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Global trends of columnar and vertically distributed properties of aerosols with emphasis on dust, polluted dust and smoke - inferences from 10-year long CALIOP observations

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ABSTRACT

In this paper, the decadal datasets available from the space-borne lidar, Cloud Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) are analyzed in order to understand the spatial and vertical distributions of aerosols at a global scale. Decadal (September 2006–August 2016) Level 3 night time Standard All-sky data products, created using quality controlled Level 2 datasets are utilized in the study. Columnar aerosol properties are discussed in conjunction with vertical properties of the three major aerosol types i.e. dust, polluted dust and smoke. It is found that the global mean aerosol optical depth (AOD) amounts to 0.10, with AOD values of 0.13 and 0.09 for land and ocean respectively, during the last decade. Mean aerosol extinction coefficients are also reported for four altitude bins i.e. 0–1 km, 1–2 km, 2–3 km and 3–4 km above mean sea level (a.m.s.l.). It is observed that dust and smoke particles have stronger vertical transport compared to polluted dust particles, which are generally found to be confined within the lower altitudes. In order to observe the changes in aerosol loading over different parts of the globe, de-seasonalized trends of AOD and vertical extinction coefficients are computed using linear regression technique. Globally, the total columnar particle load shows a significant negative trend during the last decade. In particular, trends of total particle loading (AOD and extinction) are decreasing over North America, South America, East China and Australia. However, the smoke emissions (columnar and vertically distributed) have increased over India, Russia, North America, Australia and Central Africa. This is of concern in the context of rising temperatures accompanied with increasing wildfires throughout the globe. Additionally, enhanced levels of polluted dust over the developing regions of Africa and Asia are also revealed.

1. Introduction

Evaluation of aerosols' impact over climate requires accurate information of their physical, chemical and optical properties at regional and global scales (Carslaw et al., 2013; Charlson et al., 1992; Menon, 2004; Myhre et al., 2013; Ramanathan et al., 2001a, b). The longer lifetimes of aerosols in free troposphere allow them to get transported over farther distances, thereby affecting their spatial distribution away from their sources. It should also be noted that not only the precise information of columnar distribution, but also knowledge of the vertical structure of aerosols is required to correctly understand the aerosol transport and removal processes, emission properties and vertical uplifts (Schulz et al., 2006; Winker et al., 2013). Specifically, the uncertainty in the simulation of transport and removal processes is one of the major factors responsible for the diversity in distribution of aerosols predicted by the global aerosol models (Huneeus et al., 2011; Kinne et al., 2006; Textor et al., 2006). A global perspective of columnar aerosol properties along with the vertically distributed ones, henceforth, is crucial to assess their role in the atmospheric dynamics. In order to understand the vertical structure of the aerosol distribution in the atmosphere, several regional studies have been performed in different parts of the world using ground based and airborne Lidar datasets (Cavalieri et al., 2010; Chen et al., 2013; Gadhavi and Jayaraman, 2006; L'eon et al., 2009; Menzies and Tratt, 2002; Mona et al., 2006, 2012; Navas-Guzmán et al., 2013; Solanki and Singh, 2014). While in-situ observations provide repeated, accurate and precise data of the aerosol properties, satellite measurements enable irreplaceable and continuous spatio-temporal coverage, though accompanied by retrieval

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uncertainties. To this end, Cloud Aerosol Lidar with Orthogonal Polarization (CALIOP), which is onboard NASA's platform i.e., Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), has been gathering the information of aerosol vertical distribution over the last ten years. Studies have been performed to evaluate regional and global aerosol columnar and vertical properties using CALIOP data. In this context, Liu et al. (2008) presented a height resolved global distribution of dust aerosols using cloud-free nighttime CALIOP measurements. Later, Yu et al. (2010) studied seasonal variations in vertical aerosol profiles obtained from CALIPSO over selected regions in comparison with those from GOCART simulations. In yet another study, regionally averaged monthly aerosol extinction profiles from CALIPSO Level 2 data were employed in Aero Com model inter-comparisons (Koffi et al., 2012). Also, Schuster et al. (2012) provided a climatology for lidar ratio of dust over the AERONET sites using CALISPO data. In addition, Winker et al. (2013) reported global 3-D climatology of tropospheric aerosols using 6-year datasets of CALIPSO Level 3 aerosol product (CL3AP). Recently, Papagiannopoulos et al. (2016) have evaluated modified CL3AP over European Aerosol Research Lidar Network (EARLINET) locations. They found that the modified product showed an overall 25% deviation from EARLINET observations in extinction coefficients. The comparisons of the modified CL3AP products with respect to other satellite retrievals reveal a bias in CALIOP AOD data compared to other instruments (Kittaka et al., 2011; Redemann et al., 2012). Further, Ma et al. (2013) found that though CL3AP could demonstrate seasonal variability in AOD, however, it was observed that the CALIPSO retrieved AOD was lower over deserts and higher over the biomass burning regions when compared with MODerate resolution Imaging Spectroradiometer (MODIS) AOD datasets.

