlation run is significantly higher as compared with the CTRL and FDDA runs. Table 3 also indicates a significantly lower RMSE of the sea level pressure fields for the FASDAS and the FDDA runs as compared with the CTRL run. These results point to the clear quantitative impact of the improved analysis resulting from the assimilation of satellite and other conventional meteorological data through FASDAS and FDDA.

d. Time series of RMS error of surface temperature and mixing ratio

Figures 12a,b depict the time series of the RMS error of surface temperature (Fig. 12a) and mixing ratio (Fig. 12b; averaged over land) from all three model simulations with respect to the available surface observations. The model values corresponding to each observation are taken from the nearest model grid corresponding to the observation location. Although the error values for surface temperature are fairly close for FASDAS and FDDA runs, for the surface mixing ratio for the day 1 forecast the FASDAS run has consistently lower RMS error values.

5. Conclusions

This study investigated the impact of surface and upper-air assimilation of satellite and conventional meteorological observations with conventional FDDA as well as FASDAS approach. The impact on the simulation of the structure and spatial distribution of monsoon depression precipitation that formed during the 1999 BOBMEX campaign field phase was examined. The FASDAS and FDDA ingestion and assimilation for the simulations were restricted to the first 24 h of

<table>
<thead>
<tr>
<th>Date</th>
<th>Spatial correlation</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CTRL</td>
<td>FDDA</td>
</tr>
<tr>
<td>0000 UTC 26 Jul 1999</td>
<td>0.4293</td>
<td>0.8524</td>
</tr>
<tr>
<td>1200 UTC 26 Jul 1999</td>
<td>0.2832</td>
<td>0.8409</td>
</tr>
<tr>
<td>0000 UTC 27 Jul 1999</td>
<td>0.2975</td>
<td>0.6772</td>
</tr>
<tr>
<td>1200 UTC 27 Jul 1999</td>
<td>0.4467</td>
<td>0.7523</td>
</tr>
<tr>
<td>0000 UTC 28 Jul 1999</td>
<td>0.3219</td>
<td>0.6224</td>
</tr>
<tr>
<td>1200 UTC 28 Jul 1999</td>
<td>0.2832</td>
<td>0.4091</td>
</tr>
<tr>
<td>0000 UTC 29 Jul 1999</td>
<td>0.1025</td>
<td>0.0559</td>
</tr>
</tbody>
</table>

Table 3. Spatial correlation and RMSE of the sea level pressure field for both the experiments (with and without FASDAS and FDDA) with respect to NCEP–NCAR reanalysis for a $15^\circ \times 15^\circ$ region around the depression center.
the integration, and subsequently the model was run in the free-forecast mode. The results suggest that the FASDAS run's performance is best overall, highlighting the benefit of assimilating satellite and conventional upper-air and surface observations through FASDAS and FDDA. Also, the results of the comparison with the BOBMEX observations indicate that the use of FASDAS and FDDA in the FASDAS run reduces surface field errors.

The FASDAS scheme involves the indirect assimilation of soil moisture and ground/skin temperature over land with the simultaneous application of direct continuous assimilation of surface temperature and surface humidity and provides realistic surface latent and sensible heat flux simulations. These simulations ensure that the model's surface fluxes are adjusted so that greater consistency is maintained between the soil temperature, moisture, and surface mass-field variables. The assimilation of the offshore QuikSCAT surface wind vector and surface-analyzed winds over the land improved the simulation of surface winds. The improved surface fields with FASDAS influenced the PBL and possibly to the free atmosphere through entrainment. The coupling of deep convection with boundary layer dynamics facilitates the assimilation of NOAA TOVS satellite-derived temperature and humidity vertical profiles over the land and sea and over the land by radiosonde. Such coupling can also directly influence moisture convergence, and consequently precipitation, in addition to improving thermodynamic structure.

The CTRL run, after day 1, indicated a weak system with a central pressure higher by about 2–4 hPa compared to the FASDAS and the FDDA runs. The comparison of the model results with the BOBMEX 1999 observations indicated reduced errors on all surface fields for the FASDAS run as compared to the CTRL and FDDA runs. Since the performance of FASDAS depends on the density and accuracy of the surface-analyzed data, and since the numbers of surface stations were limited, we used a method to estimate the surface temperature and humidity data from NOAA TOVS. The estimated surface temperature and humidity data obtained from NOAA TOVS were also ingested into the FASDAS scheme and yielded good results. Overall, an attempt has been made to test the FASDAS and FDDA schemes over the Indian monsoon region in order to validate model results with additional data acquired through a field campaign.

As anticipated, these results also show the added value of FASDAS and similar assimilation approaches to NWP forecasts over the Indian region.

The study demonstrated the benefits of ingesting and assimilating different satellite and conventional observations using FASDAS and FDDA. The statistical significance of the differences between the FASDAS and the FDDA results, as well as the differences between FASDAS and no data assimilation (CTRL) results for the BOBMEX buoy and surface observations, have been calculated using the two-tailed Student's t statistics and were found to be statistically significant. Unlike the conventional observations, the NOAA TOVS satellite data also provide for additional temperature and humidity profiles over the data-sparse sea regions. Furthermore, in this study a method of estimating surface temperature and surface humidity values from the NOAA TOVS data has been utilized to provide for additional surface observations, for the effective application of FASDAS. Hence, the NOAA TOVS satellite data have contributed significantly to the improvements in the FASDAS results of this study. Future and new satellite-based sounding data such Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC), and soil moisture products from Advanced Microwave Scanning Radiometer (AMSR), and the planned Soil Moisture and Ocean Salinity (SMOS) datasets could be of significant value over the Indian monsoon region.

