Hindawi Publishing Corporation
Advances in Meteorology
Volume 2011, Article ID 390826, 9 pages
doi:10.1155/2011/390826

Research Article

Characterization of the Vertical Structure of Coastal Atmospheric Boundary Layer over Thumba (8.5°N, 76.9°E) during Different Seasons

Sandhya K. Nair,[1] T. J. Anurose,[1] D. Bala Subrahamanyam,[1] N. V. P. Kiran Kumar,[1] M. Santosh,[1] S. Sijikumar,[1] Mannil Mohan,[1] and K. V. S. Namboodiri[2]

[1] *Space Physics Laboratory, Vikram Sarabhai Space Centre, Department of Space, Indian Space Research Organization, Government of India, Thiruvananthapuram 695 022, India*
[2] *MET Facility, Vikram Sarabhai Space Centre, Department of Space, Indian Space Research Organization, Government of India, Thiruvananthapuram 695 022, India*

Correspondence should be addressed to D. Bala Subrahamanyam, subrahamanyam@gmail.com

Received 24 December 2010; Revised 8 March 2011; Accepted 23 March 2011

Academic Editor: Branko Grisogono

Vertical profiles of meteorological parameters obtained from balloon-borne GPS Radiosonde for a period of more than two years are analyzed for characterization of the coastal atmospheric boundary layer (CABL) over Thumba (8.5°N, 76.9°E, India). The study reports seasonal variability in the thickness of three different sublayers of the CABL, namely, mixed layer, turbulent flow, and sea breeze flow. Among the three, the vertical thickness of sea breeze flow showed considerable dominance on the other two throughout the year. Mixed layer heights derived through gradients in virtual potential temperature (θ_v) showed large seasonal variability with a peak in the Summer and Post-Monsoon. On the other hand, the vertical thickness of turbulent flow remained steady all through the year. Results from the present study indicate that the magnitudes of mixed layer heights are often larger than the turbulent flow thickness.

1. Introduction

In Physics and Fluid Dynamics, a boundary layer is generally defined as a layer of the fluid in the immediate vicinity of a bounding surface, where viscosity variations are dealt in detail. The atmospheric boundary layer (ABL) is defined as the lowest part of the Earth's atmosphere, where physical quantities such as flow velocity, temperature, and moisture display rapid fluctuations and vertical mixing is strong [1–3]. The ABL processes control exchanges of momentum, water, and trace substances between the Earth's surface and the free troposphere. Substances, once emitted into the ABL, are gradually dispersed horizontally and vertically through turbulent processes and become completely mixed over this layer. All the ABL processes largely dependent on atmospheric turbulence are represented in parameterized form in atmospheric models. The thickness of ABL is commonly used to characterize the vertical extent of mixing within the boundary layer and the level at which exchange with the free troposphere occurs [4–6]. In principle, the ABL thickness can be retrieved from atmospheric global circulation models since they contain algorithms which determine the intensity of the turbulence as a function of height [7, 8]. However, these data are not routinely available or on a vertical resolution which is too crude in view of the application.

In the field of boundary layer meteorology and air pollution dispersion, the vertical thickness of ABL remain one of the important parameters governing the dispersion of pollutants and measured concentrations of trace gases and atmospheric aerosols [4–6]. Therefore, accurate knowledge and broad overview of the factors that influence the ABL thickness is of prime importance in understanding the ABL processes over a given region. The practical and theoretical problems associated with the determination of the ABL thickness are reflected in the numerous definitions found in the literature [1, 3, 5, 9–11]. Seibert et al. [5] reviewed and intercompared some of the most important operational methods including direct measuring techniques and remote sensing techniques for determination of ABL thickness. Seidel et al. [12] used seven different methods on 10-year, 505-station global radiosonde data sets for the development of a global climatology of the ABL thickness.

Even though, several techniques are suggested in literature, there is still no unique definition and a single overall accepted method of quantification of the ABL thickness [5, 9, 13–15]. The complexity in determination of thickness of the Coastal Atmospheric Boundary Layer (CABL) is generally more complicated as it is effectively influenced by presence of mesoscale atmospheric circulations such as Sea/Land Breeze Circulation (SLBC) [15–18]. In this paper, we make use of high-resolution upper-air meteorological observations obtained through balloon-borne GPS Radiosonde for a period of about two and half years for characterization of the vertical structure of CABL over Thumba (8.5° N, 76.9° E), one of the Coastal Stations in the Indian subcontinent. Most of the earlier studies in the field of CABL processes conducted over Thumba and adjoining inland coastal stations over the Indian subcontinent were confined to surface-layer characteristics based on meteorological towers, acoustic remote sensing, and vertical ascents of opportunity confined to a few days only [16–19]. Rani et al. [15] attempted to explain the vertical structure of the SLBC over the western coastline of the Indian subcontinent through numerical atmospheric model, but their study was confined to pre-monsoon season only and could not address the variability in the structure of SLBC over different seasons. In all these studies, one of the missing components was the seasonal variability in the vertical structure of the CABL and its linkage to large-scale atmospheric circulations such as winter and summer monsoon. On one hand, the onset of summer monsoon over the Indian subcontinent is vastly studied with reference to the accumulated rainfall and moisture variability in the lower atmosphere; however, its role over a coastal station, particularly, in modulating the ABL processes remained unexplored in a systematic fashion. The present article attempts to fulfil these missing components by using two-year database of upper-air meteorological observations obtained from Thumba to broaden our understanding on the direct impacts on large-scale monsoonal circulation on the CABL processes. The objectives of this paper can be summarized under two heads.

(1) With reference to the CABL processes prevailing over the study domain, we describe three techniques for the determination of mixed layer height, turbulent flow depth, and sea breeze flow thickness, respectively. The plausible linkage between these layers is also described in detail.

(2) Prevailing meteorological conditions over the study domain are largely modulated by dry and wet monsoon seasons; therefore, the study is extended towards investigation of probable modulations in the above-mentioned layers during different seasons.

