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Simulation on Some Aspect of Air-sea Interaction Parameters over Bay of Bengal (Indian Ocean) Using One-dimensional Numerical Model

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Abstract Air-sea interaction plays a dominant role in modulating the ocean-atmospheric circulation pattern and in bringing about changes in global weather and climatic systems. In the present paper a one-dimensional multi-level numerical planetary boundary layer (PBL) model with a TKE-ε closure scheme was applied to simulate the air-sea interaction parameters over northern part of Bay of Bengal (Indian Ocean). The oceanographic research ship observed high-resolution sounding data comprising of the vertical profiles of temperature, humidity, zonal and meridional component of wind was used as initial and boundary conditions to integrate the model. The temporal evolution of turbulent kinetic energy (TKE), marine boundary layer (MBL) height, sensible and latent heat fluxes are simulated for the duration of study. The model simulated vertical profiles of potential temperature, specific humidity, zonal and meridional wind compare reasonably well with the observations.

Keywords: *air-sea interaction, marine boundary layer (MBL) height, sensible and Latent heat fluxes, turbulent kinetic energy (TKE)*

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1. Introduction

Surface Ocean and lower atmosphere plays a dominant role in controlling the general circulation of the ocean and atmosphere in modulating the weather systems and global climatic pattern. A net input of heat and moisture from ocean into the atmosphere and the vertical structure of the MBL in the tropics and the subtropics depends on an interaction cycle of the air-sea energy and momentum exchanges as well as the vertical transport mechanism and large scale flow in different spatial and temporal scales as revealed by comprehensive heat and moisture budget studies in the North Atlantic, Pacific and Indian Ocean regimes [22]. The MBL are characterized with the development and sustenance of tropical disturbances through the exchanges and transport of heat and moisture that lead to the intraseasonal variability of the convection processes [17,31]. The frequency of such disturbances in the tropical Indian Ocean and Bay of Bengal (BOB) are relatively large and are assign to be their genesis in the warmer waters around the Indian subcontinent [20]. These disturbances play a crucial role in summer monsoon rainfall over Indian subcontinent; hence the modulating factors responsibly for their growth and development find special attention from the scientific community in order to link them with the variability of monsoon over India, since despite their economic and scientific importance there have been very few observational and modeling studies carried out over the BOB during the monsoon period [1]. In this context Monsoon Experiment over Bay of Bengal was conducted by scientific organizations of India during the monsoon months (July-August) of 1999 to understand the variability of convection over the BOB with the main objectives to understand the coupling between the atmosphere and the ocean and to monitor the development of convective systems of different spatial and temporal scales [1,11]; which proved a major thrusts in this field which enabled studies on the various aspects of air-sea coupling and monsoon systems that are linked with the variability of BOB characteristics on various time scale ranging from sub seasonal, interannual and decadal [5]. Major experiments conducted over the Bay prior to 1999, namely Monsoon experiment of 1977 (MONEX-77), Monsoon experiment of 1979 (MONEX-79) contribute significant insight in this field, though during these experimental programmes different phases of convection and monsoon systems could not be explained well due to the lack of adequate observational data sets. Subsequently, The Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA COARE) was executed in the west Pacific warm pool region to study the ocean-atmosphere coupling processes on intraseasonal time scale and to accurate estimate the air-sea fluxes [8,28]. The role of air–sea interaction for prediction of Australian summer monsoon rainfall has been studied by

[10] based on 25 years of hindcasts using the Predictive Ocean Atmosphere Model for Australia (POAMA) coupled model seasonal forecast system. [30] in their studies in the tropical western-central Pacific and the North Indian Ocean, found the CGCM-simulated evaporation–SST correlation opposite to that observed because of an excessive dependence of the sea–air humidity difference on the SST. Surface flux, wind profiler, oceanic temperature and salinity, and atmospheric moisture, cloud, and wind observations gathered from the R/V *Altair* during the North American Monsoon Experiment (NAME) are used extensively for air-sea parameters and marine surface boundary layer studies in the Gulf of California region by [18,32] studied the impact of coupled air–sea feedbacks on the simulation of tropical intraseasonal variability using the National Centers for Environmental Prediction Climate Forecast System. [6] have investigated the air-sea interaction processes and the mechanisms that give rise to and sustain the Tropical Indian Ocean (TIO) warming after El Nino by using atmospheric reanalyzes, satellite measurements, and ocean and atmospheric GCM simulations. [12] have investigated the effects of air-sea interaction on the simulated East Asian summer monsoon (EASM) climate in a regional climate model and advocated that the methodology designed in this study can be an efficient way to represent the air-sea interaction in regional atmospheric models for numerical weather prediction and climate simulation. A long-term simulation of a hybrid coupled model (HCM) is conducted to study the role of air-sea interaction over the Indian Ocean in the in-phase transition from the Indian summer monsoon to the Australian boreal winter monsoon [2] .The Joint Air-Sea Monsoon Interaction Experiment (JASMINE) was carried out in 1999 over the tropical Indian Ocean with intraseasonal variability of the south Asian monsoon as a major focus [29]. The extensive studies on the processes of convective activity and rainfall characteristics over the southeast Arabian Sea (off shore Goa) and coastal station Goa have been carried out during Arabian Sea Monsoon Experiment-I (ARMEX-I) [1,15,20].

However, very few studies have been made to illustrate the MBL characteristics relating air-sea interaction processes and the role of surface fluxes in influencing its variability during different weather conditions over BOB due to the paucity of data. Therefore, it warrant to study the air-sea interaction parameters in terms of the exchanges of turbulent fluxes across the boundary layer, its height, and thermal stratification of the atmosphere over the region in order to understand with well the mode of convective processes in the study regimes.

In this paper an attempt has been made to analyze the air-sea interaction parameters over the ocean surfaces (Bay of Bengal, Indian Ocean) during the month of August 1999, using 1-D numerical model with the objectives to address the factors responsible for the variability of air-sea interaction parameters viz. the surface fluxes and height of BL. The analysis further provides insights into the temporal evolution of turbulent kinetic energy (TKE) and the contribution due to shear and buoyancy under varied synoptic situation during the study period. At a same time, as the secondary objectives of the study is to validate the model using the available observations (vertical profiles of winds, temperature and humidity) during the study period. These are presented in the result and discussion section. Such studies using numerical models are utmost importance in tropical oceanic regions in changing global climatic for better understanding the characteristics of dynamical and thermodnamical parameters during monsoons.

