

Study of heavy rainfall event over West Coast of India using analysis nudging in MM5 during ARMEX-I

A. ROUSTRAY, U. C. MOHANTY[†], ANANDA K. DAS* and N. V. SAM

Indian Institute of Technology, New Delhi - 110 016, India

**India Meteorological Department, New Delhi - 110 003, India*

[†]e mail : mohanty@cas.iitd.ernet.in

सार – मेसोस्केल माडलिंग तंत्र (एम. एम. 5) का उपयोग करके भारत में पश्चिमी तट के साथ 7–9 अगस्त 2002 के दौरान प्रेक्षित भारी वर्षा की घटना को संख्यात्मक रूप में अनुकरण करने का इस शोध-पत्र में प्रयास किया गया है। इस अध्ययन का मुख्य उद्देश्य मेसोस्केल मॉडल में उच्च विभेदन पर लिए गए परम्परागत और अपरम्परागत प्रेक्षणों का उपयोग करके नजिंग विश्लेषण के प्रभाव की जाँच करना है।

इस भारी वर्षा की घटना का अध्ययन करने के लिए 60 कि. मी. (स्थूल) और 20 कि.मी. (भीतरी) के डबल नेस्टेड प्रेक्षेत्र वाले एम. एम. 5 के साथ दो संख्यात्मक प्रयोग किए गए हैं। पहले प्रयोग में, नामतः नियंत्रण अनुकरण (सी. एन. टी. एल.), आरंभिक और परिसीमा परिस्थितियों के रूप में भूमंडलीय विश्लेषण का उपयोग किया गया है। यह देखा गया है कि यह मॉडल व्यवस्थित संवहनीय प्रक्रियाओं से संबंधित मुख्य लक्षणों को व्यापक रूप से दर्शाने के योग्य नहीं है। दूसरे प्रयोग में, नामतः नजिंग अनुकरण (एन. यू. डी. जी.), प्रेक्षणात्मक आँकड़ों को शामिल करने के बाद मॉडल आरंभिक और परिसीमा परिस्थितियों में सुधार हुआ है। तदुपरांत, मॉडल का मुक्त समाकलन करने से पहले, उसकी आरंभिक स्थिति में और अधिक सुधार लाने के लिए 12 घंटे के नजिंग विश्लेषण का भी अनुप्रयोग किया गया है। परिणाम दर्शाते हैं कि जब नजिंग विश्लेषण का उपयोग करके चार विमीय आँकड़ा संग्रहण का निष्पादन किया गया तब अनुकरणों में सुधार हुआ।

ABSTRACT. An attempt is made to numerically simulate one heavy rainfall event observed during 7-9 August 2002 along the west coast of India using mesoscale modeling system (MM5). The prime objective of the present study is to investigate the impact of analysis nudging using conventional and non-conventional observations at high-resolution in the mesoscale model.

Two numerical experiments are carried out with MM5 having a double nested domain *viz.* 60 km (coarse) and 20 km (inner) to study this heavy rainfall event. The first experiment, namely the control simulation (CNTL), global analyses is used as initial and boundary conditions. It is noticed that the model is not able to comprehensively capture the prominent features associated with organized convective processes. A second experiment, called the nudging simulation (NUDG), is carried out where the model initial and boundary conditions are improved after the insertion of observational data. Thereafter, 12 hrs analysis nudging is also applied to further improve the initial condition, before the model is allowed for free integration. Results indicate that the simulations are improved when four dimensional data assimilation using analysis nudging is performed.

Key words – ARMEX, Analysis nudging, Heavy rainfall, MM5.

1. Introduction

Several heavy rainfall episodes are observed over the west-coast of India during Arabian Sea Monsoon Experiment (ARMEX-I) 2002. One of the main objectives of ARMEX-I (20 June to 15 August, 2002) was to study

the Arabian Sea convection and intense rainfall events often associated with off-shore trough along the west coast of India.

Most of the heavy rainfall episodes along the west-coast of India and other parts of the country are caused by

TABLE 1

MM5 model overview

Dynamics	Non-hydrostatic	
Main prognostic variables	u, v, w, T, p' and q	
Number of domain	2	
Central point of the domain	18.0° N, 76.0° E	
Horizontal grid distance	60 km (coarse) and 20 km (inner)	
Number of grid points	Domain-1	Domain-2
	• Y-direction 95 (7° S, 44° N)	103 (12° N, 31° N)
	• X-direction 121 (43° E, 109° E)	103 (62° E, 81° E)
Map projection	• Mercator	
Horizontal grid distribution	• Arakawa B-grid	
	• Multiple nested moveable grids are also possible	
Vertical co-ordinate	• Terrain-following sigma co-ordinate	
Time scheme	• Leapfrog scheme (time split technique)	
Spatial differencing scheme	• 2 nd order centered	
Lateral boundary condition	• Relaxation (domain-1)	
	• Time dependent (domain-2)	
Top boundary condition	• Rigid Lid (non-hydro.)	
Radiation scheme	• Dudhia's long and short wave radiation	
Surface layer parameterization	• 13 land-use category	
Cumulus parameterization schemes	• Grell scheme	
PBL parameterization	• MRF (Hong & Pan 1996)	

organized meso-convective systems. Sikka and Gadgil (1980) studied the intense convection over the Arabian Sea resulting in heavy rainfall over the west coast of the India. The nature of the mesoscale convection embedded in the larger scale convection during onset phase of the south-west monsoon in the year 1979 over the eastern Arabian Sea was elucidated using wealth of aircraft data collected during MONEX-79. Benson and Rao (1987) showed that several convective bands were embedded in the synoptic scale cloud cluster over the Arabian Sea on 20 June 1979. They had also suggested that these bands formed and decayed as a result of the complex interactions between the low-level westerly flow, and the upper-level tropical easterly jet-stream and the mesoscale convective features. Roy Bhowmik and Prasad (2001) have used the operational limited area model (LAM) of the India Meteorological Department (IMD) to study the spatial and temporal pattern of monsoon rainfall. However, their study is unable to quantify the orographic rainfall along the Western Ghats of India. Roswintiarti *et al.* (2001) carried out similar modeling studies of convective episodes leading to heavy rainfall events over the Arabian Sea off the west coast of India during the Indian Ocean Experiment (INDOEX). From the above mentioned studies it becomes appropriate and suitable to predict

meso-convective systems that produce heavy rainfall events using a mesoscale model. One of the Intense Observation Period (IOP) from 7 to 9 August, 2002 during ARMEX-I when heavy rainfall was observed along the west coast of India is considered for the present study. The initial and boundary conditions are provided to the mesoscale model from large scale global analyses. However, the model is not able to comprehensively capture the prominent features associated with organized convective processes when large scale global analyses are used as initial and boundary condition. Therefore, an acceptable improvement in the large scale analyses is essential through assimilation of additional observations. The prime objective of the present study is to investigate the impact of analysis nudging using conventional and non-conventional observations at high-resolution in the mesoscale model.