2. Instrumentation and Database

In the present study, upper-air meteorological observations obtained through indigenously developed low-cost GPS Radiosonde (hereafter referred to as Pisharoty Sonde, as named by the Manufacturers) form the main database [20] for determination of the CABL thickness over Thumba. Table 1 provides some of the details on accuracies and response time of different sensors used in Pisharoty Sondes. Further technical details on functioning of Pisharoty Sonde are described elsewhere [20]. As part of the routine meteorological observations at Thumba, balloon-borne Pisharoty Sondes are launched on Wednesdays from MET-Facility, Vikram Sarabhai Space Centre (VSSC), typically at about 14:30 local time. A total of 92 good soundings between September 2008 to November 2010 formed the main database for the present study, and it was reasonably good enough to characterize the vertical structure of the CABL over Thumba. We have confined our analysis strictly to the afternoon soundings, so as to stick to the well-developed convective activities.

3. Data Processing and Quality Checks

The raw data collected from balloon-borne Pisharoty Sondes consist of pressure, temperature, relative humidity, and geographical position of balloon in the terms of its latitude, longitude, and altitude as a function of time, approximately at the rate of 1 Hz. In the present study, we have adopted the following procedure for smoothening of the raw data.

(1) Firstly, all the exceptionally unusual values including the measurements corresponding to the descent phase of the balloon are rejected.

(2) All the individual values beyond 2.5 times of the standard deviation from the corresponding mean for each 100 m bins are considered as spikes and are rejected.

(3) Subsequently, the vertical profiles of meteorological parameters are smoothened through running average technique and the data are regridded at regular intervals of 10 m in vertical.

(4) Missing data for more than 100 m altitudinal bins are left blank, and we have confined our analysis of all the profiles to an altitude of 3500 m.

(5) After regrinding of all the meteorological parameters to regular intervals of 10 m, virtual potential temperature (θ_v), bulk Richardson number (Ri_B), and sea breeze component (SBC) are derived for delineation of different sublayers within the CABL.

4. Method of Analysis

In general, the ABL over a given region is classified into different sublayers depending on the degree of convection, clouds, and the amount of moisture present in the lower

Table 1: Technical details of Pisharoty GPS Sondes (Make: VSSC, ISRO, India).

Name of the sensor (measured parameter)	Range	Response time	Accuracy
Platinum RTD (air temperature)	−200°C to 400°C	<2 second	±0.1°C
Capacitive humidity sensor (relative humidity)	0 to 100%	<4 second	±1.5%
MEMS sensor (atmospheric pressure)	5 hPa to 1500 hPa	2 second	±2% span

atmosphere. Since the CABL dynamics is effectively influenced by the presence of SLBC, it can be classified into three different sublayers such as

(1) mixed layer: it is the layer, where atmospheric moisture remain uniformly well mixed, and its thickness depends on the degree of convection prevailing over the region. Under the influence of SLBC, when horizontal advection of onshore moist flow determines the depth of the mixed layer, it is also referred to as the thermal internal boundary layer (TIBL);

(2) turbulent flow: it is a classical fluid dynamics concept, where it is discriminated from the laminar flow through a critical threshold values of Richardson number;

(3) sea breeze flow: it is the moist onshore wind flow obtained through segregation of horizontal speeds perpendicular to the Coastline.

On one hand, the definition of mixed layer is directly linked with the amount of moisture well mixed in the lower atmosphere; the turbulent flow is described in the terms of frictional influence of the Earth's surface on lower atmospheric layer. Similarly, the sea breeze flow is just one of the ways to discriminate the influence of the SLBC with the prevailing wind flow based on the wind direction and alignment of the coastline. It is obvious that these three layers form three unique approaches based on atmospheric thermodynamics, fluid dynamics, and land-sea thermal contrast, respectively. With a view to investigating the probable linkage between these three stratified layers described through three standard methods, we have quantified them through the following approach.

4.1. Virtual Potential Temperature (θ_v) Gradient Method. Radiosonde temperature and wind profiles in the lower part of the troposphere are often used for a subjective estimation of the mixed layer [5]. Holzworth [7, 21] and others have developed objective methods to simplify and homogenise the estimation of the mixed layer under convective conditions. The exact definition of top of the mixed layer in many cases is very intuitive and different methods are found in the literature. In this regard, virtual potential temperature (θ_v) happens to be very useful thermodynamic parameter [14] for markation of the mixed layer and can be estimated using the following equations [1, 3]:

$$\theta = T \cdot \left(\frac{1000}{P}\right)^{0.286}, \qquad \theta_v = \theta \cdot (1 + 0.61 \cdot r), \tag{1}$$

where θ, T, P, and r represent the potential temperature (in Kelvin), ambient temperature (in Kelvin), air pressure (in hPa), and mixing ratio (in g/kg). In the present study, we define the top of the mixed layer at an altitude, where the vertical gradients in θ_v exceed $3\,\mathrm{K \cdot km^{-1}}$ [22].

4.2. Bulk Richardson Number (Ri_B) Method. The bulk Richardson number (Ri_B) is a dimensionless number in meteorology relating vertical stability and vertical shear, which provide a measure of the dynamic stability of the flow and is given by the following expression for an altitude z as

$$\mathrm{Ri}_B = \frac{g \cdot (\partial\theta_v/\partial z)}{\overline{\theta_v}\left[(\partial u/\partial z)^2 + (\partial v/\partial z)^2\right]}, \tag{2}$$

where $(\partial\theta_v/\partial z)$, $(\partial u/\partial z)$, and $(\partial v/\partial z)$ are the gradients in virtual potential temperature (θ_v) and zonal and meridional components (u, v) of horizontal winds, respectively. The term $\overline{\theta_v}$ in the denominator represents the mean of virtual potential temperature for the two levels, and g is the acceleration due to gravity. Sorensen recommended a value of 0.25 for the critical value of Ri_B above which the turbulent flow becomes the laminar flow [23]. In the present study also, we use 0.25 as the critical value of Ri_B for markation of the turbulent flow depth.

