A study on marine boundary layer processes in the ITCZ and non-ITCZ regimes over Indian Ocean with INDOEX IFP-99 data

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A one-dimensional numerical planetary boundary layer (PBL) model was applied to simulate the dynamical and thermodynamical characteristics of the tropical Indian Ocean under varying convective regimes. Using sounding as well as surface meteorological data obtained during the INDOEX field phase, the PBL was validated for three different regions within the INDOEX domain. The three regions identified were, a coastal location representing suppressed convection, an open ocean region with medium convection, and a region of intense convection in the vicinity of the Inter-Tropical Convergence Zone (ITCZ). The model was integrated using observed sounding as initial as well as lateral boundary conditions, for a period up to 48 h. The model simulated surface fields as well as vertical profiles were compared with observations for the three cases. In general the model performance was good. The one-dimensional model could not simulate the dynamical features associated with advection and winds satisfactorily. However, the convective regimes are well simulated. As such, the PBL processes near the ITCZ were better simulated compared to the coastal regions. Results suggest that such a model can be used as a tool to develop high resolution, time-varying profiles over data-sparse regions to enhance mesoscale analysis.

ONE of the significant objectives of INDOEX was to understand the transport of the continental air masses into the Inter-Tropical Convergence Zone (ITCZ). The ITCZ is a region of wind discontinuity in the lower troposphere where the trade winds from the two hemispheres converge. This convergence zone is located in the Southern Hemisphere. For the INDOEX study period (January to March), the ITCZ is located mostly in the Southern Hemisphere around 5°S and is migratory. The ITCZ can also be regarded as a zone of horizontal velocity convergence associated with ascending motion, and persistent organized convective activities. Thus, this region can be identified as a cloud belt with east–west elongated shear zone with westward moving cloud clusters embedded in this structure. ITCZ thus acts as a sink of continental materials. One of the central hypotheses tested during INDOEX related to the understanding of this continental transport is the lower troposphere.

The aim of this study is to understand the marine boundary layer (MBL) characteristics with respect to the varying convection associated with coastal effects and the ITCZ regimes. Variation of the MBL characteristics under three different convective regimes, viz. coastal ocean representing suppressed convection, open ocean with medium convection, and in the vicinity of the ITCZ, an active convective zone, is investigated in this paper. This is achieved by using a numerical MBL model[1] along with shipboard observations during the 1999 INDOEX intensive field phase (IFP) from RV *Ronald Brown*. One of the secondary objectives of this study is to validate the MBL model for the tropical ocean environment using INDOEX observations.

Model initial conditions and numerical experiments

During the INDOEX intensive field phase (IFP), upper air sounding and surface observations were obtained onboard R/V *Ronald Brown* between 21 February 1999 and 29 March 1999. The sounding data comprised high-resolution (average 50 m vertical resolution) profiles using a GPS sonde system[2]. This contained winds and thermodynamic variables from surface (~ 10 m) to about 15 km. Since our aim is to study the MBL characteristics, we focus on the first 2 km in the vertical. Additional data comprised surface meteorological variables and the sea surface temperature (SST). Surface data corresponding to the radiosonde launches are used in the model as described subsequently. The ship track for RV *Ronald Brown* during IFP is shown in Figure 1. The ship resumed its course from Mauritius to Maldives and crossed the ITCZ during this leg. From Maldives it went to the Arabian Sea and

