

Latitude variation of boundary layer height over Indian Ocean during pre- and First Field Phase (FFP-98) of INDOEX



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This paper describes the results of the measurement of the Marine Boundary Layer (MBL) height from spectral analysis of the u and v components of the wind and from CLASS/radiosonde temperature profiles. The data were collected on ORV *Sagar Kanya* during the pre-INDOEX (27 December 1996 through 31 January 1997) and FFP-98 (18 February to 31 March 1998) over the latitude range 15°N to 14°S and 15°N to 20°S respectively. During the pre-INDOEX, the MBL heights gradually decrease from 2.5 km at 13°N to around 500 to 600 m at 10°S . Similar results are observed in the return track. The MBL heights (0.5 to 1 km) obtained during FFP-98 are less compared to those obtained during pre-INDOEX. The MBL heights during FFP-98 are less compared to the pre-INDOEX and are believed to be due to the presence of stratus, stratocumulus and cumulus clouds during the cruise period, compared to a relatively cloud free pre-INDOEX cruise.

THE atmosphere over the tropical Indian Ocean is acknowledged to be an excellent 'natural laboratory' to perform a combined study on the large scale impact of the aerosols and their transport, clouds and tropospheric chemistry on the climate. Keeping this in view a major field experiment, the Indian Ocean Experiment (INDOEX), has been launched during the Indian northeast monsoon flows. Several intensive research and field experiments have focused in the tropical MBL, including Atlantic Tradewind Experiment (ATEX), Global atmospheric research program Atlantic Tropical Experiment (GATE), Tropical Ocean Global Atmosphere (TOGA), TOGA and Coupled Ocean Atmosphere Response Experiment (TOGA-COARE). However, our knowledge of the tropical MBL over the Indian Ocean is practically nil. The study has provided a comprehensive picture of the tropical MBL, its dynamics, structure and diurnal variability over the Indian Ocean across the Inter-Tropical

Convergence Zone (ITCZ). The dynamics of the Tropical Boundary Layer (TBL)/MBL play an important role on the aerosol transport and diffusion processes.

During the winter months, the atmosphere over the continental areas in the north is cooler relative to the Ocean forming a region of general subsidence. This higher pressure system in turn gives rise to dry season over India and generates a persistent northeasterly flow to the north of the equator and north westerlies from south of the equator and north of the ITCZ, over the Indian Ocean region. It is in this synoptic condition that the pre- and First Field Phase-98 (cruise 133) of the INDOEX programme occurred. Under the programme, data were collected onboard Oceanic Research Vessel (ORV) *Sagar Kanya* for the study of MBL.

The layer between the trade wind inversion and the surface is usually termed the 'tropical boundary layer'. The trade wind inversion region is a very stable stratified layer. The inversion provides a lid on cumulus convection and hence impedes vertical transfers. Under certain conditions the developing cumulus clouds will have sufficient energy to penetrate the inversion whereby a coupling and interchange take place between the surface layer and all layers up to the tropopause. This condition, seen very often in the vicinity of the ITCZ, is called the 'disturbed condition'. In contrast, during undisturbed conditions when the trade wind inversion effectively caps the MBL, the MBL exhibits a well-defined vertical layering. With high sea surface temperature (SST) and moisture, the MBL has a sharp, well-defined vertical structure characterized by the following: (i) Surface layer which extends from the surface to a maximum height of about 100 m, featuring a slight decrease in potential temperature but a significant decrease in moisture content. (ii) Mixed layer where the profiles of potential temperature and relative humidity are nearly constant, normally extending from the top of the surface layer to about 100 m below the cloud base. (iii) Transition layer where a stable potential temperature and a marked decrease in moisture content is seen. Extending to the cloud base, this layer is significant in that it separates the regime of cloud convection above to that of mecha-

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nical convection below. (iv) Cloud layer which shows a nearly adiabatic lapse rate and a decrease in moisture content. The layer extends from the cloud base to the base of the inversion, and (v) Inversion layer where the temperature gradient is extremely stable and there is a strong decrease in humidity. This layer tops the MBL during undisturbed conditions.