2. Methodology

The MM5 model is a fifth generation Pennsylvania (PSU)/National Centre for Atmospheric Research (NCAR) limited area mesoscale model, non-hydrostatic, terrain-following sigma co-ordinate, designed to simulate mesoscale and regional scale atmospheric circulation

TABLE 2

Description of data used in the assimilation cycle

Types of Data	Stations
Surface	
Automatic Weather System (AWS)	Cannore (11.8° N, 75.4° E)
	Goa (14.7° N, 74.1° E)
	Harnai (17.8° N, 73.1° E)
	Mumbai (19.1° N, 72.8° E)
	Ratnagiri (16.9° N, 73.3° E)
Quick Scatterometer (QSCAT)	Cover oceanic region
Upper-air	
Radio Sonde (RS)	Ahmedabad (23.0° N, 72.4° E)
	Amini Devi (11.1° N, 72.7° E)
	Mumbai (19.1° N, 72.8° E)
	Goa (15.0° N, 74.1° E)
	Kochin (9.9° N, 76.2° E)
	Mangalore (12.6° N, 74.5° E)
Meteorological Satellite (Meteosat)	Aerial coverage (5° S-30° N and 65° E-105° E)
Global Telecommunication System (GTS)	-do-
ORV-Sagar Kanya	Off the west coast of India
Hansa-Goa (RS/RW)	Indian Naval station (Goa)

(Dudhia *et al.*, 2002). A logical combination of multiple-nest-domain configuration, variety of physical parameterization schemes and four dimensional data assimilation technique makes the model capable of simulating a meteorological event on any scale. The performance of a numerical model while simulating any heavy rainfall event depends mainly on parameterization of different meso-scale convective systems (MCSs). In this study the model is run using the Grell scheme (Grell *et al.* 1993) for cumulus parameterization and a non-local closure (Hong and Pan, 1996) scheme for the boundary layer parameterization. The MM5 model configuration used in the present study is given in Table 1.

The initial condition and lateral boundary conditions are obtained from National Centers for Environmental Prediction (NCEP) global analysis. The quality of model simulation depends upon the initial and boundary condition provided to the model. The initial condition can be improved with the insertion of additional observations through objective analysis. This is very crucial and important in the numerical model data assimilation cycle. It is also used as a tool to interpolate and smooth the unwarranted spikes in the observed data. To develop a high-resolution analysis from special observations obtained from field experiments and satellite data, the meteorological community often uses an objective analysis technique of successive corrections. However, from the analysis done by Benjamin & Seaman (1985) it

can be noted that these methods have strong scale dependency, as mesh size is decreased, which introduces relatively large errors. Hardy (1971) developed a mathematical method referred to as multiquadric interpolation (MQD) that produces a more accurate analysis. This method has been implemented for actual meteorological observations by Nuss and Titley (1994). The basic theory of multiquadric interpolation is reviewed by Hardy (1990). The multiquadric technique involves inverting a symmetric observation correlation matrix, where the correlation is based upon distance (the distance between each observation). The diagonal elements are based on information such as variable type and number of observations. This inverse is pre-multiplied by a rectangular matrix which has as elements the distance of every observation to every grid point and post multiplied by the perturbation observation vector. This provides an influence array for each grid point by each observation. In this paper MQD technique is used to develop a high-resolution analysis for the initial and boundary inputs of MM5.

3. Data

The meteorological data sets used in this study are categorized into regular and special observations (ARMEX-I). Heavy rainfall was observed during 7-9 August 2002 seemingly the result of an off-shore trough that extended from Kerala to Maharashtra along the west

coast of India. A cyclonic circulation (somewhat like a mid-tropospheric cyclone) was noticed between 2.1 and 7.6 km over the Saurashtra, Kutch and its neighborhood.

The initial first guess fields are taken from low-resolution ($1^\circ \times 1^\circ$) global AVN (USA Aviations) analysis except Sea Surface Temperature (SST) which is extracted from the FNL (Fluid Naval Laboratory) global analysis. The special observations obtained during this period that are used to refine the first guess are as follows: (a) Surface and upper-air data, both over the Arabian Sea off the west coast of India and west coast land stations; (b) Satellite observations from Meteosat and QSCAT. Details of the data sets used in the study are described in Table 2. The United State Geological Survey (USGS) 25-category global coverage data having 30 and 10 minutes resolution terrain, land use/vegetation, soil and land water mask are used in the coarser and finer domain of the model respectively.

4. Numerical experiments

Two numerical experiments are carried out using the MM5 (version 3.6) model with double nested domain to study the heavy rainfall event observed during 7-9 August, 2002. The model domain is centered at 18° N, 76° E. The coarser domain is integrated with 60 km resolution over India and the finer domain with 20 km resolution over west coast of India. During different numerical experiments one-way interaction is allowed between two domains (from outer to inner). The first experiment, namely the control simulation (CNTL) is carried out with the grid spacing of 60 km in the coarser domain and 20 km in finer domain. The initial and boundary condition is provided to the model directly from the coarse resolution global analyses. The resulting simulations from CNTL are named as CNTL60 and CNTL20 for outer and inner domains respectively. The second experiment *i.e.*, the nudging simulation (NUDG), is carried out after the model initial and boundary conditions are improved with the insertion of observational data. In this experiment 12 hrs analysis nudging with improved analysis is applied upto 0000 UTC of 06 August, 2002 and then model is allowed to integrate freely for 48 hrs. Therefore, the initial condition is achieved at 0000 UTC of 06 August, 2002 for model free run is improved one compared to CNTL experiment and more close to the observation. The outputs from NUDG are called as NUDG60 and NUDG20 for outer and inner domain respectively.

4.1. Analysis nudging

In the grid nudging, Newtonian relaxation terms are added to the prognostic equations for wind, temperature and moisture fields. The model linearly interpolates the

analyses in time to determine the value towards which the model relaxes its solution. The model values are relaxed towards the analysis using the nudging terms. This process can be described in MM5 for any variable α with the following equation:

$$\frac{\partial p^* \alpha}{\partial t} = F(\alpha, \bar{x}, t) + G_\alpha W(\bar{x}, t) \varepsilon p^* (\alpha_o - \alpha) \quad (1)$$

$F(\alpha, \bar{x}, t)$ represents the natural meteorological processes. For example, if α is zonal component of the wind (u), then F will include terms such as pressure gradient force, Coriolis force, diffusion terms and model physics such as momentum fluxes.

