A study on the performance of a triple nested mesoscale model over tropical Indian Ocean during INDOEX

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A triple nested version of the fifth generation PSU–NCAR Mesoscale Model (MM5) was used over the INDOEX domain. A 3-dimensional model study over the tropical Indian Ocean was performed. The domain extended from 40.12°N–32.04°S; 32.10°E–117.90°E for the outermost grid (horizontal resolution of 180 km), while the inner most grid (20 km horizontal resolution) extended from 19.81°N–13.92S; 56.20°E–91.64°E, with 17 vertical s levels. The model was integrated for 48 h starting from 00 UTC 5 March 1999. The model results were validated against analysis for large-scale characteristics (circulation pattern, ITCZ location and rainfall). MM5 was able to realistically simulate these large-scale features. In addition to this validation, objective evaluation of the model performance was undertaken by comparing GPS sonde vertical soundings obtained from RV *Ronald H. Brown* for the times of model integration. MM5 results were in good agreement with both dynamical (wind components) and thermodynamical (temperature and humidity) fields over the INDOEX domain.

THE Indian Ocean Experiment (INDOEX) is a multidisciplinary international field experiment directed towards studying the transport of continental air masses from the Northern Hemisphere towards the Inter Tropical Convergence Zone (ITCZ). The principal hypothesis was that the aerosol loaded continental air could alter the radiative properties of the ITCZ, leading to higher uncertainties in the radiation balance over tropical Indian Ocean. To study this phenomenon, ship and air-based observations were conducted over the Arabian Sea and equatorial Indian Ocean extending up to 20°S (ref. 1). The study period was chosen during northeasterly monsoon (January to March) over the Indian subcontinent. The field phase of the INDOEX was conducted in 1999. During the field phase, emphasis was on identifying the lower troposheric meteorology and air chemistry related to the transport and the corresponding boundary layer processes, along with ship-based physio-chemical measurements. The measurements composed of six-hourly vertical profiles and continuous meteorological observations of the mean state of the marine atmosphere. These observations by their very nature are point measurements and several studies[2–5] have identified distinct inhomogeneities and variations in the boundary layer as well as physiochemical characteristics over the INDOEX domain. For these reasons there was an immediate need to develop a more comprehensive understanding of the temporal and spatial variability of the marine environment during the INDOEX. Such an understanding can be achieved using a three-dimensional modeling approach in conjunction with the observations. However, to have confidence on any comprehensive simulations of a model, it is important that the model results are validated over the region. The INDOEX domain is traditionally a data-sparse region and the analysis is greatly biased on the first-guess (six-hourly forecast) from the general circulation models (GCM). Hence one of the first steps in applying atmospheric models for INDOEX, is validation through evaluations using special observations made during the Intensive Field Phase (IFP). This study reports the validation exercise undertaken for one such state-of-the-art atmospheric model over the INDOEX domain.

The mesoscale model used is the fifth generation PSU-NCAR-Mesoscale Model (MM5) of Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model (MM5)[6]. It is a non-hydrostatic, primitive equation limited-area model. The model has been extensively tested and validated over various regions for different applications. However, no validation exists for the INDOEX domain. The aim of this study is hence to validate the performance of MM5 over the tropical Indian Ocean environment with large scale analysis and observations (sounding) made during the INDOEX IFP from RV *Ronald H. Brown*.

Model description and design of experiment

Model description

The mesoscale model used in this study is the three-dimensional, non-hydrostatic version of the fifth generation

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PSU-NCAR Mesoscale Model (MM5). It is a primitive equation model in a non-dimensional s-vertical coordinate system. s is defined by $(p - p_{top})/(p_{sfc} - p_{top})$, where p is the pressure at any model level, p_{top} is a specified constant top pressure, and p_{sfc} is the surface pressure. By definition s is equal to one at the surface and zero at the top of the model domain. The model is integrated to solve prognostic equations for horizontal momentum, vertical momentum, surface pressure, moisture and temperature. Other dependent variables are diagnostically determined at each time step. The model uses surface layer similarity for the constant flux layer and the Blackadar planetary boundary layer (PBL) parameterization scheme[7] for the mixed layer. It also has explicit equations for cloud water, rain water, ice and water vapour. The Anthes-Kuo cumulus parameterization scheme[8,9] is used for sub-grid scale convection. Lower boundary condition is prognostically maintained using a atmospheric radiation scheme and surface energy balance along with prognostic equation for ground temperature using Force–Restore method. One of the important features within MM5, is the multiple nesting capability. Up to nine domains can be integrated at the same time. For each of these domains a one-way or two-way interaction can be prescribed. One-way interaction involves prescribing boundary values for a sub-domain from its mother domain interior, while no feedback occurs to the mother domain. Two-way interaction means that the sub-domain input from the mother domain comes via its boundary, while feedback to the mother domain occurs over the sub-domain interior. In this study we use three nests with one-way interaction as discussed in the next section. An Arakawa B-grid staggering is utilized for the finite difference in the horizontal. Vertical velocity is staggered vertically. A second order derivative spatial differencing scheme is adopted. Time differencing in using the leapfrog steps with an Asselian filter. For short-time step, a semi-implicit scheme is adopted[10]. More details regarding the model formulations can be found in Grell *et al.*[11].