2. The Data Sets Used and the Synoptic Situations During the Study Period

Meteorological data utilized in this study are 6-hourly (00, 06, 12 and 18 UTC) observed data sets for the month of August 1999. These upper air sounding and surface data sets are obtained from research cruise ship (Cruise No. SK-147B) named Oceanic Research Vessel (ORV) Sagar Kanya over the northwestern part of Bay of Bengal (Indian Ocean).

The high-resolution soundings data comprising profiles of temperature, humidity, zonal and meridional winds were obtained using GPS sonde system from surface (~10 m) to ~15 Km (vertical). Surface data corresponding to radiosonde launches are used in the model as described subsequently. Additional data comprised surface meteorological variables including sea surface temperature (SST). As the objective of the present study is MBL characteristics (air-sea parameters), focus have been given on the first 2 Km in the vertical with the duration of study chosen from 23rd August to 26th August 1999 during which the suppressed to active convective situations were marked based on the surface synoptic observations taken onboard ORV Sagar Kanya, Indian Daily Weather Reports (IDWR's), National Centre for Environmental Prediction/ National Centre for Atmospheric Research (NCEP/NCAR) reanalysis Outgoing Longwave Radiation (OLR) and Meteosat-5 (Meteosat Transition Programme (MTP) product family, level 1.5) cloud imageries. The MTP was the EUMETSAT programme responsible for the Meteosat system of geostationary meteorological satellites. Detailed synoptic conditions prevailed during the study period are presented by [11,24].

During 23rd to 26th August, 1999 ORV Sagar Kanya cruised between position (17.59°N and 88.84°E) and (15.5°N, 88.0°E). Two significant cloud masses were noticed covering the Maldives around (0- 6.5°N, 70-85°E) and the other over south Andaman Sea and adjoining southeast BOB between latitude 5-11°N and longitude 90-102°E during 23-24th August 1999. During this period Sagar Kanya cruised through a relatively cloud free zone as revealed by INSAT satellite imageries (Figure. not shown) (Sam et al., 2003) and Meteosat-5 (MTP product, level 1.5) satellite imageries Figure 1 (http://www.eumetsat.int). The observed wind speeds were of the order of 4 ms$^{-1.}$ The National Centre for Medium Range Weather Forecasting (NCMRWF) 850 hpa wind analysis show weak circulation pattern in the north of head Bay region, that lay out side the cruise track of the ship which could not influence the wind stress induced convective systems to be developed [15]. On 25th August 1999, a low-pressure area over west central Bay off north coastal Andhra Pradesh was noticed. Meteosat-5 (MTP product, level 1.5) imageries at 12 UTC Figure 1a-d indicates the convection in the west central and southwest Bay west of 85°E and growth in convective activity were noticed on 26th August 1999 Figure 1d. [11]

has reported that a low pressure system moved northward and lay over northwest and adjoining west central Bay on 26-27th August, 1999. Again, 850 hpa NCMRWF wind analysis reveal the northward advance of strong wind zone during this period and observed wind speeds were of the order of 20ms^{-1}. The NCEP/NCAR reanalysis daily OLR from 23rd to 26th August, 1999 produced by Physical Sciences Division (PSD) of Earth System Research Laboratory (ESRL)/National Oceanic and Atmospheric Administration (NOAA), USA is shown in Figure 2(a-d) (http://www.cdc.noaa.gov). It is evident from the Figure 2a that OLR is ~270 Wm^{-2} on 23rd August 1999 and it is ~140 Wm^{-2} on 26th August, 1999 Figure 2d. If carefully noticed, Figure 2(a-d) from 23rd to 26th August, 1999, we see that values of OLR are in decreasing order (from 23rd to 26th August, 1999) indicating the growth of active convectivity. Low OLR values are often associated with the deep convection [9] presented the details of daily OLR pattern during this period. During 23-26 August, 1999. Point in the imageries show the approximate ship position which was positioned approximately between 17.59°E, 88.54°N and 15.5°N, 88.0°E during the study period.

