Application of three-dimensional triple nested mesoscale model for assessing the transport and boundary layer variability over the Indian Ocean during INDOEX

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A three-dimensional triple nested domain version of MM5 was applied for INDOEX region (40.12°N–32.04°S; 32.10°E–117.90°E) to study the regional flow patterns and associated transport using backward and forward trajectories. The model was integrated for 48-h period starting 00 UTC 5 March 1999. From the simulations a mapping of the temporal and spatial variations in the marine boundary layer (MBL) heights were obtained. The boundary layer heights were verified using actual ship-based sounding from RV *Ronald H. Brown* and a good agreement was found. The model simulated significant variability in the MBL heights both spatially and temporally. During the daytime, the continental boundary layer was ~ 1500 m deep while over the ocean, the MBL was shallow (~ 300 m) near the coast, and it increased steadily towards the ITCZ where MBL heights of ~ 1000 m were encountered. During night there was a reversal with the continental boundary layer heights averaging less than 500 m while over the ocean, particularly over the ITCZ, the MBL heights were ~ 1000 to 1500 m. This variability in the MBL heights significantly affected the transport pattern over the INDOEX region. Both the backward and forward trajectories showed distinct characteristics depending on the source region (eastern or western coastal landmass, equator, or near ITCZ). Near the coast, there was an evidence for localized circulation in which the air parcels were trapped along the coast. For the open oceans (both near the ITCZ as well as equator) the air parcel trajectories continued over a significant distance. Results suggest that MM5 can be successfully applied for diagnostic studies related to INDOEX, and that the boundary layer heights and the variations in the air parcel transport need to be considered for interpreting the surface measurements.

THE Indian Ocean Experiment (INDOEX) was designed to understand the impact of transport of continental aerosols to the ITCZ on cloud radiative properties and surface energy balance over equatorial Indian Ocean. The central hypothesis was that the aerosol-rich continental air parcels would eventually reach ITCZ, and entrain into the convective clouds making their response more uncertain in terms of regional warming or cooling. Thus pertinent to INDOEX objective is the need to develop an understanding of the transport and aerosol entrainment from the continental landmasses. These transport and entrainment processes are governed by the regional circulation (airflow trajectories) and convection (buoyancy). For INDOEX, these processes have been studied mainly using point observation over ship-based platforms[1]. Observations have suggested that the INDOEX study region is fairly inhomogeneous and there are several mesoscale processes interacting with the large-scale dynamics. Thus, a regional analysis for a domain with such a spatial and temporal variability cannot be addressed by point observations alone. Further, large scale analysis generated from coarse resolution global circulation models (GCMs) is inadequate as it cannot capture the mesoscale features such as land–sea breeze circulation, orographic convection, and modification of the lower tropospheric circulation due to surface inhomogeneities. In addition to the circulation, another important aspect is the distribution of the transported material aloft to the lower troposphere, which depends on the entrainment potential. This further depends on the boundary layer depth and the surface turbulent heat fluxes. To address these issues, a mesoscale numerical modeling study was attempted for the INDOEX region. A triple nested, nonhydrostatic version of the Fifth generation PSU–NCAR Mesoscale Model (MM5) was used.

Experimental design

A three-dimensional, triple nested MM5 domain was set up over the INODEX region. The Coarse Grid Mesh (CGM), Medium Grid Mesh (MGM), and Fine Grid Mesh

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(FGM) covered areas between (40.12°N–32.04°S; 32.10°E–117.90°E, 50 × 55 grids, 180 km resolution), (27.14°N–19.44°S; 49.37°E–103.87°E, 91 × 103 grids with 60 km horizontal resolution) and (19.81°N–13.92°S; 56.20°E–91.64°E, 193 × 199 grids with 20 km resolution) respectively. All the three domains had 17 vertical s levels (between 1000 hPa and 10 hPa). Details regarding the model formulation can be found in Grell *et al.*[2] and are summarized in Table 1. The model was integrated with initial conditions corresponding to 00 UTC 5 March 1999 for 48 h. These initial data were obtained from National Center for Atmospheric Research (NCAR) archive and consisted of 2.5 degree resolution, 15 standard pressure level data from the European Centre for Medium Range Weather Forecast (ECMWF) operational analysis, and the daily analysis SST fields from the National Center for Environmental Prediction (NCEP) archive. Additional input to the model pertaining to surface boundary conditions such as land use, topography and surface roughness were obtained from the MM5 data libraries. All these data were interpolated to the model grids. The model performance was validated for this domain and is reported in a companion study (Roswintiarti *et al.*, this issue). In this study the focus is on applying the model simulated fields for assessing the transport and entrainment over the INDOEX region. This was achieved by analysing the spatial and temporal variations in the boundary layer depths over the study domain, as well as a forward and backward trajectory analysis. The trajectory analysis was performed by feeding the MM5 simulated wind fields in to Vis5D (ftp://www.ssec.wisc.edu/pub/vis5d-5.1).