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traveled parallel to western coast of India. On reaching its north-most point, the ship again went southwards to Maldives. Once again during this stage the ship crossed ITCZ. The ITCZ crossing was inferred mostly from ship-based surface meteorological observations and was later verified using satellite data (not shown). The three regimes representing varying convective activity are selected from each of the three legs. Accordingly, on reviewing the ship track, data availability, and the synoptic conditions in the vicinity of the ship, the study period selected was: 24–26 February 1999, 11–13 March 1999, and 20–22 March 1999. For 24–26 February 1999, referred to as Case 1, the ship was between 13°S and 5°S (averaged around 60°E) in the Southern Hemisphere where trade winds prevailed with zones of active ITCZ and high convection. During 11–13 March 1999, referred to as Case 2, the ship was cruising in the Arabian Sea along the western coast of India (between 18°N and 9°N, along ~ 67°E). These data thus represent the suppressed convection activity under the influence of cold and dry continental air from the Indian subcontinent. The third data period (20–22 March 1999), or Case 3, is representative of an open ocean with moderate convection due to a weakened ITCZ. The ship was between 11°S and 2°S for this period around 72.5°E. For these three cases, the MBL characteristics are analysed by studying the MBL height, surface turbulent sensible and latent heat fluxes, friction velocity and the turbulent kinetic energy (TKE) evolution using a multilevel one-dimensional MBL model with TKE-*e* closure. The simulated profiles are compared with observations. This gives an understanding of the temporal variations in the MBL which observations alone could not provide. Additionally, the observations serve as an initial and time varying boundary conditions and provide verification of the predicted model fields, as discussed in the following section.

The MBL model used in this study is a primitive equation, one-dimensional, TKE-*e* closure based, planetary boundary layer (PBL) model. The model has 40 vertical levels with an average layer thickness of 50 m from the surface to 2000 m. There are prognostic equations for winds, temperature, humidity, cloud water and pressure. While setting the model initial conditions and subsequent integration, geostrophic balance is achieved through pressure gradient and thermal wind equations[3]. As mentioned, the model adopts TKE-*e* mixed layer parameterization, while the surface layer similarity approach is used for the constant flux layer close to the surface (ocean in this case). Additional details regarding the model can be found in refs 1, 4, 5. A brief overview is also presented in Table 1.

For the model initial and boundary conditions, data comprising vertical profiles of winds, temperature and humidity at different pressure levels are utilized. Using linear interpolation technique the data sets of vertical profiles of the above cited parameters are prepared at every 50 m in vertical from sea level to the top of model domain. The maximum height of the turbulent boundary layer (top of the PBL) is chosen as the upper boundary. At the top of the boundary layer, the wind speeds, the potential temperature and the moisture attain the observed values at that height. The TKE and energy dissipation is assumed to vanish at that height. Analysis of the observed boundary layer heights indicated a maximum of 1600 m. Hence the top of the model domain was kept at 2000 m. These data sets served as an input to the PBL model as well as time-varying lateral boundary conditions to study the MBL characteristics. The model generated the vertical profiles of zonal and meridional wind, potential temperature and specific humidity, which are then compared with observed profiles for validation. For Case 1, initial conditions were prepared using interpolated vertical profile for

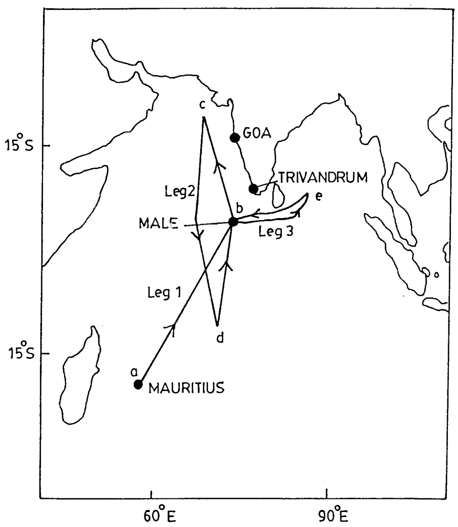

Figure 1. Cruise track of *Ronald H. Brown* during IFP-99.

Table 1. An overview of the marine boundary layer model

Model description	1-D PBL model with one and half order TKE-*e* closure scheme
Vertical domain	Surface to 2000 m
Vertical levels	40, ΔZ = 50 m
Independent variables	Z, t
Prognostic variables	U, V, q, q, qw, E, e
Diagnostic variables	Kuo
Numerical scheme	Second order accuracy
Time integration	Implicit, Δt = 600 s
Boundary conditions	For lower boundary, Monin–Obukhov similarity theory. For upper boundary, the geostrophic conditions, actual observed values at 2000 m for TKE, *e*, zero energy flux at 2000 m
Physical processes	Dry and moist convective adjustment Sensible and latent heat fluxes Fluxes under stormy conditions Long-wave and short-wave radiation fluxes

24 February 1999, 00 UTC and the model was integrated for 48 h. Similarly for Case 2, the model was initialized at 11 March 1999, 00 UTC and integrated for a 42 h period. The 48 h (13 March 1999, 00 UTC) observed profiles were not available for this case hence the model integration had to be limited till 42 h. For Case 3, the model was initialized with observed sounding for 20 March 1999, 00 UTC and was integrated for 48 h. The model was integrated with a 10 min time step for the ocean environment. Every 6 h, simulation outputs were archived for comparison with observations as discussed in the following section.