4.3. Sea Breeze Flow Thickness. Borne et al. [24] described a unique approach for identification of the sea breeze days under stable synoptic conditions for the Swedish West Coast. Their approach was based on hourly meteorological records and empirical knowledge of the physical processes responsible for the occurrence of a sea breeze system. In the present study, we have adopted an approach explicitly based on the ambient wind direction and alignment of the coastline only. The west coastline of Indian subcontinent is roughly aligned into along 145°–325°; thus the winds blowing between 145° and 325° are considered as sea breeze, while the seaward winds flowing between 325° and 145° are considered as land breeze [15]. Given the alignment of Indian western coastline (Figure 1), it is appropriate to resolve the wind components in perpendicular direction to the Coastline, so as to enable the measurement of sea breeze strength. Thus, the sea breeze component (SBC) and coastal breeze component (CBC) along Thumba Coastline are defined as given below [25]

$$\mathrm{SBC} = \mathrm{WS} \cdot \sin(325 - \mathrm{WD}), \qquad \mathrm{CBC} = -\mathrm{WS} \cdot \cos(325 - \mathrm{WD}), \tag{3}$$

where WS: mean wind speed ($\mathrm{ms^{-1}}$) and WD: wind direction (°). As defined in the above equation, positive values of

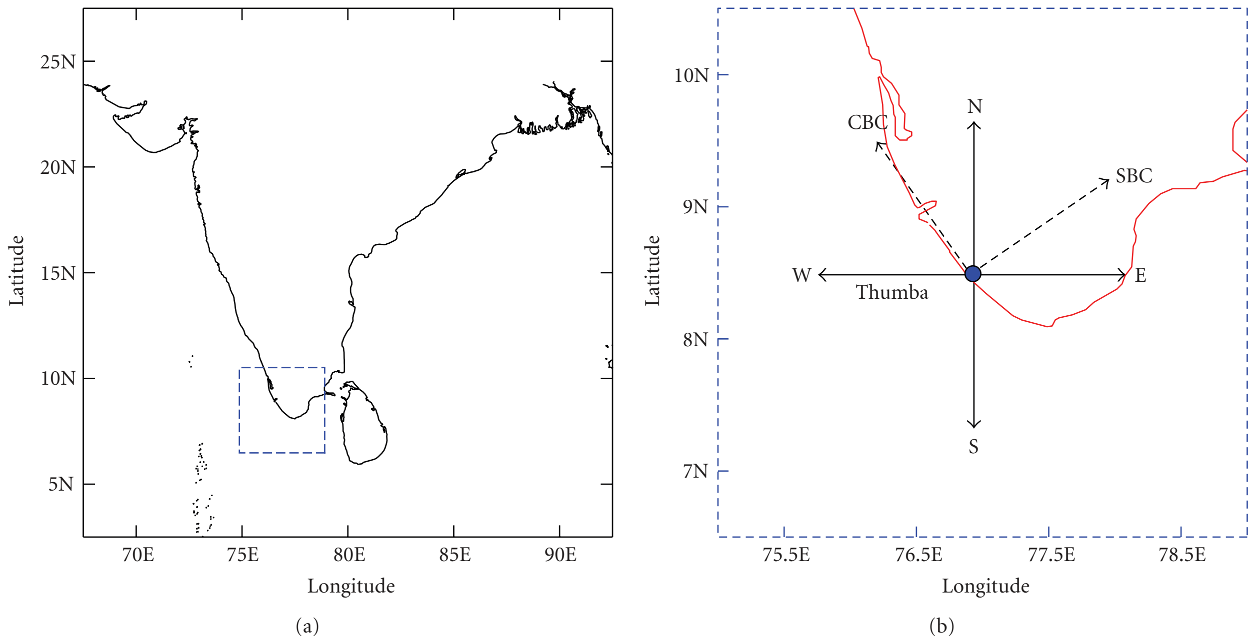


Figure 1: Location of Thumba depicting the direction of sea and coastal breeze components.

SBC indicate the sea breeze flow while the negative values represent the land breeze flow. During the sea breeze conditions, magnitudes of SBC remain positive in the lower altitudes representing the onshore flow of moist air from sea to land. Above a certain altitude, the magnitudes of SBC become negative, in turn, indicating the presence of a compensatory return flow aloft. Thus, the altitude, where this changeover in SBC from positive to negative values is seen, can be taken as the top of the sea breeze flow.

Figures 2(a)–2(c) show one of the typical plots of θ_v and its gradient, Ri_B and SBC, corresponding to afternoon balloon ascent (13:50 LT) on 11th December 2009 depicting the methodology of delineation of MLH, TFD, and SBFT adopted in the present study. The level of the maximum vertical gradient in θ_v is generally indicative of a transition from a convectively less stable region below to a more stable region above. In the lower altitudes, the magnitudes of θ_v remain more or less constant and steady due to convective heating and turbulent mixing within this layer, hence this part of the lower atmosphere is termed as the mixed layer, as shown in Figure 2(a). The top of this mixed layer is marked at an altitude of about 450 m, where $d\theta_v/dz$ gradient exceeds 3.0 K/Km. From the vertical profiles of Ri_B shown in Figure 2(b), it is apparent to notice negative values of Ri_B, indicating the presence of turbulent flow in the lower atmosphere. At an altitude of about 500 m, the atmospheric flow becomes laminar, as the magnitudes of Ri_B exceed a critical threshold value of 0.25 [23]. The atmospheric circulation over Thumba is often modulated by presence of the SLBC, hence it is equally important to quantify the thickness of the lower atmosphere, where signature of the sea breeze flow is eminent. Figure 2(c) shows vertical profile of SBC representing the strength of onshore flow. Positive magnitudes of SBC below 700 m altitudinal range indicate presence of sea breeze flow in this layer, whereas, in the high altitudes (>700 m), the magnitudes of SBC become negative, in turn, indicating the reversal of sea breeze flow aloft.