Results and discussion

In this section we first discuss the model simulated low-level winds (925 hPa) and their distribution over the INDOEX region. Then, the results from the forward and backward trajectories (each over a 2-day period) would be interpreted. Finally the transport and entrainment issues will be discussed with relation to the temporal changes in the surface sensible heat fluxes, convective rainfall and boundary layer heights over the entire domain.

Figure 1 shows the wind fields for day-1 over the FGM (00 UTC 6 March 1999). The model could fairly well simulate an active ITCZ located around 10°S, embedded within two low-pressure systems. In general, the model could predict the wind features over the Indian Ocean quite reasonably well. The tropical depressions over the southern (13°S; 80°E) and equatorial (1°N; 87°E) Indian Ocean were well predicted. The northerly winds over the Arabian Sea converging with easterly winds over the equator were also reasonably simulated. On the other hand, the anticyclone over the Bay of Bengal was not simulated. The low-pressure system over the Himalayas (30°N; 100°E) was not accurately located. Similarly, the overall features associated with the wind fields at 925 hPa for day-2 of the simulation (00 UTC 7 March 1999) were well simulated by MM5. Once again, the low-pressure systems over the Indian Ocean were not predicted well. However the overall cross-equatorial flow patterns were in good agreement with the analysis. Most of the major centers of activities were well predicted by the model. In general, there is a close agreement between the

Table 1. An overview of the PSU-NCAR Mesoscale Model (MM5)

	CGM	MGM	FGM
Independent variable	x, y, s, t	x, y, s, t	x, y, s, t
Dependent variable	$u, v, w, T, q(q_v, q_c, q_r), P_s$	$u, v, w, T, q(q_v, q_c, q_r), P_s$	$u, v, w, T, q(q_v, q_c, q_r), P_s$
Domain coverage	40.12°N–32.04°S; 32.10°E–117.90°E (50 × 55)	27.14°N–19.44°S; 49.37°E–103.87°E (91 × 103)	19.81°N–13.92°S; 56.20°E–91.64°E (193 × 199)
Horizontal resolution	180 km	60 km	20 km
Horizontal grid system	Arakawa B-grid	60 km	20 km
Vertical levels	17 (0.997, 0.991, 0.981, 0.966, 0.946, 0.920, 0.887, 0.845, 0.784, 0.698, 0.599, 0.5, 0.399, 0.299, 0.2, 0.1, 0.025)	60 km	20 km
Time steps	210 s	70 s	23 s
Time integration scheme	Semi-implicit scheme[5]		
Precipitation physics: • Cumulus parameterization scheme • Resolvable-scale micro physics scheme	 • Anthes-Kuo[7] • Dudhia's simple ice sheme[8]		
PBL scheme	Blackadar[9]		
Atmospheric radiation scheme	Simple cooling		
Surface layer process parameterization	• Surface fluxes (similarity theory) • Ground temperature prediction using energy balance equation		
Topography	10' US Navy		
Sea surface temperature	NCEP operational analysis		