The paper presents the MBL structure and variation of the MBL height during cruise 120 (27 December 1996–31 January 1997) in the latitude range 15°N to 14°S and cruise 133 (18 February to 31 March 1998) in the latitude range 15°N to 20°S from the observations made onboard ORV *Sagar Kanya*, cruise #120 and 133 respectively. Henceforth pre-INDOEX and FFP-98 will be referred to as cruise 120 and cruise 133 respectively. The MBL heights were derived from the high resolution radiosonde profiles and spectra of u and v components of wind obtained from fast response wind velocity probes.

Measurements on-board ORV *Sagar Kanya*

In both the cruises fast temperature, humidity, and 3-axis wind sensors were mounted on a 7 m long retractable boom close to the ship bow nearly 10 m above the ocean surface. The data from these sensors were used for estimating MBL height and ocean surface fluxes of heat, momentum, and moisture. In the cruise 133, the measurements were made at two additional levels 6.5 and 11 m above the ocean surface. The ship was stationed at regular intervals to make the measurements. The data were collected at 5 Hz sampling rate and stored on computer hard disk through data logger. Time series were recorded continuously for about 1 h. During cruise 120 the ship was stationed at 0600 and 1300 h and 0600, 1800 and 2330 h every day and 1200 h on alternate days during the cruise 133 for a duration of one hour (all times are in IST).

During the cruise 120, CLASS (Cross-chain Loren Atmospheric Sounding System) SONDES along with Global Positioning System (GPS) were used for profiling temperature (T), wind speed (WS), wind direction (WD) and humidity (RH) from the ship along the entire cruise track. The CLASS SONDE system was made available by National Centre for Atmospheric Research (NCAR). A total of 46 ascents were successfully undertaken with vertical height resolution of the order of 20 to 30 m, and an average height of 17 to 20 km altitude. Similarly, during the cruise 133, CLASS SONDES were used for profiling without GPS; hence, only T, RH and pressure (P) profiling could be calculated. A total of 47 sonde ascents were executed and they too obtained 17 to 20 km altitude.

Method of estimation of MBL height from CLASS SONDE profiles and u and v components of wind

Method of estimation of MBL height from profiles

A typical boundary layer is capped by a temperature inversion that limits exchange with the free atmosphere¹. Cloud top usually coincides with the base of the inversion. Stratus clouds are generally associated with a well-mixed MBL.

All CLASS SONDE temperature profiles obtained during the cruise period were converted into profiles of potential temperature ($\theta = T (P_0/P)^{0.286}$) and virtual potential temperature $\theta_v = \theta(1 + 0.61 \cdot r)$, where T is air temperature, P is air pressure, P_0 is reference pressure set to 1000 mb, and r is water vapour mixing ratio which is derived from humidity profiles. The MBL height (z_i) was estimated from the derived, virtual potential temperature profiles against pressure. The base of the stable temperature inversion is taken as z_i . However, at low pressure regions like the ITCZ, the upward motions carry boundary layer air away from surface to large altitudes throughout the troposphere; under such conditions, it is difficult to define a boundary layer top. In such cases, the cloud base is used as an arbitrary cut-off mixed layer height².

Method of estimation of MBL height from u and v components of spectra

The spectral analysis of meteorological variables enables us to study the various aspects of boundary layer structure like the predominant scales of motion, the nature of energy containing eddies, the nature of cascading in the inertial sub-range and the estimation of the eddies size that carry maximum energy.

The evolution of MBL height (z_i) has been estimated using spectral method. In this method the time series of u and v components of wind are subjected to FFT to identify the frequency (f_m) at which the frequency weighted spectral power peaks³. Kaimal *et al.*⁴ have established a relation

$$\lambda_m = \frac{U}{f_m} = 1.5 z_i. \quad (1)$$

for the spectra of u and v components of wind. Here λ_m is the scale size of the eddies which carry maximum energy, U is the mean horizontal wind, f_m is the frequency at which the frequency weighted spectrum has maximum power and z_i is the depth of the MBL.