Data and experimental design

In this study, we have used the operational analysis from the European Centre for Medium Range Weather Forecast (ECMWF), archived at the National Center for Atmospheric Research in the TOGA format. The horizontal resolution of the archived data is $2.5° \times 2.5°$ latitude–longitude with 15 standard pressure levels. The sea surface temperature (SST) data were obtained from the National Center for Environmental Prediction (NCEP) archive. The default surface variables such as land-use, vegetation type, surface roughness, and topography within MM5 data libraries are considered for lateral surface boundary conditions for the model and kept constant during integration of the model. All these data are interpolated to the model grid (discussed below) to serve as initial values and boundary conditions for model integration. The above data corresponding to 00 UTC 5 March 1999 were utilized. The model was integrated up to a period of 48 h until 00 UTC 7 March 1999. This period was within the INDOEX IFP-99 (20 January 1999 to 29 March 1999). The model integration period was chosen after examining the synoptic charts, satellite imagery, and OLR data for the INDOEX IFP. On 5 March 1999, an active ITCZ was present embedded within two cyclonic circulations in the Southern Hemisphere as shown in Figure 1. Presence of these large-scale circulations, and

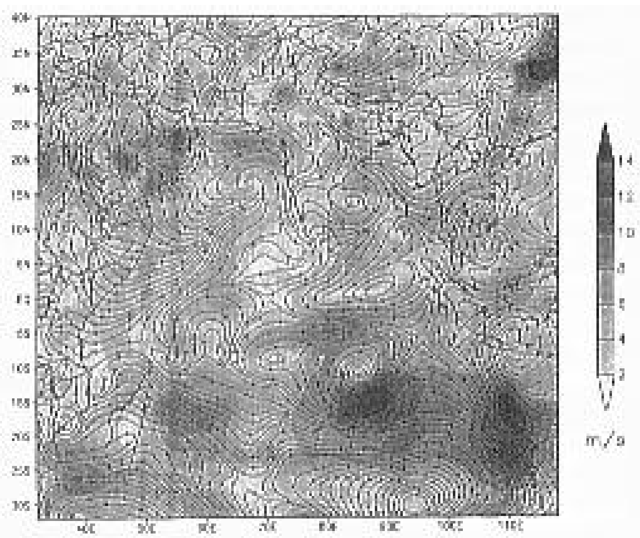

Figure 1. Analysed wind fields at 925 hPa for 00 UTC 5 March 1999 (initial conditions) for the CGM domain.

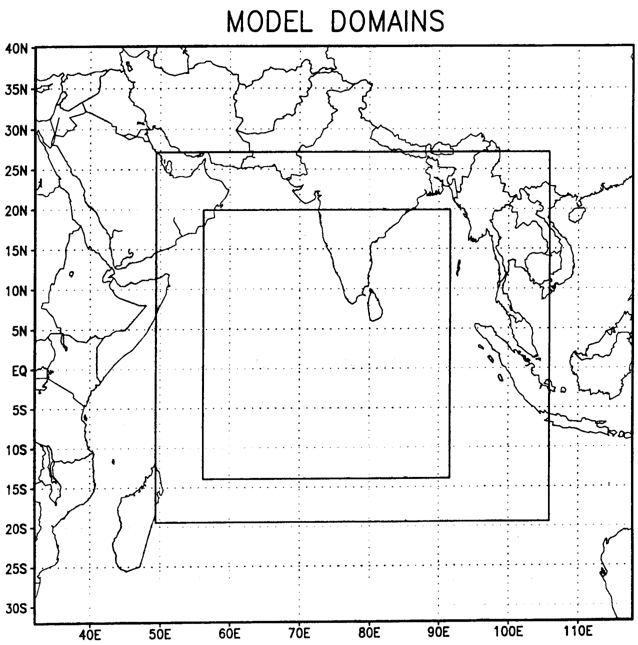

Figure 2. Model simulation domains for the Coarse-Grid Mesh (CGM), the Medium-Grid Mesh (MGM) and the Fine-Grid Mesh (FGM) for the INDOEX region.

associated cyclonic low-pressure systems along with a strong ITCZ band between equator and 15°S represented very active oceanic dynamics and convective conditions typical of an active ITCZ during the northeast monsoon (INDOEX) period. In addition to these synoptic dynamical conditions, availability of ship-based observations for model validation purpose was another motivating factor, as discussed below. Two types of data are utilized for model validation. First is the large-scale verification analysis from the ECMWF and the OLR data from the NCEP–CIRES. The OLR data were used as precipitation fields were not available for the oceanic domain. This was used for verification of the large-scale convective activities and rainfall. The second set of verification data are the ship-based GPS radiosonde sounding specially available during INDOEX IFP-99. During the 48-h model simulation, total five vertical soundings of winds and thermodynamic variables were available. These soundings provided high-resolution wind and thermodynamic variables and were at six or twelve hour interval.

For this study, a triple nested version of MM5 is adopted: The Coarse Grid Mesh (CGM), Medium Grid Mesh (MGM) and Fine Grid Mesh (FGM) covered area of (40.12°N–32.04°S; 32.10°E–117.90°E), (27.14°N–19.44°S; 49.37°E–103.87°E) and (19.81°N–13.92°S; 56.20°E–91.64°E), respectively as shown in Figure 2. The horizontal resolutions for the CGM, MGM and FGM were 180 km, 60 km, and 20 km respectively. Thus the CGM, MGM and FGM domains comprised of (50×55), (91×103) and (193×199) grid points, respectively. All the three domains had 17 vertical s levels (between 1000 hPa and 10 hPa): 1.0, 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 and 0.0. The model was run