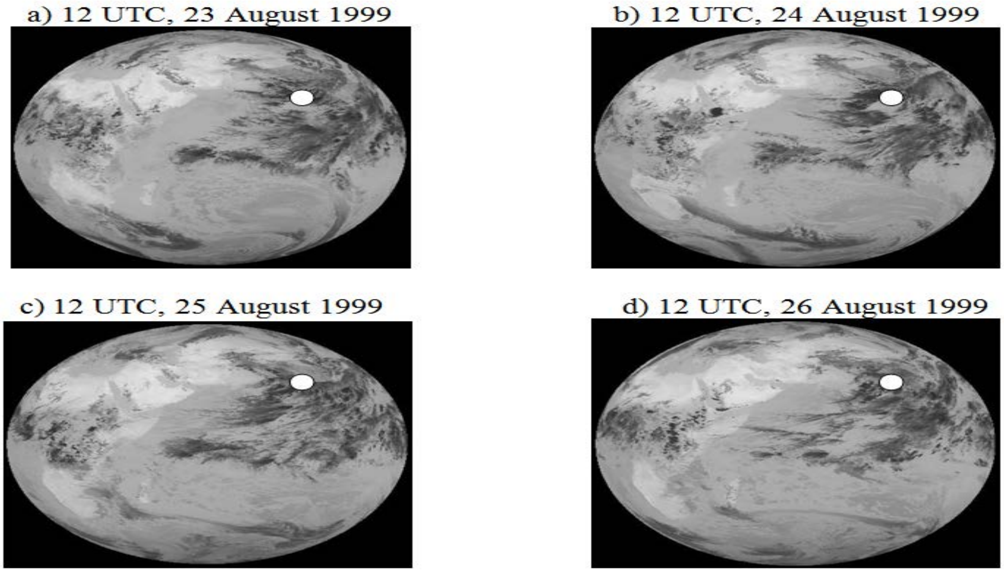

Figure 1. (a-d): METEOSAT-5 (MTP product) cloud imageries (1.5 levels) at 12 UTC

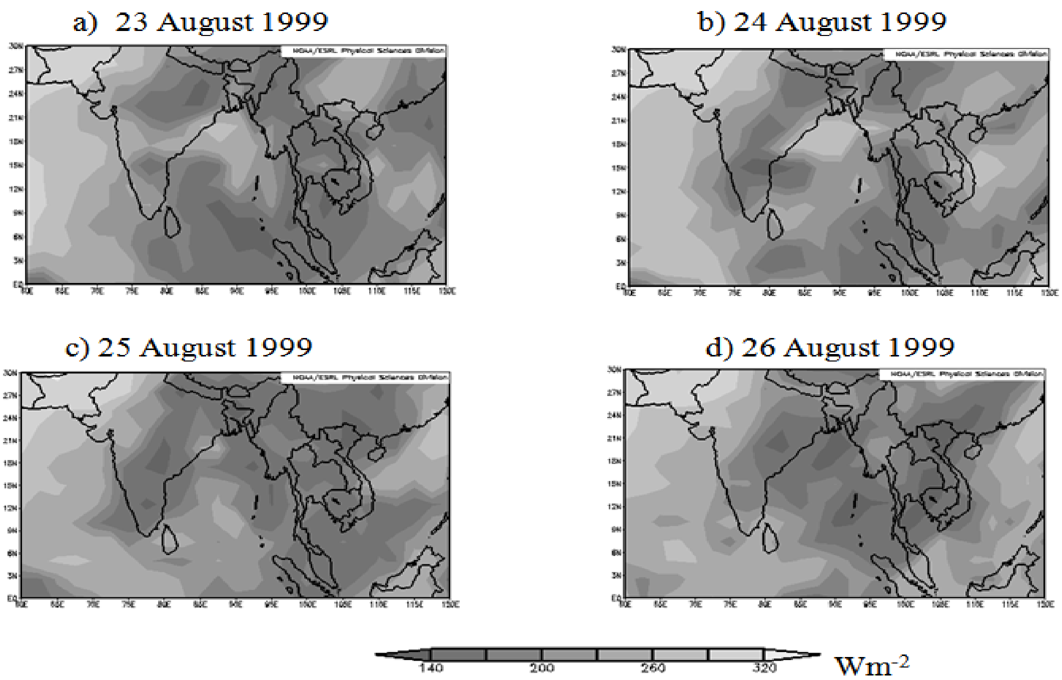

Figure 2. (a-d): Daily outgoing long wave radiation (OLR) during 23 - 26 August, 1999

3. Model and Experimental Setup (Initial and Boundary Conditions)

Model used in this study is a multi-level 1-D numerical 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 Land surface. [3,4,14,16,21,22,23], give details of the model. A brief overview of the model is presented in Table 1.

Table 1. Overview of the model

Model Description	One Dimensional PBL model with one and half order TKE closure scheme
Vertical Domain	2000 m
Vertical Levels	40 and ΔZ=50 m
Independent Variables	Z, t
Prognostic Variables	U, V, θ, q, E, ε, qw,
Diagnostic Variables	K_u, l
Numerical Scheme	Second order accuracy
Time Integration	Implicit, Δt=600 sec
Boundary Conditions	• Lower Boundary: Monin - Obukhovsimilarity theory • Upper Boundary: The Geostrophic conditions; Observed values at 2000m • TKE and ε: 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

In a Cartesian co-ordinate system, where the horizontal axes x and y are directed in the east and north, respectively, and the vertical axis z is directed upwards, the model solves the following equations

$$\frac{\partial u}{\partial t}=-\frac{\partial \overline{u'w'}}{\partial z}+fv+\tilde{p}_x/\tilde{\rho} \quad (1)$$

$$\frac{\partial v}{\partial t}=-\frac{\partial \overline{v'w'}}{\partial z}-fu-\tilde{p}_y/\tilde{\rho} \quad (2)$$

$$\frac{\partial \theta}{\partial t}+u\tilde{\theta}_x+v\tilde{\theta}_y=-\frac{\partial \overline{\theta'w'}}{\partial z}+Q_r+Q_f \quad (3)$$

$$\frac{\partial q}{\partial t}+u\tilde{q}_x+v\tilde{q}_y=-\frac{\partial \overline{q'w'}}{\partial z}+E_p-C \quad (4)$$

$$\frac{\partial q_w}{\partial t}+u\tilde{q}_{wx}+v\tilde{q}_{wy}=-\frac{\partial \overline{q_w'w'}}{\partial z}-E_p+C-P \quad (5)$$

$$\frac{\partial E}{\partial t}=(-\overline{u'w'}\frac{\partial u}{\partial z}+\overline{v'w'}\frac{\partial v}{\partial z}+\frac{g}{\rho}\overline{\rho'w'}+\varepsilon)-\frac{\partial \overline{w'\varepsilon'}}{\partial z} \quad (6)$$

$$\frac{\partial \varepsilon}{\partial t}=-C_1\frac{\varepsilon}{b}(-\overline{u'w'}\frac{\partial u}{\partial z}+\overline{v'w'}\frac{\partial v}{\partial z}+\frac{g}{\rho}\overline{\rho'w'}+\varepsilon)-\frac{\partial \overline{w'\varepsilon'}}{\partial z} \quad (7)$$

Where

u, v and w = x, y and z components of the wind velocity respectively,

θ = the potential temperature,

q = the specific humidity,

q_w = the specific liquid-water content,

E = the turbulent kinetic energy,

ε = the dissipation,

ρ = the density of the air-water-water vapour mixture,

$(\tilde{p}_x,\tilde{p}_y),(\tilde{\theta}_x,\tilde{\theta}_y),(\tilde{q}_x,\tilde{q}_y),(\tilde{q}_{wx},\tilde{q}_{wy})$ = components of horizontal gradients of the pressure, potential temperature, specific humidity and specific liquid-water content in the free atmosphere respectively,

fv, fu = coriolis forces in the x and y-directions, respectively

Q_r , Q_f = the rates of the heat change due to radiation and phase transitions of the water respectively,

C , E_p = the rates of phase changes, viz. water vapour to liquid water and water to water vapour respectively,

P = the precipitation rate,

$\rho\overline{u'w'}, \rho\overline{v'w'}, \rho\overline{\theta'w'}, \rho\overline{q'w'}$ and $\rho\overline{q_w'w'}$ = the vertical turbulent fluxes of momentum, heat, water vapour and liquid water respectively,

f = the coriolis parameter,

g = the acceleration due to gravity, and

C_1 and b are the constants.