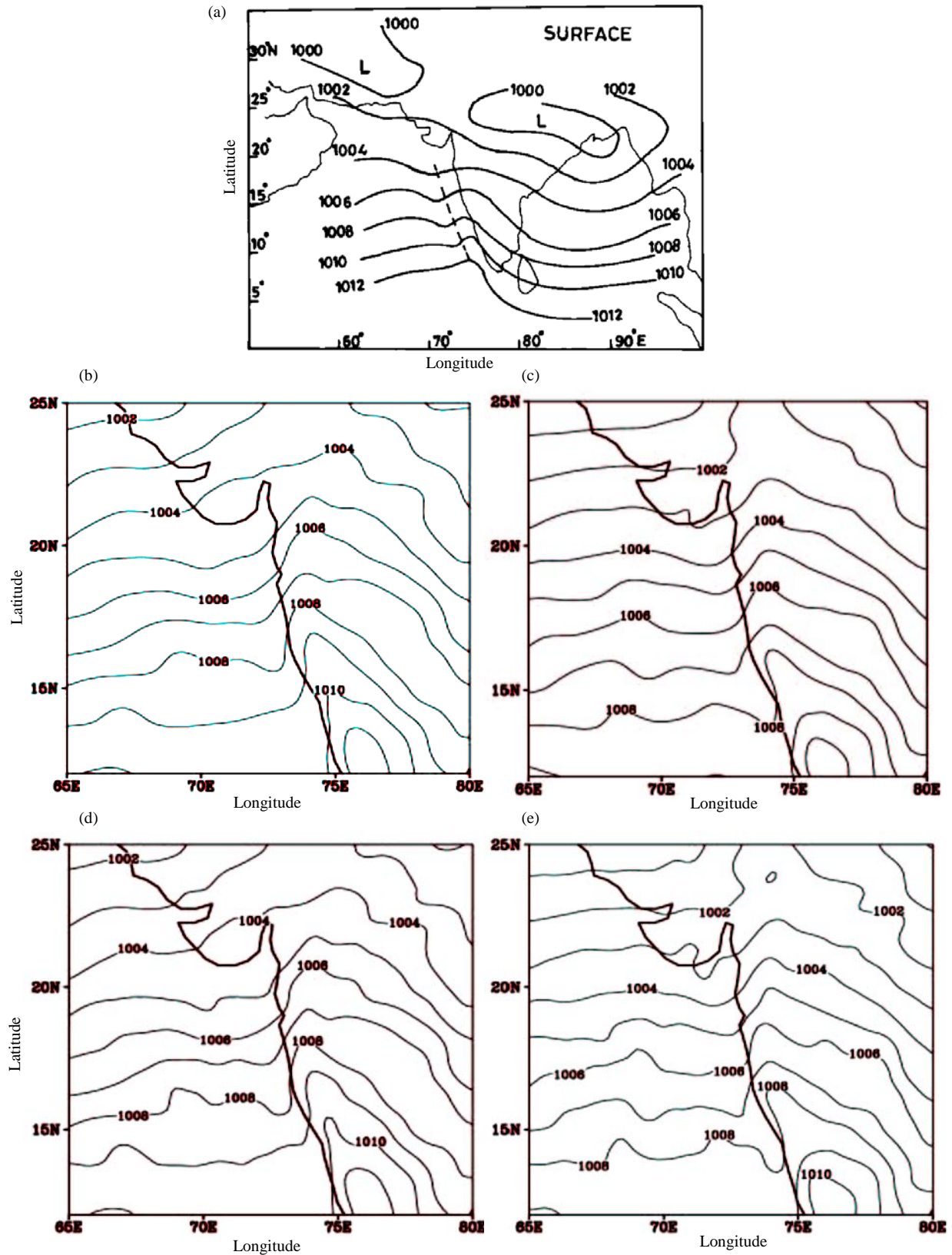
G_α is the analysis nudging term for a given variable α . According to Stauffer and Seaman (1990), the nudging term should be much smaller than the magnitude of the other terms in the given model equation. This can inhibit the model equations from generating the natural, necessary atmospheric responses. On other hand, if G_α is too small, the observations will have minimal effect on the evolution of the model state, allowing phase and amplitude errors to grow.

$W(\bar{x}, t)$ is the analysis weighting function, which specifies the horizontal, vertical and time weighting applied to the analysis. The symbol ε is defined as the analysis quality factor which ranges between 0 and 1, is based on the quality and distribution of the data used to produce the gridded analysis. In the present study the value of ε varied from 0.5-0.8 for different parameters. The P^* is the model atmosphere depth. The symbol α_o is an observed value and α represents the interpolated model value.