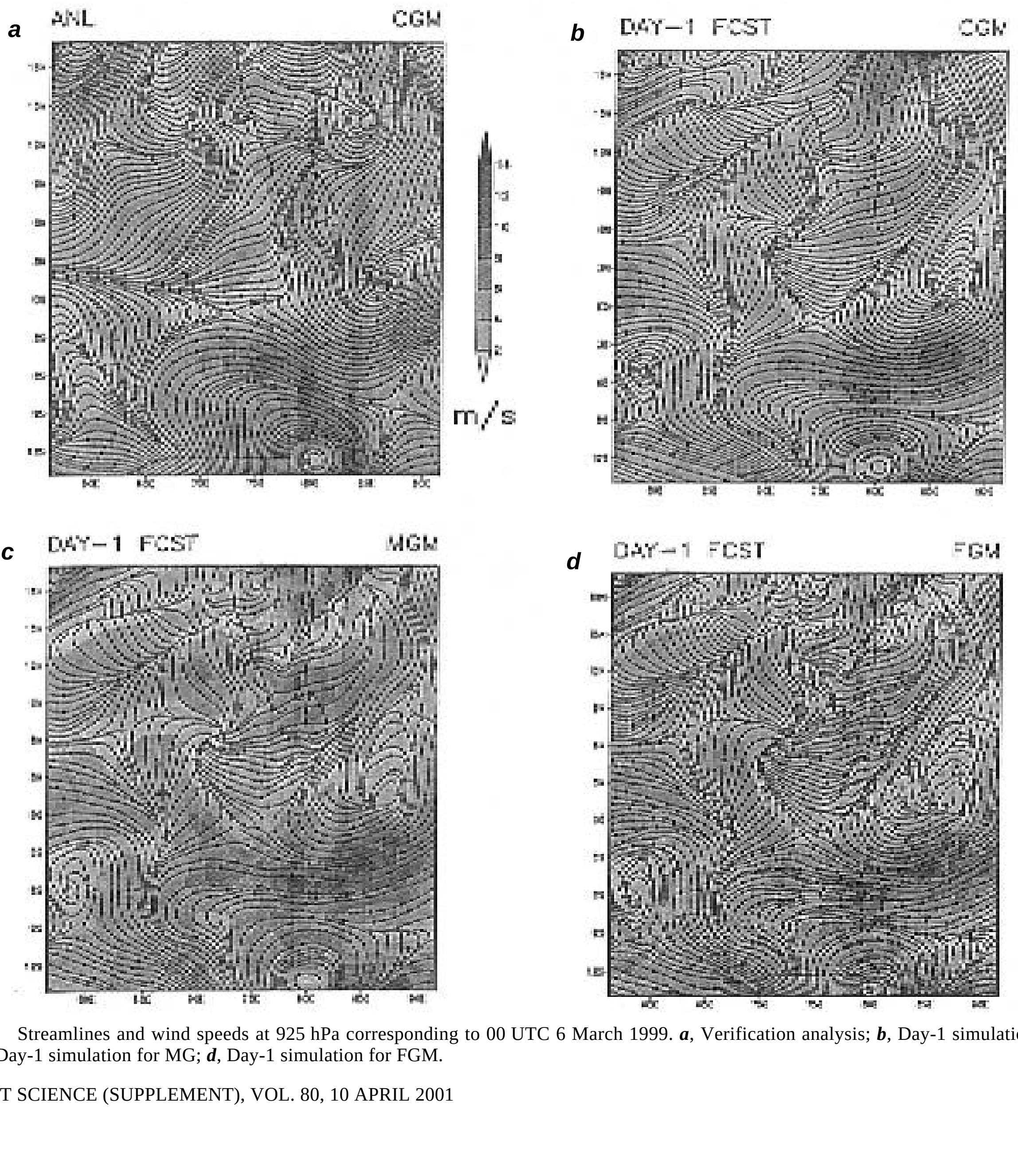

Figure 3. Streamlines and wind speeds at 925 hPa corresponding to 00 UTC 6 March 1999. ***a***, Verification analysis; ***b***, Day-1 simulation for the CGM; ***c***, Day-1 simulation for MG; ***d***, Day-1 simulation for FGM.

for 48-h and the six-hourly outputs were analysed as discussed in the following section.

Results and discussions

We will first compare the model output with the large scale circulation obtained from ECMWF analysis (2.5 degree resolution), and then with the OLR data for large scale convection and rainfall. Subsequently, individual observation profiles and corresponding model grid profiles are compared.

Figure 3 shows the verifying analysis corresponding to 00 UTC 6 March 1999. For the three domains (CGM, MGM and FGM) the corresponding simulated streamlines and wind speeds at 925 hPa for day-1 are also presented. In general, all the three different resolutions (domains) produced fairly similar wind speeds and flow patterns. The northeasterly winds over the Arabian Sea and Bay of Bengal were well simulated for all the three domains. The model also captured cyclonic low-pressure systems over (13°S; 80°E) and over (1°N; 82°E) reasonably well. However, the model failed to simulate at 13°N, 84°E an anticyclone at 13°N, 84°E over the Bay of Bengal. Note that for the oceanic domain there is no significant change in the numerical results with change in horizontal resolution, except for a few additional details in the finer resolutions. This could also be due to the synoptic dominance rather than surface-induced mesoscale variability for the study period. Similar results are obtained for other large-scale variables. For instance, Figures 4 and 5 show the model simulated rainfall and the verifying OLR for the CGM and FGM. Figure 4 show the convective bands from the OLR distribution around 15°S with a threshold value of OLR ≤ 240 Wm^{-2}. Corresponding to this, the model simulated CGM rainfall for day-1 and day-2 is shown in Figure 4 *b–d*. The predicted rainfall location coincides with the