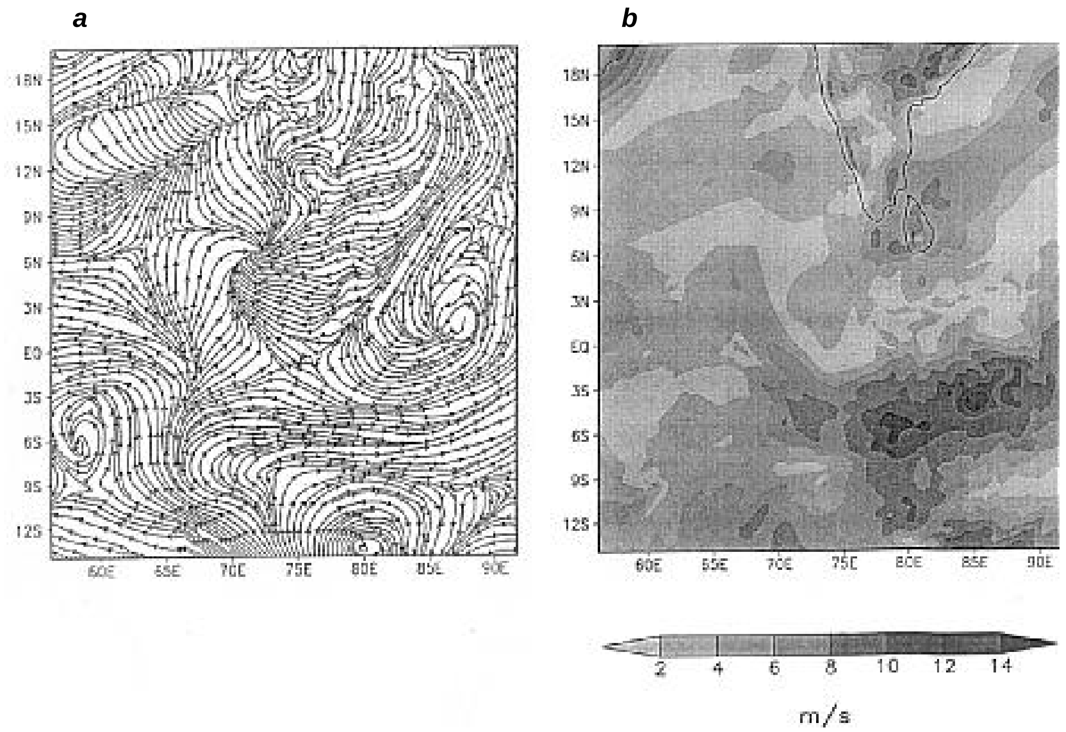

Figure 1. Simulated day-1 streamlines (***a***) and wind speeds (***b***) over FGM at 925 hPa for 00 UTC 6 March 1999 over the INDOEX domain.

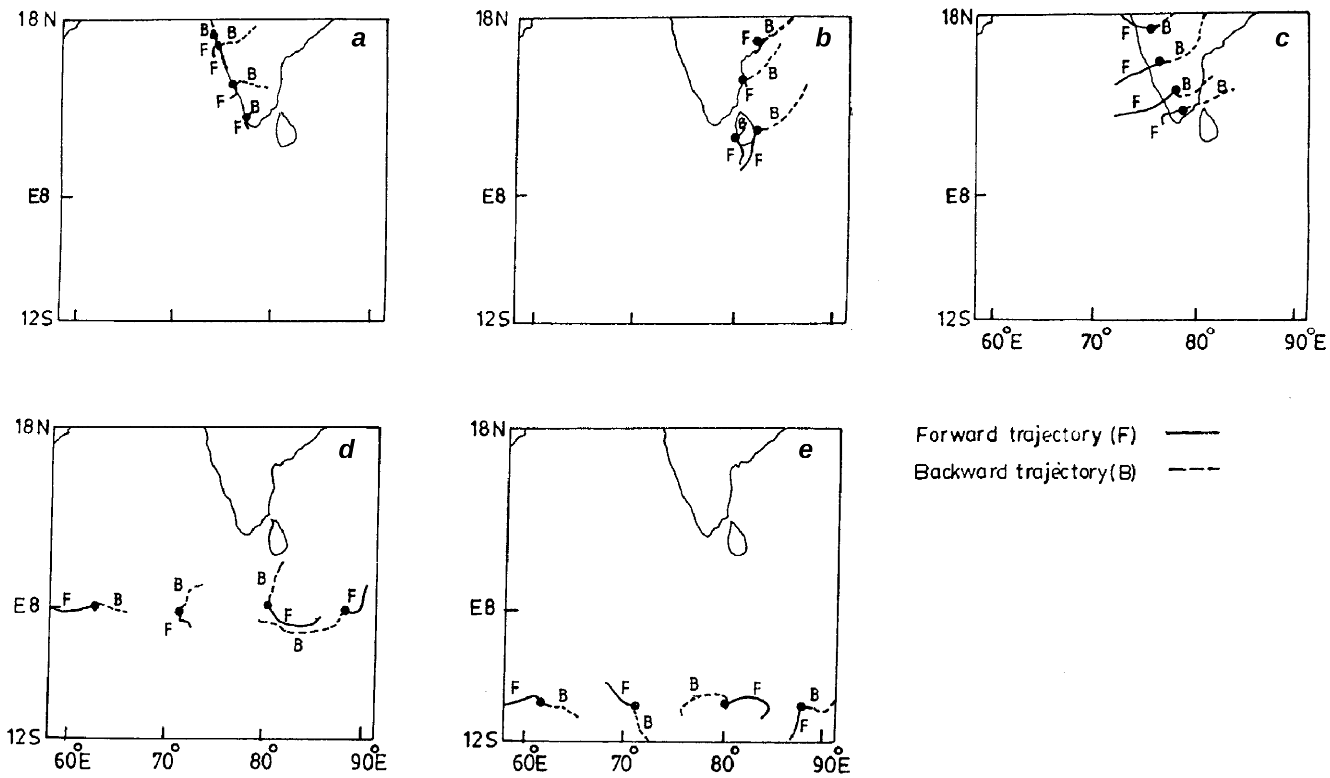

Figure 2. Same as Figure 1, except for 00 UTC 7 March 1999.

model-simulations and analysed wind fields at 925 hPa up to 48 h for this case. Additionally, both the day-1 and day-2 forecasts for the fine grid mesh (20 km resolution) shows various mesoscale circulations embedded within the large-scale flow. These mesoscale features are localized mostly along the coast, which the coarse grid mesh and analysis cannot resolve due to lack of grid resolution.