Results and discussion

The results consist of the simulated vertical profiles of zonal and meridional components of wind, potential temperature, specific humidity; marine boundary layer height, sensible and latent heat fluxes, friction velocity and drag coefficient along with the TKE. This was generated for all the three cases. These simulated profiles were compared with corresponding observations. The observed profiles of zonal and meridional wind component, potential temperature and specific humidity were linearly interpolated in the vertical and the resultant values (at every 50 m interval up to 2000 m) used.

The diurnal variation of the model simulations of surface layer parameters such as friction velocity, sensible heat flux and latent heat flux, and drag coefficients for momentum (C_D) and heat (C_T) for Case 1, Case 2 and Case 3 is presented in Figures 2, 3, and 4 respectively. On comparing all the three cases, it is noticed that the surface heat fluxes are highest (maximum sensible heat flux is 33 Wm^{-2}) in Case 1 (near ITCZ), and least (maximum sensible heat flux is less than 10 Wm^{-2}) in Case 2 (coastal case), while the Case 3 (open ocean) has values between Case 1 and Case 2 (maximum sensible heat flux is 22 Wm^{-2}). The latent heat fluxes follow similar trend as the sensible heat flux with Case 1 showing a maximum value of 155 Wm^{-2}, Case 2 yielding 80 Wm^{-2} and Case 3 giving 130 Wm^{-2}. Thus the simulated surface fluxes are in

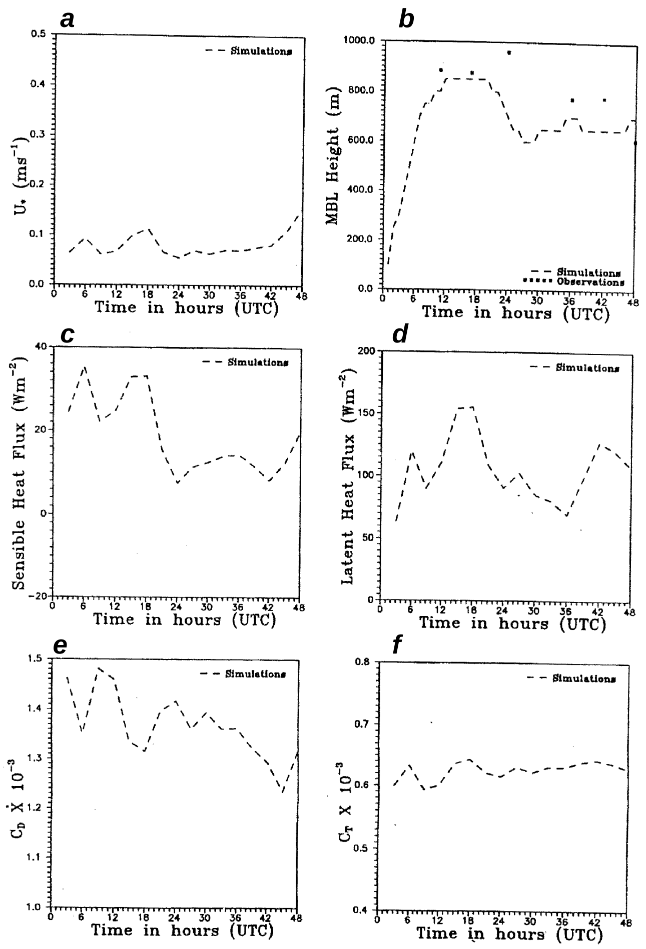

Figure 2. Diurnal variation of (***a***) U (m s^{-1}), (***b***) marine boundary layer height (m), (***c***) sensible heat flux (Wm^{-2}), (***d***) latent heat flux (Wm^{-2}), (***e***) C_D and (***f***) C_T during 24–26 February 1999.

