Simulation of marine boundary layer characteristics over the Indian Ocean during INDOEX-IFP’99

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The characteristic features of the marine boundary layer (MBL) over the Indian Ocean during the north-east monsoon and the factors influencing it have been investigated. The Indian Ocean Experiment (INDOEX) Intensive Field Phase-1999 (IFP’99) has provided the atmospheric sounding data for this study. This is for the first time that such high-resolution upper air data are obtained over the Indian Ocean. Different synoptic scenarios corresponding to convectively active and convectively suppressed situations over the Indian Ocean are considered to study the variability in MBL characteristics using one-dimensional (1-D) multi-level PBL model with a TKE-ε closure scheme. The NCMRWF-GCM was also used to simulate surface layer parameters such as sensible heat and latent heat fluxes, the marine boundary layer height, etc. The simulations also include the vertical profiles of potential temperature, specific humidity and zonal and meridional wind components. It is noticed that, in general, the non-local closure and the scheme due to turbulent kinetic energy (TKE) can simulate vertical profiles closer to the observations. The 1-D PBL model simulates the temporal evolution of TKE, marine boundary layer height (MBLH) and sensible and latent heat fluxes. The model also generates the vertical profiles of potential temperature, specific humidity, and zonal and meridional wind. These simulated values are comparable with the observations available from INDOEX experiment. The 1-D model could not simulate the dynamical features associated with advection and winds satisfactorily. However, the convective regimes are well simulated.

1 Introduction
One of the main objectives of the Indian Ocean Experiment (INDOEX) was to understand the transport of the aerosols-carrying air of the northern hemisphere that meets the pristine air brought by the south-east trade winds of the southern hemisphere in the Inter-Tropical Convergence Zone (ITCZ) regime. The ITCZ is the region of wind discontinuity in the lower troposphere where the trade winds from the two hemispheres converge. The transport of aerosols from source regions on the continents to remote oceans could play a significant direct as well as indirect role in global radiative forcing. Mitra1, who led the Indian team in this internationally coordinated INDOEX programme, had discussed in his introductory note on the Indian component of INDOEX that it is important to study the natural and climatic forcing by aerosols and its feedback on regional and global climate. The INDOEX, thus, addresses this question by having its focus on the Arabian Sea and the Indian Ocean regime during January-March 1999. Ramanathan et al.2 described in their paper that in the boreal winter, the prevalent northerly winds and the presence of a significant source of pollutants to its northern boundary, make the tropical Indian Ocean an ideal natural laboratory to study the export of aerosols and their influence on climate. However, in this regime the pre-existing data on the chemical, physical and radiative properties of the atmosphere are sparse3. The dearth of data over the Indian Ocean was the major force in designing the first major international experiment INDOEX1,3,4 to study the transport of aerosols and pollutants by tropical atmospheric dynamics and their interaction with clouds and radiation that may affect the climate.

The dynamics of ITCZ and the characteristic processes within the marine boundary layer (MBL) were also one of the focused areas of this experiment, as these processes predominantly govern the low-level transport and redistribution of aerosols and pollutants over the Indian seas. The MBL acts as the interface between the underlying oceans and overlying atmosphere, through which momentum, heat and moisture are exchanged by the interactive processes. The INDOEX observational network provides an opportunity to evaluate the MBL structure
over the Indian Ocean and to have its realistic representation in the numerical models in order to obtain meaningful simulation of boundary layer processes.

Studies conducted over the east central Arabian Sea and north central Bay of Bengal, respectively, by Meyer and Rao5 and Holt and Raman6, depict the importance of the meteorological processes influencing the MBL characteristics. However, very few studies have been made to illustrate the MBL structure and related role of surface fluxes in influencing the variability during significant synoptic situation over the Indian ocean due to the lack of data over the Indian Ocean. With INDOEX as the platform, Satyanarayana et al.7, Basu8, Manghanani et al.9 and Mohanty et al.10 contributed in explaining the MBL characteristics over the Indian Ocean.

As further extension to the above studies, the primary objective of this paper is to analyze the MBL characteristics during INDOEX using IITD-INMR (Indian Institute of Technology, Delhi–Institute of Numerical Mathematics, Russia) I-D model. How does the MBL structure vary over the Indian Ocean with time during the north-east monsoon? How well the NCMRWF-GCM (National Centre for Medium Range Weather Forecasting–General Circulation Model) is able to simulate MBL features closer to the observations? Are there any local factors that influence the spatial and temporal variability in the MBL height? These are some of the questions that are addressed in this paper.