In order to assess the changing aerosol distribution across the globe, continuous efforts are needed to investigate the trends from various satellite sensors. This is because the results from one sensor might vary from the other owing to the differences in instruments, their calibration/characterization, retrieval algorithms, sampling (orbital coverage), pixel selection methods along with the masking/aggregation techniques (Hsu et al., 2013). In this context, several studies have been conducted to understand the climatology and changing trends in the columnar aerosol properties at regional and global scales using data from ground based measurements and satellite sensors (de Meij et al., 2010; Chylek et al., 2007; Li et al., 2014; Mishchenko et al., 2007; Hsu et al., 2012; Mehta et al., 2016; Yoon et al., 2012, 2014; Zhang and Reid, 2010). However, most of the previously carried out studies emphasize on trends in total column aerosol optical depth (AOD), but a comprehensive study investigating the AOD trends due to major aerosol types is still lacking. Further, the global trends of aerosol vertical distribution have not been yet reported. Knowledge of the changing particle loading due to different aerosols types and their vertical distribution could serve as one of the important inputs to understand the aerosol-induced climate changes. With this motivation, the main objectives of the study are to understand the global distribution and trends in columnar and vertically resolved properties of aerosols, with specific reference to dust, polluted dust and smoke, using Level 3 CALIOP datasets for the last ten years (September 2006–August 2016). The results are discussed in conjugation with those from previously reported studies in literature. In our previous work using passive sensors i.e., MODIS and MISR (Mehta et al., 2016), we found strong seasonality in the behavior of aerosols across the globe at various locations. Hence, in this paper, we have presented de-seasonalized linear trends both for columnar and vertically resolved parameters. To the best of our knowledge, this is the first study of its kind based on space-borne data which not only presents the decadal trends of columnar aerosol loading, but also provides the global scenario of changing aerosol amounts at different altitude levels, with special emphasis on dust, polluted dust and smoke. Section 2 briefly describes CALIOP Level 3 aerosol data products. Section 3 discusses in detail the spatial variability and trends of aerosols with specific emphasis on the three major aerosol types.

2. CALIPSO level 3 aerosol product

Cloud-Aerosol Lidar and Infrared Path-finder Satellite Observations (CALIPSO) mission was launched by NASA in sun-synchronous orbit at an altitude of 705 km, with a repeat cycle of 16 days (Hunt et al., 2009; Winker et al., 2009). With an aim to improve our understanding of vertically distributed properties of aerosols, CALIPSO is providing information since June 2006. CALISPO orbits around the earth 15 times every day. It carries Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) which provides vertically distributed properties of aerosols and clouds at two wavelengths, i.e., 532 nm and 1064 nm respectively. In addition, at 532 nm, both parallel and polarized returns are received. Its capabilities include determination of locations of aerosols layers, discrimination of aerosols from clouds, categorization of aerosols into different sub types and estimation of optical depth of each detected aerosol layer (Hunt et al., 2009; Vaughan et al., 2009; Liu et al., 2009; Omar et al., 2009; Young and Vaughan, 2009). The retrieval process first initiates with identification of features within the lidar signals (aerosol, cloud and surface returns) followed by determination of feature type (Liu et al., 2009; Vaughan et al., 2009). Further, the aerosol subtyping is performed to classify the layers as clean marine, dust, smoke, polluted dust, clean continental and polluted continental particles (Omar et al., 2009). At this stage, cloud phase is also determined, finally followed by retrieval of aerosol extinction profiles (Hu et al., 2007, 2009; Young and Vaughan, 2009).

We have used CALIOP Level 3 night-time global gridded monthly datasets, CAL_LID_L3_APro_AllSky-Standard-V3-00, which are available at spatial resolution of $2^\circ \times 5^\circ$ and vertical resolution of 60 m (from -0.5 to 12 km a.m.s.l.). The screening of the Level 2 data is done using several quality control flags before creating the Level 3 product (Winker et al., 2013). Specifically, cloud identification and removal is done before averaging the multiple lidar shots to detect aerosol layers. The major parameters used in this study are the aerosol extinction coefficient (532 nm) and the mean AOD, in particular for dust, polluted dust and smoke. For more information on clear-sky and all-sky mean aerosol profile inter-comparisons, the reader may refer to Winker et al. (2013). Evaluation with respect to other satellite sensors and ground based measurements has not been addressed in this paper. For details regarding the evaluation of CALIPSO AOD data sets, you may see the works by Kim et al. (2013); Kittaka et al. (2011); Ma et al. (2013); Omar et al. (2013); Redemann et al. (2012) and Schuster et al. (2012). For studies aimed at investigating the aerosol vertical profile products, reader may refer to works by Mamouri et al. (2009); Mona et al. (2009); Pappalardo et al. (2010); Wandinger et al. (2011); Papagiannopoulos et al. (2016) and the references therein. The seasonality of aerosols using CALIPSO data is not the subject of this paper but has been extensively discussed in the works by Huang et al. (2015) and Winker et al. (2013).

3. Results and discussion

3.1. Global AOD distribution based on different aerosol types

The distribution of mean AOD due to dust, polluted dust, smoke and total particle loading during the last decade is presented in Fig. 1. AOD maxima over land (Fig. 1(a)) are clearly captured over Africa, East China, India, Middle-East and Amazon basin of South America. Similar findings have been reported earlier in Ma et al. (2013) and Winker et al. (2013). Table 1 presents the quantitative estimates of decadal mean AOD over different continents. The maximum total columnar AOD is observed over Africa, with competing particle loading over Asia. Over land, the decadal averaged AOD is estimated to be 0.13 compared to that over ocean which is 0.09. Further, the major dust regions including the Saharan belt are clearly evident over the dust source regions in Africa, Arabia, India and China; similar to what have been reported earlier by Dayan et al. (2008); Dey et al. (2004); Kaufman et al. (2005);