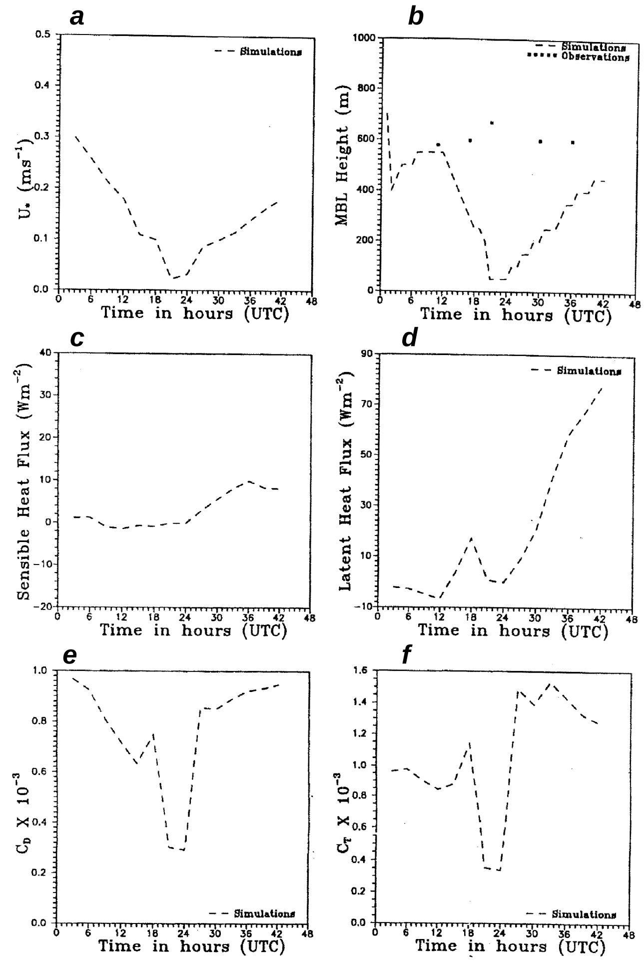

Figure 3. Diurnal variation of (***a***) U (m s^{-1}), (***b***) marine boundary layer height (m), (***c***) sensible heat flux (Wm^{-2}), (***d***) latent heat flux (Wm^{-2}), (***e***) C_D and (***f***) C_T during 11–13 March 1999.

general agreement with the relevant synoptic situation. The magnitudes of friction velocity, and the transfer coefficients are reasonable and in agreement with values reported in the literature for similar scenario (e.g. Stull[6]). Additionally all the variables, for all the three regimes, show distinct diurnal variation in the surface variables. Interestingly, Case 2 outcome has least diurnal amplitude. This damped diurnal variation for the near-coast (suppressed convection) regime is consistent with observations[7,8] and can be attributed to the influence of land masses affecting off shore circulation and mixing. The variations in the surface fluxes and momentum as well as heat transfer coefficients discussed above would directly modulate the MBL heights.

In the model, the MBL height is taken as the model level for which the turbulence ceases in the vertical for the TKE closure scheme. The MBL height variation is plotted with respect to simulation hours in UTC on the abscissa. For example for Case 1, the first hour of simulation corresponds to 00 UTC for 24 February 1999. Consistent with the sensible heat flux variation, Case 1 has maximum MBL heights, Case 2 has the lowest