Results

First, let us consider the meteorological conditions during the cruise 120 and 133. During cruise 120, the sea surface temperature (SST) was recorded every three hours, whereas during cruise 133, SST was recorded whenever the ship was stationary in the international waters, both using bucket thermometer. It was seen that SST was increasing gradually from 28 to 30°C over the latitudinal range from 14°N to 14°S, with a maxima around 10°S during cruise 120 period. Whereas in cruise 133 period, SST was nearly uniform from 10°N to 17°S with a mean close to 30°C. Along the entire track, the minimum SST was above 28°C and the maximum below 32°C. During cruise 133 period, SSTs were overall higher compared to that of cruise 120. The SST was sufficiently high for the occurrence of deep convection^{5,6}. During cruise 120 and 133 periods, the surface winds were generally calm, and only on few occasions the wind speed exceeded 11 m/sec in cruise 120 period and 6 m/sec in cruise 133 period. The surface pressure minimum was located between 9°S and 10°S during the onward journey of both the cruise period. During cruise 133 the relative humidity increased from 50 to 60% in the Northern hemisphere (10–14°N) to 80–85% in the southern hemisphere (10–16°S). Owing to warmer SSTs and higher moisture levels, convection was very active south of the equator.

A selected pressure altitude profile of θ_v over the entire latitude range from the cruise 120 period is shown in Figure 1. The profiles shown in the figure represent

measurements made during the period 1300 and 1500 h. In general, all these profiles show three distinct layers. Up to 950 mb, there is a well-mixed layer with a constant θ_v . The mixed layer is followed by a conditionally unstable layer where the clouds could grow, that extends from 850 to 750 mb. On the top of this layer there is an absolutely stable inversion layer in which θ_v increases strongly with height. The base of this inversion was considered as z_i . It can be seen from the figure, at 10°N that the z_i is found to be 2.25 km whereas at 10°S as clouds were present, cloud base height is taken as z_i , which is of the order of 500 m. The z_i during onward and return track more or less followed the same pattern.

Figure 2 similarly shows selected profiles of θ_v for cruise 133. These profiles also represent the period 1300–1500 h. The vertical profiles are structured and are believed to be due to the presence of clouds^{7,8}. Here, in all of the soundings the profiles of θ_v above the surface layer show a shallow layer in which the vertical gradients are nearly zero. This layer showed a nearly dry adiabatic lapse rate, characteristic of the mixed layer. The vertical gradients of θ_v are positive from the top of this layer to the inversion and a layer of strato-cumulus always occupies some fraction of the upper position of this layer. In general, all profiles show a change of slope near 950–900 mb, which separates a nearly well-mixed sub cloud layer from more stable cloud layer above. Due to the presence of strato-cumulus clouds throughout the 133 cruise track, the latitudinal variation of z_i was quite different from the cruise 120 variation. During cruise 133, outward track z_i is found

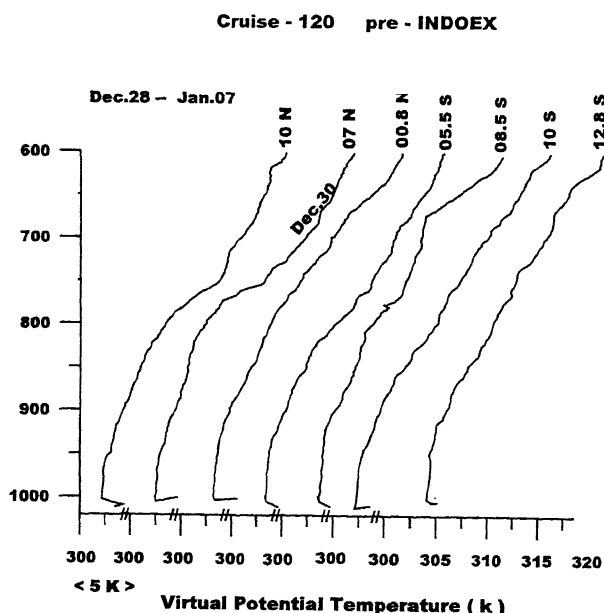


Figure 1. Virtual potential temperature, θ_v (K) as a function of pressure height (mb) at selected latitude between 10°N and 12.8°S obtained using CLASS SONDE during cruise 120 period. All the profiles are obtained between 1300 and 1500 h.