Also it is for the first time that such a high-resolution data were collected using radiosondes on-board Oceanographic Research Vessel (ORV), Sagar Kanya, and Research Vessel (R V), Ronald H. Brown, in the Indian Ocean. These sondes had provided the vertical profiles of pressure, temperature, humidity, geopotential height and wind speed and wind direction. These data sets had provided very good opportunity to validate the IITD-INMR, one-dimensional (hereafter 1-D), multi-level planetary boundary layer (PBL) model with a TKE-ε closure scheme over the Indian Ocean regime. This I-D model is used to simulate the vertical profiles of zonal and meridional wind, potential temperature and specific humidity that compared well with the observations. Other surface parameters that determine the MBL characteristics, viz. MBLH, sensible heat flux (SHF), latent heat flux (LHF), evolution of total turbulent kinetic energy (TKE) etc. are also presented in this paper.

2 Data

As part of the INDOEX research, during the Intensive Field Phase (IFP’99), surface and upper air observations were obtained over the Indian Ocean, on-board ORV Sagar Kanya and R V Ronald H Brown. Figures 1[(a) and (b)] shows the tracks of these two ships during IFP’99. High-resolution vertical profiles of temperature, moisture, wind speed and direction at different pressure levels were obtained from Vaisala soundings during INDOEX. Such observations were unique and first of its kind over the Indian Ocean region. For the present study
two cases from the IFP'99 were taken. The case of 24-26 Feb. 1999 was taken as one of the active case
and 7-9 Mar. 1999 as the suppressed convection case
during IFP'99. These two different synoptic episodes
were considered to be based on the surface synoptic
observations taken on-board ORV Sagar Kanya, India
Daily Weather Report (IDWR), satellite pictures and
NCMRWF analysis. A linear interpolation technique
is used to interpolate the above-cited parameters
(vertical profiles) for every 50 m in the vertical
profiles. These data sets provide input for the 1-D
model in simulating the MBL characteristic features.
It is worth mentioning that these high-resolution data
that are of a class of its own, served the purpose of
validating the 1-D model over the Indian Ocean
region. The NCMRWF-GCM having the global data
assimilation and forecast system (GDAFS) takes in
the surface and upper air data from global
transmission system (GTS) for obtaining a 5-day
forecast. However, for the present study only two-day
forecasts are used for comparison, as real-time
consistent observations from Vaisala sondes were
available for two-day periods during the IFP'99.

3 Methodology
The 1-D PBL model with TKE-ε closure is used to
simulate the MBL characteristics during the two
different convective episodes considered from IFP'99.
The experiment has served the purpose of validating
the 1-D model over the Indian Ocean region using the
high-resolution data. The NCMRWF-GCM, an
operational model at the NCMRWF with three
different PBL parametrization schemes, viz. (a) first­
order local closure, (b) non-local closure and (c)
TKE-ε closure (hereafter TKE), is used to examine
the MBL features during the different convective
episodes. For the present study we have used the
NCMRWF-GCM having the TKE scheme. A brief
description of the 1-D model and the NCMRWF­
GCM is given below.

3.1 IITD-INMR 1-D PBL model
This model is a multi-level 1-D model with TKE-ε closure scheme. The model has 40 levels in the
vertical with each layer having a uniform thickness of
50 m from surface to the top of the model (2000 m).
The TKE-ε closure is used for the mixed layer, while
the surface layer similarity approach is used for the
constant flux layer close to the ocean surface. Details
of the model are given elsewhere.

The model equations are:

\[ \frac{\partial u}{\partial t} = -\frac{\partial u w}{\partial z} + f v + \bar{P} x / \bar{P} \]

\[ \frac{\partial v}{\partial t} = -\frac{\partial v w}{\partial z} - f u - \bar{P} y / \bar{P} \]

\[ \frac{\partial \theta}{\partial t} + u \bar{\theta} x + v \bar{\theta} y = -\frac{\partial \bar{w} \bar{w}}{\partial z} + Q_r + Q_f \]

\[ \frac{\partial q}{\partial t} + u \bar{q} x + v \bar{q} y = -\frac{\partial \bar{w} q}{\partial z} + E_p - C \]