The high resolution 48 h wind fields simulated by MM5 fine mesh (20 km horizontal resolution), were used to generate backward and forward trajectories using Vis5D. For this purpose, simulated wind fields at hourly intervals were utilized. Figure 2 shows the forward (represented by 'F') and the backward (indicated by 'B') trajectories for the 48-h simulation period. In the first set of analysis, shown in Figure 2 *a*, the air parcels on the western Indian subcontinent were targeted. The back trajectories for the period ending at the 2-day simulation suggest the parcels travel from the interior of the Indian subcontinent. Interestingly however, the forward trajectories originating from the coastal points do not go beyond the coastal influence and circulate in a closed loop around the source point in a land–sea breeze circulation. This closed loop circulation for the forward trajectories was confirmed for the east coast source points as well, as shown in Figure 2 *b*. In both the coastal cases, the backward trajectories were dictated by the large-scale flow patterns (reflected in the streamline analysis, Figures 1 and 3), while the coastal mesoscale circulations (land–sea breeze) controlled the forward trajectories. The isotachs along the coastal boundaries for this case indicated the wind speeds to be fairly small (~ 3–4 ms^{-1}). It is hence hypothesized that for low wind speeds (generally observed in the tropics), the air parcels will remain trapped within the closed land–sea breeze circulation, while with strong wind such trapping may not occur. Interestingly, ship-based observations of aerosol concentrations show high values off the west coast[4]. To explain such high values, we hypothesize the following. The air parcels west of the Western Ghats are confined within the land–sea breeze circulation. However, bulk of the parcels east of the Western Ghats during the northeast monsoonal flow are orographically lifted and are transported into the Arabian Sea above coastal mesoscale circulation. To verify this, trajectories were drawn from the eastern side of the Western Ghats (~ 200 km inland). These trajectories travel a significant distance offshore confirming the hypothesis. Two additional trajectory analyses were performed: one along the equator and the other at 10°S. These locations were chosen for the air parcel trajectories as they represent the open ocean. These trajectories follow along the large-scale streamline patterns (shown in Figures 1 and 2). The parcels then get entrained into the boundary layer from above. However, it is important to note that some of the near surface transport will occur through the divergent flow in the offshore limb of the sea breeze