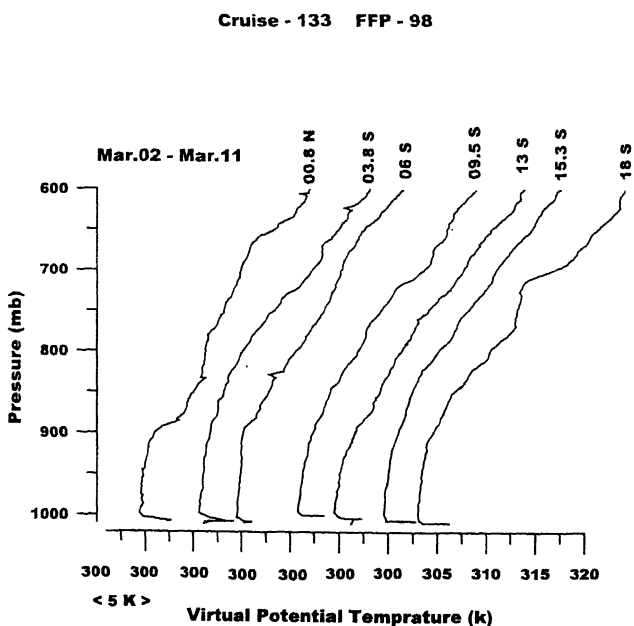


Figure 2. Same as Figure 1 but for FFP-98 in the latitude range 0.8°N to 18°S.

Cruise - 120 pre - INDOEX

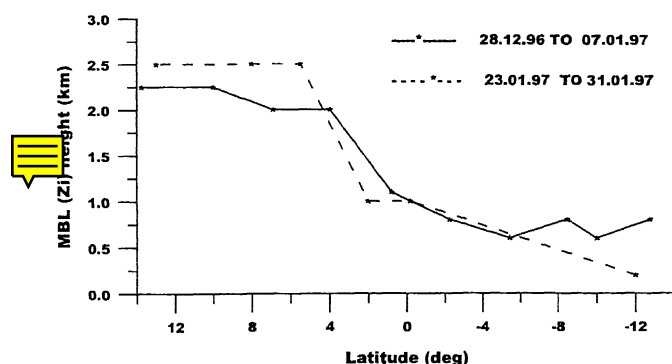


Figure 3. MBL height (z_i) as a function of latitude during outward and return track of cruise 120.

Cruise - 133 FFP - 98

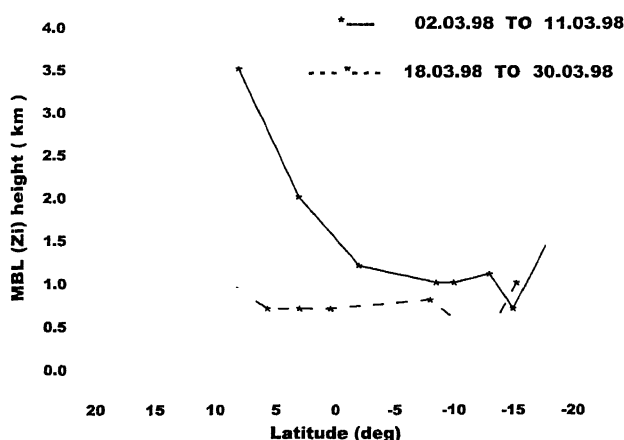


Figure 4. Same as Figure 3 but for FFP-98.

to vary from 1 km to 500 m, whereas in the return path throughout it is found to be in the range 500 to 600 m only.

Both the latitudinal variations of the MBL height for cruise 120 and cruise 133 are shown in Figures 3 and 4. The MBL heights shown are, for the time period 1300–1500 h and of both southward and northward cruise track.

Figure 5 shows frequency weighted day time spectra of u component of wind obtained using 1 Hz sampled data of cruise 120 (30 December 1996) during 1400–1500 h. A one hour data length has been used for obtaining spectra. A well-defined spectral peak and an extensive inertial subrange is evident. The z_i was computed from the frequency at which the spectral power peaks (f_m) and using mean wind (\bar{U}) data in equation (1).