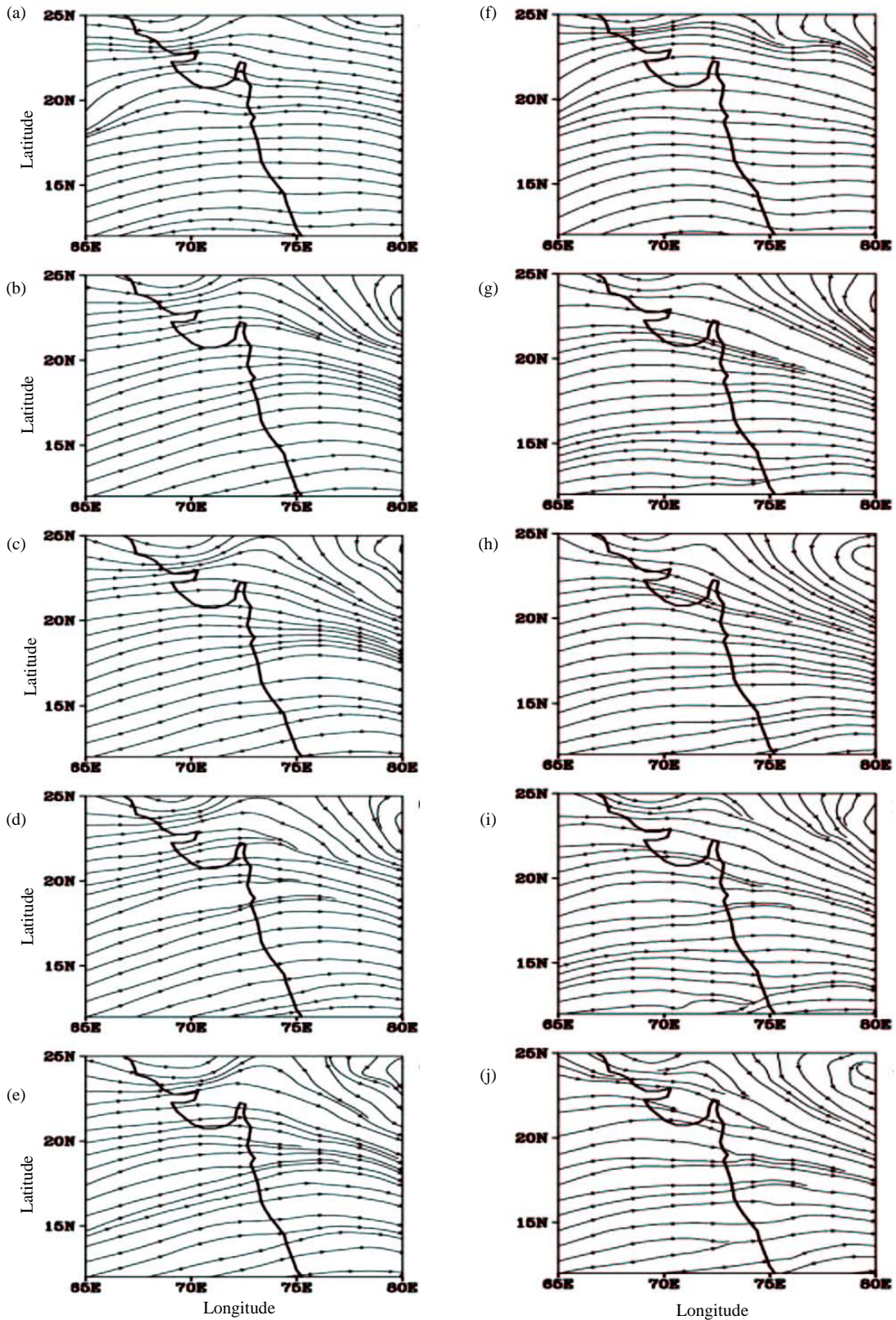
5. Result and discussions

5.1. Mean sea level pressure

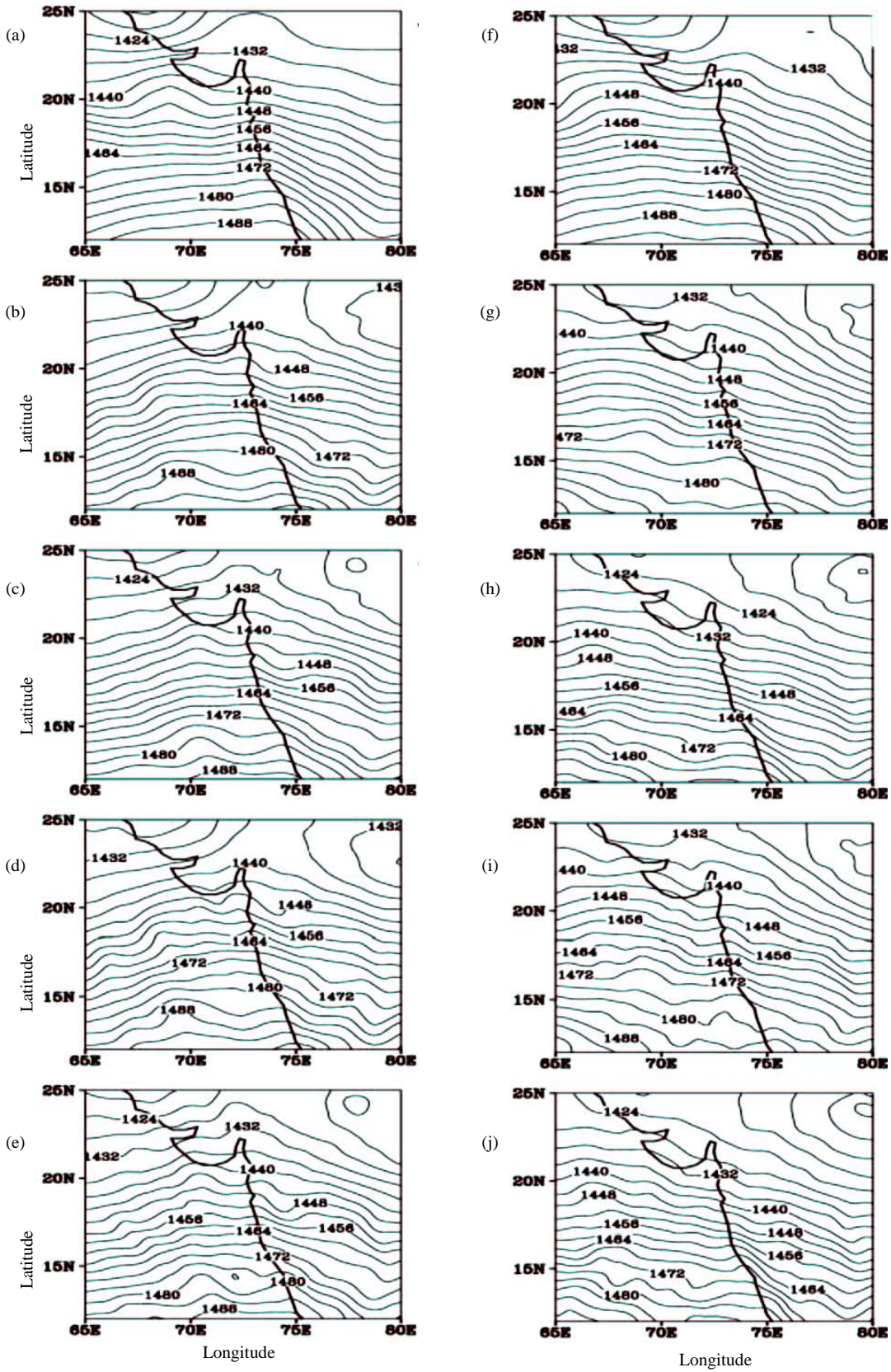
Fig. 1 represents observed and simulated mean sea level pressure (MSLP) valid at 0300 UTC of 7 August 2002. Fig. 1(a) shows the subjectively analyzed MSLP (not perfectly scaled with other figures) by IMD, while Figs. 1 (b-e) depicts the model simulated MSLP. Figs. 1 (b&d) represent CNTL60 and CNTL20 simulation, while Figs. 1(c&e) depict NUDG60 and NUDG20 simulation respectively. Comparing the simulations from all the numerical experiments with the observations [Fig. 1(a)], it is noted that the general characteristics in the MSLP pattern over the region is fairly captured in the simulations. It is noticed that over the Arabian Sea, isobars are nearly parallel to each other and oriented along



