Atmospheric Research 195 (2017) 44–61

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

# Planetary boundary layer height over the Indian subcontinent: Variability and controls with respect to monsoon

Anusha Sathyanadh[a], Thara Prabhakaran[b], Chetana Patil[a], Anandakumar Karipot[a],*

[a] Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune 411 007, Maharashtra, India
[b] Indian Institute of Tropical Meteorology, Pune 411 008, Maharashtra, India

ARTICLE INFO

*Keywords:*
Planetary boundary layer height
Boundary layer regimes
Monsoon boundary layer
Controls on PBL
MERRA PBL

ABSTRACT

Planetary boundary layer (PBL) height characteristics over the Indian sub-continent at diurnal to seasonal scales and its controlling factors in relation to monsoon are investigated. The reanalysis (Modern Era Retrospective analysis for Research and Applications, MERRA) PBL heights (PBLH) used for the study are validated against those derived from radiosonde observations and radio occultation air temperature and humidity profiles. The radiosonde observations include routine India Meteorological Department observations at two locations (coastal and an inland) for one full year and campaign based early afternoon radiosonde observations at six inland locations over the study region for selected days from May–September 2011. The temperature and humidity profiles from radio occultations spread over the sub-continent at irregular timings during the year 2011. The correlations and root mean square errors are in the range 0.74–0.83 and 407 m–643 m, respectively. Large pre-monsoon, monsoon and post-monsoon variations in PBL maximum height (1000 m–4000 m), time of occurrence of maximum height (11:00 LST–17:00 LST) and growth rate (100 to 400 m $h^{-1}$) are noted over the land, depending on geographical location and more significantly on the moisture availability which influences the surface sensible and latent heat fluxes. The PBLH variations associated with active-break intra-seasonal monsoon oscillations are up to 1000 m over central Indian locations. Inter relationship between the PBLH and the controlling factors, i.e. Evaporative Fraction, net radiation, friction velocity, surface Richardson number, and scalar diffusivity fraction, show significant variation between dry and wet PBL regimes, which also varies with geographical location. Evaporative fraction has dominant influence on the PBLH over the region. Enhanced entrainment during monsoon contributes to reduction in PBLH, whereas the opposite effect is noted during dry period. Linear regression, cross wavelet and Analysis of Variance (ANOVA) methods are used to elucidate the role of controlling factors and interactions on PBLH in relation to monsoon.

## 1. Introduction

The Planetary Boundary Layer (PBL), the lowest layer of the atmosphere in contact with Earth's surface, undergoes large spatio-temporal variations in relation to geographical location, land surface cover, soil characteristics, terrain elevation, seasons and weather conditions. The PBL height (PBLH) could vary over a wide range, from a few tens of meters to couple of kilometres. The PBLH variability is dominated by strong diurnal cycle (Stull, 1988; Garratt, 1992), mainly driven by the incoming solar radiation (Breuer et al., 2012). Besides this, the growth and characteristics of PBL over land depends on multiple forcing mechanisms related to cloudiness, soil moisture, surface temperature, mesoscale convergence, low-level cold-air advection, and synoptic-scale subsidence (Gupta and Ramachandran, 1998; Santanello et al., 2005; Bianco et al., 2011). The oceanic boundary layers are shallow and PBLH variations are rather slow and weak (McGrath-Spangler and Denning, 2013). The understanding of the PBLH variations are a key problem in properly simulating the weather and climate. The numerical models illustrate different controls on the PBLH and its variations depending on the type of PBL (Jousse et al., 2016).

Several studies were carried out globally to understand the causes of PBLH variations. Medeiros et al. (2005) in their investigation on 'what controls the mean depth of PBL' found that increase in surface temperature destabilizes the lower atmosphere which allows convective mixing to increase the PBL depth up to the lifting condensation level (LCL). Over continental areas, mainly through its influence on partitioning energy between sensible and latent heat fluxes, soil moisture affects the boundary layer structure and growth (e.g., McCumber and Pielke, 1981; Pan and Mahrt, 1987; Findell and Eltahir, 2003; Breuer

* Corresponding author.
*E-mail address:* akaripot@unipune.ac.in (A. Karipot).

http://dx.doi.org/10.1016/j.atmosres.2017.05.010
Received 22 July 2016; Received in revised form 18 May 2017; Accepted 18 May 2017
Available online 19 May 2017
0169-8095/ 

et al., 2012). Findell and Eltahir (2003) reported that dry soils are more probable for triggering convective BL compared to wet soils. Santanello et al. (2005) investigated the evolution of boundary layer and its relationship with land surface processes and demonstrated that 76% of the variance in PBLH can be explained by atmospheric stability and soil moisture content. Clouds influence the mean structure and turbulence of the PBL through induced circulations, shading effects, modification in radiation fields and through precipitation (Randall et al., 1985; Jousse et al., 2016). Seasonal shift of large-scale high/low pressure systems can suppress/facilitate the development of boundary layer through the associated large- scale motion (Medeiros et al., 2005; Guo et al., 2016).

Several regional studies were also reported on the controlling factors of PBLH. Tang et al. (2016) have shown that sensible heat flux influence the enhancement of mixed layer height over Beijing, China. Another sounding based study over China (Guo et al., 2016) noticed climatologically strongest near-surface wind speed in spring (Zhao et al., 2009; Guo et al., 2011) and the intense solar radiation in summer (Miao et al., 2012, 2015) are favouring the development and growth of boundary layer. A tendency of higher PBLH over high elevation regions in the United States have been reported by Seidel et al. (2012) and are assumed to be due to the local land surface and hydrological processes. The BLs over coastal regions are highly influenced by land-sea breeze circulations and associated internal boundary layer formation (Nair et al., 2011; De Tomasi et al., 2011). Jousse et al. (2016) showed that sensible and latent heat fluxes are potential drivers of the BL deepening/thinning over the southeast Pacific stratocumulus region. Liu and Liang (2010) presented an observational climatology of the PBLH across a wide range of geographical locations with various surface characteristics. The PBL in the tropics differ from those in the middle and high latitudes due to the dominance of moist processes. The controlling factors on the PBL growth and evolution over the continental Indian monsoon region are addressed in the present study.