5. Background Meteorological Conditions

Local weather over the Indian subcontinent is mostly influenced by monsoonal and prevailing large-scale wind circulation, surface heating, and topographic friction. Thumba (8.5°N, 76.9°E), one of the Coastal stations located on the West Coastline of Indian subcontinent, is a remote, plain, coastal area, not in proximity to any major industrial or urban activities, and is located about 500 m due east of the Arabian Sea and 10 Kms north, north-west of the urban area (Figure 1). This experimental site experiences well-defined diurnal variations in wind speed and direction with persistent sea breeze circulation during daytime and land breeze during nighttime. In general, the ambient meteorological conditions over Thumba during a year can be classified into two broad categories: (1) Summer Monsoon (also referred to as South-West Monsoon) and (2) Winter Monsoon (also referred to as North-East Monsoon). The period between December to February, when the study domain experiences typically dry season is termed as the Winter Monsoon, while the period between June to September is classified as the Summer Monsoon and is generally enriched with good amount of precipitation over the subcontinent. The months of March to May is termed as Pre-Monsoon months, while the months of October and November are referred to as Post-Monsoon months. After withdrawal of the Summer Monsoon and until onset of the next monsoon, that is, roughly during November to May, winds in the coastal region of India are dominated by sea breeze. During the Summer Monsoon over Thumba, a sea breeze is superimposed on

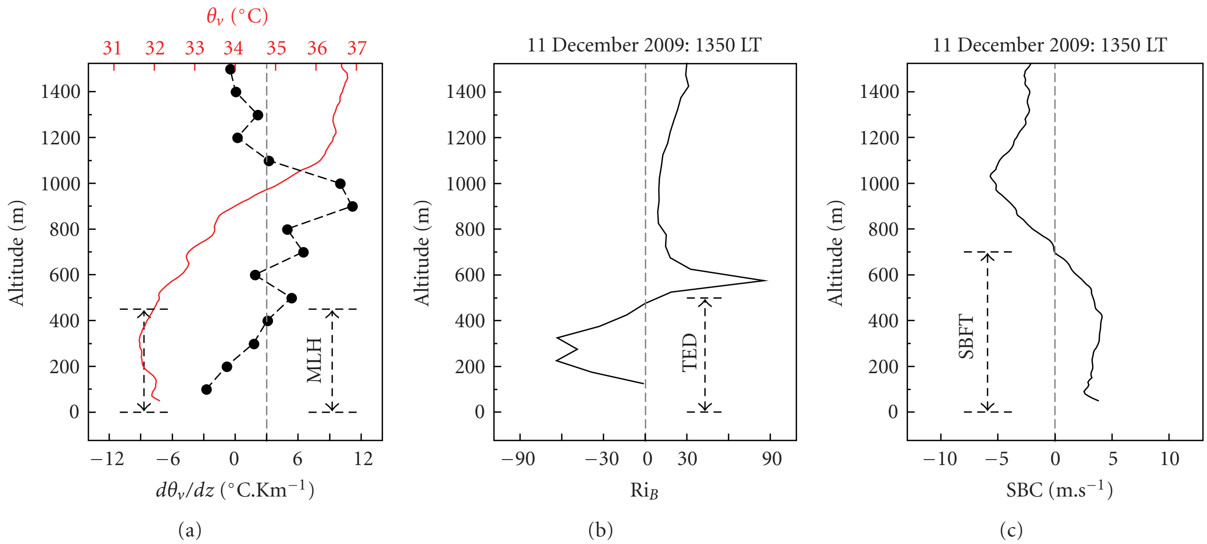


FIGURE 2: Vertical Profiles of (a) virtual potential temperature (θ_v) and ($d\theta_v/dz$), (b) bulk Richardson number (Ri_B), and (c) sea breeze component (SBC) depicting three different techniques adopted for determination of mixed layer height (MLH), turbulent flow depth (TFD), and sea breeze flow thickness (SBFT), respectively. These layers are marked by arrows in Figure.

the prevailing wind. Since the flow is then already onshore, it does not constitute a "sea breeze" although it might be termed a "sea wind". However, for the months of December to March, the prevailing wind is from the north-east and is not so intense as the Summer Monsoon wind; sea breeze activity then becomes striking [26]. Substantial work has been carried out on characterization of the CABL over Thumba [15–17, 19, 27, 28]. Observational and modelling studies conducted over Thumba coast show existence of onshore flow to a vertical thickness of about 1 km during the Summer Monsoon and about 800 m during the Winter Monsoon [15, 26].

With a view to presenting the mean characteristics of the atmospheric circulation pattern over Thumba during different seasons, we make use of the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) Reanalysis to show the wind circulation at 1000 hPa, roughly corresponding to surface in Figure 3 [29]. Figures 3(a)–3(d) show seasonal averaged wind circulation pattern for the Winter Monsoon (DJF), Pre-Monsoon (MAM), Summer Monsoon (JJAS), and Post-Monsoon (ON), respectively. In general, the surface-layer winds over Thumba remain low (<2 m/s) during the Winter, in turn, indicating absence of any strong convective activities (Figure 3(a)). During this season, the wind direction over Thumba Coast is, generally, between 0° to 90° indicating a flow of airmass from landmass to oceanic counterpart (Figure 3(a)). It is important to note that due to the prevailing north-easterly winds in this season, the formation of SLBC is remarkable and easily traceable [15]. With the beginning of Pre-monsoon season during March to May, the wind circulation over Thumba undergoes a gradual transition from Winter (dry) Monsoon to Summer (wet) Monsoon. During this period, the wind direction is mostly in the fourth quadrant (between 270° to 360°) and wind magnitudes are relatively higher than that in the Winter Monsoon (Figures 3(a) and 3(b)). It is also the period when convective activities built up and the experimental site undergoes frequent thundershowers [30]. During the Summer Monsoon, onshore winds with high magnitudes ranging between 5 to 7 m/s dominate the ambient wind flow over Thumba, as can be seen from Figure 3(c), and the SLBC is superposed on the prevailing wind and at time is even masked [26]. During this period, the experimental site and southern part of the Indian subcontinent receive good amount of rain-bearing clouds associated with frequent precipitation. Later in the months of October and November (Post-Monsoon season), the wind circulation undergoes a transition from onshore flow to offshore flow and the wind magnitudes show a gradual decrease (Figure 3(d)).

6. Results and Discussion

6.1. Seasonal Variations in Vertical Structure of the CABL. In Figure 4, we show the monthly mean of MLH, TFD, and SBFT with their standard deviations for each month as the error bars. Table 2 provides exact details on the total number of observations used for deriving these histograms. During the period between May to August, exact discrimination between the sea breeze flow and prevailing wind circulation was quite difficult as both were aligned in the same direction; therefore, we have not shown any histogram for SBFT for these months. Similarly, we could not ascertain a clear-cut markation of MLH in the month of August and its histogram is also not shown for this particular month.