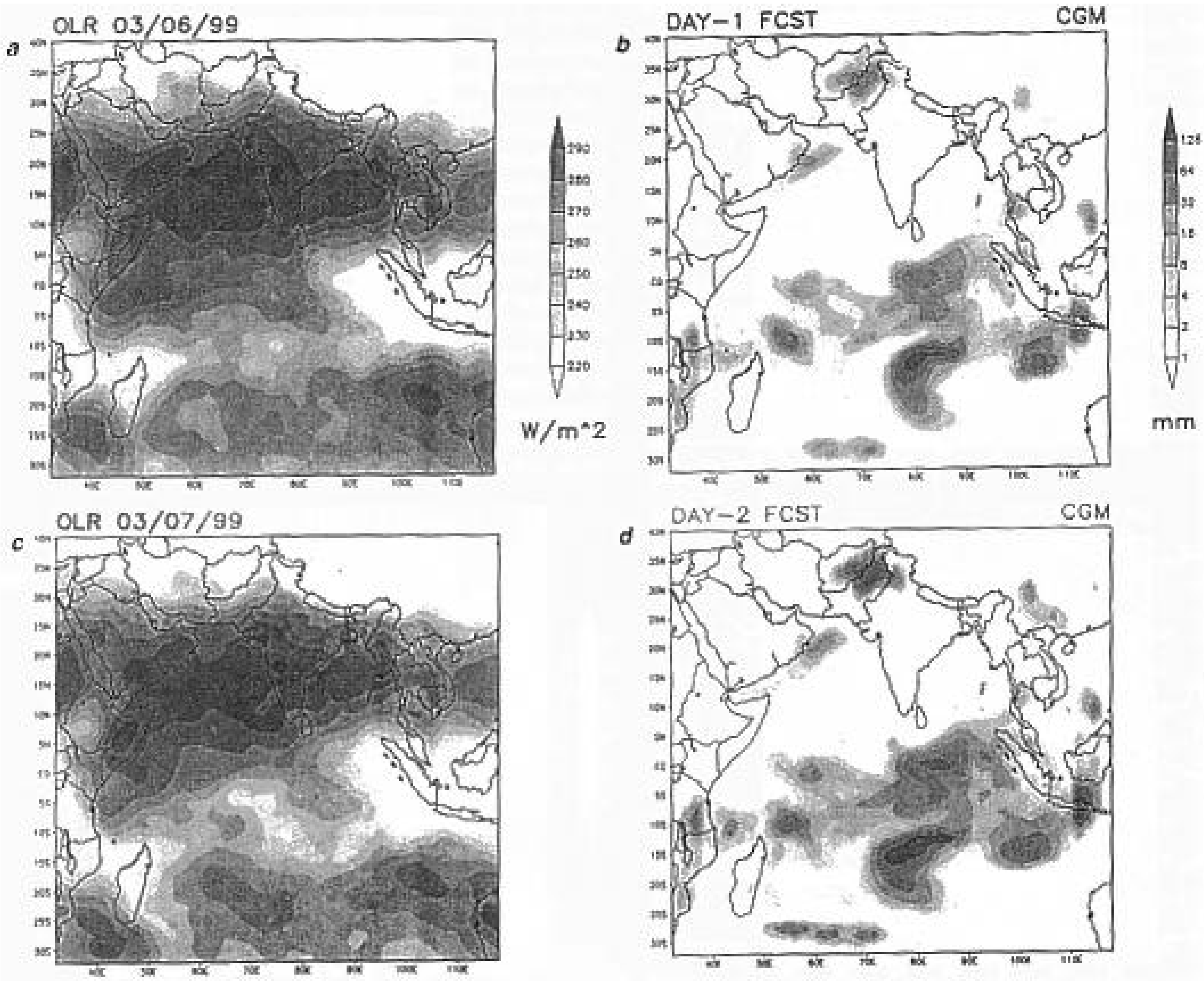

Figure 4. OLR and simulated 24-hourly accumulated rainfall distribution over the CGM domain. (***a***, ***b***) ending 00 UTC 6 March 1999; and (***c***, ***d***) ending 00 UTC 7 March 1999.

ITCZ position obtained from the OLR data. For day-1 the maximum rainfall rate was 80 mm day^{-1} and during day-2 simulation was 130 mm day^{-1}. These maxima values are located in the vicinity of the low-pressure system (13°S; 80°E).

Figure 4 shows the OLR distribution and accumulated rainfall for day-1 and day-2 simulations over the CGM domain. Rainfall was simulated over the ITCZ band as confirmed by low values of the OLR (OLR ≤ 240 Wm^{-2}). The rainfall rate maxima were located over the low-pressure system (13°S; 80°E). It was typically around 80 mm day^{-1}. The FGM accumulated rainfall for day-1 and day-2 is shown in Figure 5. In general, an increase in the rainfall was simulated as the model resolution became finer. In addition to the enhanced rainfall, the FGM also provided more details regarding the spatial distribution of rainfall over the ocean.