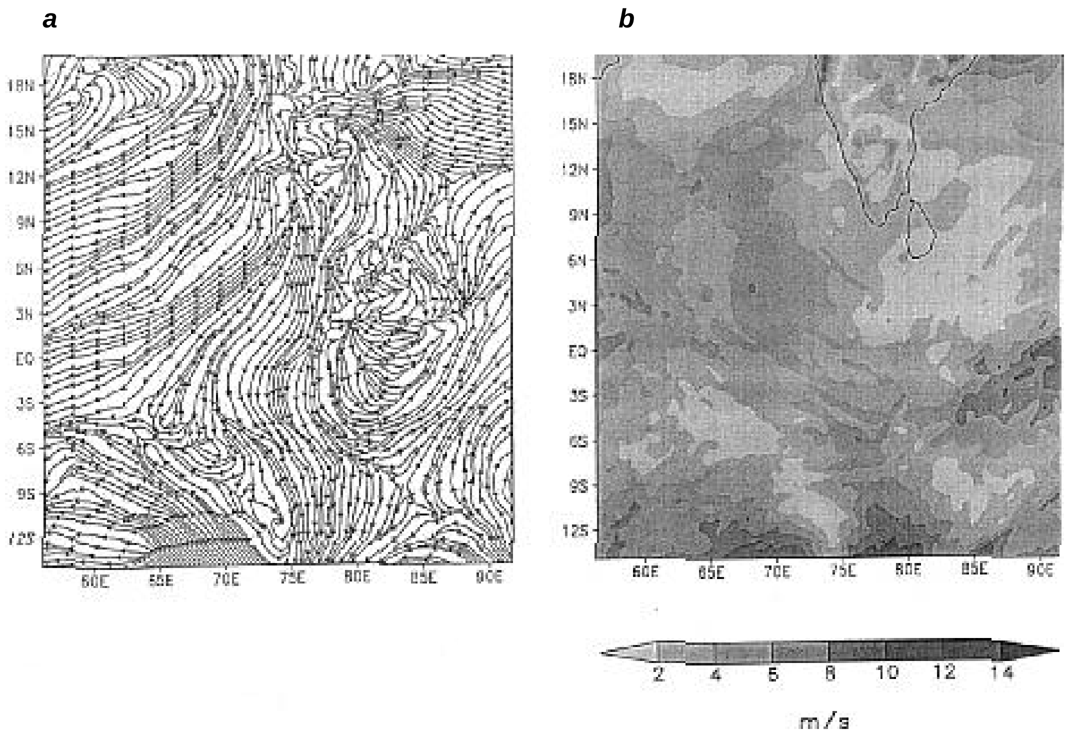

Figure 3. Simulated forward (F) and backward (B) trajectories from 00 UTC 5 March to 00 UTC 7 March 1999 for regions over (***a***) Indian west coast, (***b***) Indian east coast, (***c***) peninsular India, (***d***) along the equator, and (***e***) near the ITCZ.

during day-time and convergent flow offshore in the land breeze.

Another application of MM5 relates to the mapping of the surface heat fluxes and the planetary boundary layer (PBL) heights over the INDOEX domain. Figure 4 *a–d* shows the six-hourly plots for the PBL heights corresponding to 12 LT, 18 LT, 24 LT and 06 LT (next day) respectively. During noon (Figure 4 *a*), the land was significantly heated compared to the ocean. Correspondingly, the predicted PBL height over the land was considerably large (~ 1500 m) while over water it was typically between 300 m and 500 m. The highest PBL height over the ocean was around the ITCZ and corresponded to around 800 m. Six hours later (approximate local time 1800 h), during the boreal winter the PBL heights over land fall rapidly with sunset and remain below 500 m. However, over the ocean the simulated PBL heights start increasing steadily during the night. This is due to the cooling of the air over the assumed constant temperature warm ocean in the model which leads to enhanced surface heat fluxes and convection. In particular, in the ITCZ region where an intense vortex was present during this case, the PBL heights were ~ 2000 m by 06 LT. These large values of PBL heights are consistent with the observations made during pre-INDOEX[1] and during INDOEX. Table 2 shows the observed and model simulated PBL heights over the ocean. The observations were obtained from *Ronald H. Brown* and the simulated values are for the corresponding locations in the three-dimensional grid of the model. As can be seen there is a reasonably good agreement between the observed values and the model simulated PBL heights. There can be some uncertainty in

