Journal of Atmospheric and Solar-Terrestrial Physics 92 (2013) 94–99

Contents lists available at SciVerse ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

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

Planetary Boundary Layer height over the Indian subcontinent during extreme monsoon years

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ARTICLE INFO

Article history:
Received 13 February 2012
Received in revised form
27 August 2012
Accepted 9 October 2012
Available online 9 November 2012

Keywords:
Planetary Boundary Layer
Indian summer monsoon
Extreme monsoon years
Convection
Low level jet

ABSTRACT

Planetary Boundary Layer (PBL) plays an important role in the regional monsoon circulation by exchanging heat and moisture between the earth surface and free atmosphere. However, PBL climatology over the Indian sub-continent in the context of extreme monsoon conditions is not available for its use in the regional climate models. In this study, a large-scale seasonal feature of PBL height over the Indian sub-continent is explored with 40 years (1961–2000) ERA-40 reanalysis data. The variations in the PBL height associated with excess and deficient monsoons over India are examined. The seasonal climatology showed higher PBL height during pre-monsoon (spring) and monsoon seasons as compared to post-monsoon and winter. For the extreme monsoon situations, PBL over the north-west (NW) India has greatly reciprocated. Over the NW India, during deficient monsoon years, composite anomalies of the PBL are observed to be negative indicating large reduction in PBL. Whereas during excess monsoon years, observed positive anomalies suggest increase in the PBL. During excess (deficient) monsoon years, the convection and the LLJ are found to be stronger (weaker) associated with the higher (lower) PBL height.

1. Introduction

The Planetary Boundary Layer (PBL) located in the lower part of troposphere, forms as a consequence of interactions between the atmosphere and the underlying surface (land or water) over time scale of a few hours to about a day (Garratt, 1992; Arya, 1988; Stull, 1988). The PBL disperses (horizontally and vertically) heat and moisture from surface, effectively air-conditioning the biosphere and providing a conduit for energy to power the weather system on all scales. Thus, the turbulent nature of the PBL is one of its most conspicuous features and can be considered as the circulatory system of the biosphere in many aspects. The large-scale monsoon over India is characterized by the intra-seasonal oscillations (Sikka and Gadgil, 1980) associated with PBL. During weak and active phases of the monsoon, the PBL over Indian sub-continent showed different characteristics (Parasnis and Morwal, 1991; Parasnis, 1991; Kusuma et al., 1991). During active monsoon conditions, the surface wind speed, sensible and latent heat fluxes were increased over the Arabian Sea (Holt and Sethuraman, 1987) and Bay of Bengal (Sivaramakrishnan et al., 1996).

El Niño and La Niña are well known to be associated with significant monthly/seasonal climate anomalies at many places around the globe. El Niño/La Niña events have significant relationship with the relative frequency of climate extremes (Wolter et al., 1999) and deficient/excess Indian summer monsoon rainfall (ISMR) respectively. However, with the changing atmospheric general circulation pattern across the globe, decreasing influence of El Niño (Krishna Kumar et al., 1999; Annamalai et al., 2007; Turner et al., 2007) and increasing influence of the Indian Ocean Dipole (IOD) (Behera et al., 1999; Ashok et al., 2001) on the ISMR have been reported. The response of the ISMR to the tropical Pacific SST anomaly pattern is more sensitive (Keshavamurthy, 1982; Krishna Kumar et al., 2006; Kim et al., 2009).

Most of the PBL studies mentioned above are based on small period data particularly over the Indian monsoon trough region, Arabian Sea and Bay of Bengal, but its large-scale feature as well as dynamics and thermodynamics with extreme Indian summer monsoons are not yet studied due to unavailability of PBL height dataset. In this study, we analyzed the ERA-40 reanalysis data to bring out the anomalous feature of PBL height in the excess and deficient monsoon years. Its interaction with the convection and the low level jet (LLJ) stream is explored. Also, the long-term 40 years (1961–2000) means seasonal PBL height climatology over the Indian sub-continent is brought out.

2. Data and analysis

European Center for Medium-Range Weather Forecasts (ECMWF) has produced an ERA-40 re-analysis data set from meteorological

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http://dx.doi.org/10.1016/j.jastp.2012.10.011

Table 1
All-India summer monsoon rainfall (AISMR) in mm for excess and deficient monsoon years during the period 1961–2000 (Parthasarathy et al., 1994).

Excess monsoon rainfall			Deficient monsoon rainfall		
Year	AISMR (mm)	% departure from normal	Year	AISMR (mm)	% departure from normal
1961	1020.3	20.1	1965	709.4	−16.5
1970	939.8	10.6	1966	739.9	−12.9
1975	962.9	13.3	1968	754.6	−11.2
1983	955.7	12.5	1972	652.9	−23.1
1988	961.5	13.2	1974	748.2	−12.0
1994	952.1	12.1	1979	707.8	−16.7
			1982	735.4	−13.5
			1987	697.3	−17.9

observations accumulated from many sources. The 'second-generation' ERA-40 re-analysis would provide better products than those from the first-generation ERA-15 and NCEP-NCAR re-analysis (Uppala et al., 2005). Further, it has been suggested that ERA-40 provided higher horizontal and vertical resolution in the PBL than the ones provided by the earlier re-analyses ERA-15. The ERA-40 re-analysis fields showed good agreement with the PBL heights derived from radiosonde data (Von Engeln et al., 2003) over ten stations spread in the latitudinal and longitudinal domain of 32°63′N to 37°8′S and 77°53′E to 22°95′W respectively. Long-term re-analysis runs such as ERA-40 reanalysis dataset are still the best source of global climatological information for many variables (Simmons and Gibson, 2000; Simmons et al., 2006–07) and hence are widely used by numerous researchers across the globe.