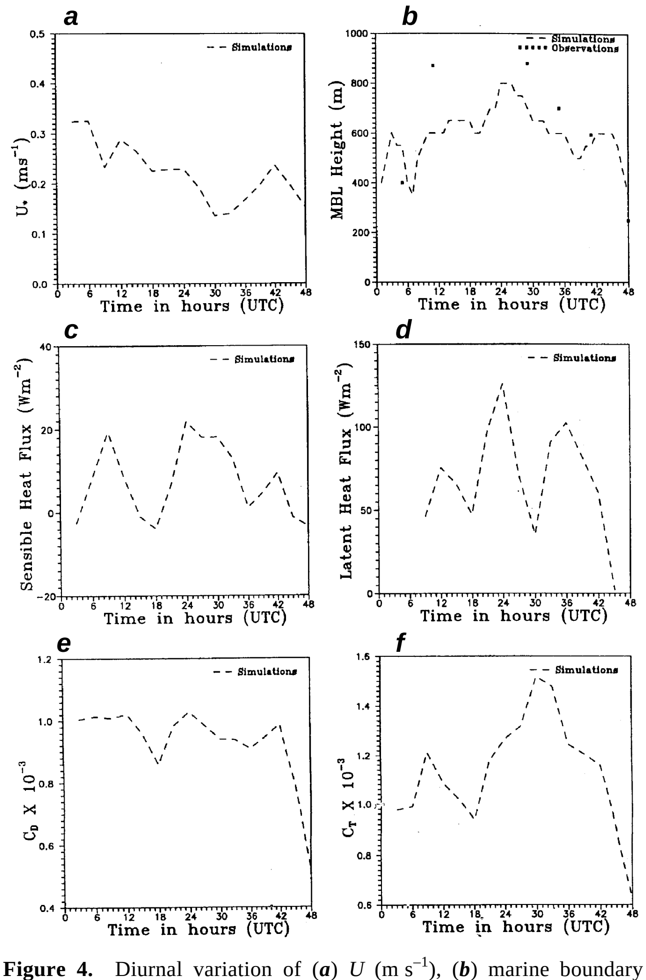

Figure 4. Diurnal variation of (***a***) U (m s^{-1}), (***b***) marine boundary layer height (m), (***c***) sensible heat flux (Wm^{-2}), (***d***) latent heat flux (Wm^{-2}), (***e***) C_D and (***f***) C_T during 20–22 March 1999.

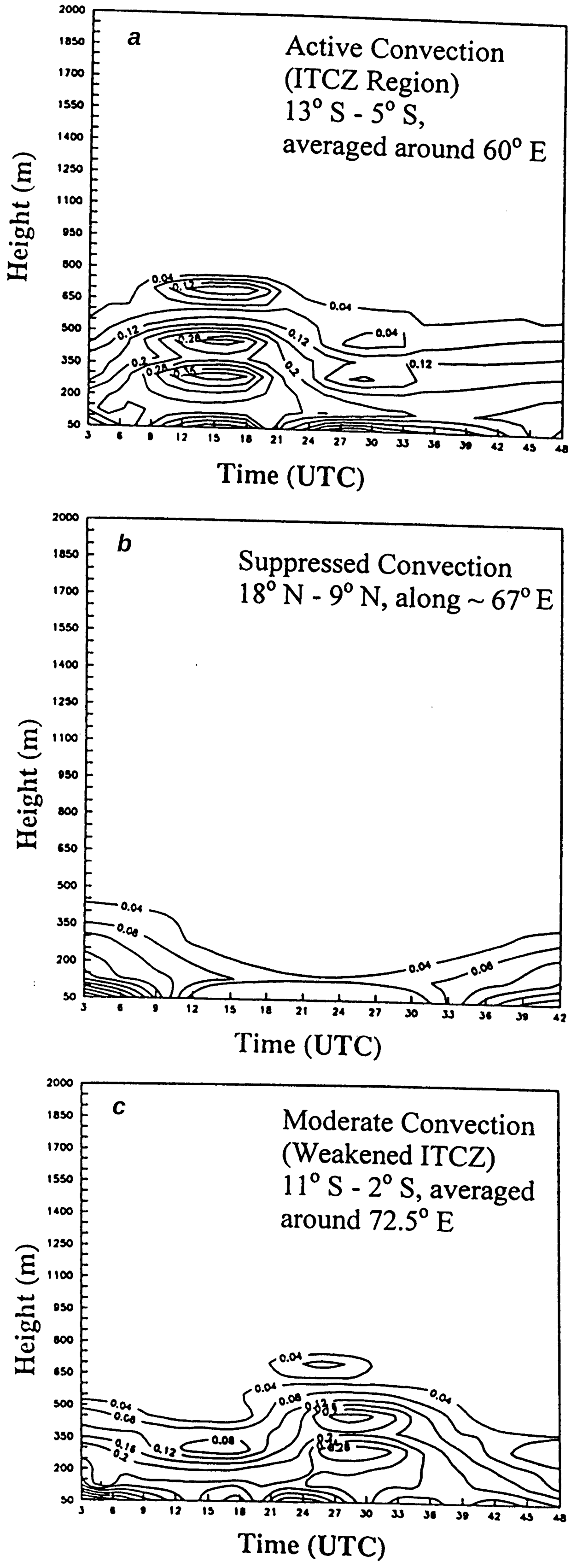

Figure 5. Time evolution of turbulent kinetic energy (m^2 s^{-2}) (***a***) 24–26 February 1999, (***b***) 11–13 March 1999 and (***c***) 20–22 March 1999.