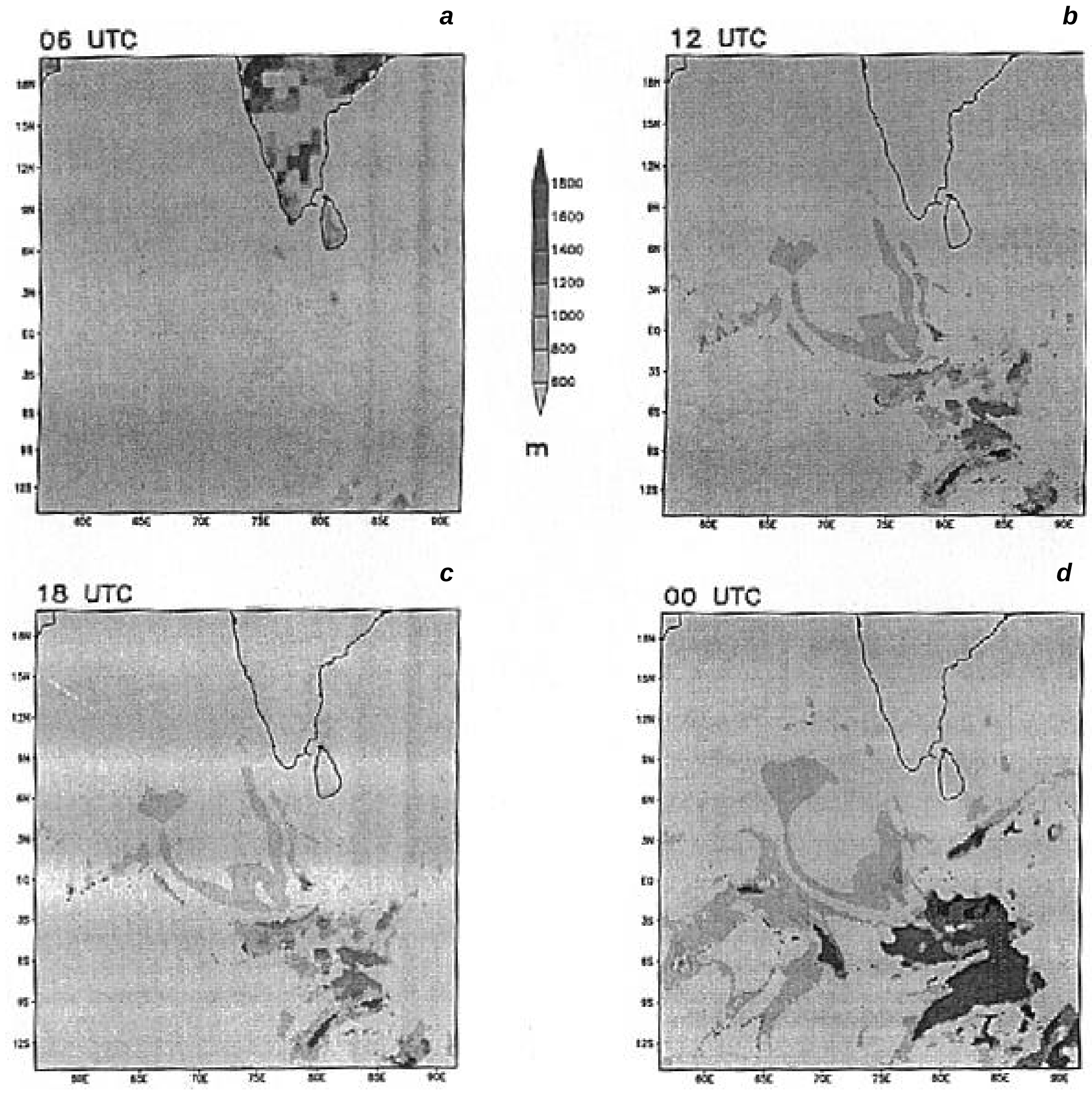

Figure 4. Spatial distribution of six hourly simulated PBL heights (m) over the FGM domain for (***a***) 06 UTC 5 March, or 12 LT, (***b***) 12 UTC 5 March or 18 LT, (***c***) 18 UTC 5 March or 24 LT and (***d***) 00 UTC 6 March 1999 or 06 LT.

the estimation of the PBL height from vertical sounding of temperature over the oceans. Considering this limitation, it can be stated that model is able to simulate the PBL heights fairly well. However, it is clear that MM5 needs better PBL physics as well. In summary, as expected, PBL height over the land show strong diurnal variation, while that over the oceans varies relatively slowly, except over meso lows where strong rising motions occur and there is a strong spatial variation in PBL heights.

Table 2. Observed and MM5 simulated PBL heights over Indian Ocean

Date	Location	PBL height (m)	
		Observed	MM5
18 UTC 5 March 1999	5.0°N; 72.5°E	800	550
00 UTC 6 March 1999	5.9°N; 71.6°E	600	615
12 UTC 6 March 1999	6.6°N; 69.9°E	1000	780
18 UTC 6 March 1999	8.3°E; 69.2°E	900	540
00 UTC 7 March 1999	9.5°N; 68.8°E	500	855

The variations in the PBL heights and mesoscale low-level circulations are modulated by the surface heat fluxes and convection. Figures 5 *a–d* and 6 *a–d* show the six-hourly map of the total surface heat fluxes and the six-hourly accumulated rainfall (representing convective activity), for the INDOEX region. The model predicts total heat fluxes ~ 500 Wm^{-2} over the continental land-mass for the noon time (12 LT) with significant spatial variability. These fluxes are higher than expected and could be due to the prescribed latent heat fluxes (as a function of land use[2]). Over the ocean, typical values ranged from ~ 200 to 400 Wm^{-2}. With sunset (18 LT), continental heat flux values are significantly reduced but were once again higher (~ 100 Wm^{-2}) than expected. This sudden reduction in the total heat fluxes could be due to the