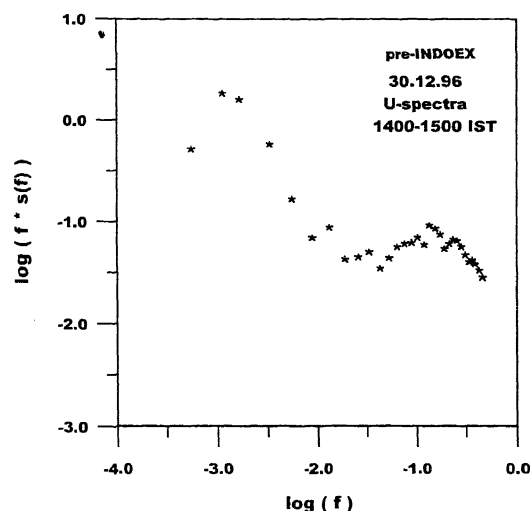


Figure 5. Frequency weighted spectrum of u component of wind with frequency for 30 December 1997 (cruise 120). The peak at the low frequency side corresponds to $z_i = 2.2$ km using equation (1). The second peak at the high frequency side is due to the ship motion caused by sea swell.

The z_i computed from the spectral method is 2.2 km, which matches very well with inversion height from θ_v profile, which is shown in Figure 1. The second peak in the inertial subrange is due to the ship motion caused by sea swell.

Figure 6 shows frequency weighted night-time spectra of component of wind obtained using 1 Hz sampled data of cruise 133 for 3 March and 17 March 1998, 30 to 45 min data lengths have been used for obtaining the spectra. The z_i computed from the spectral method are of the order of 1 km and 600 m respectively, which matches very well with inversion height from θ_v profile around the same time period which are shown in Figure 7. The θ_v profile shown in Figure 7 represents night-time condition. It may be noted that the profiles represent a typical convective MBL structure, and the u and v spectra for the corresponding time do show presence of microscale turbulence. In general, over land surface during night-time such microscale turbulence is not usually found. The microscale turbulence detected over the ocean surface during night time could be due to higher SST and moisture levels. The matching of z_i obtained from θ_v profile and spectral estimates show that the largest eddy present is of the size of the MBL height.

Conclusions

The MBL structure and its height over the INDOEX latitude range have been studied using CLASS/radiosonde profiles and data obtained from the sensors mounted on a retractable boom onboard ORV *Sagar Kanya*. The

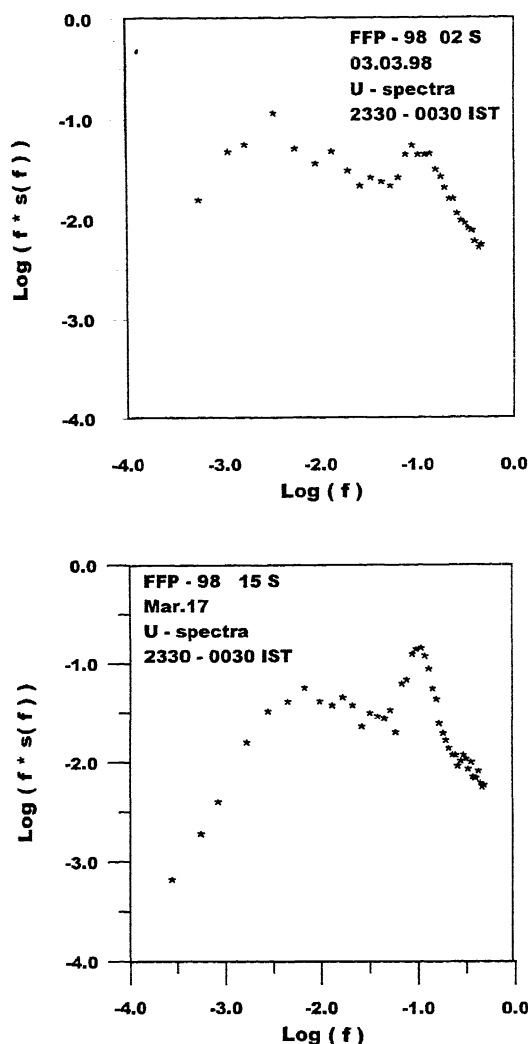


Figure 6. Frequency weighted spectra of u component of wind with frequency for 3 March and 17 March 1998. Spectra show distinct peak at low frequency side which correspond to z_i equal to 1 km and 600 m respectively using equation (1). The second peak at the high frequency side is due to the ship motion caused by sea swell.