From Figure 4, it can be seen that the magnitudes of SBFT are generally larger than those of the MLH and TFD, indicating a dominant role of the SLBC in modulations of CABL dynamics over Thumba. During October to April months, SBFT magnitudes are almost two times

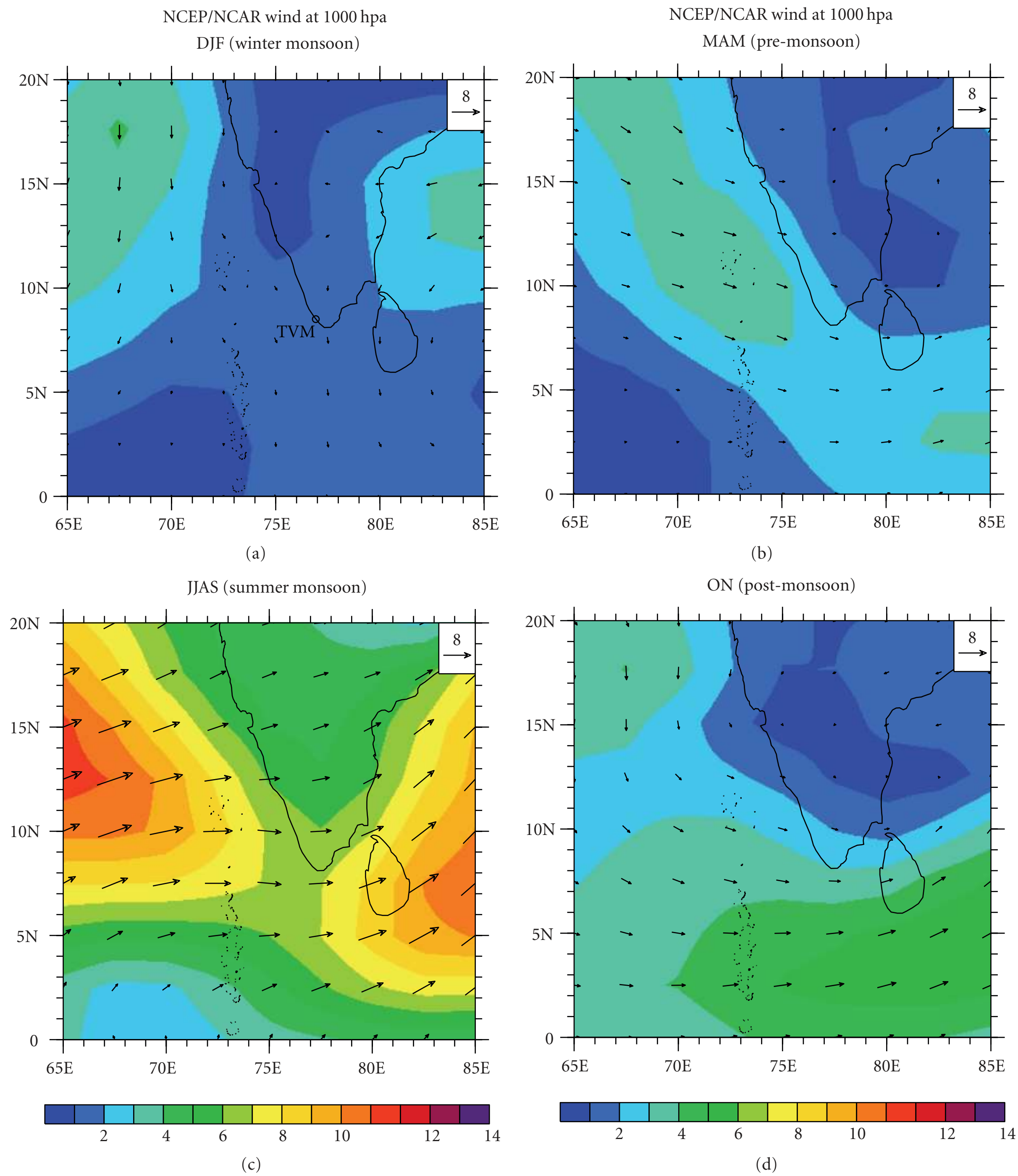


Figure 3: Seasonally averaged wind circulation corresponding to 1000 hPa from NCEP/NCAR Reanalysis for (a) Winter Monsoon (December, January, and February), (b) Pre-Monsoon (March, April, and May), (c) Summer Monsoon (June, July, August, and September), and (d) Post-Monsoon (October and November).

the magnitudes of MLH and TFD. Such a large difference between the magnitudes of SBFT and MLH are indicative of formation of the TIBL within the sea breeze flow, as generally expected over a Coastal station. Atmospheric Modelling and observational studies on the SLBC over Thumba in the past have also revealed similar results [15, 27]. With the available database of about two and half years, the MLH variations were recorded in a range of 310 m to 650 m with a mean of about 420 m, whereas TFD showed variations in a range of 175 m to 560 m with a mean of about 330 m, significantly lower than that of the MLH. In contrast to MLH and TFD magnitudes, the vertical thickness of SBFT showed large variability within a range of 500 m to 910 m with a mean of about 760 m. The magnitudes of MLH for different months

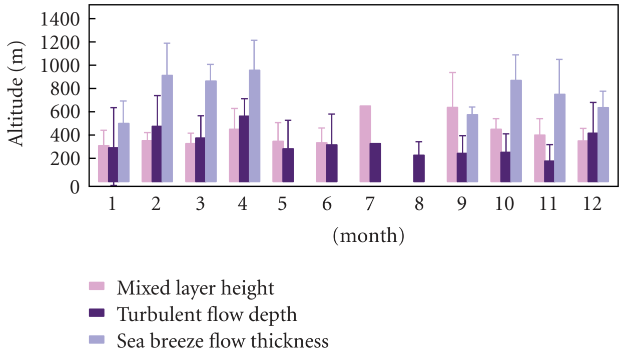


Figure 4: Monthly variations in mixed layer height (MLH), turbulent flow depth (TFD), and sea breeze flow thickness (SBFT) shown as histograms. Error Bars associated with these parameters indicate the standard deviations for each month, respectively.