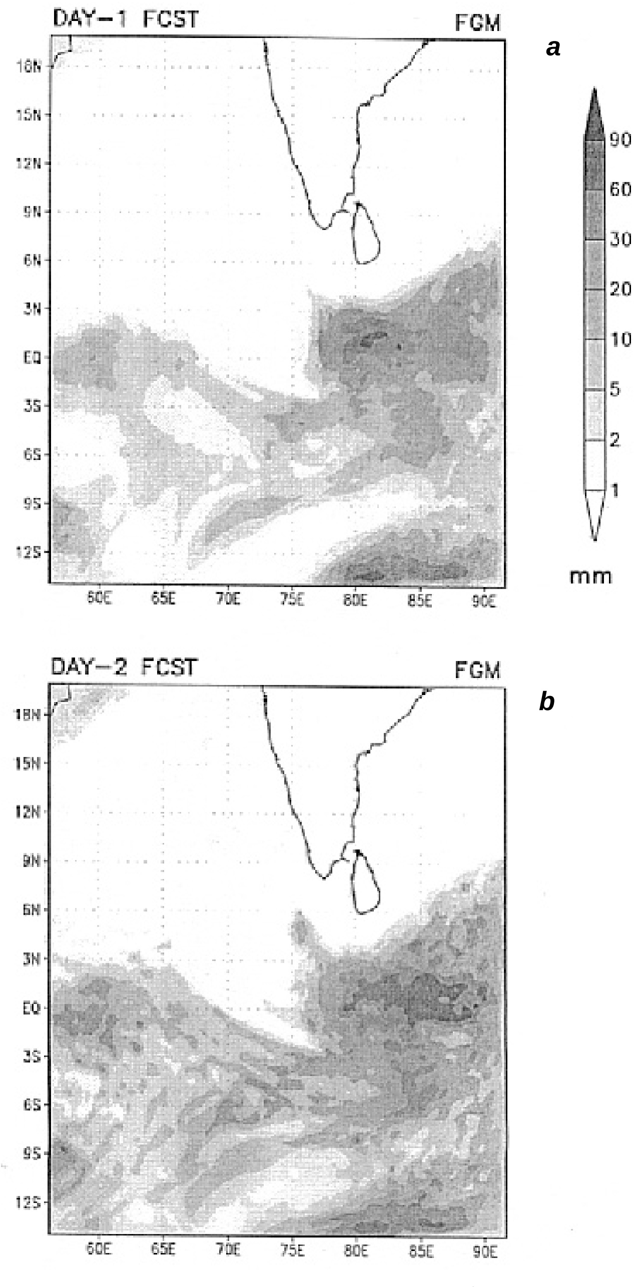

Figure 5. Simulated 24-hourly accumulated rainfall over the FGM domain ending at (***a***) 00 UTC 6 March 1999 and (***b***) 00 UTC 7 March 1999.

Thus overall, there is a good agreement between MM5 simulations and the verifying observations of large-scale feature such as circulation and convection (rainfall). The large-scale features described above provided a qualitative validation of MM5 capabilities over Indian Ocean during INDOEX. To assess the performance quantitatively at specific locations over the ocean, ship-based soundings are compared with the model simulated wind and thermodynamic profiles. The time and location of the five observed soundings available for the 48-h model integration are shown in Table 1.

Figure 6 shows the observed and the model simulated zonal wind profiles corresponding to the time and location within the study domain. Overall the vertical structure of the zonal wind is well simulated. However, observations show a jet-like structure around 700 hPa that was not captured in the MM5 results. Similar results are obtained for the meridional wind component and are shown in Figure 7. In general, both the observations and model show northeasterly winds during the study periods. The comparison suggests there is a fair agreement between the modeled and observed wind profiles in the lower and middle troposphere.

Figure 8 compares the observed and simulated temperature profiles for different times and locations. The model can simulate temperature profiles reasonably well. There is a good agreement between the two both in terms of the trend and the numerical values. There is a consistent bias between the 800 hPa and 900 hPa layers in which the model predicted cooler temperatures compared to the observations. This could be due to possible boundary layer entrainment processes that the model fails to reproduce. The model also shows partial success in simulating the humidity structure within the lower troposphere. For two ascents (12 UTC 5 March 1999 and 18 UTC 5 March 1999), the model predictions are considerably drier in the PBL and for the other three there is a good agreement both in terms of the vertical structure and the magnitude of the moisture availability. It was noted that the observed marine boundary layer (MBL) was humid and then the vertical layers above the MBL are significantly drier.

Table 1. CLASS profiles used for model performance statistics

Time and date of ascent	Location	Model simulation hour
12 UTC 5 March 1999	5.0°N; 71.9°E	12 h
18 UTC 5 March 1999	5.0°N; 72.5°E	18 h
00 UTC 6 March 1999	5.9°N; 71.6°E	24 h
12 UTC 6 March 1999	6.6°N; 69.9°E	36 h
18 UTC 6 March 1999	8.3°N; 69.2°E	42 h