\[ \frac{\partial q_w}{\partial t} + u \bar{q}_w x + v \bar{q}_w y = -\frac{\partial \bar{w} q_w}{\partial z} - E_p + C - P \]

\[ \frac{\partial E}{\partial t} = \left( -\frac{u w}{\rho} \frac{\partial u}{\partial z} + v w \frac{\partial v}{\partial z} + \frac{g}{\rho} \frac{\partial \bar{w}}{\partial z} + \varepsilon \right) \]

\[ \frac{\partial E}{\partial t} = -C_1 e \left( -\frac{u w}{\rho} \frac{\partial u}{\partial z} + v w \frac{\partial v}{\partial z} + \frac{g}{\rho} \frac{\partial \bar{w}}{\partial z} + \varepsilon \right) \]
vertical turbulent fluxes of momentum, heat, water vapour and liquid water, \( f \) is the coriolis parameter, \( g \) the acceleration due to gravity, and \( C_i \) and \( b \) are the constants. A brief overview of the model is presented in Table 1.

### 3.1.1 Turbulence closure

In the IITD-INMR 1-D model, the PBL is separated into two domains: (i) the near-surface constant-flux layer \((z \leq h)\) and (ii) the interfacial layer \((h < z \leq H)\). It is assumed that \( h \) and \( H \) do not vary in time. In order to calculate vertical turbulent fluxes of momentum, heat and moisture in the interfacial layer, the following Boussinesq hypothesis is used.

\[
\frac{a}{a} w' = K_a \frac{\partial a}{\partial z} \quad \ldots (8)
\]

where, \( a \) is any of the prognostic variables \( u, v, \theta, q \) and \( q_w \) and \( K_a \) is the eddy exchange coefficient. It is assumed that \( K_a = \alpha a K \), where, \( \alpha \) is a dimensionless constant (equal to unity for the momentum flux). The coefficient \( K \) is related to the turbulent kinetic energy \( E \) and the dissipation rate \( \varepsilon \) following Kolmogrov equation

\[
K = \frac{C_k E^2}{\varepsilon} \quad \ldots (9)
\]

where, \( C_k \) is a dimensionless constant.

### 3.1.2 Lower boundary conditions

Since in the constant flux layer (a layer of nearly 50 m from the ocean surface) the turbulent fluxes are nearly constant, it is customary to represent the lower boundary. The maximum heights for the variables \( \bar{u}, \bar{v}, \bar{\theta}, \bar{q} \) and \( \bar{e} \) at the constant flux layer height in order are:

\[
K_u \left( \frac{\partial \bar{u}}{\partial z} - \gamma_u \right) = C_D |\bar{u}| \quad \ldots (10)
\]
\[
K_v \left( \frac{\partial \bar{v}}{\partial z} - \gamma_v \right) = C_D |\bar{v}| \quad \ldots (11)
\]
\[
K_\theta \left( \frac{\partial \bar{\theta}}{\partial z} - \gamma_\theta \right) = C_D |\bar{\theta}| \quad \ldots (12)
\]
\[
K_q \left( \frac{\partial \bar{q}}{\partial z} - \gamma_q \right) = C_D |\bar{q}| \quad \ldots (13)
\]

Table 1—Overview of the IITD-INM 1-D model

<table>
<thead>
<tr>
<th>Model Description</th>
<th>1-D PBL model with one and half order TKE-( \varepsilon ) closure scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical domain</td>
<td>Surface to 2000 m</td>
</tr>
<tr>
<td>Vertical levels</td>
<td>40, ( \Delta z=50 ) m</td>
</tr>
<tr>
<td>Independent variables</td>
<td>( Z, t )</td>
</tr>
<tr>
<td>Prognostic variables</td>
<td>( U, V, \theta, q, q_w, \varepsilon )</td>
</tr>
<tr>
<td>Diagnostic variables</td>
<td>( K_a )</td>
</tr>
<tr>
<td>Numerical scheme</td>
<td>Second order accuracy</td>
</tr>
<tr>
<td>Time integration</td>
<td>Implicit, ( \Delta t = 600 ) s</td>
</tr>
<tr>
<td>Boundary conditions</td>
<td>For lower boundary, Monin-Obukhov similarity theory;</td>
</tr>
<tr>
<td></td>
<td>For upper boundary, the geostrophic conditions, actual observed values at 2000 m;</td>
</tr>
<tr>
<td></td>
<td>For TKE-( \varepsilon ), zero energy flux at 2000 m.</td>
</tr>
<tr>
<td>Physical processes</td>
<td>Dry and moist convective adjustment;</td>
</tr>
<tr>
<td></td>
<td>Sensible and latent heat fluxes;</td>
</tr>
<tr>
<td></td>
<td>Fluxes under stormy conditions;</td>
</tr>
<tr>
<td></td>
<td>Longwave and short-wave radiation fluxes.</td>
</tr>
</tbody>
</table>
\[ \frac{\partial e}{\partial z} = 0 \quad \ldots \quad (19) \]