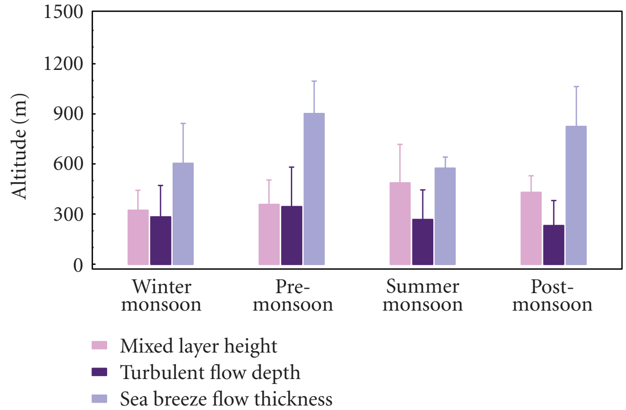


Figure 5: Seasonal variations in mixed layer height (MLH), turbulent flow depth (TFD), and sea breeze flow thickness (SBFT) shown as histograms. Error Bars associated with these parameters indicate the standard deviations for each season, respectively.

Table 2: Statistics on the availability of Pisharoty Sonde data.

Season	Month	No. of soundings	Total no. of soundings
Winter Monsoon	December	10	34
	January	19	
	February	5	
Pre-Monsoon	March	9	32
	April	6	
	May	17	
Summer-Monsoon	June	5	15
	July	1	
	August	5	
	September	4	
Post-Monsoon	October	7	11
	November	4	
Complete year			92

are comparable to TFD, except for the Summer Monsoon and Post-Monsoon season, when the thickness of mixed layer is found to be almost double of the turbulent flow. This can be attributed to the fact that, during this two seasons, the lower atmosphere generally experiences high wind speeds, in turn reducing the thickness of turbulent flow, whereas the thermal convection helps in the rise of altitude of mixed layer.

In Figure 5, we show the seasonal variations in MLH, TFD, and SBFT by grouping all the datasets to respective seasons. The error bars associated to these parameters indicate their standard deviations for the season. The mean MLH variations are found to be ranging from 300 m to 500 m, with a peak during the summer monsoon, which can be attributed to strong convective activities prevailing over this season. In contrast to this, the MLH exhibits relatively lower values during the Winter Monsoon, as an indication of suppressed convection in the season. Seasonal variability in TFD is almost in tune with that of the MLH, except for the Summer Monsoon and Post-Monsoon season, where MLH is high, and can be attributed to prevailing convective conditions in the season. It is interesting to note that Srivastava et al. (2010) have also shown a similar variability in MLH over Ahmedabad, one of the tropical urban sites in India [31]. The magnitudes of TFD exhibit a steady picture throughout the year with a mean of about 330 m, as against large variabilities in the MLH magnitudes. From the estimates of TFD for different seasons, it is coincidental to see that larger wind speeds for a given season (such as during the Summer Monsoon and Post-Monsoon) often results in suppressed magnitudes of TFD, in turn indicating the shrinking of turbulent flow in presence of strong winds. The vertical thickness in sea breeze flow, shown by SBFT, shows a large peak of about 900 m in the Pre-Monsoon and Post-Monsoon seasons, indicating the increased strength of sea breeze flow in the respective season. During the Summer Monsoon, the sea breeze flow coincides with the prevailing wind circulation, hence it is difficult to comment on its variability.

7. Summary and Concluding Remarks

In this paper, we made use of upper-air meteorological observations for a period of more than two years obtained from balloon-borne Pisharoty Sondes over Thumba, a coastal station on the Western Coastline of the Indian subcontinent, for characterization of the vertical structure of the CABL. Three different techniques were adopted for quantification of mixed layer heights, turbulent flow depth, and sea breeze flow thickness. The important findings from the study are summarized below.

(1) Mixed layer heights (MLH) quantified through θ_v gradient method showed variations within a range of 310 m to 650 m with a mean of about 420 m, whereas the turbulent flow depth (TFD) derived through Ri_B varied between 175 m to 560 m with a mean of about 330 m. The magnitudes of MLH were always larger than those of the TFD.

(2) Thickness of sea breeze flow (SBFT) varied between 500 m to 910 m with a mean of about 760 m. In general, the magnitudes of SBFT were larger than those of the MLH and TFD, indicating the dominance of sea breeze flow over the study domain. Large values of SBFT occur in the Pre- and Post-Monsoon seasons.

(3) Due to strong influence of the sea/land breeze circulation during Winter Monsoon, Pre-Monsoon, and Post-Monsoon seasons, formation of thermal internal boundary layer was eminent over the study domain, which was not very clear in the Summer Monsoon.

(4) Irrespective of the prevailing season, the magnitudes of TFD remained steady all through the year, whereas the MLH showed large variability with a peculiar peak in the Summer Monsoon and is attributed to enhanced convective activities prevailing in the season.

Acknowledgments

The authors sincerely acknowledge Dr. K. Krishnamoorthy, Director, SPL for his consistent support to Boundary Layer Physics and Atmospheric Modelling activities at SPL, VSSC. The authors are very much grateful to Dr. S. Satyanarayana, Group Director, RF Advanced Technology and Facilities Division, VSSC and his colleagues for their technical support related to balloon-borne GPS ascents and data recording. The authors wish to mention a special word of thanks to all the members of MET Facility, VSSC for their logistic and technical support in smooth functioning of balloon-borne GPS ascents during the period of study. The NCEP-FNL Reanalysis data for this study are from the Research Data Archive (RDA) which is maintained by the Computational and Information Systems Laboratory (CISL) at the National Center for Atmospheric Research (NCAR). NCAR is sponsored by the National Science Foundation (NSF). The original data are available from the RDA (http://dss.ucar.edu/) in dataset number ds083.2. One of the authors, Ms. T. J. Anurose, is thankful to the Indian Space Research Organization for sponsoring fellowship for her Ph.D. research work.