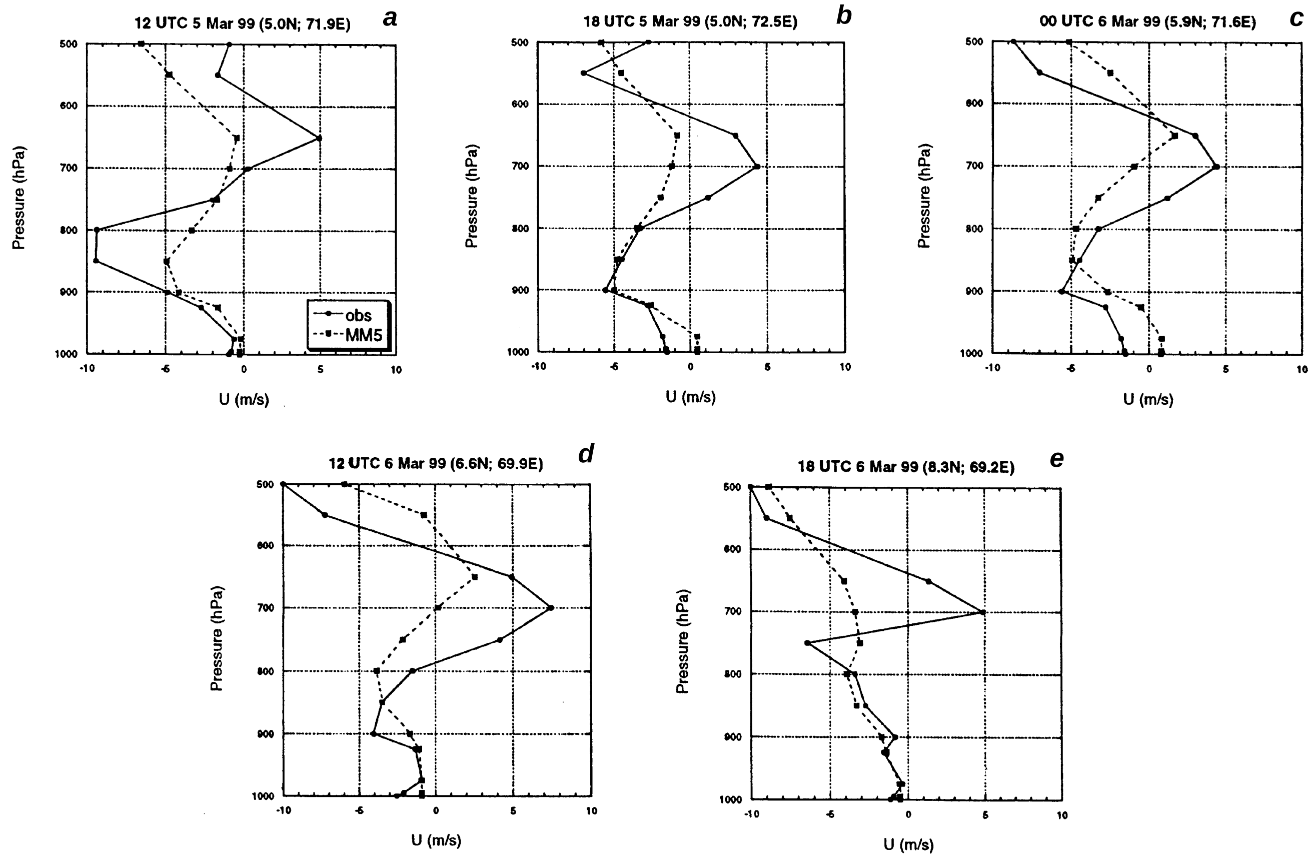

Figure 6. Observed and model simulated zonal wind profiles for (***a***) 12 h, (***b***) 18 h, (***c***) 24 h, (***d***) 36 h, (***e***) 42 h and (***f***) 42 h of model integration.

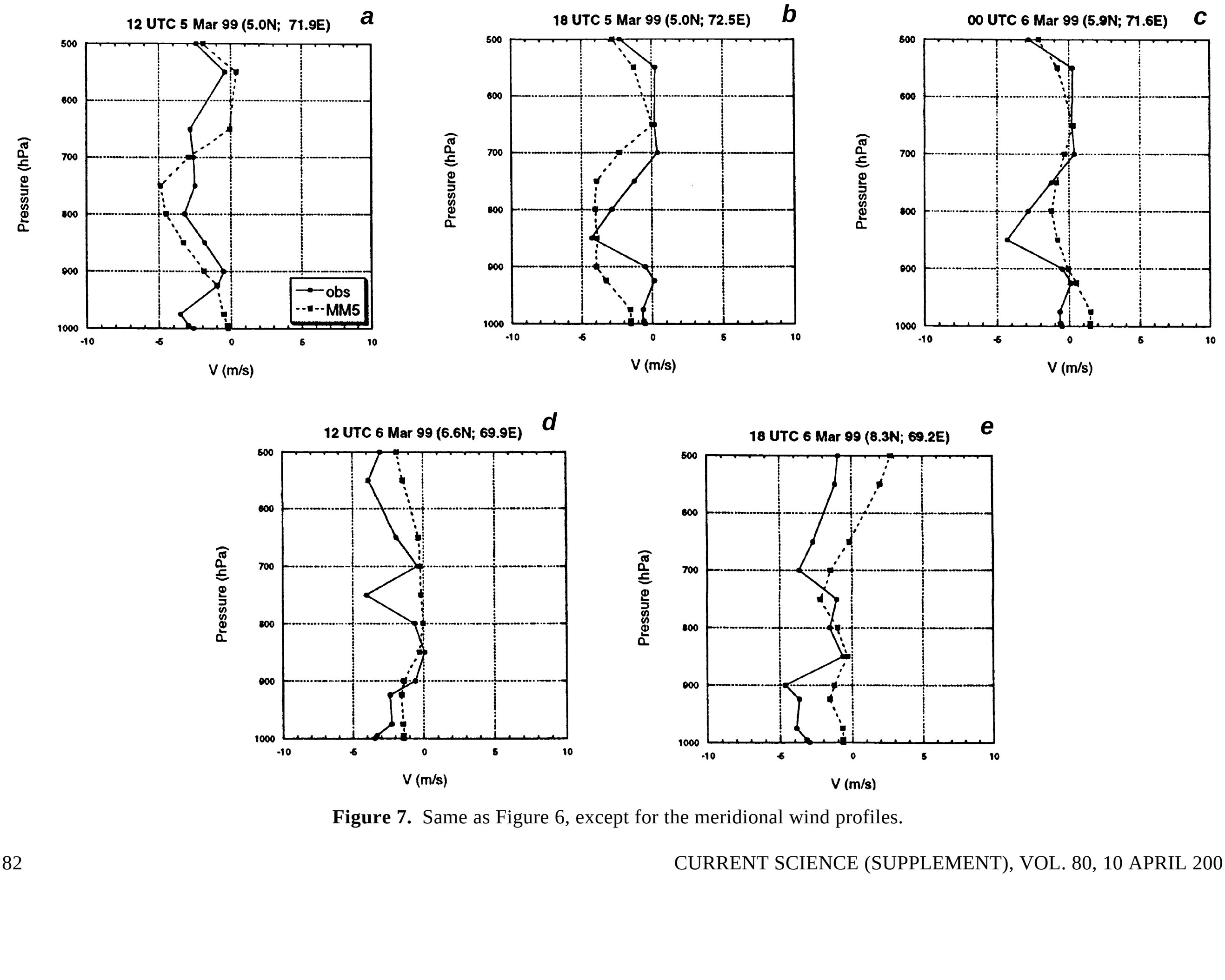

Figure 7. Same as Figure 6, except for the meridional wind profiles.