During Indian southwest monsoon season (June–September), surface conditions and forcing mechanisms undergo large variations in relation to associated circulation and rainfall, which significantly influences PBL characteristics. Observational studies over selected locations have indicated that PBLHs are higher during break phase induced by strong surface heating and related convection, whereas lower PBL heights prevail during active monsoon with mostly cloudy and wet surface conditions. Kusuma et al. (1991) reported a PBLH difference of 1 to 2 km between active and break spells near the northwestern desert region and 100 to 500 m near the coastal locations. Sandeep et al. (2014) studied the boundary layer characteristics using wind profiler and micrometeorological measurements over a Southern Peninsular location, and found low BL height as well as delayed growth during wet active periods, which they attributed mainly to reduced buoyancy fluxes. Similar results were also found by Mohan and Rao (2012) at the same location. Variations in monsoon low-level jet speed during active and break phases of monsoon are found to influence the friction velocity and convective boundary layer (CBL) height (Hamza et al., 2007; Sandeep et al., 2014). Active - break variations in PBL features are also reported over the oceans surrounding Indian subcontinent, the Arabian Sea and Bay of Bengal (Holt and Sethuraman, 1987; Sam et al., 2003).

Over the Indian subcontinent, very few detailed studies have been carried out to understand spatio-temporal characteristics of PBLH and their controlling factors. The reported studies are limited to selected locations, mainly due to lack of spatially distributed continuous observational data. Considering this aspect, the present study is formulated with the following objectives: i) to validate PBLH from a recent reanalysis product, Modern Era Retrospective analysis for Research and Applications version 2 (MERRA-2), against radiosonde and Global Positioning System Radio Occultation (GPS RO) derived PBL height over the Indian subcontinent and ii) to investigate spatial and temporal variations of PBLH in relation to monsoon and iii) to understand the influence of controlling factors on PBLH. The controlling factors are investigated with the help of wavelet cross-product and Analysis of variance (ANOVA) methods.

## 2. Data and methods

Indian subcontinent and surrounding oceans confined between 5°N to 38.5°N and 60°E to 100°E is selected for the present study. One very important feature of the study region is the occurrence of seasonal reversal of winds, referred as monsoon circulations, and associated rainfall. The country as a whole, except south-eastern peninsula, receives rainfall largely from southwest (SW) monsoon during June–September (JJAS) whereas southeast peninsular region's major rainfall contribution is from northeast (NE) monsoon in the months of October–December. The onset of SW monsoon takes place over southwestern tip of peninsular India near 1st June, advances northwards and covers most of continental India by 1st week of July. Indian Summer Monsoon Rainfall (ISMR) is well known for its large intra-seasonal and inter-annual spatio-temporal variability (e.g. Ramamurthy, 1969; Goswami and Ajayamohan, 2001), which comprises of active periods of high rainfall and break periods with weak or no rainfall over central India and the west coast, each phase lasting for a few days (Krishnamurthy and Kinter, 2003). Primary reasons for these large variations are associated with the intensification and displacement of the monsoon trough (or ITCZ) and the monsoon depressions (e.g., Gadgil, 2003; Rajeevan et al., 2010). In addition to monsoon rainfall, several geographical regions receive pre-monsoon showers between March–May and northern India receives rainfall in winter months from western disturbance. The annual average rainfall over different geographical locations exhibit large variations between 20 and 400 cm, with an average all India annual rainfall of 90 cm (Guhathakurta and Rajeevan, 2008). The PBL height characteristics and its variation in relation to the above monsoon features is the focus of present study.

### 2.1. Data

Various datasets used in the present study is summarized in Table 1. All estimates of PBLH are with reference to the height above ground level, to rule out the effect of topographic variation. Primary source of data used is MERRA-2 reanalysis products (Bosilovich et al., 2015), an improved version of MERRA-1 (Bosilovich, 2008; Rienecker et al., 2011), which include long-term continuous reanalysis data (from 1980 to present day) produced using the Goddard Earth Observing System-version 5 (GEOS-5) global atmospheric general circulation model by assimilating a host of ground based in situ observations, satellite remote sensing data, hyperspectral microwave observations and GPS RO data. MERRA-2 will be referred as MERRA hereafter. The MERRA PBL height corresponds to the lowest model level at which the eddy diffusivity falls below a threshold value of $2\ m^2\ s^{-1}$.

The MERRA PBL heights are validated against PBL heights derived from GPS RO (Kursinski et al., 1997) refractivity profiles over the study domain, and routine as well as campaign based radiosonde observations at selected locations. The satellite based GPS RO soundings at a particular location is available only when an occultation occurs over that location (Anthes et al., 2008), and thus the time and location of the profiles are not fixed. A total of 5582 GPS occultation occurred over the study domain at different timings during 2011. The refractivity profiles reaching up to the surface are only used for PBLH estimation, which counts to 1140 RO profiles. The RO measurements are insensitive to clouds and precipitation, so it is considered to be best suited for studying the tropospheric characteristics (Kursinski et al., 1997; Zeng et al., 2008).

Validation using radiosonde data are carried out with two datasets: i) Observations conducted by the Indian Institute of Tropical Meteorology as a part of the Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX; Kulkarni et al.,