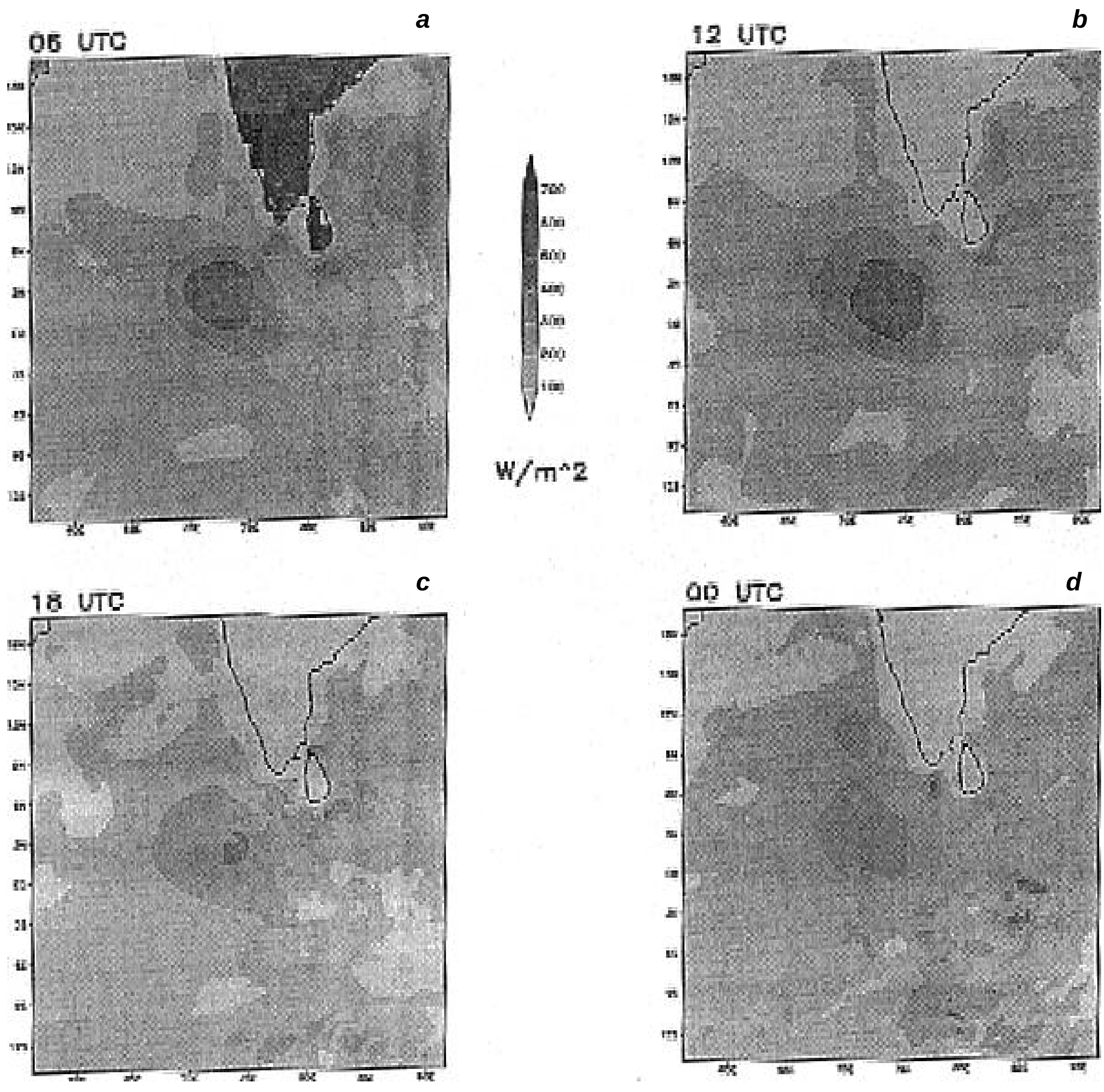

Figure 5. Same as Figure 4, except for total (sensible + latent) heat flux (Wm^{-2}).

significant cooling of the winter period, after sunset. All through the night the land heat fluxes are small. No such significant diurnal variability was simulated over the oceans though the spatial variations were more pronounced. Only over the low pressure system along the ITCZ, there was an enhancement in the total heat fluxes with time with a domain maxima of around 400 Wm^{-2}. This general lack of strong diurnal variability of surface heat flux over the ocean and the enhanced deep convection over the low pressures (system) is inherent in the precipitation field predicted by MM5, as shown in Figure 6 *a–d*. It is found that the rainfall is predicted mainly around the ITCZ (around 5°N to 13°S). The model results indicate enhanced deep convection with sunset over the tropical ocean. For the entire simulation period, the convective activity was persistent over the ITCZ and the low-pressure system in the Southern Hemisphere. These features associated with surface heat flux and convection are consistent with the variations in the PBL height obtained in MM5.

Summary and conclusions

A triple domain, three-dimensional version of MM5 was successfully integrated over the INDOEX region using ECMWF operational analysis for a period of 48 h starting 00 UTC 5 March 1999. The flow patterns associated with this case were analysed. The high-resolution model output brought out several mesoscale circulations embedded within large-scale dynamics due to land air sea interactions. Forward and backward trajectories corresponding