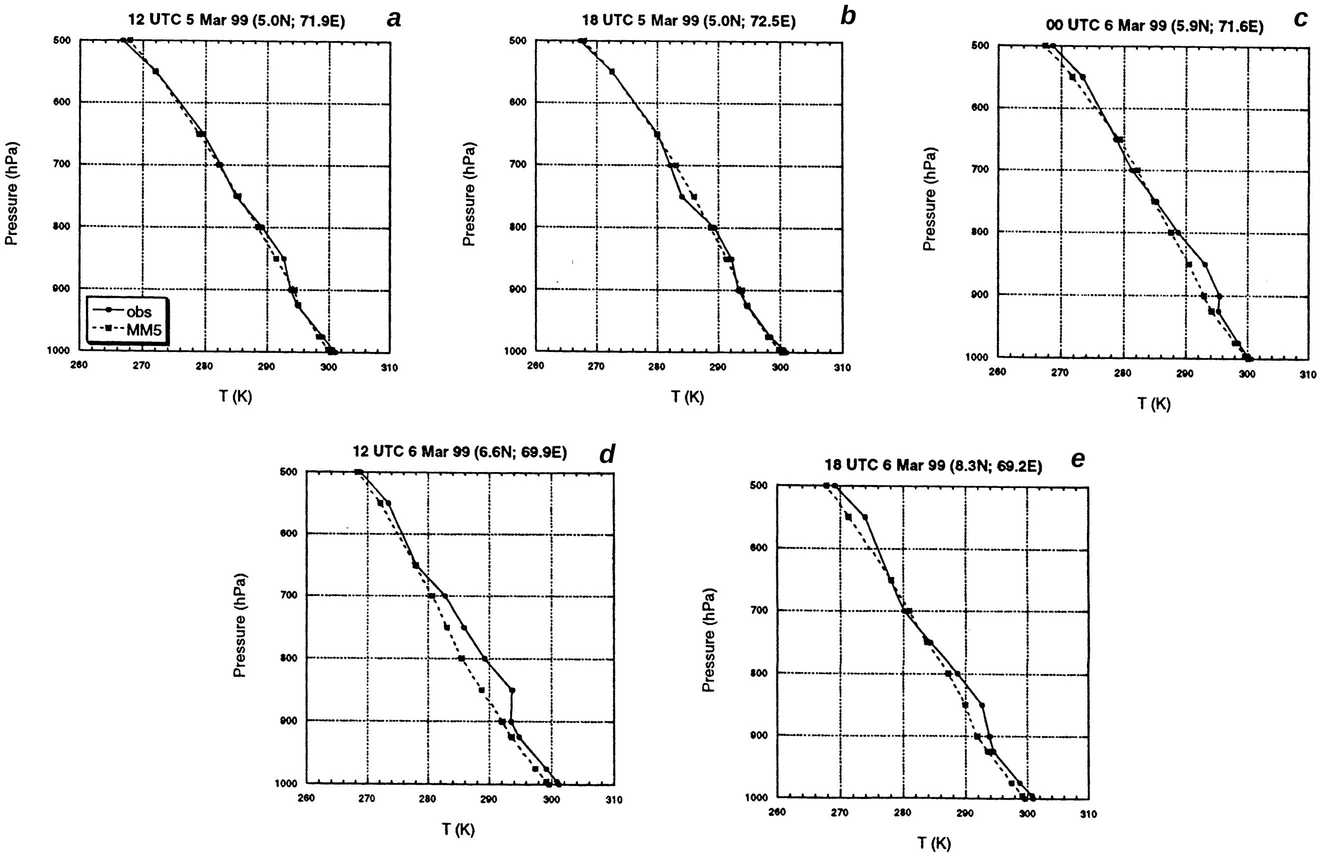

Figure 8. Same as Figure 6, except for the temperature profiles.