In order to calculate vertical turbulent fluxes of momentum, heat and moisture in the interfacial layer, the Bousssinesq hypothesis is used:

$$\overline{a'w'}=K_a\frac{\partial a}{\partial z}, \quad (8)$$

Where a is any of the prognostic variables u, v, θ, q and q_w, and K_a is the eddy exchange coefficient. It is assumed that $K_a=\alpha_a K$, where, α_a 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 ε following [13] equation

$$K=\frac{C_k E^2}{\varepsilon} \quad (9)$$

where, C_k is a dimensionless constant.

The model initial and boundary conditions are prepared from the data comprising of high-resolution observational data obtained over north BOB using GPS sonde. The high-resolution upper air data consisting of zonal and meridional wind components, potential temperature and specific humidity are linearly interpolated to obtain the initial values at the model grid points. 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 (as shown in Figure 3, mean for four days (00 UTC 23 - 00 UTC 27, August, 1999) observed profiles, 6-hourly at 00, 06, 12 and 18 UTC). The maximum height of the turbulent boundary layer (top of the PBL) is chosen as the upper boundary. The MBL height is taken as the height where turbulence ceases to exist. 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. Surface observations obtained at the same location are used for preparing the lower boundary conditions. Climatological ozone data are prescribed for radiation parameterization scheme. For the model simulation from 00 UTC of 23^{rd} August to 12 UTC of 26^{th} August, 1999, initial conditions are prepared from the observations at 00 UTC of 23^{rd} August 1999 and the model was integrated for 84h (23-26 August, 1999), which includes both the suppress as well as transition phases (tending towards convectively active phase).The time step of integration of the model is 600 sec. and hourly simulation output of the model during the combined episode (transitioning from suppress to active) are stored for analysis and comparison with the observations. In earlier studies [20] model integration was performed separately for 48h, 48h and 42h respectively by considering the cases of active (13-15 August., 1999), suppress (22-24 August, 1999) and transition (24-26 August., 1999) phases, and results have also been presented separately for each episodes, however they have not performed a model integration for combined episode (which captures suppress to transition phases).

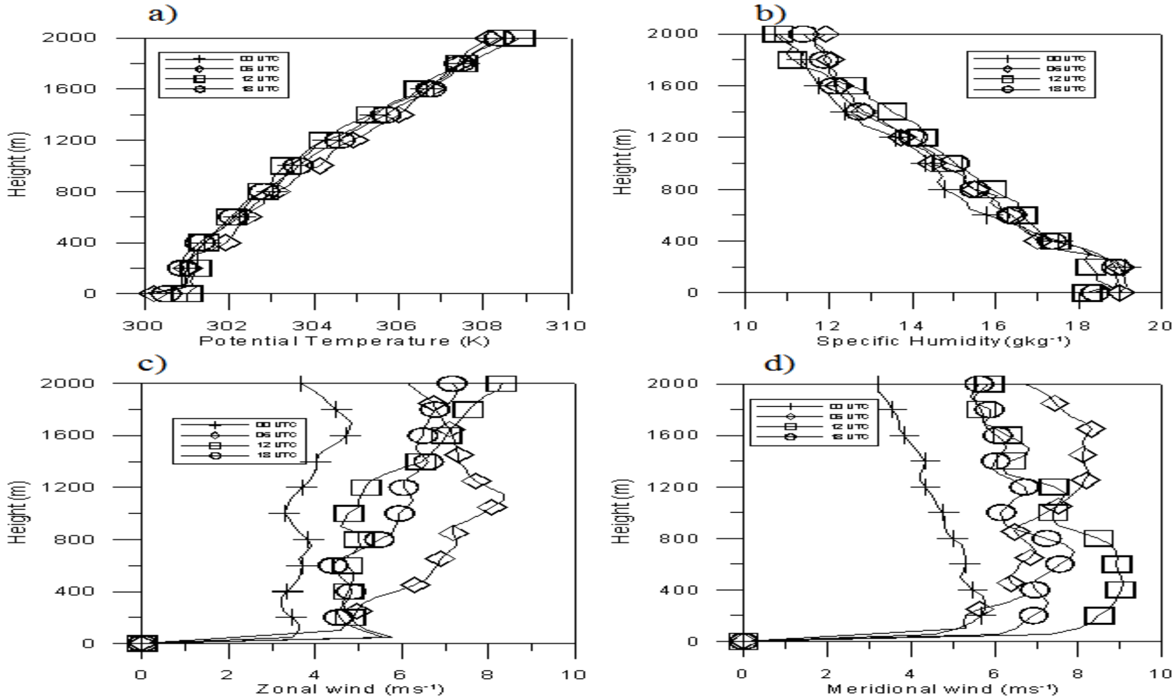

Figure 3. Four-day (00 UTC 23, August – 00 UTC 27, August, 1999) mean profiles at 00, 06, 12 and 18 UTC of a) Potential temperature, b) Specific humidity, c) Zonal wind and d) Meridional wind. On the basis of these observations, profiles were chosen for model initialization

4. Results and Discussion

The results consist of the simulations of the diurnal variation of the fluxes of sensible heat (H) and latent heat (LE), marine boundary layer (MBL) height, and the evolution of the turbulent kinetic energy (TKE) during the study period. The 1-D model simulated vertical profiles of zonal (u) and meridional (v) wind components, potential temperature (θ) and specific humidity (q) over BOB are also presented here. The observed profiles of u and v wind components, θ and q were linearly interpolated in the vertical and the resultant values (at every 50 m interval up to 2000 m) are used for comparison with model outputs. These model outputs are used for comparison with observations wherever available.