3.2 NCMRWF-GCM

The NCMRWF-GCM is an adapted version of the national centre for environmental prediction (NCEP), 18-layer spectral triangular truncation at T-80 model having a terrain following sigma coordinate system. Relative vorticity, divergence, virtual temperature, surface pressure and specific humidity are the main prognostic variables in the model. The PBL has two layers, viz. the surface layer and the mixed layer. Monin-Obukhov similarity theory is used in the surface layer, while the eddy transport that takes place through the mixed layer is dependent on the Richardson number which stands as criteria for the vertical diffusion processes. Kanamitsu and Parish and Derber give the details of the NCEP forecast and assimilation model system, respectively. Detailed descriptions of the three-parametrization schemes, namely the first-order (K-Theory) closure, the non-local closure and the TKE-ε closure employed in the NCMRWF-GCM are given by Basu and Basu et al. A brief overview of the model is given in Table 2.

4 Initial conditions and experiments

4.1 IITD-INMR 1-D PBL model

The initial values for the 1-D PBL model, \( u = u_{\text{obs}}(z,0), \quad v = v_{\text{obs}}(z,0), \quad \theta = \theta_{\text{obs}}(z,0), \quad q = q_{\text{obs}}(z,0), \) are prepared from Vaisala sonde observational data obtained on-board ORV Sagar Kanya over the Indian Ocean. The data obtained over R V Ronald H Brown, from Maldives and other west-coast Indian stations, were also used for 1-D simulations, especially, in the study of the temporal and spatial variation of marine boundary layer height (MBLH) and TKE. The initial values at the model grid points are obtained by linearly interpolating the high-resolution upper air data consisting of zonal (u) and meridional (v) wind components, potential temperature (\( \theta \)) and specific humidity (q). These parameters that are interpolated at every 50 m in the vertical to 2000 m (top of the model domain) are taken as input to the model.

The lower boundary conditions are prepared using the six-hourly surface observations obtained on-board ORV Sagar Kanya and for the radiation parametrization scheme, climatological ozone data are prescribed.

For Case-1, the convectively active episode during IFP’99, i.e. 24-26 Feb. 1999, initial conditions are prepared using Vaisala sonde observations at 0000 hrs of 24 Feb. 1999 and the model is integrated for 48 h. For Case-2, the convectively suppressed case (7-9 Mar. 1999), the initial conditions are prepared at 0000 hrs of 7 Mar. 1999.

The time step of integration of the model is 600 s and hourly simulations of the model are stored for comparison with the observations.