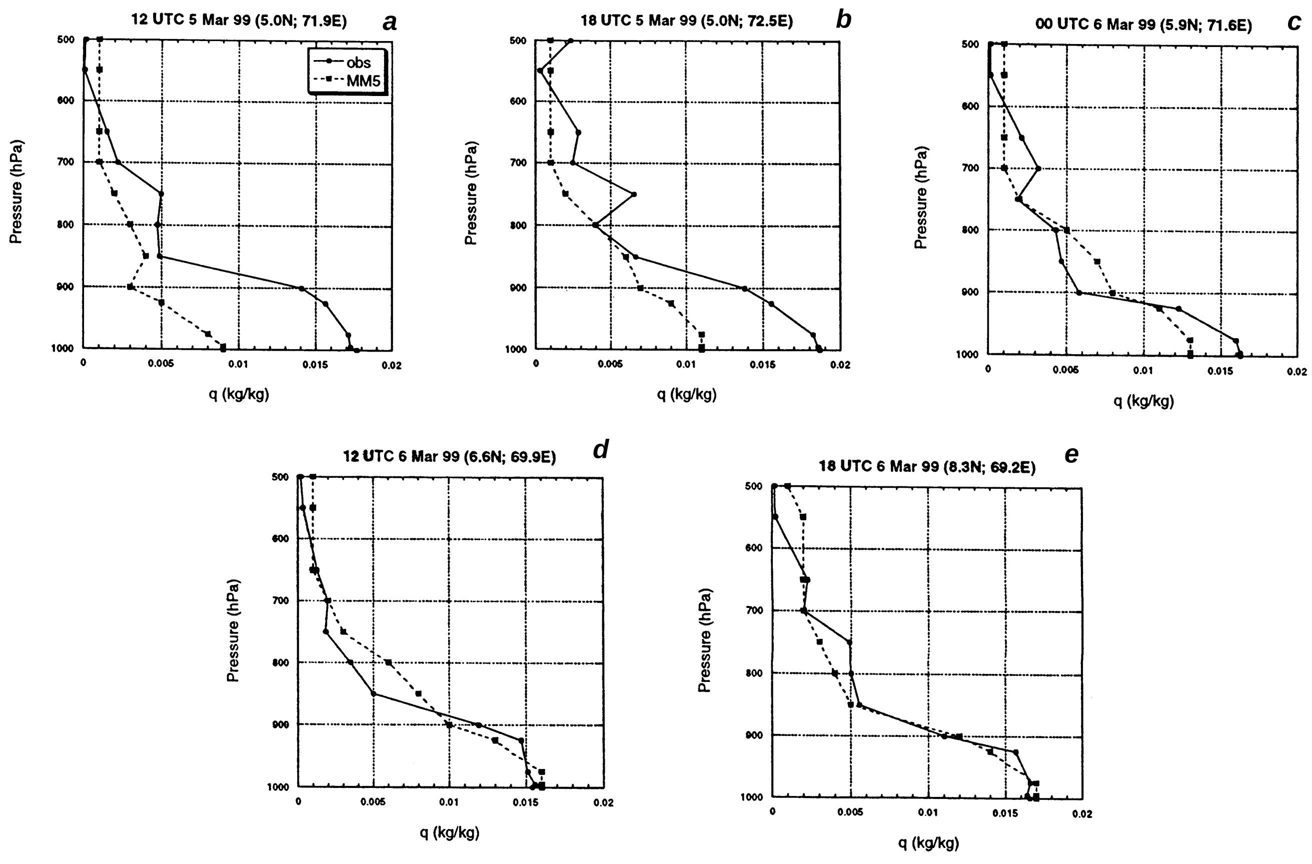

Figure 9. Same as Figure 6, except for the specific humidity profiles.

Table 2. Mean day-1 forecast error statistics for 850 hPa

	Mean		STD				
Variable	Observed	MM5	Observed	MM5	RMSE	*R*	*d*
U (m/s)	–2.22	–2.26	4.30	2.36	3.37	0.62	0.69
V (m/s)	–1.77	–1.14	1.47	1.56	1.94	0.25	0.34
T (K)	288.14	287.30	10.50	10.25	1.47	0.99	0.99
Q (kg/kg)	0.0079	0.0063	0.0067	0.0053	0.0038	0.86	0.89

Figures 9 *a–e* also correspond to the 12, 18, 14, 26 and 42 h of integration. As the integration time increased, model predictions improved significantly after 18 h. The difference between predicted and the observed values can be attributed to the uncertainty in the initial values over this data-sparse region. There is better agreement between the observed and the simulated humidity profiles.

In summary, the model performance is reasonable and shows good agreement with observations over the tropical oceanic environment. Table 2 shows the forecast error statistics regarding the model performance. The analysis includes calculations of mean, standard deviation (STD), root mean square error (RMSE), correlation coefficient (*R*) and index of agreement (*d*). In general, average easterly and northeasterly to easterly winds, temperatures and specific humidities were simulated well by the model. Higher variability derived from higher STD was found for zonal and meridional winds, while smaller variability was found for temperature and specific humidity profiles. Consequently, high RMSE (higher than mean values) were resulted for zonal and meridional wind profiles and much smaller RMSE for temperature and specific humidity. Both *R* and *d* for these variables show similar results. Although all correlation coefficients reached higher than 90% level of significance (≥ 0.214), the highest *R* was found for temperature and the lowest for meridional winds.

Conclusions

Mesoscale model, MM5 was successfully integrated over the INDOEX domain. Using large-scale analysis data and special observations made during INDOEX, the model was validated over tropical Indian Ocean. Results from the MM5 simulations are in good agreement with both the large-scale convection and with the wind fields from individual profiles for wind and thermodynamic variables. Thus, MM5 can be used as a modeling tool for INDOEX to study the transport (trajectories) and the thermodynamic characteristics of the lower troposphere.

1. Ramanthan, V. *et al.*, Indian Ocean Experiment (INDOEX) White Paper, C-4 Publication #143, Scripps Inst. Ocean., UCSD, 1995.
2. Krishnamurti, T. N., Jha, B. Prospero, J. M., Jayaraman, A. and Ramanathan, V., *Tellus*, 1998, **50**, 521–542.
3. Rhoads, K. P., Kelley, P., Dickerson, R. R., Carsey, T. P., Farmer, M., Oltmans, S. J., Savoie, D. and Prospero, J. M., *J. Geophys. Res. (Atmos.)*, 1997, **102**, 18981–18996.
4. Niyogi, D. S., Raman, S. and Mohanty, U., 9th AMS Conf. on Interaction of the Sea and Atmosphere, 11–16 January 1998, Phoenix, Amer. Meteor. Soc. Boston, 1998.
5. Jayaraman, A., Lubin, D., Ramachandran, S., Ramanathan, V., Woodbridge, E., Collins, W. and Zalpuri, K. S., *J. Geophys. Res. (Atmos.)*, 1998, **103**, 13827–13836.
6. Grell, G. A., *Mon. Wea. Rev*., 1995, **121**, 764–787.
7. Blackadar, A. K., Preprints of Third Symposium on Atmospheric Turbulence, Diffusion, and Air Quality, Raleigh, NC, 19–22 October 1976, Amer. Meteor. Soc., Boston, 1976, pp. 46–49.
8. Anthes, R. A., *Mon. Wea. Rev*., 1977, **105**, 270–286.
9. Kuo, H. L., *J. Atmos. Sci*., 1974, **31**, 1232–1240.
10. Klemp, J. B. and Wilhemson, R. B., *J. Atmos. Sci*., 1978, **35**, 1070–1096.
11. Grell, G. A., Dudhia, J. and Stauffer, D., *NCAR Technical Note, NCAR/TN-398+STR*, National Center for Atmospheric Research, Boulder, CO, 1995, p. 117.

ACKNOWLEDGEMENTS. The Division of Atmospheric Sciences, National Science Foundation (NSF), the Naval Research Laboratory and the Office of Naval Research, Washington DC, and the Council for Scientific and Industrial Research, New Delhi and the Department of Space, Govt of India, supported this study. Model simulations were performed using computing resources from the North Carolina Supercomputing Center, Research Triangle Park, NC.