References

[1] J. R. Garratt, *The Atmospheric Boundary Layer*, Cambridge University Press, New York, NY, USA, 1992.

[2] T. R. Oke, *Boundary Layer Climates*, Halsted Press, New York, NY, USA, 1988.

[3] R. B. Stull, *An Introduction to Boundary Layer Meteorology*, Kluwer Academic, Dodrecht, The Netherlands, 1988.

[4] C. M. Bhumralkar, "Parameterization of the planetary boundary layer in atmospheric general circulation models," *Reviews of Geophysics and Space Physics*, vol. 14, no. 2, pp. 215–226, 1976.

[5] P. Seibert, F. Beyrich, S. E. Gryning, S. Joffre, A. Rasmussen, and P. Tercier, "Review and intercomparison of operational methods for the determination of the mixing height," *Atmospheric Environment*, vol. 34, no. 7, pp. 1001–1027, 2000.

[6] B. Medeiros, A. Hall, and B. Stevens, "What controls the climatological depth of the PBL?" *Journal of Climate*, vol. 18, pp. 2877–2892, 2005.

[7] G. C. Holzworth, "Mixing depths, wind speeds and air pollution potential for selected locations in the United States," *Journal of Applied Meteorology*, vol. 6, pp. 1039–1044, 1967.

[8] D. H. P. Vogelezang and A. A. M. Holtslag, "Evaluation and model impacts of alternative boundary-layer height formulations," *Boundary-Layer Meteorology*, vol. 81, no. 3-4, pp. 245–269, 1996.

[9] D. B. Subrahamanyam, R. Ramachandran, K. S. Gupta, and T. K. Mandal, "Variability of mixed-layer heights over the Indian ocean and Central Arabian sea during Indoex, IFP-99," *Boundary-Layer Meteorology*, vol. 107, no. 3, pp. 683–695, 2003.

[10] D. P. Alappattu, D. B. Subrahamanyam, and P. K. Kunhikrishnan, "On the marine atmospheric boundary layer characteristics over Bay of Bengal and Arabian Sea during the Integrated Campaign for Aerosols, gases and Radiation Budget (ICARB)," *Journal of Earth System Science*, vol. 960, no. S1, pp. 281–291, 2008.

[11] M. V. Ramana, P. Krishnan, S. M. Nair, and P. K. Kunhikrishnan, "Thermodynamic structure of the atmospheric boundary layer over the Arabian Sea and the Indian Ocean during pre-INDOEX and INDOEX-FFP campaigns," *Annales Geophysicae*, vol. 22, no. 8, pp. 2679–2691, 2004.

[12] D. J. Seidel, C. O. Ao, and K. Li, "Estimating climatological planetary boundary layer heights from radiosonde observations: comparison of methods and uncertainty analysis," *Journal of Geophysical Research D*, vol. 115, no. 16, 2010.

[13] A. K. Georgoulias, D. K. Papanastasiou, D. Melas, V. Amiridis, and G. Alexandri, "Statistical analysis of boundary layer heights in a suburban environment," *Meteorology and Atmospheric Physics*, vol. 104, no. 1-2, pp. 103–111, 2009.

[14] D. B. Subrahamanyam and R. Ramachandran, "Structural characteristics of marine atmospheric boundary layer and its associated dynamics over the Central Arabian Sea during INDOEX, IFP-99 campaign," *Current Science*, vol. 85, no. 9, pp. 1334–1340, 2003.

[15] S. I. Rani, R. Ramachandran, D. B. Subrahamanyam, D. P. Alappattu, and P. K. Kunhikrishnan, "Characterization of sea/land breeze circulation along the west coast of Indian subcontinent during pre-monsoon season," *Atmospheric Research*, vol. 95, no. 4, pp. 367–378, 2010.

[16] P. K. Kunhikrishnan, K. S. Gupta, R. Radhika, J. W. J. Prakash, and K. N. Nai, "Study on thermal internal boundary layer structure over Thumba, India," *Annales Geophysicae*, vol. 11, pp. 52–60, 1993.

[17] J. W. Jeeva Prakash, R. Ramachandran, K. N. Nair, K. Sen Gupta, and P. K. Kunhikrishnan, "On the structure of sea-breeze fronts observed near the coastline of Thumba, India," *Boundary-Layer Meteorology*, vol. 59, no. 1-2, pp. 111–124, 1992.

[18] R. Ramachandran, J. W. J. Prakash, K. S. Gupta, K. N. Nair, and P. K. Kunhikrishnan, "Variability of surface roughness and turbulence intensities at a coastal site in India," *Boundary-Layer Meteorology*, vol. 70, no. 4, pp. 385–400, 1994.

[19] D. B. Subrahamanyam, K. S. Gupta, S. Ravindran, and P. Krishnan, "Study of sea breeze and land breeze along the west coast of Indian sub-continent over the latitude range 15N to 8N during INDOEX IFP-99 (SK-141) cruise," *Current Science*, vol. 80, supplement, pp. 85–88, 2001.

[20] S. Satyanarayana, "GPS radiosonde development," *Technology Development for Atmospheric Research and Applications*, pp. 142–188, 2008.

[21] C. G. Holzworth, "Estimates of mean maximum mixing depths in the contiguous united states," *Monthly Weather Review*, vol. 92, no. 1964, pp. 235–242, 1964.

[22] X. Zeng, M. A. Brunke, M. Zhou, C. Fairall, N. A. Bond, and D. H. Lenschow, "Marine atmospheric boundary layer height over the Eastern Pacific: data analysis and model evaluation," *Journal of Climate*, vol. 17, no. 21, pp. 4159–4170, 2004.

[23] J. H. Sørensen, "Sensitivity of the derma long-range gaussian dispersion model to meteorological input and diffusion parameters," *Atmospheric Environment*, vol. 32, no. 24, pp. 4195–4206, 1998.

[24] K. Borne, D. Chen, and M. Nunez, "A method for finding sea breeze days under stable synoptic conditions and its application to the Swedish west coast," *International Journal of Climatology*, vol. 18, no. 8, pp. 901–914, 1998.