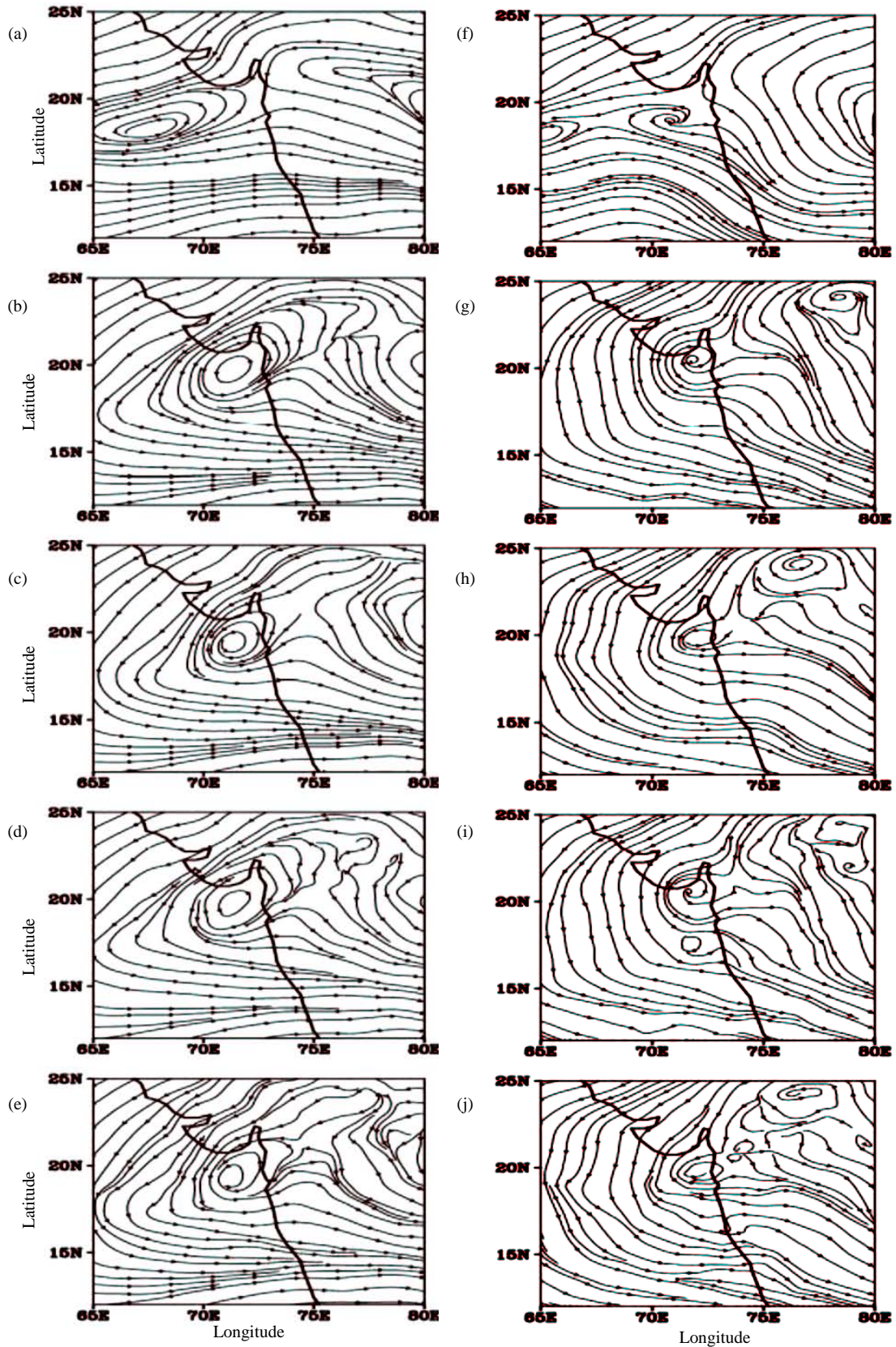
Figs. 1(a-e). Observed and forecast of MSLP (a) Observed, (b) CNTL60, (c) NUDG60, (d) CNTL20 and (e) NUDG20 valid at 0300 UTC 07 August, 2002



Figs. 2(a-j). Stream lines at 850 hPa for (a) Verification analysis, (b) CNTL60, (c) NUDG60, (d) CNTL20 and (e) NUDG20 valid at 0000 UTC on 07 August,2002 and (f) to (j) are same as (a) to (e) respectively but valid at 0000 UTC on 08 August, 2002



Figs. 3(a-j). Same as Fig. 2 but for geopotential height (m)



Figs. 4(a-j). Same as Fig. 2 but for 500 hPa

the monsoonal flow during this period. The isobars in all simulations show the trough formation along the west coast of India that extends from coastal Karnataka upto Konkan Goa. This feature is also clearly supported by the observed off-shore trough shown in the [Fig. 1(a)]. The manifestation of the off-shore trough is most prominent in NUDG20 [Fig. 1(e)]. The isobars cross the coastal line and run towards the southeast direction, even as the monsoon trough extends over head Bay and the orientation of isobars shifts towards southeast over the Bay of Bengal. Although, all the figures show a similar pressure pattern, but there are a definite differences in the pressure gradients along the west coast from Kerala to Gujarat. CNTL simulations establish a pressure change of 7 hPa from southern part of the coastal Karnataka to Gujarat coast where as the northward decrease of pressure over same region is about 9 hPa in NUDG simulations. Correspondingly NUDG simulations generate strong pressure gradients along west coast of India compare to CNTL simulations. Henceforth, the location of isobars and their corresponding orientations in NUDG60 [Fig. 1(c)] and NUDG20 [Fig. 1 (e)] fairly match with observations.

The large scale MSLP pattern for both the domains in two experiments are nearly similar although in the inner domain the resolution is increased three fold. But the differences in other fields *e.g.* wind and rainfall are significant for both the domains. The small-scale processes which modulate locally the large-scale circulation can be captured by the model simulations with an increase in resolution but their existence associated with the variations in large-scale pressure pattern with a specified time-scale can not be established as long as the initial condition (interpolated global analysis) does not reflect them.

The model simulation for day-2 of MSLP field is not presented in this paper as the results did not show significant variations from that inferred during day-1.