Air-sea interaction parameters (Sensible heat fluxes, Latent heat fluxes, Height of boundary layer over ocean and TKE)

The diurnal variation of the model simulated surface fluxes of H and LE are presented in Figure 4(a-b). H and LE show prompt diurnal variation during the study period. It is noticed from the Figure 4a that during the first 42h of integration (i.e., from 00 UTC of 23rd August 1999 to 18 UTC of 24th August 1999), H has lower in values when the suppressed convection process was encountered after that peak value of H has been simulated at ~06 UTC of 25th August, 1999 amounting to ~67 Wm^{-2} , indicating the growth of active convective activity. It has the lower values of ~13.36 Wm^{-2} at ~00 UTC of 26th August 1999 and then again sudden rise in H is noticed at ~06 UTC of 26th August 1999. The lower values of H during weak convection period whereas, higher values during the active convection period were also reported by [1] and [20] in their studies in the Bay.

LE showed higher values (~152.76 Wm^{-2}) at ~00 UTC of 23rd August 1999 and then it is in decreasing spree up to the 18 UTC of 23rd August 1999 attaining a lower value amounting to ~19.29 Wm^{-2}. LE is ~72.52 Wm^{-2} at 00 UTC of 24th August 1999 and then again it is in decreasing spree up to 18 UTC of 24th August 1999 with a simulated lower values of ~ -7.52 Wm^{-2} during weak convection situation. Then again LE shows sudden rise with a maximum value of ~239 Wm^{-2} at ~12 UTC of 25th August 1999. LE tends to follow the similar trend as that of H between ~48h to ~72h of integration (i.e., 00 UTC 25 - 00 UTC 26/August, 1999), however, at 06 UTC of 26th August 1999, it shows the lower values amounting to ~68.8 Wm^{-2} , Figure 4b.

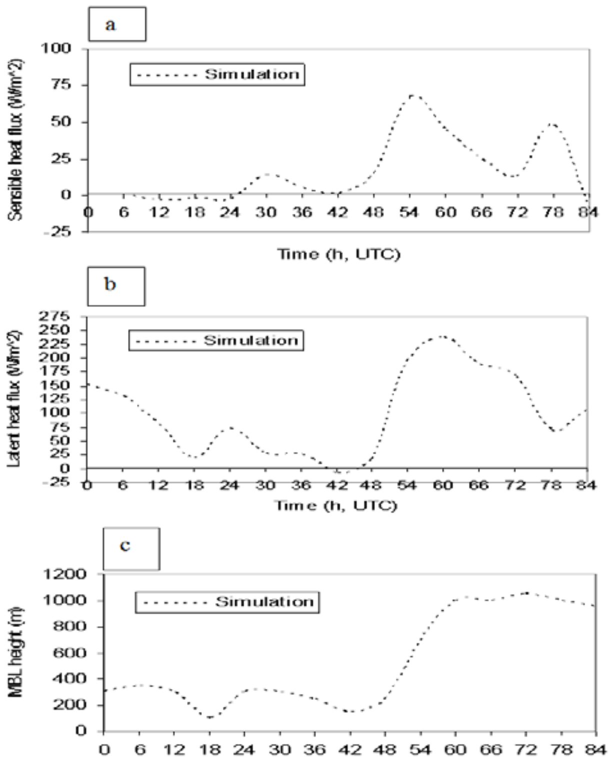

Figure 4. Diurnal variation of a) Sensible heat flux (H), b) Latent heat flux (LE) and c) Marine boundary layer (MBL) height during 00 UTC, 23 August to 12 UTC, 26 August, 1999.

Both the H and LE show higher values between 12-18 UTC of 25th August 1999 when the active spell of convection was exist. Although, amplitude of H remains relatively small; the LE, however, is seen to be a strong function of convective activity [25]. Thus simulated surface fluxes are in general agreement with the relevant synoptic conditions representing weak and active convective processes during the study period.

The surface fluxes simulated in the boundary layer greatly modulate the MBL height. 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 Figure 4(c) shown is simulated MBL height vs time (UTC) plot. During the first 42h (00 UTC of 23rd August 1999 to 18 UTC of 24th August 1999) of integration as the H values are lower the MBL height also has the lower height (avg. ~255.5 m).The higher MBL height ~1050 m is simulated at ~60h (~12 UTC of 25th August 1999) of integration as the atmosphere begin to be convectively active. However, MBL height variation is not as systematic as the surface variables. There is some discrepancy in the variation of MBL height with surface fluxes. This could be due to the influence of lower surface winds and hence advection which 1-D model could not able to resolve.

TKE variation in the lower layer of the atmosphere plays a dominant role. 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 (Satyanarayana et al., 2001). Figure 5a shows the evolution of the TKE with time during the study period (00 UTC, 23 August – 12 UTC, 26 August, 1999). The TKE simulations (1-D) could capture the highly turbulent boundary layer rising to a height ~1000 m with maximum TKE value of ~0.89 m^2s^{-2} (~15 UTC of 25th August 1999), predicted during nighttime. This could be due to high sensible heating (due to cooling of the air after sunset, while SST being constant) and hence generation of turbulence. TKE has the higher values during the growth of convective activity (higher MBL height) as compared to suppressed convection period (little mixing resulting in minimum MBL height) (00 UTC of 23rd August 1999 to 18 UTC of 24th August 1999), as expected. This is consistent with the relevant synoptic situation. Shear term represents the interaction of the turbulent momentum flux with mean vertical wind shear that generates turbulence. If carefully noticed Figure 5b, this term is very large (~1.2 m^2s^{-1}) during ~12 UTC of 26th August 1999. This term is obviously going to be larger on windy conditions (larger vertical shear). Maximum buoyancy contribution ~1.1 m^2s^{-1} was simulated at ~12-15 UTC of 25th August 1999 Figure 5c. However, between 00 UTC of 23rd August 1999 to 18 UTC of 24th August 1999, owing to clear and calm atmosphere and low surface winds, a reduction in the evolution of TKE is noticed. Similar is the case for shear and buoyancy contribution. That is, the mechanical generations as well as the buoyancy production Figure 5b & 5c too are very small in the vertical. The static stability (an air parcel displaced vertically by turbulence would experience a buoyancy force pushing it back towards its starting height) suppresses the TKE. The variability of TKE evolutions are greatly influenced by the wind condition and shear production, though the sensible heating can add to the TKE through buoyancy, which is comparatively lower than shear production for TKE generation [20].