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and the NOAA TOVS, TRMM, and QuikSCAT were available from NASA. The authors thank the IMD and the India Department of Science and Technology for providing the INSAT IR imagery, RS, RW, PB, and surface data together with buoy, ship, and radiosonde observations collected during the 1999 BOBME field campaign. This work is funded as a research project by the Space Applications Center (SAC) and the Indian Space Research Organization, Ahmedabad, India; one of the authors (AC) thanks SAC for its support. The author (AC) thanks Dr. P. C. Joshi and Dr. B. Simon for providing estimates of the surface humidity and surface moisture used in this study. The first author (VK) acknowledges the Council of Scientific and Industrial Research, India for providing a research fellowship to carry out the present work. The study also benefited from NSF-ATM 0233780 (S. Nelson), the Joint Center for Satellite Data Assimilation, as well as the NASA Terrestrial Hydrology Program (NNG04G184G, J. Entin), NASA Land Use Land Cover Change Program (G. Gutman), and NASA Interdisciplinary Sciences NNG04GLGIG (J. Entin and G. Gutman).

APPENDIX

Estimation of Surface Temperature and Surface Humidity from TIROS Data

The following methods of obtaining the surface humidity and surface temperature are from Simon and Desai (1986); the exponential density method is based on the exponential fit of the water vapor density, using the layerwise (i.e., 1000–700, 700–500 hPa) water vapor content from TIROS data:

\[ \rho_w = \rho_0 \exp\left(-\frac{Z}{H}\right), \]

where \( \rho_w \) is the water vapor density at height \( Z \) and \( H \) is the scale height of the water vapor. The TIROS satellite provides layerwise temperature. Using the average pressure \( p \) between the levels, the average air density \( p \) was determined. Then using the hydrostatic equation, the heights of the pressure levels were obtained. A lapse rate of \( \gamma \) in this layer was found from the vertical temperature profile. This lapse rate was used with the layer temperature and average height of the first layer to get the surface air temperature as \( T_0 \) from the equation \( T_0 = T_1 + \gamma Z \). This new surface air temperature was utilized to improve upon the cumulative height of previous pressure levels.

Knowing the heights and the total water vapor content in the layers (from TOVS), the scale height was found. The water vapor content in the (1000–700 and 700–500 hPa) layers were denoted as \( W_1 \) and \( W_2 \) and were given as

\[
W_1 = \rho_0 \int_{Z_{1000}}^{Z_{700}} \exp(-Z/H) \, dz \quad \text{and} \\
W_2 = \rho_0 \int_{Z_{700}}^{Z_{500}} \exp(-Z/H) \, dz.
\]

Once the ratios of these two equations were taken, \( \rho_0 \) was eliminated and the scale height could be calculated using the Newton–Raphson technique. Knowing \( H \), \( \rho_0 \) was determined. The specific humidity of the air at the surface was given by

\[ q_a = \frac{\rho_0}{\rho_{a(0)}}, \]

and the specific humidity of the air at the sea surface was calculated as

\[ q_s = \frac{5}{8} \frac{e_{SS}}{p_S - e_{SS}}, \]

where \( e_{SS} = T_S^3 \times 10^{[B + (C/T_s)]} \) was the saturated vapor pressure at the sea surface and \( A = -4.928, B = 23.55, C = -2937.0 \), and where \( T_S \) was the sea surface temperature and \( p_S \) was the sea level pressure. The surface temperature was estimated by assuming that the temperature falls linearly (uniform lapse rate \( \gamma \)) from the surface to 700 hPa, and the lapse rate was found from

\[ \gamma = \frac{(T_1 - T_2)}{(Z_2 - Z_1)}, \]

where \( T_1, T_2 \) were the mean temperatures of the 1000–850 and 850–700 hPa layers, whereas \( Z_1, Z_2 \) were their mean heights as obtained by the following steps:

\[
Z_{1000} = \frac{p_S - 1000}{g m p_s} R T_S, \quad Z_{850} = \frac{150}{g m 925} R T_1, \\
Z_{700} = \frac{150}{g m 775} R T_2, \quad Z_{500} = \frac{200}{g m 600} R T_3, \\
Z_1 = \frac{Z_{1000} + Z_{850}}{2}, \quad \text{and} \quad Z_2 = \frac{Z_{850} + Z_{700}}{2},
\]

where the symbols have their usual meanings. The average temperature between the surface and the 1000-hPa level was called \( T_m \). Then the surface air temperature was given as

\[ T_0 = T_1 + \gamma Z_1, \ldots, T_m = T_0 - \frac{\gamma Z_{1000}}{2}. \]

For iteration, \( T_S \) was replaced by \( T_m \) in \( Z_{1000} \).