5.2. Upper-air circulation

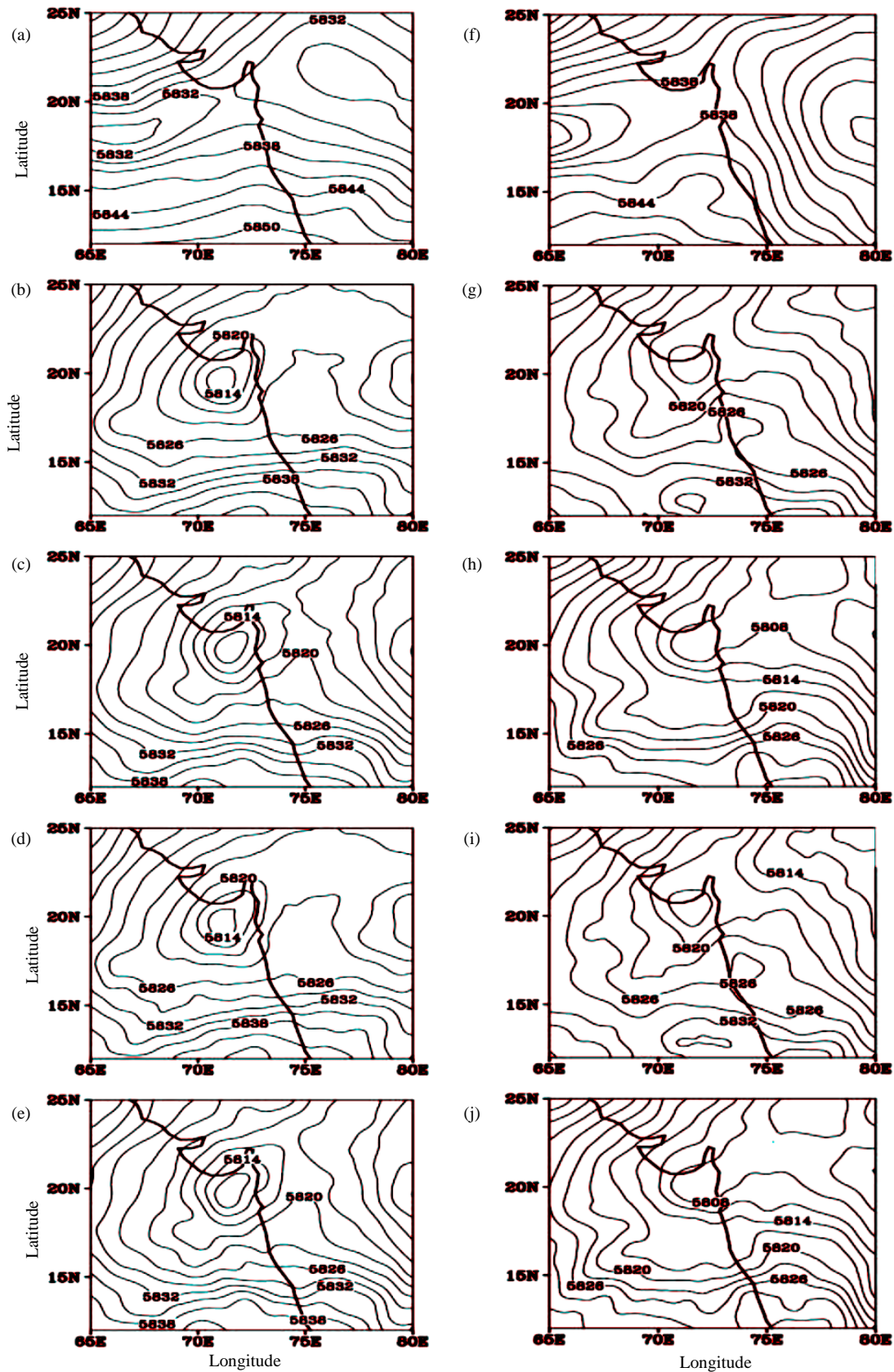
5.2.1. 850 hPa

The left and right panels of Fig. 2 describe stream lines at 850 hPa valid at 0000 UTC of 7th and 8th August, 2002 respectively. Fig. 2 (a) represents the stream lines from AVN analysis for 07 August 2002 at 850 hPa. Figs. 2 (b & d) illustrate CNTL60 and CNTL20 simulated stream lines at 850 hPa respectively, whereas NUDG60 and NUDG20 simulations are demonstrated in Figs. 2 (c&e) respectively. The right panels [Figs. 2 (f-j)] follow the same representations as described for the left panel. Fig. 3 is same as Fig. 2 but for geopotential height.

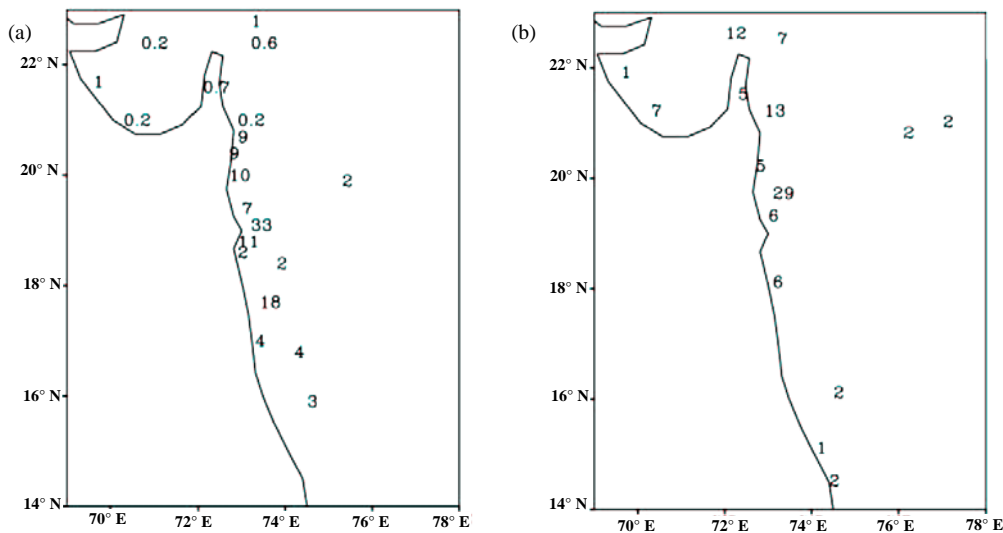
A comprehensive analysis of all the figures [Figs. 2 (a -j)] in Fig. 2 depicts a zonal flow pattern over the Arabian Sea, which after crossing the west coast line acquires a meridional component towards the south. The stream lines mostly follow geopotential height over the sea region during day-1 (0000 UTC, 07 August 2002) simulation [Figs. (2&3)]. Close observation of near surface MSLP pattern and geopotential at 850 hPa (Fig. 3) indicate the presence of off-shore trough. However, the turning of stream lines at 850 hPa (Fig. 2) is not very clear. At this level the wind flow is primarily characterized by low level jet and the strong westerlies all over the west coast of India. The gradual creation of a shear zone around the latitude 20° N due to the perpendicular action of northerly wind over westerly flow at the south-west side of the low over central India is a distinct feature in all simulations in day-1 and day-2 [Figs. 2 (b-e and g-j)]. Especially, in day-1 NUDG simulations established this circulation characteristics comparatively well, which is nearly absent in the verification analysis [Fig. 2 (a)]. The simulated trough in geopotential during day-1 by CNTL60 [Fig. 3(b)] and CNTL20 [Fig. 3(d)] is far off from west coast line of India, but they are well represented and closer to the west coast line of India from NUDG60 [Fig. 3(c)] and NUDG20 [Fig. 3(e)] simulations. There is not much variability observed in day-2 (0000 UTC, 08 August 2002) simulations, where both control and nudging experiments show the same location of the off-shore trough. The rate of decrease in the geopotential height during day-1 using the nudging experiment [Figs. 3 (c&e)] compares very well with AVN verification analysis [Fig. 3(a)]. The simulated geopotential heights due to the control experiments [Figs. 3(b&c)] are higher when compared to the verification analysis [Fig. 3(a)]. Also the rate of decrease in the geopotential height along increasing latitude is lower than that observed in the verification analysis, as the spacing between isoheights increases. The geopotential distribution in control simulation during day-1 [Figs. 3(b&d)] and day-2 [Figs. 3(g&i)] do not show much difference. However the geopotential height shows a southward shift in nudging simulation during day-2 [Figs. 3(h&j)]. The trough like structure observed over central India in the verification analysis [Fig. 3(f)] during day-2 is well defined in the nudging simulations [Figs. 3(h&j)] where the movement of this low pressure area from central India towards west is noticed. The control simulations [Figs. 3(g&i)] during day-2 do not show this circulation feature.

5.2.2. 500 hPa

The left and right panels of Fig. 4 describe stream lines at 500 hPa valid at 0000 UTC of 7th and 8th August, 2002 respectively. Fig. 4 (a) represents the stream lines



Figs. 5(a-j). Same as Fig. 2 but geopotential height for 500 hPa



Figs. 6(a&b). Observed precipitations (cm) (a) Day-1 (b) Day-2 valid at 0300 UTC on 07 and 08 August, 2002 respectively

from AVN analysis for 07 August 2002 at 500 hPa. Figs. 4 (b&d) illustrate CNTL60 and CNTL20 simulated stream lines at 500 hPa respectively, whereas NUDG60 and NUDG20 simulations are demonstrated in [Figs. 4(c and e)] respectively. The right panels [Figs. 4 (f-j)] of Fig. 4 follow the same representations as described for the left panels. Fig. 5 is same as Fig. 4 but for geopotential height.