<table>
<thead>
<tr>
<th>Model elements</th>
<th>Components</th>
<th>Schemes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>Horizontal</td>
<td>T-80, spectral, global</td>
</tr>
<tr>
<td></td>
<td>Vertical</td>
<td>18 sigma layers [( \sigma = 0.995, 0.981, 0.960, 0.920, 0.856, 0.777, 0.668, 0.594, 0.497, 0.425, 0.375, 0.325, 0.275, 0.225, 0.175, 0.124, 0.074, 0.021 )]</td>
</tr>
<tr>
<td>Dynamics</td>
<td>Prognostic variables</td>
<td>Rel. vorticity, divergence, virtual temp., log surface press, water vapour mixing ratio, Orzag's technique</td>
</tr>
<tr>
<td></td>
<td>Horizontal transform</td>
<td>Arakawa's energy conserving scheme</td>
</tr>
<tr>
<td></td>
<td>Vertical differencing</td>
<td>Semi-implicit (divergence, surface press and virtual temp.)</td>
</tr>
<tr>
<td></td>
<td>Time differencing</td>
<td>Explicit leap-frog (vorticity and mixing ratio)</td>
</tr>
<tr>
<td></td>
<td>Time filtering</td>
<td>Robert's method</td>
</tr>
<tr>
<td></td>
<td>Horizontal diffusion</td>
<td>Fourth order</td>
</tr>
<tr>
<td>Physics</td>
<td>Surface fluxes</td>
<td>Monin and Obukhov similarity</td>
</tr>
<tr>
<td></td>
<td>Turbulent diffusion</td>
<td>K-theory</td>
</tr>
<tr>
<td></td>
<td>Radiation</td>
<td>Short wave - Lacias and Hansen (1974), Long wave - Fels and Schwarzkopf (1975)</td>
</tr>
<tr>
<td></td>
<td>Deep convection</td>
<td>Kuo scheme modified</td>
</tr>
<tr>
<td></td>
<td>Shallow convection</td>
<td>Tiedtke method (Tiedtke, 1983)</td>
</tr>
<tr>
<td></td>
<td>Large-scale condensation</td>
<td>Manabe-modified</td>
</tr>
<tr>
<td></td>
<td>Cloud generation</td>
<td>Slingo scheme (Slingo, 1987)</td>
</tr>
<tr>
<td></td>
<td>Rainfall evaporation</td>
<td>Kessler's scheme</td>
</tr>
<tr>
<td></td>
<td>Land surface processes</td>
<td>Pan method</td>
</tr>
</tbody>
</table>
4.2 NCMRWF-GCM

In the global model integrations, as mentioned before, 6 hourly assimilation cycles are run as part of the GDAMS using global observations from GTS and 6-hourly forecast from global model serves as the first guess. These analysis fields, valid for 0000 hrs on 24 Feb. and 7 Mar. 1999, are used as initial conditions for the global model. The model is integrated up to 5 days for obtaining the forecasts. The simulations are compared with observations wherever available. Only the first 48-h simulations are used for the comparison and evaluation purposes for both 1-D and NCMRWF-GCM.

5 Results and discussion

The results consist of IITD-INMR 1-D model and the NCMRWF-GCM simulations of vertical profiles of zonal ($u$) and meridional ($v$) wind components, potential temperature ($\theta$) and specific humidity ($q$). These models give hourly simulations, and the simulated profiles are so chosen to verify the performance of the models as a validation over the Indian Ocean region. The diurnal variation of the surface fluxes of latent and sensible heat, MBLH and the evolution of the total TKE are also illustrated for few cases. Spatial variation of TKE and MBLH are examined during both the convectively active episode (24-26 Feb. 1999) and convectively suppressed episode (7-9 Mar. 1999) during IFP ’99. The simulations are compared with the observations wherever information are available.

5.1 Sensible and latent heat fluxes

The SHF and LHF during the convectively active case (24-26 Feb. 1999) during IFP ’99 are illustrated in Fig. 2(a) and (b). The values of SHF [Fig. 2(a)] due to both 1-D and GCM are comparable. Sharp variations are noticed in the 1-D simulated SHF, whereas the NCMRWF-GCM-simulated SHF is rather smooth. However, the diurnal pattern is quite visible. Maximum SHFs due to both 1-D and NCMRWF-GCM show a systematic difference of ~2 Wm$^{-2}$. The 1-D simulated LHF [Fig. 2(b)] maxima of 170 Wm$^{-2}$ and 120 Wm$^{-2}$ compare very well with the same time maxima due to the NCMRWF-GCM, which are, respectively, of the order of 135 Wm$^{-2}$ and 137 Wm$^{-2}$. The diurnal variability is very well brought out. The NCMRWF-GCM is able to simulate the LHF very well when compared to the 1-D simulations. Figure 2(d) and (e) shows the simulated SHF and LHF during the convectively suppressed case (7-9 Mar. 1999, IFP’99). The SHF values [Fig. 2(d), due to both NCMRWF-GCM and 1-D, are below 10 Wm$^{-2}$, depicting the inactivity of the atmosphere. The diurnal pattern is observed in both NCMRWF-GCM and 1-D simulation of SHF. The LHF [Fig. 2(e)] too shows a diurnal pattern and both the simulations match well. The maximum value of LHF with the NCMRWF-GCM and 1-D simulations is below 100 Wm$^{-2}$. Lower values of SHF and LHF are due to the calm atmospheric conditions during the convectively suppressed case.

