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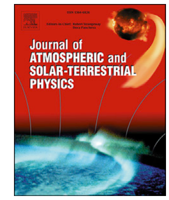

Global distribution of aerosol optical depth in 2015 using CALIPSO level 3 data

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ABSTRACT

We used Level 3 CALIPSO (Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations) averaged monthly data to (1) study the climatology of mean aerosol optical depth (AOD) from 2010 to 2015, (2) to compare the mean AOD for different satellites for the period of 2015 and (3) to study the monthly and seasonal variations of mean AOD and extinction coefficient for the period of 2015. The climatology of mean AOD from 2010 to 2015 showed similar patterns of global mean AOD distribution but showed variation in magnitude. The dominance of mean AOD was observed in the latitudes of 0°N to 40°N. Monthly global mean AOD source regions showed dominance in West Africa, India and East Asia. The highest mean AOD (dust + smoke) for these regions was observed in April while the lowest AOD (dust + smoke) was observed in November. The highest extinction coefficients were observed in the MAM season at latitudes of 50°N and 58°S at altitudes of 0.16 and 0.22 km respectively. The highest aerosols in altitude (6 km) were observed during this season.

1. Introduction

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) was launched together with CloudSat into the A-train orbit in April 2006 with the intention to fill gaps in our ability to observe the global distribution and properties of aerosols and clouds (Winker et al., 2003). CALIPSO payload consists of three co-aligned nadir-viewing instruments; the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), the Imaging Infrared Radiometer (IIR), and the Wide Field Camera (WFC). The key instrument specifications of the payloads are discussed in Winker et al. (2010). The CALIPSO satellite provides insight into the role that clouds and atmospheric aerosols play in regulating the earth's weather, climate, and air quality (Winker et al., 2010). CALIPSO combines an active Light Detection and Ranging (Lidar) instrument with passive infrared and visible imagers to probe the vertical structure and properties of thin clouds and aerosols over the globe. Several studies on aerosols and/or clouds using CALIPSO have been reported by various researchers such as [Shikwambana and Sivakumar (2016), Perrone et al. (2011), Kim et al. (2014), Mioche et al. (2010), Zong et al. (2015), Chen et al. (2010), Wong et al. (2013), Yu et al. (2010), Misra et al., 2012, Rogers et al., 2011, Liu et al. (2008), Yu et al. (2010), Adams et al. (2012), Yang et al. (2012), Huang et al. (2015), Tsamalis et al. (2013), Gkikas et al. (2016), Marinou et al. (2017) and Proestakis et al. (2018)]. These researchers either used CALIPSO for validation studies or global aerosol studies. As a way of example, Rogers et al. (2011) showed that the High Spectral Resolution Lidar (HSRL) and CALIOP 532 nm total attenuated backscatter agreed on average within 2.7% ± 2.1% at night and within 2.9% ± 3.9% during the day, demonstrating the accuracy of the CALIOP 532 nm calibration algorithms. On the other hand, Liu et al. (2008) used CALIPSO measurements under cloud-free conditions to study the global distribution of dust aerosols for the first time. However, these studies have concentrated more on CALIPSO Level 2 (L2) data products which are daily mean products. CALIPSO products have been evaluated by several authors using the columnar aerosol optical depth (AOD) from the Aerosol Robotic Network (AERONET) measurements (Omar et al., 2013; Schuster et al., 2012). The extinction retrieval follows the processes of signal calibration, feature (layer) detection, and feature type identification (cloud–aerosol discrimination and subtyping) (Young et al., 2013). The Hybrid Extinction Retrieval Algorithms (HERAs) are then used to retrieve the profiles of backscatter and extinction coefficients and computing optical depth in those atmospheric regions where the preceding processes have identified clouds or aerosols. HERAs rely on the correct calibration and identification of cloud or aerosol subtype and any errors in these parameters will lead to errors in the

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optical properties. More recently CALIPSO Level 3 (L3) data products are available with the aim to provide climatology of the global aerosol distribution including seasonal and inter-annual variations (Papagiannopoulos et al., 2016; Winker et al., 2013). The product consists of monthly gridded extinction profiles separated into a daytime and night time segment.

Since the release of the L3 data products a few studies using the data set have been reported. Ma et al. (2013) carried out a six-year comparison study of CALIPSO monthly mean gridded AOD products (daytime and night time) for cloud-free conditions with the Moderate Resolution Imaging Spectroradiometer (MODIS) Terra/Aqua level 3 monthly mean AOD dataset. Their study found that CALIPSO AOD is significantly lower than MODIS AOD over dust regions during the whole time period, with a maximum difference of 0.3 over the Saharan region and 0.25 over Northwest China. They further found that for biomass burning regions, CALIPSO AOD is significantly higher than MODIS AOD over South Africa, with a maximum difference of 0.25. Winker et al. (2013) used a six-year data set to characterize the global 3-dimensional distribution of tropospheric aerosol. They found that vertical distributions of aerosols vary with season as the source strengths and transport mechanisms vary. More recently, Papagiannopoulos et al. (2016) compared the European Aerosol Research Lidar Network (EARLINET) monthly averaged aerosol extinction coefficient profiles against the CALIPSO data. They found good agreement on the aerosol extinction coefficient but there were cases were small CALIPSO underestimation were observed. In general, an average mean AOD difference of −0.05 was reported.