MBL heights while Case 3 values are intermediate in the simulations. The peak daytime MBL heights for the different regimes are ~ 900 m for Case 1, about 550 m for Case 2, and ~ 800 m for Case 3. Unlike the surface variables, the MBL heights do not show any systematic diurnal variation. Corresponding to the model simulations, from the observations of potential temperature profiles, MBL height was also estimated[2]. The observed MBL heights are overlaid on the predicted MBL height curve. As can be seen, for Case 1, near ITCZ, and Case 3, in open ocean, there is a fair agreement between the 'observed' and the model predicted MBL heights. There is an overall agreement both in terms of the actual numeric value as well as temporal variation. However, there is some discrepancy between the observed MBL heights for Case 2 (Coastal case) and the corresponding model values. Typical observed MBL height for this case is of the order of 600 m while the predicted MBL height is averaged around 400 m. The MBL heights predicted in the model are directly related to the predicted sensible heat fluxes, while the 'observed' MBL heights (first significant inversion in the observed thermodynamic profile) can be influenced significantly by coastal circulation and advection. Hence the underestimation in modelled MBL height is attributed to the non-homogeneity of the coastal case which cannot be resolved in a 1-D simulation.

An important parameter the model provided that was not observed is the TKE variation. TKE is taken as a measure of turbulence intensity in the boundary layer and is responsible for various boundary layer processes such as entrainment, stability and effective transport under low wind conditions. Figure 5 *a–c* shows the TKE variation with time and height. As expected, Case 1 has the highest TKE values while the least values are associated with Case 2. Interestingly, for the 'high convection regime' (Case 1), maximum TKE values were predicted for the night-time. This could be due to the cooling of the air during night and the constant SSTs, leading to higher sensible heating and hence turbulence generation due to both buoyancy and shear. This is consistent with the observations reported by Warrior[2]. On the other hand, the suppressed convection regime (Case 2), an opposite scenario is evident with maximum TKE values in the daytime. Referring to the wind and surface thermodynamic fields (not shown), as well as the vertical wind profiles (discussed below), we conclude that the coastal case (Case 2) is windier, while Case 1 and Case 3 are low wind cases. Hence the Case 2 TKE can be mostly due to shear production and in the other two cases, sensible heating can add to the TKE production through buoyancy. Note that the SST-based buoyancy production does not show much diurnal variation and hence Case 1 and Case 3 results do not show much diurnal variability. On the other hand, shear-based TKE at coastal zone will be affected by the wind speeds. Owing to the land–sea interaction there would be a varying intensity of winds for the coastal case hence there is a maxima for the daytime and reduced TKE for the night (opposing buoyancy and shear).

Figures 6–8 show the model generated and the observed vertical profiles of zonal and meridional wind, potential temperature and specific humidity. Considering all the cases, the model-simulated winds are in fair agreement with the observations, the potential temperature profiles are in good agreement and the specific humidity fields are