Fig. 2—Variability of (a) sensible heat flux, (b) latent heat flux and (c) marine boundary layer height during 24-26 Feb. 1999 (during the convectively active episode: IFP ’99); similarly (d), (e) and (f), respectively, represent variability of same parameters during 7-9 Mar. 1999 (during the convectively suppressed episode: IFP’99)
5.2 Marine boundary layer height

Figure [2(c) and (f)] depicts the NCMRWF-GCM-simulated MBLH compared with 1-D-simulated value during both convectively active (24-26 Feb. 1999) and convectively suppressed cases (7-9 Mar. 1999). During the active convection period, it is found that the simulated MBLH [Fig. 2(c)] due to NCMRWF-GCM reaches up to a maximum of 1000 m and corresponding to it the 1-D-simulated value reaches a maximum of 875 m. The diurnal variation is clearly seen in both the simulations. In case of the convectively suppressed case [Fig. 2(f)] the NCMRWF-GCM-simulated MBLH matches very well with the 1-D simulated MBLH. The diurnal variation is very well simulated in the convectively suppressed case. The average MBLH is well below 400 m.

5.3 Vertical profiles

5.3.1 Convectively active episode—Figures 3-6 represent the 1-D and NCMRWF-GCM-simulated vertical profiles of zonal wind (u), meridional wind (v), potential temperature (θ), and specific humidity (q), respectively, along with the observations from the Vaisala sondes for the convectively active (24-26 Feb. 1999) episode during IFP'99. Although hourly simulations are available, only representative profiles are given for which observations are available. The simulations given in Figs 3-6 are at 10 00 hrs UTC (24 Feb. 1999), 00 00 hrs UTC (25 Feb. 1999), 10 00 hrs UTC (25 Feb. 1999) and 00 00 hrs UTC(26 Feb. 1999). They correspond to 10 h, 24 h, 34 h and 48 h of simulations with initial values at 0000 UTC of 24 Feb. 1999.

It is noticed that the 1-D model, except for a few sharp variations noticed in the observed wind profiles, very well simulates both the wind components. This could be due to the limitations that are encountered in a 1-D model to simulate all the processes active for any given scenario due to non-homogeneity and advection. However, we find that there is a larger discrepancy between the simulations and observed values for regimes near ITCZ.

If closely examined, the simulated u profile [Fig. 3(a)-(d)] due to NCMRWF-GCM shows an
easterly bias during the first day of simulation. However, the 1-D is able to simulate the $u$ wind very well except for the kinks. It is worth mentioning that even the magnitudes are comparable. In case of $v$ component of the wind [Fig. 4(a)-(d)], both 1-D and NCMRWF-GCM compare well with the observations in magnitude and direction.

The NCMRWF-GCM-simulated potential temperature ($\theta$) [Fig. 5(a)-(d)] is seen to be consistently lower than the 1-D and the observed values of $\theta$. An overall analysis indicates that the 1-D simulated potential temperature profiles compare better with the observed profiles. Similarly the simulated $q$ profiles [Fig. 6(a)-(d)] due to NCMRWF-GCM are lower throughout 48 h of simulation. However, the trend followed by the simulated profiles (NCMRWF-GCM) compares well with the observations. The 1-D is able to simulate $q$ very well, and the NCMRWF-GCM shows an overall drier atmosphere by an order of 2-3 g/Kg. If the 1-D simulations are compared with the simulations due to the NCMRWF-GCM, it is seen that on 24 Feb. 1999 [first day of simulation; Fig. 6(a)-(d)], the NCMRWF-GCM is able to simulate the $q$ field much better.

5.3.2 Convectively suppressed episode—Similar to the representation of simulated vertical profiles in the convectively active case, the simulated vertical profiles in the convectively suppressed case during 7-9 Mar. 1999 are illustrated in Figs 7-10 for the $u$ and $v$ components of wind, $\theta$ and $q$ profiles, respectively, along with the observations. The representative profiles are at 18 00 hrs UTC (7 Mar. 1999), 0000 hrs UTC (8 Mar. 1999), 0800 hrs UTC (8 Mar. 1999) and 0000 hrs UTC (9 Mar. 1999) and correspond to 18 h, 24 h, 32 h and 48 h of simulations respectively. During this period too, the 1-D simulated $u$ [Fig. 7(a)-(d)] and $v$ [Fig. 8(a)-(d)] have got a definitive edge over the NCMRWF-GCM simulations. The observed $u$ and $v$ profiles are noticed to be very much variable in the vertical with lot of kinks. Both the models
could not capture these kinks noticed in the observed wind profiles. The magnitude of the winds in the vertical is lesser than that observed during the convectively active case.