Since CALIPSO data has been evaluated by numerous instruments (as discussed earlier), we take advantage of this and study the day time global distribution of aerosol products using the CALIPSO L3 dataset. AOD is generally higher during the night time in comparison to day time over hot spots (source regions of the aerosols). The L3 dataset products will be discussed in detail in section 2.1. The aims of this paper are to (1) study the climatology of the mean AOD from 2010 to 2015; (2) compare the mean AOD for different satellites for the period of 2015 and (3) study the monthly and seasonal variations of mean AOD and extinction coefficient for the period of 2015. Several volcanic eruptions in 2015 were observed globally. These volcanic eruptions include Mount Etna in Italy, Wolf volcano in the Galapagos Islands, Cotopaxi in Ecuador, Villarrica in Chile, Hunga Tonga-Hunga Ha'apai in Tonga, Mount Sinabung in Indonesia, Piton de la Fournaise in Réunion Island, Kilauea in Hawaii, Momotombo in Nicaragua, Colima in Mexico and Calbuco in Chile.

The study presented here is organized as follows: a discussion of the instrumentation employed in this study is discussed in section 2. Section 3 presents a discussion of the results obtained and final conclusions are outlined in section 4.

2. Data

Carn et al. (2017) showed global eruptive sulphur dioxide (SO_2) emissions from 2005 to 2016. They showed that during the period of study, 2015 showed the highest SO_2 emission of ~10.5 Tg compared to the other years of study (between ~0.0.2 and 9.6 Tg). This result further motivates why we choose to study AOD during 2015. We investigate if there was a noticeable increase in AOD during the 2015 period using CALIPSO.

2.1. CALIPSO

CALIPSO has been in orbit for over eleven years and has been collecting data ever since. The technical specifications are discussed in detail by Winker et al. (2003) and Winker et al. (2010). The main objectives for the CALIPSO is to (1) provide statistics on the vertical structure of clouds around the globe, (2) detect sub-visible clouds in the upper troposphere and Polar Stratospheric Clouds (PSC) and (3) provide statistics on the geographic and vertical distribution of aerosols around the globe. There are three basic types of L2 data products: layer products, profile products, and the vertical feature mask (VFM). Layer products provide layer-averaged properties of detected aerosol and cloud layers. Profile products provide retrieved extinction and backscatter profiles within these layers. The data products are provided at various spatial resolutions. VFM provides information on cloud and aerosol locations and types. The information in the VFM is derived from the layer products and interpolated onto a vertical grid at the resolution of the downlinked data. Winker et al. (2009) gives a detailed discussion on the algorithm that has been developed to identify aerosol and cloud layers and to retrieve a variety of optical and microphysical properties.

L3 aerosol data product reports monthly mean profiles of aerosol optical properties on a uniform spatial grid. The tropospheric product reports averaged values at altitudes below 12 km. L3 products are derived from the version 3 CALIOP L2 aerosol profile products and are quality screened prior to averaging. Winker et al. (2013) Appendix gives a summary of the methodology used for the generation of the L3 product. L3 has four data products generated each month depending on sky condition and temporal coverage, and are separated into day/night segments. Monthly mean-extinction profiles are computed for the above four categories i.e., all-sky, cloud-free, above clouds and combined (cloud-free and above clouds). The output monthly mean L3 aerosol extinction coefficients are mapped onto a global 2° x 5° latitude-longitude grid.

2.2. Moderate Resolution Imaging Spectroradiometer (MODIS)

Moderate Resolution Imaging Spectroradiometer (MODIS) views a 2300 km wide swath, from polar orbit of 700 km, providing near daily coverage of Earth's surface and atmosphere (Cheng et al., 2012). MODIS measures radiance in 36 channels spanning the spectral range 0.44–15 μm, with a varying spatial resolution of 250 m (bands 1 and 2), 500 m (bands 3–7) and 1 km (bands 8–36). A detailed description and operation of the Terra MODIS has been described by several authors Kaskaoutis et al. (2008), El-Metwally et al. (2010) and Baddock et al. (2009). In this study, monthly mean level 3 products from MODIS Terra (MOD08M3.051) were used for the period of 2015.

2.3. Multi-angle Imaging SpectroRadiometer (MISR)

The Multi-angle Imaging SpectroRadiometer (MISR) provides ongoing global coverage with high spatial resolution. MISR uses nine cameras pointed at fixed angles, one viewing the nadir direction and four each viewing the forward and afterward directions along the spacecraft ground track. Information on the MSIR technical specifications is described by Diner et al. (1998). MISR data products are grouped into three levels of processing. Level 3 processing will produce data aggregated over various time scales (monthly, seasonally, annually) on a global map grid. For this study, the monthly MISR Level - 3 data Global $0.5 \times 0.5°$ aerosol product were used for the period of 2015.

2.4. Modern-era retrospective analysis for research and applications, version 2 (MERRA-2)

MERRA – 2 is a NASA reanalysis product using a major new version of the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5) (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/). The Global Modeling and Assimilation Office (GMAO) has used its GEOS¬-5 atmospheric data assimilation system (ADAS) to synthesize the various observations collected over the satellite era (from 1980 to the present) into dataset that is as consistent as possible over time as it uses a fixed assimilation system. MERRA is being conducted with version 5.2.0 of the GEOS-5 ADAS with a 0.5° latitude × 0.625° longitude × 72 layers model configuration (Rienecker et al., 2011). More details on MERRA can be found in Rienecker et al. (2011). In this work, MERRA-2 is used to produce mean AOD for the period of 2015.