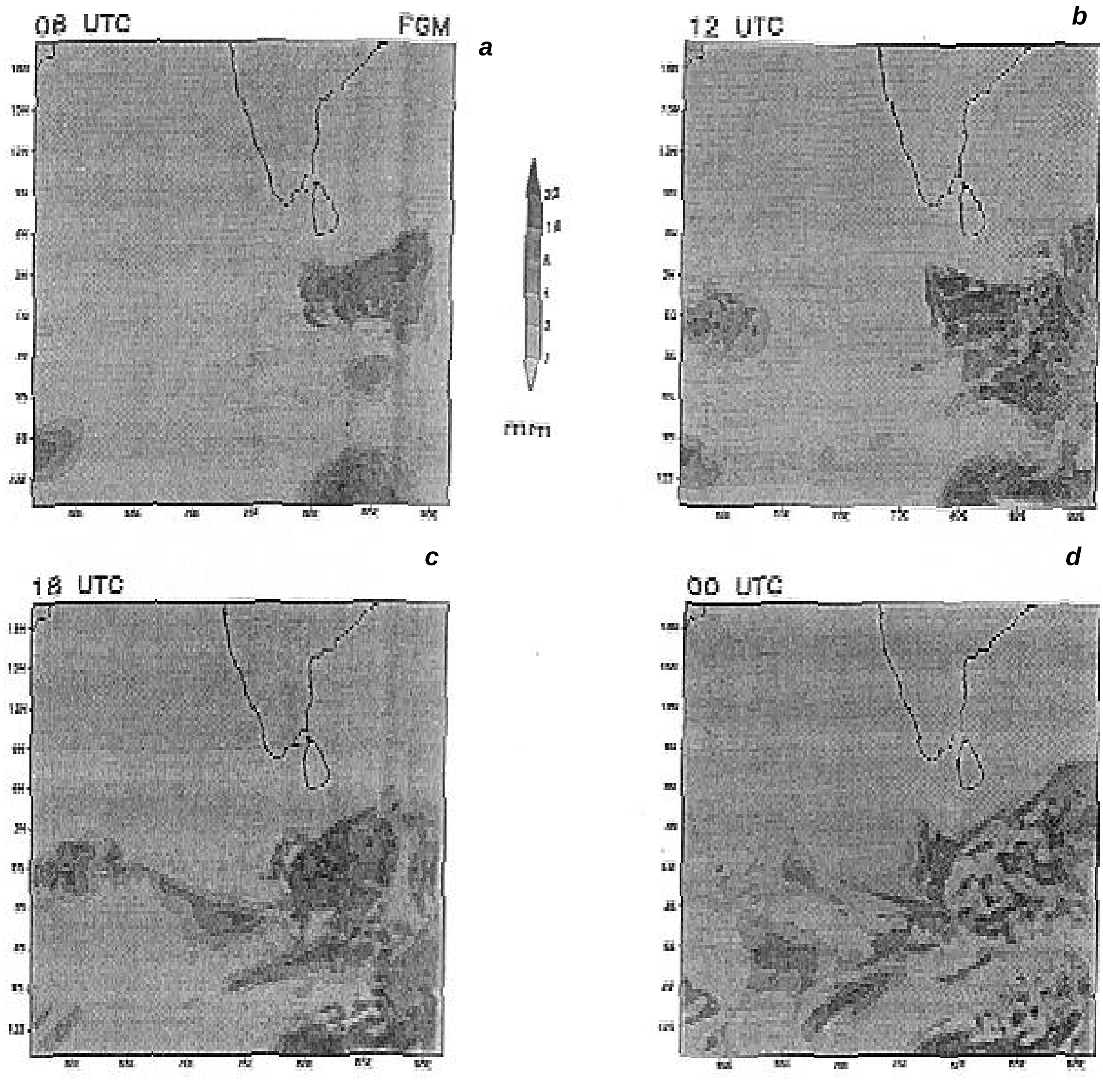

Figure 6. Simulated six-hourly accumulated rainfall over the FGM domain ending at (***a***) 06 UTC or 5 March, (***b***) 12 UTC 5 March, (***c***) 18 UTC 5 March and (***d***) 00 UTC 6 March 1999.

to this period suggest that the coastal air parcels are predominantly confined within the land–sea breeze closed circulation. This suggests that in order to make a realistic assessment of the transport from the continental landmasses a high-resolution (~ 10–20 km) mesoscale analysis/forecast is necessary. The coastal circulations are further modulated by the presence of the Western Ghat mountains located at about 100 km inland in the downstream flow (for the northeast monsoon). Results suggest that the air parcels upwind of the Western Ghat can be orographically lifted and transported to a significant distance off shore while those along the coast will remain predominantly confined to the coast during the day time. The mesoscale variability in the surface and the boundary layer characteristics were further studied by mapping the PBL heights, surface heat fluxes, and convection over the INDOEX region. Results show a significant diurnal variability in PBL height over the continental landmass while over the ocean it is dominated by convection near the ITCZ. The diurnal variations in the deep convection resulted in persistent rainfall during the entire simulation period over the ITCZ and meso low regions in the model domain. In summary, results suggest that mesoscale models such as MM5, when used with high resolution nesting can provide realistic features and detailed insight regarding the transport and entrainment issues pertinent to the INDOEX objectives.

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