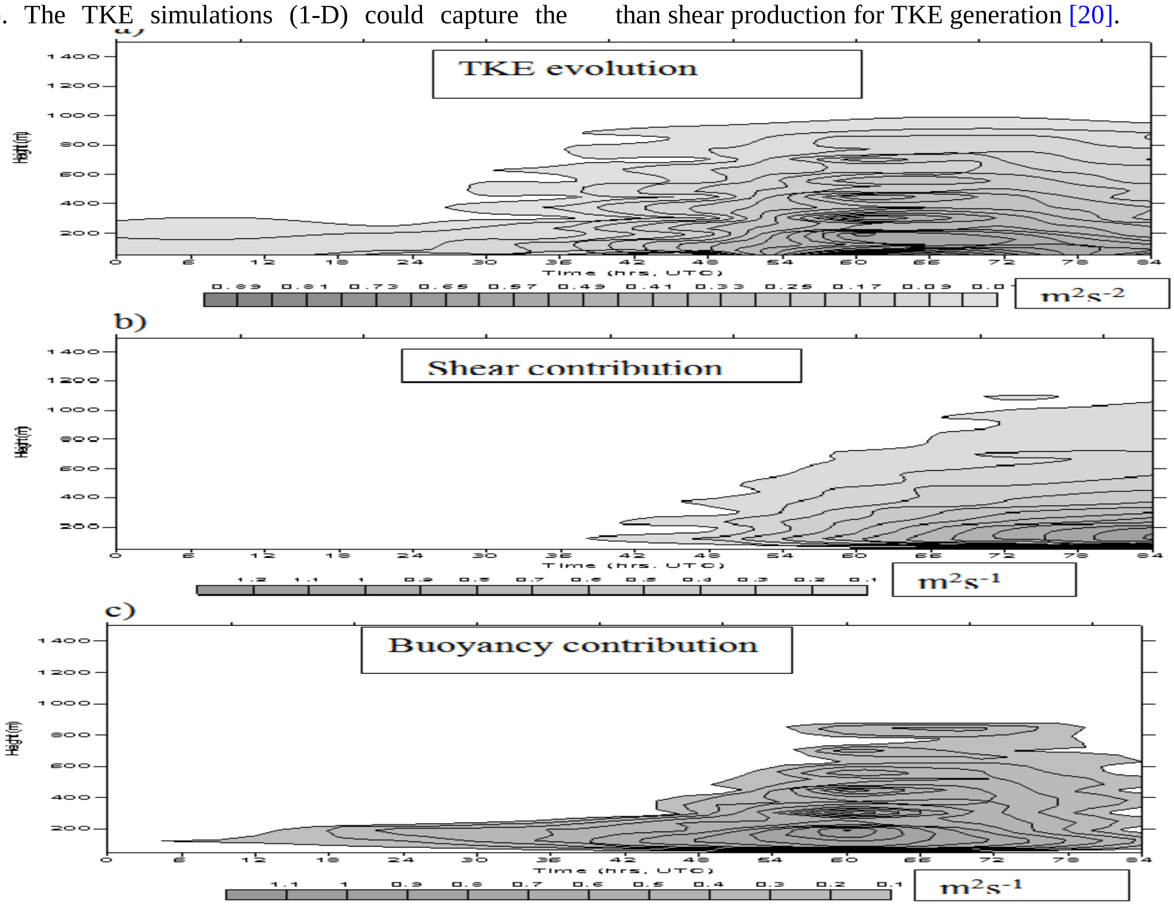

Figure 5. Time evolution of a) Turbulent kinetic energy (TKE), b) Shear contribution and c) Buoyancy contribution during 00 UTC, 23 August to 12 UTC, 26 August, 1999

4.1. Model Validation

Figure 6(a-z) & Figure 6(a1-b1) represent the 1-D simulation of u, v, θ and q profiles for the period (00 UTC 23 - 00 UTC 26, August, 1999). Although hourly simulations are available, only representative profiles are shown for which observations are available. The simulations given in Figure 6(a-z) & Figure 6(a1-b1) are at 12 UTC (23 August, 1999), 00 UTC (24 August, 1999), 12 UTC (24 August, 1999), 00 UTC (25 August, 1999), 12 UTC (25 August, 1999), 00 UTC (26 August, 1999) and 12 UTC (26 August, 1999). They correspond to 12h, 24h, 36h, 48h, 60h, 72h and 84h of simulations, with initial values at 00 UTC of 23rd August 1999.