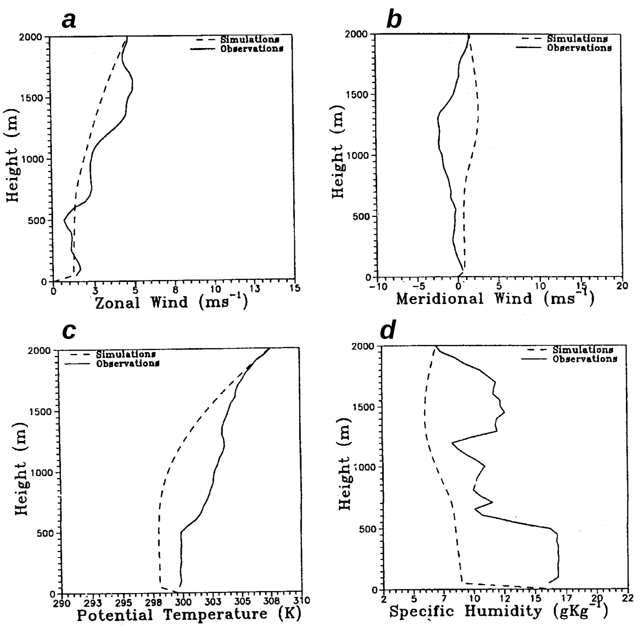

Figure 6. Vertical profiles of (***a***) zonal wind (m s^{-1}), (***b***) meridional wind (m s^{-1}), (***c***) potential temperature (K) and (***d***) specific humidity (g/kg) at 24th hour of simulation (23 UTC on 24 February 1999).

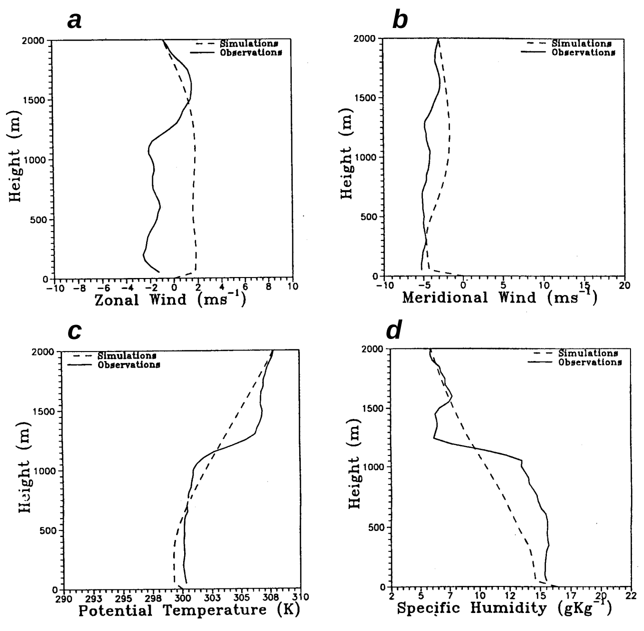

Figure 7. Vertical profiles of (***a***) zonal wind (m s^{-1}), (***b***) meridional wind (m s^{-1}), (***c***) potential temperature (K) and (***d***) specific humidity (g/kg^{-1}) at 36th hour of simulation (11 UTC on 12 March 1999).

Table 2. Statistical evaluation of the model performance in simulating the zonal wind (U, m s^{-1}), meridional wind (V, m s^{-1}), potential temperature (q, K) and specific humidity (q, g kg^{-1})

Simulation hours for Case 1/Case 2/Case 3	Variable	Case 1		Case 2		Case 3	
		RMS error	Corr. coeff.	RMS error	Corr. coeff.	RMS error	Corr. coeff.
12/12/12	U	1.23	0.87	2.91	0.42	2.32	0.86
	V	0.72	0.84	1.70	0.86	1.88	0.42
	q	3.93	0.95	0.67	0.98	0.22	0.98
	q	5.70	0.49	2.53	0.87	1.89	0.83
24/24/24	U	0.55	0.89	1.86	0.58	2.07	0.88
	V	2.20	– 0.20	5.84	0.44	2.11	0.24
	q	2.42	0.89	0.88	0.95	1.17	0.98
	q	4.74	0.54	1.20	0.94	1.51	0.93
36/36/36	U	2.77	0.35	2.36	– 0.44	3.43	0.88
	V	0.79	– 0.09	1.60	0.43	2.30	0.62
	q	2.10	0.83	0.85	0.96	0.00	0.99
	q	2.31	0.70	1.47	0.93	2.56	0.78
48/42/48	U	0.72	0.47	2.02	0.68	1.83	0.28
	V	1.08	0.79	0.89	0.39	2.87	0.78
	q	1.79	0.94	0.81	0.96	0.00	0.99
	q	1.97	0.85	1.32	0.93	0.94	0.95