The simulations due to both CNTL [Figs. 4 (b&d)] and NUDG [Figs. 4 (c&e)] experiments are able to fairly capture the mid tropospheric cyclone (MTC) [Figs. 4 (a&f)] over the Arabian Sea off the west coast of India during day-1 and day-2 respectively. Fig. 4 (a) and Fig. 4 (f) AVN verification analysis clearly depicts the presence of MTC circulation centered at (18° N, 67° E) in day-1 and at (19° N, 70.5° E) in day-2 respectively over the Arabian Sea. However, in Fig. 4 (f) a comparatively weak MTC is observed. Analyzing the day-1 and day-2 simulations for control and nudging experiments, it can be stated that all of the simulations are able to capture the MTC. Although the day-1 [Figs. 4 (b-e)] simulations are able to produce MTC circulation, its centre is shifted (by an order of 1-2° N, 3-4° E) towards East of North East (E-NE) from the central position in verification analysis [Fig. 4(a)]. Looking closely at the CNTL and NUDG experiments, during day-1 it is noted that CNTL20 [Fig. 4(d)] and NUDG20 [Fig. 4(e)] simulations are a bit closer to the verification analysis. Therefore, it can be stated that at higher resolution the location of the MTC is simulated reasonably well.

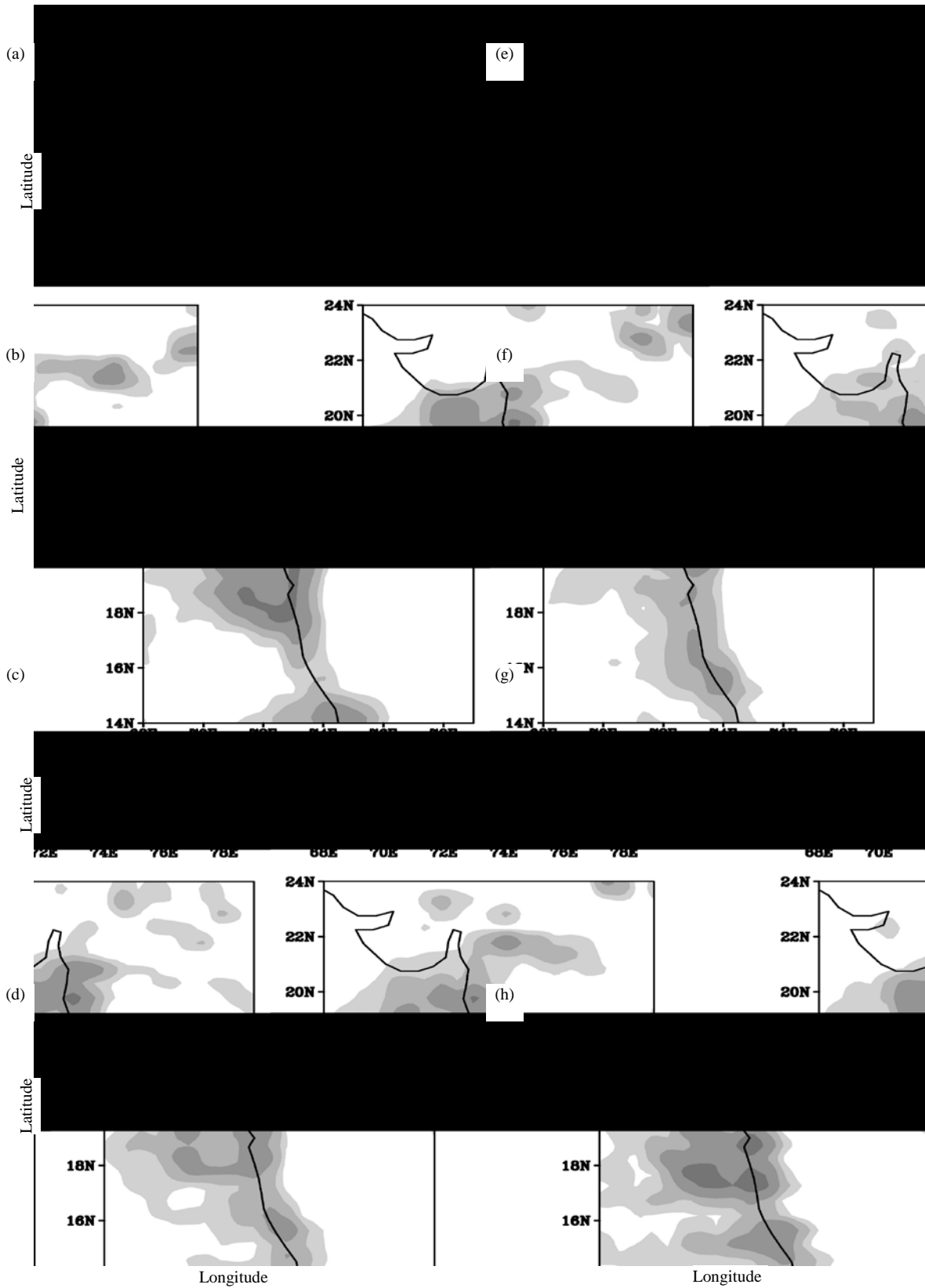
The structures of geopotential height (Fig. 5) also represent the existence of the MTC and its intensity. In the verification analysis [Figs. 5 (a&f)] the location of the

upper-air cyclonic circulation is fairly away from the Gujarat-Maharashtra coast but contrary to this all simulations [Figs. 5(b-e and g-j)] show the system closer to south Gujarat and coastal Maharashtra. At the same time the geopotential heights in both the experiments (CNTL and NUDG) are lower by 15-20 meters compared to the verification analysis. This in turn establishes the fact that the MTC is more intense in the simulations. The observed circulation pattern and mainly the rainfall distribution (Fig. 6) validate the simulated features of MTC. Furthermore, the MTC is more intense in NUDG60 [Figs. 5(c&h)] and NUDG20 [Figs. 5(e&j)], which depicts the impact of assimilation.

The day-2 simulations [Figs. 5(g-j)] do not show closed contours of geopotential heights along the west coast of India but a trough formation extending in E-NE direction can also be deciphered from the rainfall pattern [Figs. 7(e-h)] along the trough line. Although the trough formation is present in the verification analysis of day-1 [Fig. 5(a)] but it is absent in day-2 [Fig. 5(f)].

5.3. Rainfall

Figs. 6 (a&b) show the observed 24 hourly accumulated rainfall obtained from Indian Daily Weather Report (IDWR) at 0300 UTC during 7th and 8th August 2002 respectively along the west coast of India. Highest rainfall of 33 and 29 cm are noticed over Mahabaleswar in the Maharashtra regime during 7th August 2002 and 8th August 2002 respectively. The left and right panels of Fig. 7 describe day-1 and day-2, 24 hourly accumulated rainfalls valid at 0300 UTC during 7th and 8th August, 2002 respectively. Figs. 7 (a&c) illustrate CNTL60 and CNTL20 simulated 24 hours accumulated rainfall



Figs. 7(a-h). 24 hrs accumulated precipitations (cm) for (a) CNTL60, (b) NUDG60, (c) CNTL20 and (d) NUDG20 valid at 0300 UTC on 07 August, 2002 and (e) to (h) are same as (a) to (d) respectively but valid at 0300 UTC, 08 August, 2002

respectively, whereas NUDG60 and NUDG20 simulations are demonstrated in Figs. 7 (b&d) respectively. The right panels [Figs. 7(e-h)] of Fig. 7 follow the same representations as described for the left panels.