Figure [9 (a)-(d)] shows the $\theta$ profiles. A strong inversion layer is seen from above 500 m. As expected during suppressed convective activity, the atmosphere is found to be highly stable in the lower part of MBL. The 1-D is able to simulate the overall observed profiles better than the NCMRWF-GCM. During 00 00 hrs UTC (9 Mar. 1999) we find that the NCMRWF-GCM simulation almost overlaps the observation till 500 m; thereafter, the observed $\theta$, all of a sudden, increases to a maximum of 307 K, which the NCMRWF-GCM is not able to capture. Even so is the case with the 1-D. However, the 1-D simulation is still closer to the observational values. In case of the $q$ [Fig. 10 (a)-(d)] profiles for the first two representative profiles at 1800 hrs UTC (7 Mar. 1999) and 00 00 hrs UTC (8 Mar. 1999) the NCMRWF-GCM simulated $q$ in the lower MBL (surface to 500 m) does not match very well with the observed $q$ profile. As the simulation hours advance to 0800 hrs UTC (8 Mar. 1999) and 0000 hrs UTC (9 Mar. 1999) the simulations in the lower MBL match very well, but in upper MBL show disparity and do not match well with the observed $q$. The 1-D simulations of $q$ match reasonably well with the observations. It is worth mentioning at this juncture that even the kinks are simulated reasonably well. But we find that as the hours of simulation increase, the simulations deviate from being closer to the observations.

5.4 Temporal variation of MBLH

The temporal variations of the MBLH during convectively active episode and the convectively suppressed cases are presented in Fig. 11[(a) and (b)]. Figure 11(a) clearly depicts that the height of the MBL is more over the oceans (ships) than the coastal stations, except for Bombay, which shows a steady rise in the MBLH. Higher MBLH over the ocean is due to the convective activity (24-26 Feb. 1999) in the vicinity of the ITCZ. The overall MBLH [Fig. 11 (b)] is well below 500 m during the convectively suppressed case (7-9 Mar. 1999). If closely observed, the diurnal variation of the MBLH can be noticed in
both during active and suppressed convection case. However, the diurnal variations over Maldives during both the cases are well marked.

5.5 Spatial variation of MBLH

Figures 12 [(a)-(d)] and 13 [(a)-(d)] show the spatial variation of MBLH (12 h, 24 h, 36 h and 48 h of simulation) during the convectively active period (24-26 Feb. 1999) and convectively suppressed period (7-9 Mar. 1999), respectively. The 1-D model is run for 48 h at different west coast stations, namely, Bombay, Goa, Mangalore, Cochin, Trivandrum and an island station Amini Devi along with the usual runs at Maldives and using the ship data from ORV Sagar Kanya and R V Ronald H Brown. Vaisala sonde observations were available at Maldives and at both the ships during this period. The model is integrated up to 48 h over all these land and ocean stations, starting from 0000 hrs UTC of 24 Feb. 1999. From Fig. 12[(a)-(d)], a clear diurnal pattern of variability in the MBLH is seen. Two distinct pockets of convective activity can be located that could be the basic triggering force in the growth of the MBLH at these locations. One is located in the western Arabian
Sea [Fig. 12 (a)] where R V Ronald H Brown (850 m, 1200 hrs UTC) was stationed and the other in north-Indian Ocean around Maldives (650 m, 12 00 hrs UTC). The influence of these two pockets is clearly seen to extend up to the equator where ORV Sagar Kanya was stationed (550 m, 12 00 hrs UTC). At 36 00 hrs [Fig. 12(c)], it is noticed that the MBLH at Bombay has increased to 300 m (from 50 m at 1200 hrs UTC). This could be due to the land-air-sea interaction cycle. The MBLH is seen to grow near Maldives (to 850 m) by 3600 hrs UTe, while there is a decrease in the MBLH near Ronald H Brown. By the 48th h, we find that the growth in the MBLH near ORV Sagar Kanya also has decreased, thus showing a clear diurnal variability.

