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Annual variations of the altitude distribution of aerosols and effect of long-range transport over the southwest Indian Peninsula

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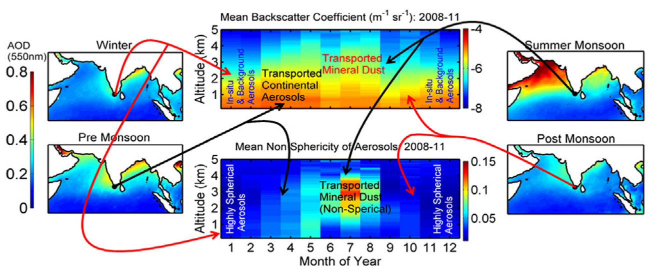
HIGHLIGHTS

- Long-term observations of aerosol altitude distribution in tropical Indian coast.
- Elevated layers of highly non-spherical aerosols in widespread aerosol plumes.
- Long-range transport enhances aerosol loading at 2–4 km altitude by 5–10 times.
- Highly systematic and prominent annual variation of aerosols at 2–4 km altitude.
- Variation of aerosol loading at <1 km altitude during different seasons are <20%.

GRAPHICAL ABSTRACT



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ABSTRACT

Annual variations of the altitude distribution of aerosols and the effect of long-range transport in modulating the aerosol loading over Thiruvananthapuram (8.5°N, 77°E), a relatively clean tropical station located in the southwest coast of Peninsular India, are investigated using dual polarization Micro Pulse Lidar observations carried out during March 2008–May 2011. Combined analysis of these lidar observations with the spatial distribution of aerosols derived from satellite data shows the occurrence of elevated layers of highly non-spherical aerosols in the 1.5–4 km altitude region, which are associated with the wide-spread aerosol plumes over the Arabian Sea during the pre-monsoon and summer-monsoon seasons. In contrast, ~90% of the column integrated aerosol backscatter coefficient (β_a) (below 5 km altitude) occurs below ~1.5 km during winter. Seasonal variation of mean β_a below ~1 km altitude is <20%. Altitude profiles of β_a above ~1 km during January – characterised by the smallest values of β_a, absence of elevated aerosol layers, and weak atmospheric winds – may be considered as the upper limit of the contribution by locally produced aerosols for quantifying the effect of long-range transport during the other months. Compared to January, a 3–10 fold increase in β_a occurs in the 2–4 km altitude region during April–May and July–August. The elevated layers contribute ~20–30% of the total aerosol loading during the above months.

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1. Introduction

Atmospheric aerosols significantly modulate the radiation budget, cloud properties, atmospheric thermodynamics, and overall climate of the Earth-atmosphere system (*e.g.*, IPCC, 2007).

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Knowledge of the spatial and vertical distribution of aerosols is essential for quantifying the effect of long-range transport in modulating the aerosol abundance at regions far from their sources (*e.g.,* Rajeev et al., 2010). Altitude distribution of aerosols has an important bearing on the radiative heating and hence the thermal stability of the atmosphere (Thampi et al., 2009) as well as the semi-direct effect of aerosols (Ackerman et al., 2000). Aerosol-cloud interaction and the indirect effect of aerosols (Albrecht, 1989) also depend on their vertical distribution. These effects of aerosols on clouds, radiation budget and hydrological cycle are among the major uncertainty factors in climate prediction (IPCC, 2007). As the atmospheric residence time of aerosols in the lower and middle troposphere is rather small (typically less than a week), the aerosol distribution undergoes considerable spatial variations, and should be studied on a regional scale.

Indian subcontinent and the oceanic regions surrounding it are considerably influenced by the long-range transport of aerosols (*e.g.,* Moorthy et al., 1997, 2010; Satheesh and Ramanathan, 2000; Ramanathan et al., 2001; Ramachandran, 2004; Jayaraman et al., 2006; Niranjan et al., 2007; Lawrence and Lelieveld, 2010). Satellite observations showed that the transport of aerosols from the Asian continent to the adjoining oceans increases from winter (December–February) to pre-monsoon (Mar–May) season and maximizes during the summer monsoon season (June–September) (Nair et al., 2005). Detailed investigations on the aerosol properties over the Arabian Sea were conducted during the Indian Ocean Experiment (INDOEX) (Ramanathan et al., 2001) and the Integrated Campaign for Aerosols, gases and Radiation Budget (ICARB) (Moorthy et al., 2010), as well as the earlier ship-borne measurements conducted as part of various scientific expeditions (*e.g.,* Moorthy et al., 1997). During the pre-monsoon season, oceanic regions around the Indian subcontinent are significantly influenced by the long-range transport of continental aerosols from Arabia, Indian subcontinent and Southeast Asia, leading to a pronounced aerosol plume off the southwest coast of Peninsular India, which reduce the diurnal mean surface-reaching solar flux by about 15–35 Wm^{-2} (Satheesh and Ramanathan, 2000; Ramanathan et al., 2001). During the summer monsoon season, intense plumes of mineral dust originating from the West Asian Deserts engulf almost the entire north and central Arabian Sea and reach at least up to the west coast of Peninsular India (*e.g.,* Nair et al., 2005; Mishra et al., 2010). On the contrary, long-range transport of aerosols and total atmospheric aerosol loading over the Arabian Sea are considerably small during the winter season (*e.g.,* Nair et al., 2005).