In the present analysis, we considered the monthly mean PBL height dataset (http://data-portal.ecmwf.int/data/d/era40_moda/) for 40 years (1961–2000) with $2.5 \times 2.5^{\circ}$ latitude/longitude grid resolution during winter (December, January and February), pre-monsoon (March, April and May), summer monsoon (June, July, August and September) and post-monsoon (October and November) seasons over the Indian sub-continent. The monthly Outgoing Longwave Radiation (OLR) and 850 hPa level zonal wind data for the period of 1961–2000 have been considered from NCEP/NCAR re-analysis (Kalnay et al., 1996). Excess as well as deficient ISMR, which is part of the natural inter-annual variability, tends to have an adverse impact on Indian economy and social life. If ISMR during the year exceeds the long-term mean by more than one standard deviation, then the year is defined as an excess rainfall year, and if it is less than the long-term mean by one standard deviation, then the year is considered as a deficient rainfall year (Parthasarathy et al., 1994). With these criteria, among the 40 years (1961–2000) dataset, we extracted 6 excess and 8 deficient monsoon rainfall years as shown in Table 1.

3. Spatial pattern of PBL height over Indian sub-continent

The PBL height depends upon the convection available at the earth surface, synoptic weather pattern and existing land surface conditions, which vary from place to place. Fig. 1 shows the climatological feature of 40 years (1961–2000) mean PBL height over the Indian sub-continent for the different seasons of India i.e. (a) pre-monsoon, (b) summer monsoon, (c) post-monsoon and (d) winter. It is seen that the PBL height is greater over the region of NW India in monsoon season and over the Tibetan plateau in winter season. Otherwise, in the pre-monsoon season, most parts of Indian sub-continent are covered with large PBL height (~1800 m) mainly because of intense solar heating in this season. Also, interestingly, it is seen that PBL height is gradually increasing from south to north and the highest PBL height is confined over the NW India in monsoon season. The minimum PBL height is seen over the Arabian Sea and the Head Bay of Bengal in the monsoon season.

The experimental observations over the Bay of Bengal showed PBL height in the range of 400–1200 m in pre-monsoon (Allappattu and Kunhikrishnan, 2010), 100–900 m in the monsoon (Bhat, 2003) and 50–900 m in the post-monsoon season (Bhat et al., 2000). The PBL height over the Arabian Sea was observed in the range of 375–1200 m in the pre-monsoon (Allappattu and Kunhikrishnan, 2010) and 300–800 m in the winter season (Ramana et al., 2004). Over the continental region of NW India, over Delhi (28°36′N. 77°12′E), the PBL maxima are observed nearly 3000, 5000, 2000 and 1000 m in pre-monsoon, monsoon, post-monsoon and winter seasons respectively (Gamo et al., 1994). Over the station Anand (22°35′N, 72°55′E) in NW India, Nagar et al. (2001) observed the PBL height in the range of 1500–3000 m in the month of May 1997 (pre-monsoon). Over the station Kharagpur (22°30′N, 87°20′E), the maximum PBL height was observed to be nearly 900 m (Parasnis and Morwal, 1994). These observed PBL heights over continental as well as oceanic stations of India are consistent with the mean climatology of PBL height shown in Fig. 1. The Inter Tropical Convergence Zone (ITCZ) is extending towards NW India in the pre-monsoon and shifts maximum northward in the monsoon season (Sikka and Gadgil, 1980). During the pre-monsoon and monsoon seasons, Zeng et al. (2004) found large PBL height in the ITCZ region corroborating our findings.

In the monsoon season, NW Indian region is the seat of relatively low pressure and it is more or less persistent throughout the monsoon. Also, it is a heat low region. The warm water of Bay of Bengal acts as a heat and moisture source and transfers it towards the north-west Indian region with monsoon winds. Therefore, PBL height is increasing from the Bay of Bengal towards the NW region (Rajasthan) of India in the monsoon season. Over the Bay of Bengal, PBL height is found to be less with more cloudiness, whereas over the NW region (Rajasthan), PBL height is higher with less cloudiness. Sikka and Narasimha (1995) have also reported that NW region of India has less moisture whereas the Bay of Bengal region has more moisture, which leads to the deep convection (more cloudiness) over Bay of Bengal and dry convection (less cloudiness) over NW India (Rajasthan). Thus, we found greater PBL height in the region of dry convection and less cloudiness.

4. PBL height during excess and deficient monsoon years

During deficient and excess monsoon years (see Table 1), the composite anomalies for PBL height computed from the 40 years (1961–2000) mean in monsoon season are shown in Fig. 2. It can be seen that during deficient years, the negative anomalies of PBL height have prevailed over the Indian subcontinent, which indicated reduction in the PBL height. Otherwise during the excess monsoon years (Fig. 2b), there were positive anomalies that show increase in PBL height. In the monsoon season, we observed the deeper PBL