MBL heights derived from the θ_v profiles have shown different patterns of latitude variation during cruise 120 and 133. During cruise 120, for example, the MBL heights were around 2.2 km at 13°N and about 500 m at 10°S southward. The decrease was gradual and the same pattern is observed during the return track. During cruise 133, however, the MBL height is between 1 km and 500 m during the southward journey and it was only about 500 to 600 m throughout the return journey. The lower height of the MBL during cruise 133 is attributed to the presence of stratocumulus clouds during that period. The spectral analyses of the components of winds show the maximum power for the eddies of the size of MBL height.

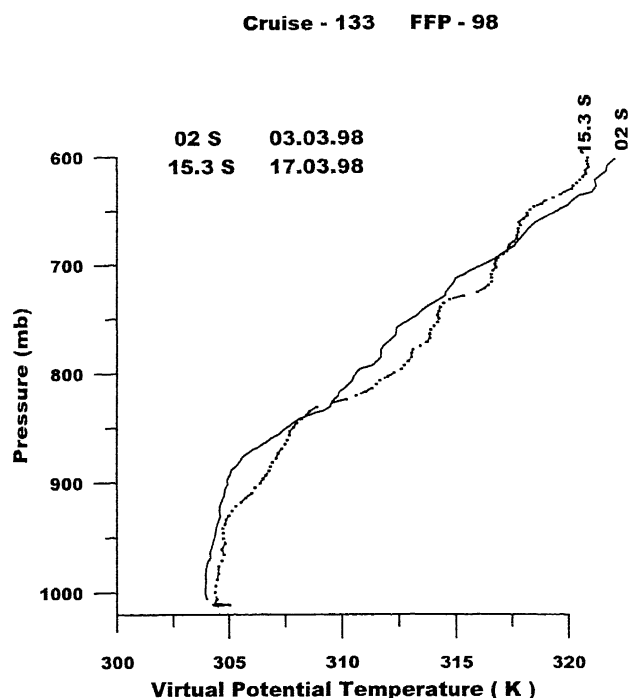


Figure 7. Virtual potential temperature as function of the pressure height for 3 March and 17 March 1998 during 2100 h (cruise 133). Profiles are of typical convective situation with z_i around 1 km and 600 m for 3 March and 17 March, as also seen in figure 6.

The thermal structure during night-time over the ocean during cruise 133 showed well-mixed region and the presence of microscale turbulence which could have been due to the relatively high SST (between 28 and 30°C) with 70 to 80% relative humidity.

1. Rogens, D. P., Yang, X., Norris, P. M., Johnson, D. W., Martin, G. M., Friehe, C. A. and Berger, B. W., *J. Atmos. Res.*, 1995, **52**, 2953.
2. Stull, R. B., Kluwer Academic Publishers, 1991.
3. Winston Jeeva Prakash, J., Radhika Ramachandran, Narayanan Nair, K., Sen Gupta, K. and Kunhikrishnan, P. K., *Q. J. R. Meteorol. Soc.*, 1993, **119**, 187.
4. Kaimal, J. C., Eversole, R. A., Lenschow, D. H., Stankov, B. B., Kahn, P. H. and Businger, J. A., *J. Atmos. Sci.*, 1982, **39**, 1198.
5. Gadgil, S., Joseph, P. V. and Joshi, N. V., *Nature*, 1984, **312**, 141.
6. Graham, N. E. and Barnett, T. P., *Science*, 1987, **238**, 657.
7. Betts, A. K. and Boers, R., *J. Atmos. Sci.*, 1990, **47**, 83.
8. Nicholls, S., Brummer, B., Fielder, F., Grant, A., Hauf, T., Jenkins, G., Readings, C. and Shaw, W., *Philos. Trans. R. Soc. London*, 1983, **A308**, 291.

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