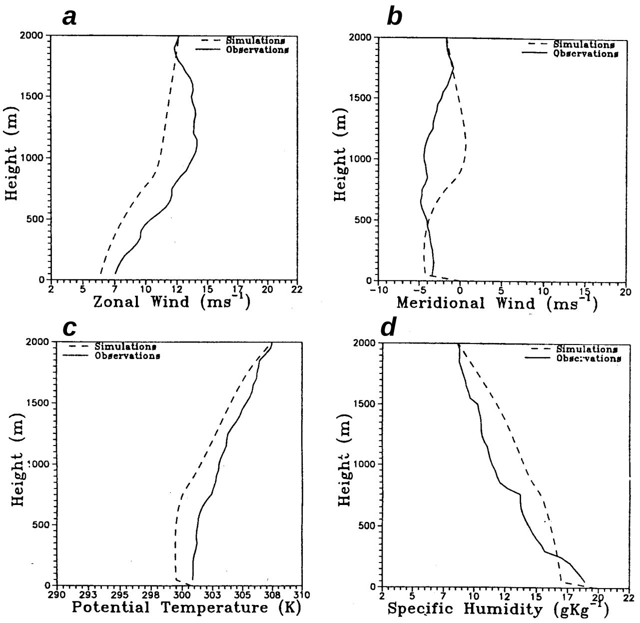

Figure 8. Vertical profiles of (***a***) zonal wind (m s^{-1}), (***b***) meridional wind (m s^{-1}), (***c***) potential temperature (K) and (***d***) specific humidity (g/kg^{-1}) at 24th hour of simulation (23 UTC on 20 March 1999).

significantly different. Although there are differences between the observed and modelled values, profiles themselves show a fair agreement. Indeed there would be limits for a 1-D model to simulate all the processes active for any given scenario due to non-homogeneity and advection. Hence there is a larger discrepancy between the simulations and observed values for regimes such as those near ITCZ. For the zones of active surface forcing such as Case 3 (intense convection) the profiles show better agreement. Thus, in general the model has been able to simulate the MBL processes in a fair manner.

To quantify the model's ability to replicate observations, a simple statistical evaluation is undertaken. The correlation coefficient and root mean square (RMS) error at different simulation hours for all the three cases are calculated and presented in Table 2. Much of the statistics is in agreement with the discussion above. The meridional winds are poorly simulated in the 1-D model. The RMS error of zonal and meridional wind components is found to be comparatively less for Case 1 than that for Case 2 and Case 3, whereas in the case of potential temperature and specific humidity it is comparatively less in Case 3.

Conclusions

A numerical marine boundary layer (MBL) model was successfully applied to simulate boundary layer features over tropical Indian Ocean during INDOEX 1999 field phase. From the observations, three distinct MBL regimes corresponding to three different convective zones (coastal, deep ocean and near ITCZ) were identified. The model was able to capture characteristic features of each of these regimes. The model was initialized using observed profiles and simulations over a period of two days were compared with the observations.

An MBL height of about 1000 m was predicted over the active convective regions close to ITCZ in agreement with the observations. However, near the coastal region, the model generally under predicted the MBL heights. This could be due to the dominance of advective processes in the coastal region, which the 1-D model cannot reproduce. As expected, the model could simulate the convectively dominant boundary layer structure better than the dynamically forced regimes. The model results also confirm the interdependence of the TKE and the MBL heights over the tropical ocean.

The model simulation of vertical profiles of potential temperature and specific humidity are found to be in good agreement with the observations. However, the model simulations of zonal and meridional wind show deviations. Thus the thermodynamic structure was better reproduced than the dynamical fields in the simulations. This suggests that in order to investigate the transport processes a 3-D model is required. However, the overall performance of the 1-D model is fairly promising. Such a model can be used as a tool over a data-sparse region along with available soundings to generate time-varying representative profiles. These simulated profiles can be used to enhance three-dimensional analysis, which in conjunction with a mesoscale model can be applied to study transport, trajectories as well as entrainment processes over a region. Additionally, such a validated model can be effectively linked to a 1-D ocean model to study the coupled response of the marine environment (such as SST and ocean mixed layer depth) with the boundary layer characteristics.

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