Figure 13((a)-(d)) shows the spatial variability during the convectively suppressed case (7-9 Mar. 1999). The overall picture from 12 h to 48 h of simulation shows that the maximum MBLH is well below 500 m. At the 12-h simulation near Maldives the MBLH has reached 400 m, which later depreciated to 100 m at 24 h and then increases to 400 m at 36th h and later came down again to 100 m at 48 h showing a clear diurnal variability. Over Sagar
Kanya also we find diurnal variability, but the maximum attained height of the MBL is only 250 m (36 h simulation, 8 Mar. 1999). Over Ronald H. Brown, the MBLH reaches a maximum of 450 m during 24 h of simulation (00 00 hrs UTC of 8 Mar. 1999) and 48 h (00 00 hrs UTC of 9 Mar. 1999).

5.6 Spatial variation of TKE

Figure 14 [(a)-(d)] represents the spatial variation of the 1-D-simulated TKE over the Indian Ocean during the convectively active episode (24-26 Feb. 1999). Figure 14[(a)-(d)] illustrates the TKE distribution at 250 m from 12 h to 48 h, model integration at every 12 h interval. Examination of Fig. 14[(a)-(d)] shows that the TKE is maximum over the oceans (ships) and near Maldives. During the initial time of this period the total turbulent kinetic energy is found to be higher near R V Ronald H Brown (0.3 m$^2$s$^{-2}$) and surrounding Maldives (0.2 m$^2$s$^{-2}$), which decreases to 0.2 and 0.1 m$^2$s$^{-2}$ at the respective locations. From 30$^{th}$ h of integration onwards, again, a growth in the TKE is seen near Maldives to have a maximum of 0.3 m$^2$s$^{-2}$. Figure 15[(a)-(d)] shows the spatial variation of the TKE during the convectively suppressed case. It is noticed that the TKE evolution...
is very less compared to the convectively active case. The values are almost one order less during this period. The maximum TKE is noticed over the Maldives where it is seen to go up to 0.1 m²s⁻². Overall the TKE evolution is very less during suppressed convection, which is well reflected in the spatial variation of the MBLH [Fig. 13 (a)-(d)].

6 Conclusions
The INDOEX Intensive Field Phase (IFP'99) was conducted during the north-east monsoon. While studying the different synoptic episodes, during this period, the heterogeneity in the convective atmosphere during convectively active and convectively suppressed regime are well figured out.

The growth in the MBLH and the sudden rise in the SHF and LHF during the convectively active case determine the ITCZ dynamics. The structure of the boundary layer is also found to be varying depending on the various factors that influence lower atmosphere. The general trend of MBLH is seen to gradually increase towards the zone of convective activity.

From the simulations of 1-D and NCMRWF-GCM during the convectively active and suppressed episode following broad conclusions can be made:

(i) In general, it is seen that by and large the simulations produced by IITD-INMR 1-D and the global model (NCMRWF-GCM) compare

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Fig. 14—Spatial variation of turbulent kinetic energy at 250 m (a.s.l) during 24-26 Feb. (IFP'99) [(a) 12 h simulation, (b) 24 h simulation, (c) 36 h simulation, and (d) 48 h simulation]
reasonably well with the observations obtained during the INDOEX (IFP'99) period. As expected, the 1-D model could simulate the convectively dominant boundary layer structure better than the dynamically forced regime.

(ii) The thermodynamic structure is well simulated by the 1-D model than the NCMRWF-GCM. This may be due to higher resolution in the vertical (40 levels) within the lower 2 km of the atmosphere.

(iii) The 1-D simulations of wind profiles could not capture the strong variability in the observed wind. This could be due to the limitations that are encountered in a 1-D model for any given scenario due to non-homogeneity and advection. However, 1-D and the NCMRWF-GCM simulations show almost similar type of discrepancies.

(iv) Higher values of sensible heat flux and latent heat flux during the convectively active episode and its variability during a suppressed convection period are reasonably well simulated with both 1-D and the NCMRWF-GCM.

(v) Temporal and spatial variations in the MBLH during convectively active and suppressed cases

Fig. 15—Same as in Fig. 14, but during 7-9 Mar. (IFP '99)
show their diurnal variability over the Arabian Sea and Indian Ocean regime. Further, it may be noted that the diurnal variability is stronger during the convectively suppressed episode.

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