[25] D. Bala Subrahamanyam and T. J. Anurose, "Solar eclipse induced impacts on sea/land breeze circulation over Thumba: a case study," *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 73, no. 5-6, pp. 703–708, 2011.

[26] V. Narayanan, "An observational study of sea breeze at an equatorial coastal station," *Indian Journal of Meteorology and Geophysics*, vol. 18, pp. 497–504, 1967.

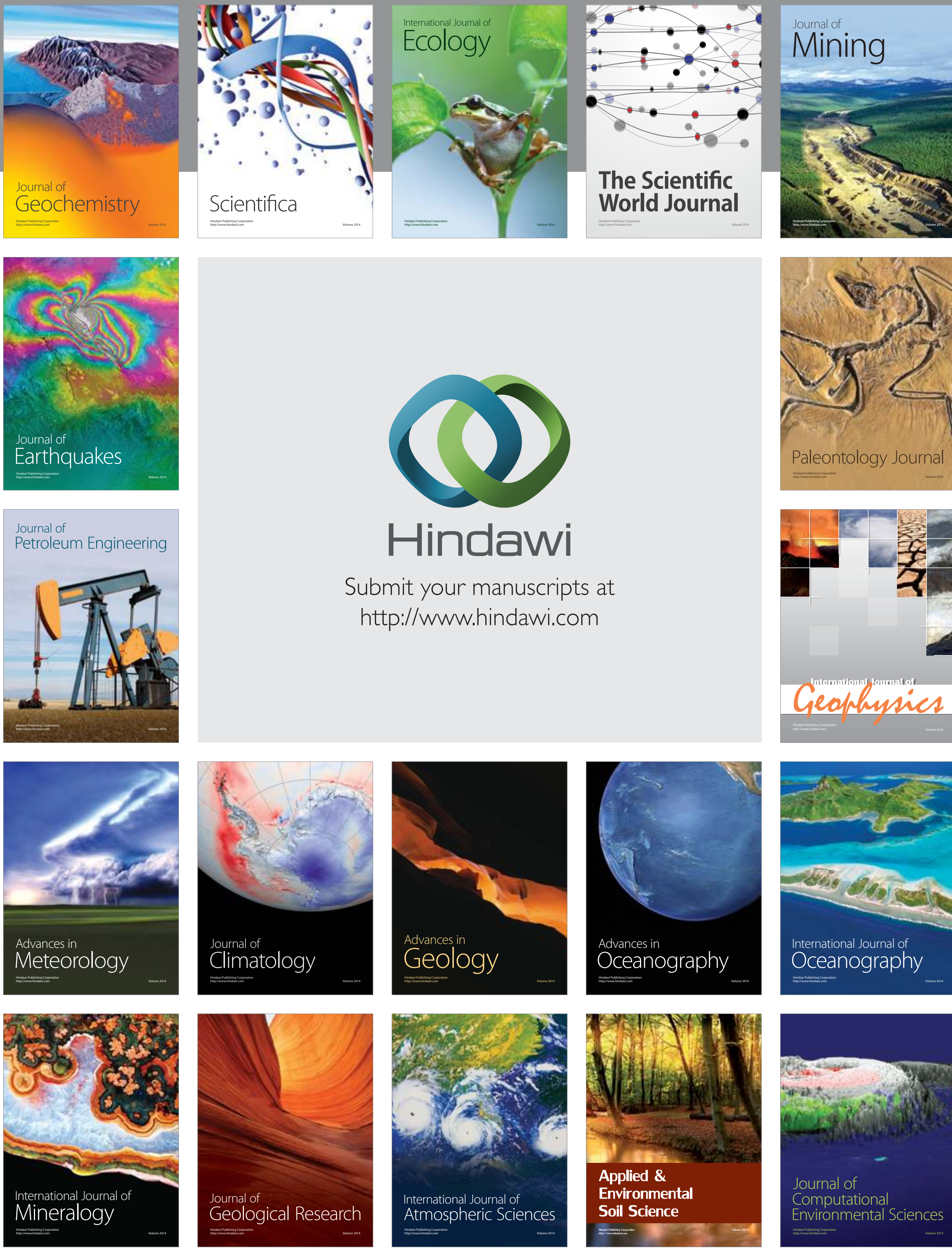
[27] P. K. Kunhikrishnan, R. Ramachandran, D. P. Alappattu, N. V.P. Kiran Kumar, and D. Bala Subrahamanyam, "A case-study of sea breeze circulation at thumba coast through observations and modelling," in *Remote Sensing and Modeling of the Atmosphere, Oceans, and Interactions*, vol. 6404 of *Proceedings of SPIE*, Goa, India, November 2006.

[28] J. W. J. Prakash, R. Ramachandran, K. N. Nair, K. S. Gupta, and P. K. Kunhikrishnan, "On the spectral behaviour of atmospheric boundary-layer parameters at Thumba, India," *Quarterly Journal—Royal Meteorological Society*, vol. 119, no. 509, pp. 187–197, 1993.

[29] E. Kalnay, M. Kanamitsu, R. Kistler et al., "The NCEP/NCAR 40-year reanalysis project," *Bulletin of the American Meteorological Society*, vol. 77, no. 3, pp. 437–471, 1996.

[30] P. K. Das, *The Monsoons*, National Book Trust, New Delhi, India, 2009.

[31] S. Srivastava, S. Lal, D. B. Subrahamanyam, S. Gupta, S. Venkataramani, and T. A. Rajesh, "Seasonal variability in mixed layer height and its impact on trace gas distribution over a tropical urban site: ahmedabad," *Atmospheric Research*, vol. 96, no. 1, pp. 79–87, 2010.


Journal of Geochemistry
Scientifica
International Journal of Ecology
The Scientific World Journal
Journal of Mining
Journal of Earthquakes
Hindawi
Submit your manuscripts at
http://www.hindawi.com
Paleontology Journal
Journal of Petroleum Engineering
International Journal of Geophysics
Advances in Meteorology
Journal of Climatology
Advances in Geology
Advances in Oceanography
International Journal of Oceanography
International Journal of Mineralogy
Journal of Geological Research
International Journal of Atmospheric Sciences
Applied & Environmental Soil Science
Journal of Computational Environmental Sciences