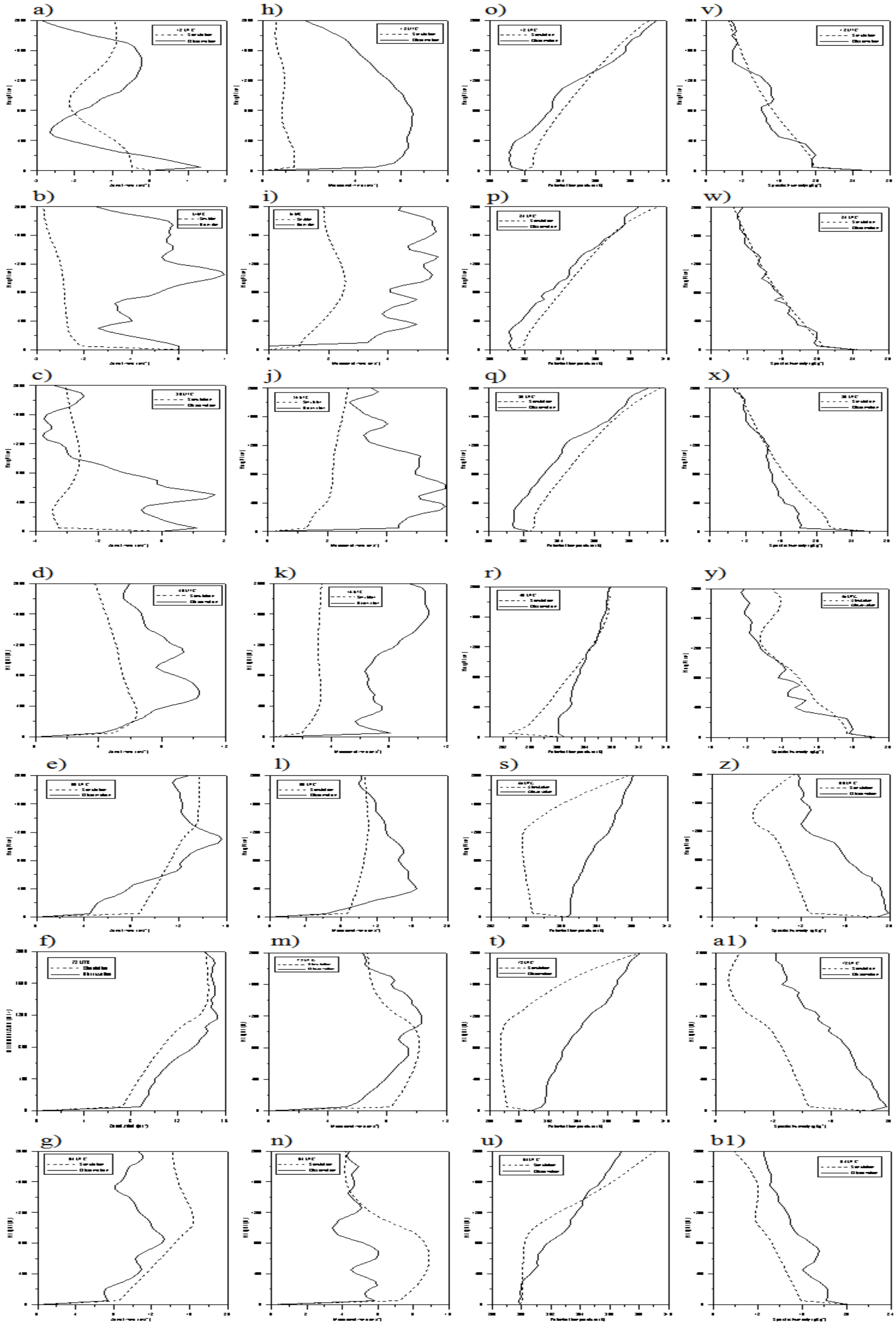

Figure 6. Vertical profiles of simulated and observed zonal wind(u) (Figures.(a-g)), meridional wind(v)(Figures.(h-n)), potential temperature(ɵ) (Figures.(o-u)) and specific humidity (q)(Figures.(v-b1)) for different representative hours of simulations

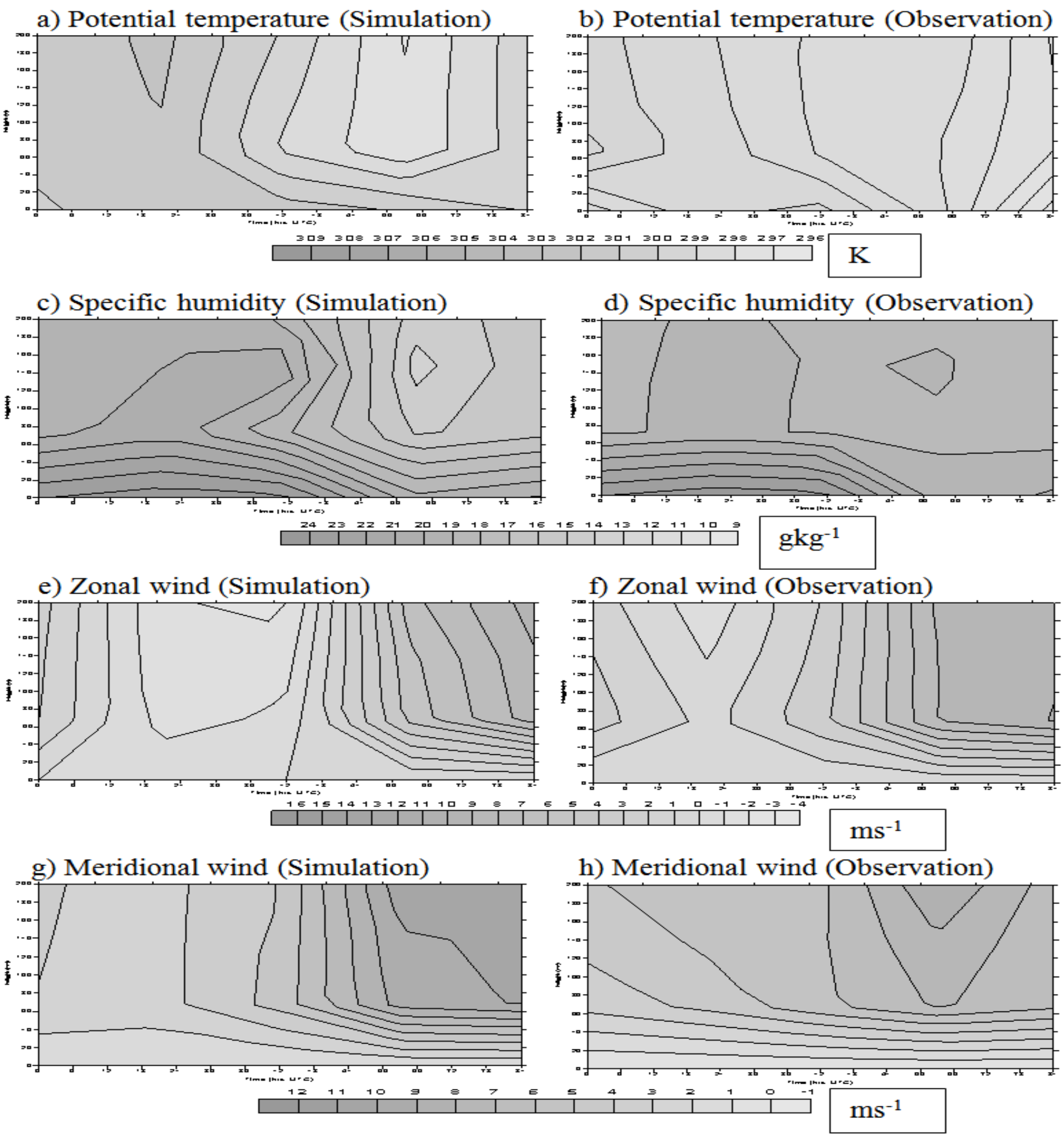

Figure 7. Contour plot of simulated and observed potential temperature, Figures (a-b), specific humidity, Figures (c-d), zonal wind, Figures (e-f) and meridional wind, Figures (g-h)