Lidar observations of the altitude profiles of aerosols over Maldives (4.1°N, 73.3°E) revealed the presence of an elevated aerosol layer in the altitude band of 1.5–3.5 km during the pre-monsoon season (Ansmann et al., 2000; Müller et al., 2003). Airborne measurements and ship-borne lidar observations showed that this elevated aerosol layer covers a wide region in the Arabian Sea during the above period (Léon et al., 2002; Welton et al., 2002). Long-term (~15 years) bi-static lidar observations of the vertical distribution of aerosols in the altitude band of 50-1000 m over Thiruvananthapuram (8.5°N, 77°E) have brought out the aerosol distribution in the nocturnal atmospheric boundary layer and their annual and inter-annual variations in this coastal environment (Parameswaran, 2001). Micro pulse lidar observations of the vertical distribution of aerosols over this location showed layers of highly non-spherical aerosols during the pre-monsoon and summer monsoon seasons (Mishra et al., 2010; Rajeev et al., 2010). The above observations clearly showed that the Arabian Sea and southwest Peninsular India witnesses large, but distinctly different aerosol plumes during the pre-monsoon and summer monsoon seasons. However, studies on the altitude distribution of tropospheric aerosols during the post-monsoon (October–November) and winter seasons as well as their annual and interannual variations over this region are highly limited. We aim to fill this gap using the dual polarization Micro Pulse Lidar (MPL) observations carried out at Thiruvananthapuram (8.5°N, 77°E), located in the southwest coast of Peninsular India adjoining the Arabian Sea. These lidar observations, integrated with satellite-based observations of regional aerosol distribution, provide improved understanding of the vertical distribution of aerosols in the highly prominent aerosol plumes which persist during different seasons. Thiruvananthapuram represents a relatively clean coastal environment devoid of major pollution sources. Hence, these observations can be used for investigating the effect of long-range transport in regulating the abundance and properties of aerosols in an otherwise clean environment. Main objectives of the present study are: (1) to present a systematic analysis of the mean altitude distribution of aerosols in the troposphere below ~5 km and its monthly, seasonal, annual and interannual variations over this region, and (2) to estimate the potential effect of long-range transport in modulating the vertical distribution of aerosols and aerosol type during different seasons.

2. Lidar site, data and method of analysis

2.1. Geographical location of Thiruvananthapuram and its meteorological conditions

Regular observations on the vertical distribution of aerosols using the dual polarization MPL were carried out at Thumba, Thiruvananthapuram (geographical location of Thumba is marked in Fig. 2). The lidar site is located ~500 m inland from the southeast Arabian Sea. Monthly mean climatology of the daily minimum and maximum air temperatures near the surface, number of days with rain and thunder (thunder being a proxy for atmospheric convection) and mean rainfall at Thiruvananthapuram obtained from the long-term (>30 years) observations carried out by the India Meteorological Department are shown in Fig. 1. The monthly mean wind speed and direction at 1 km above the mean sea level derived from radiosonde data are also shown in Fig. 1. Based on the prevailing meteorological conditions, analysis of the MPL data are grouped into 4 seasons, viz. winter (December–February), pre-monsoon (March–May), summer monsoon (June–September) and post-monsoon (October–November). Of these, winter and summer monsoon are the two contrasting seasons while pre-monsoon and post-monsoon are transition periods.

On average, dry conditions with scanty rainfall prevail at Thiruvananthapuram during winter. The daily minimum and maximum temperatures, number of days with rain and thunder, and rainfall increases with the advancement of the pre-monsoon season. Thiruvananthapuram is the gateway for the Asian summer monsoon to the Indian subcontinent. Climatological onset date of summer monsoon rain over Thiruvananthapuram is 1 June. Rainfall is largest in June and decreases with the advancement of the summer monsoon season. The convective activity as well as rainfall shows a secondary peak during the post-monsoon season. The synoptic wind speed is low during the period of November to April and increases significantly from May reaching its peak value in July and decreases subsequently. The wind direction is northeasterly during the November to March period, and changes to northerly/northwesterly during April–May and to westerly during June to October.

2.2. Lidar data and method of analysis

Details of the dual polarization MPL system, method of data processing, incorporation of correction for the detector dead-time,

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