The simulations (Fig. 7) of rainfall distribution along the west coast of India show clearly the presence of organized convective activity leading to heavy precipitation. The effect of off-shore trough over Konkan-Goa regime and the presence of MTC over the Arabian Sea off the west coast India, especially over north Maharashtra and Gujarat coast are the causative features for this heavy rainfall event over these regions. During day-1, well established circular structured systems are noticed due to NUDG [Figs. 7(b&d)] experiments, but are not clearly spotted from the CNTL [Figs. 7(a&c)] simulations. The model simulates lesser rainfall in all of these experiments. However, when comparison is made between CNTL and NUDG simulations, the nudging experiments produce simulations closer to the observations [Fig. 6(a)]. The localized distribution of rainfall during day-1 in 20 km simulations, from CNTL20 [Fig. 7(c)] and NUDG20 [Fig. 7(d)] are better represented when compared to 60 km resolution simulations from CNTL60 [Fig. 7(a)] and NUDG60 [Fig. 7(b)]. The position of maximum rainfall (33 cm) recorded at Mahabaleswar (19.2° N, 73.2° E) is well represented in all of the simulations. This location is more accurately captured by NUDG20 [Fig. 7(d)] simulation. The second maximum rainfall (18 cm) observed at Agumbe is also well represented in NUDG20 simulation. Although the location of heavy rainfall is well simulated in NUDG20 experiments, the amount is on the lower side. This could be mainly attributed to the presence of orography (Western Ghats) that needs a better representation in the model.

Day-2 simulations of rainfall pattern [Figs. 7(e-h)] correlate well with observations shown in Fig. 6(b). It is seen from Fig. 4, that the MTC is bit weakened, and spread over a larger area. The rainfall distribution pattern [Figs. 7(e-h)] too shows a larger coverage over the Arabian Sea off the west coast of India. The overall representation of the rainfall pattern due to both CNTL [Figs. 7(e&g)] and NUDG [Figs. 7(f&h)] experiments, compare reasonably well with the observations [Fig. 6(b)] along the west coast of India. In depth analysis shows that NUDG simulations are able to capture the location and amount of rainfall better than CNTL simulations. The observed maximum rainfall (29 cm) over Mahabaleswar and second maximum (13 cm) over Surat (20.9° N, 72.9° E) during day-2 is well brought out in all the experiments but is closest with NUDG20 [Fig. 7(h)] simulation. No marked variability is observed between day-1 and day-2 nudging simulations as compared to

control simulations. It is worth mentioning here that the model is not able to adequately represent the rainfall pattern over Saurashtra region of Gujarat, in all other experiments except NUDG20 [Fig. 7(h)] simulation that shows light/little rainfall over that region.

6. Summary and conclusions

The mesoscale model (MM5) with double nested domains 60 and 20 km resolution is used to study the heavy rainfall event during 7-9 August 2002 over the west coast of India during ARMEX-I. Two numerical experiments are conducted to examine the impact of high resolution analysis nudging with 60 and 20 km model resolution using conventional (RS/RW and surface data) and non-conventional (satellite data) in simulating MSLP, wind and rainfall.

The following conclusions can be drawn from the present study.

- (i) The off-shore trough observed during this period of heavy rainfall is well simulated by the NUDG20 experiment.
- (ii) The simulations due to both CNTL and NUDG experiments are able to capture the MSLP pattern observed at 850 hPa., indicating the presence of off-shore trough. However, the turning of wind at 850 hPa. for the off-shore trough is not manifested well.
- (iii) The location and the intensity of MTC is well represented by nudging simulations showing clearly the impact of additional data.
- (iv) NUDG20 experiment is able to capture the location of heavy rainfall over the west coast of India reasonably well when compared with the other simulations. However, all of the model simulations underestimate the maximum value of the observed rainfall as observed. There is definitely a need to further improve the model simulation by increasing the model resolution and inserting additional dense network surface and upper-air data. Further, the implementation of sophisticated assimilation technique like three dimensional variational assimilation system would produce even more realistic initial conditions for the mesoscale model integrations.

Acknowledgements

The authors sincerely acknowledge Department of Science and Technology Govt. of India for providing the necessary funds and facilitating to participate and obtain ARMEX-2002 data sets. We also thank the scientific team on board ORV Sagar Kanya, in particular Dr. G. S. Bhat

for providing part of the ARMEX-2002 data. The authors acknowledge IMD for providing the surface and upper air observations from the coastal stations of India. Our thanks are also due towards National Centre for Environment Prediction (NCEP) and National Centre for Medium Range Weather Forecasting (NCMRWF) for providing the necessary analyses data for the present study. We express our sincere thanks to Prof. D. V. Bhaskar Rao for his valuable comments and suggestions for improvement of the paper.

References

- Benjamin, S. G. and Seaman, N. L., 1985, "A simple scheme for objective analysis in curved flow", *Mon. Wea. Rev.*, **113**, 1184-1198.
- Benson, C. L. and Rao, G. V., 1987, "Convective bands as structural components of an Arabian Sea convective cloud cluster", *Mon. Wea. Rev.*, **115**, 3013-3023.
- Dudhia, J., Gill, D., Manning, K., Wang, W. and Bruyere, C., 2002, "PSU/NCAR Mesoscale Modeling system (MM5V3) tutorial class notes and user's guide; Available from NCAR", Boulder, Colorado, USA, June, 2002.
- Grell, G., 1993, "Prognostic evaluation of assumption used by cumulus parameterizations", *Mon. Wea. Rev.*, **121**, 764-787.
- Hardy, R. L., 1971, "Multiquadric equations of topography and other irregular surfaces", *J. Geophys. Res.*, **76**, 1905-1915.
- Hardy, R. L., 1990, "Theory and applications of the multiquadric-biharmonic method", *Comput. Math. Appl.*, **19**, 163-208.
- Hong, S. Y. and Pan, H. L., 1996, "Non-local boundary layer vertical diffusion in a medium-range forecast model", *Mon. Wea. Rev.*, **124**, 2322-2339.
- Nuss, W. A. and Titley, D. W., 1994, "Use of multiquadric interpolation for meteorological objective analysis", *Mon. Wea. Rev.*, **122**, 1611-1631.
- Roswintarti, O., Raman, S. and Mohanty, U. C., 2001, "Numerical study of the Intertropical Convergence Zone over the Indian Ocean during the 1997 and 1998 northeast monsoon episodes", *Pure Appl. Geophys.*, **158**, 989-1015.
- Roy Bhowmik, S. K. and Prasad, K., 2001, "Some characteristics of limited area model precipitation forecast of Indian monsoon and evaluation of associated flow features", *Met. Atm. Phys.*, **76**, 223-236.
- Sikka, D. R. and Sulochana Gadgil., 1980, "On the maximum cloud zone and ITCZ over the Indian longitudes during the southwest monsoon", *Mon. Wea. Rev.*, **108**, 1122-1135.
- Stauffer, D. R. and Seaman, N. L., 1990, "Use of four-dimensional data assimilation in a limited-area mesoscale model. Part I: Experiments with synoptic-scale data", *Mon. Wea. Rev.*, **118**, 1250-1277.
-