Considering a general overview of the simulation, it is clear from the Figure 6(a-z) & 6(a1-b1) that almost all the profiles of basic meteorological fields at different hours of simulation, compare well with the observed profiles irrespective of the large variation observed in the synoptic conditions prevailed during the study period. It is noticed from simulation between 12h (12 UTC of 23rd August 1999) to 48h (00 UTC of 25th August 1999) that, u and v components of wind show some deviations from the observations, Figure 6(a-n). 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 non-inclusion of advection. Although, the u and v wind components show few aberrations from the observations, the nature of variation of these fields is almost similar. Figure 6(o-z) & 6(a1-b1) reveal that the simulated θ and q profiles are in good agreement with observations during the study period of varied synoptic situations. However, a maximum difference of ~8.5 K in θ and ~6-7 gkg^{-1} in q during 60h (12 UTC of 25th August 1999) and ~5 K in θ and ~5 gkg^{-1} in q during 72h (00 UTC of 26th August 1999) of simulations respectively are noticed. It is evident from the Figures. that simulated profiles of all the basic meteorological fields are in good agreement with observations though the quantitative values are different. This is reflected in the height vs time (UTC) contour plot as shown in Figure 7(a-h) also for both the thermodynamical and dynamical fields that compare simulations with observations at the lower 200m in the vertical in the marine boundary layer.

5. Statistical Analysis

A simple statistical analysis of the model performance in simulating u, v, θ and q during the study periods is undertaken to quantify the model's ability to replicate observations. The correlation coefficient and root mean square (RMS) error of the model in the simulations of u and v components of wind, θ and q at different simulation hours with respect to observations are computed and presented in Table 2.

Table 2. Statistical evaluation of the model performance in simulating the zonal wind (u, ms^{-1}), meridional wind (v, ms^{-1}), potential temperature (ɵ, K) and specific humidity (q, g kg^{-1})

Simulation hour	u		v		ϴ		q	
	RMS Error	Cor. Coeff.	RMS Error	Cor. Coeff.	RMS Error	Cor. Coeff.	RMS Error	Cor. Coeff.
12	0.12	0.31	4.18	0.74	0.43	0.99	0.19	0.96
24	1.94	0.08	2.54	0.73	0.60	0.99	0.17	0.99
36	1.13	-0.16	2.16	0.05	0.94	0.99	1.24	0.96
48	2.35	0.77	5.03	0.64	1.29	0.97	3.35	0.24
60	0.72	0.81	2.38	0.66	6.08	0.69	4.85	0.74
72	1.30	0.96	0.22	0.69	3.55	0.84	4.27	0.92
84	3.46	0.77	1.68	0.59	0.25	0.93	2.38	0.92

Much of the statistics is in agreement with the discussion above. Simulated u and v components are failry correlated with observations, though u component show large deviations at 48h (00 UTC of 25th August 1999) and 84h (12 UTC of 26th August 1999) simulations with RMS error of the order of 2.35 and 3.46 respectively, correlation coefficient being 0.77. Whereas, v component has maximum RMS error (5.03) at 48h (00 UTC of 25th August 1999) simulation. At 12h (12 UTC of 23rd August 1999) simulation also the order of RMS error for v wind was 4.18. The RMS error of u component of wind was found to be comparatively less than v component of wind. Simulated profiles of θ and q show reasonably good agreement with the observations barring at 60h (12 UTC of 25th August 1999) simulation where, θ and q both show comparatively large deviation. These deviations may be attributed to the limitation of the 1-D model that has not been able to capture some of the sudden fluctuations in the atmosphere. However, in general the model is able to simulate various air-sea interaction parameters and MBL processes fairly well.

6. Conclusions

A multi-level 1-D PBL model was applied during the observational programme Monsoon experiment of Bay of Bengal (1999), under varied synoptic situations. The model was able to capture the main characteristics features during the study period.

Following broad conclusions could be drawn from the results of the numerical simulations.

Higher values of H and LE are noticed during the growth of convectively active situation (60h of integration) compared to the first 42h of integration when the non-active convection condition was prevailed. MBL height over the ocean surface does not show much diurnal variation; however, an MBL height of 1050 m (maximum) is predicted. The growth in the MBL and the rise in surface fluxes during the study period determine the dynamics and thermodynamical character of the convection processes. No specific diurnal variation of TKE is observed. The interdependence of the TKE and MBL height is also confirmed from the model results. The 1-D simulation of surface fluxes, the MBL height and the TKE correlate well with the prevailing synoptic conditions during the study period.

The 1-D model simulation of vertical profiles of θ and q are found to be in good agreement with the observations as a validation of the high-resolution upper air data, obtained during the study period. However, the model simulations of u and v wind show deviations depicting that the thermodynamic structure of MBL was better reproduced than the dynamical fields in the simulation. Therefore for a better simulation of the boundary layer using a 1-D model, it is important to have the advection terms incorporated in a proper manner. However, the overall performance of the 1-D model is fairly promising. It can be noted therefore that such a model with refinement can be used as a tool in data-sparse regions along with available soundings to generate time-varying representative profiles that are comparable with the observations. These simulated values can be used to enhance the analysis of a 3-D model, which along with a mesoscale model can be used to study the transport and entrainment processes in the marine atmosphere over the region. In addition to that, such a validated model can be linked with 1-D Ocean mixed layer model as a coupled system to study the various MBL characteristics to elucidate the role of oceanic heat content and mixed layer characteristics.

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