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Intercomparison and assessment of long-term (2004–2013) multiple satellite aerosol products over two contrasting sites in South Africa

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ABSTRACT

To build a long-term database and improve the accuracy of the satellite products used for aerosol studies, there is a need to carry out intercomparison and validation of these satellite observations with ground-based measurements. With this objective, we estimated the long-term inter-annual variations and percentage change in trends of aerosol optical depth (AOD) retrieved from MODerate resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging Spectro-Radiometer (MISR) sensors for a 10-year period during 2004–2013 over two distinct sites namely, Skukuza (SKZ; 24.99°S, 31.58°E) and Richards Bay (RBAY; 28.8°S, 21.1°E) in South Africa. The validation performed over SKZ site shows that MISR was better correlated with AErosol RObotic NETwork (AERONET) when compared to Terra and Aqua satellites of MODIS. Later both the MODIS products (Terra and Aqua) were compared on the annual and seasonal basis to derive the relationship between them through scattering plot. The long-term regression analysis performed at these sites shows that the annual trends were decreasing, with the MODIS products underestimating MISR. This is due to difficulties of the MODIS algorithm when dealing with highly complex surface reflectance conditions and aerosol model assumptions. Also, the temporal variations of AOD derived from the two sensors noticed maximum in spring (September/October) and minimum in winter (June). Further, the Ultra-Violet Aerosol Index (UVAI) retrieved from the Ozone Monitoring Instrument (OMI) at the two locations for 9 years (2005–2013) showed a significant increasing trend with a high value of $+0.009\ yr^{-1}$ at SKZ than $+0.006\ yr^{-1}$ at RBAY during the study period, which is due to the transport of dust and smoke particles.

1. Introduction

As efforts are being made to unravel the actual role that aerosols plays in influencing our climate, there is a need to study aerosol properties using a coordinated platform of instruments. When this is done, contributions from various instruments like satellite, surface (ground) measurements and models employed will enhance the study of aerosols (Kahn et al., 2010). Although the ground-based instruments provide precise information about the aerosol optical properties, but being sparsely located and point based, they could not provide continuous spatial and long-term measurements. Inferences from satellite-based sensors, henceforth, become important to achieve a global and temporal characterization of aerosols (Mehta et al., 2016). Several algorithms using, for example, Advanced Very High Resolution Radiometer (AVHRR), Total Ozone Mapping Spectrometer (TOMS)/Ozone Monitoring Instrument (OMI), Moderate Resolution Imaging Spectroradiometer (1MODIS), Multi-angle Imaging Spectro-Radiometer (MISR), and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) on polar-orbiting satellites (Kaufman et al., 1997; Remer et al., 2005; Martonchik et al., 2009; Kahn et al., 2005, 2010; Kang et al., 2016) have been developed to retrieve the global aerosol optical depth (AOD hereafter). The ground-based instruments are then, being employed in the validation of the satellite-based measurements (Diner et al., 1998; Ichoku et al., 2002; Kahn et al., 2007, 2010; Yoon et al., 2012). Also due to their ability to take long-term measurements, satellite products are useful in building a long-term database for climatological studies (Kaufman et al., 2002; Alam et al., 2011; Floutsi et al.,

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2016; Kang et al., 2016). However, places with high surface reflectance can pose some challenges to satellite-based measurements as errors may be introduced to the derived aerosol products (He et al., 2016).

AOD is the most far-reaching quantity from which we can infer the column aerosol loading (Mehta, 2015). Yet, this quantity somewhat differs from one satellite instrument to the other, even when their measurement is taken over the same location. The difference is due to the various retrieval algorithms, and sampling time and differences, upon which these instruments are based (Kahn et al., 2007, 2010; Mishchenko et al., 2009; Levy et al., 2010). Therefore, employing the use of specific satellite product is important for the identification and characterization of a defined aerosol property over specific surface types (Tesfaye et al., 2011; Alam et al., 2011; Sreekanth, 2013; Kumar et al., 2014, 2015; Bibi et al., 2015).

A number of intensive field campaigns had been carried out in Southern Africa during the past decade. These includes the Southern Tropical Atlantic Region Experiment (STARE) in 1992, Transport and Atmospheric Chemistry near the Equator-Atlantic (TRACE-A) and Southern African Fire-Atmosphere Research Initiative (SAFARI). While TRACE-A focused on the impact of emissions from Brazil, SAFARI concentrated on fire emission from Southern Africa (Ichoku et al., 2003). In SAFARI 2000 campaign, the ground-based measurements from AERONET were used to compare with the satellite-based observations derived from MISR and MODIS (Diner et al., 2001). Tesfaye et al. (2011) reported the long-term spatial aerosol climatology over South Africa (SA) studying the AOD characteristics on the seasonal basis for a period of 10-years using MISR data. Kumar et al. (2014) examined climatological variations and trends of aerosol optical properties using MODIS data for a 10-year period over three distinct stations of SA. Further, the long-term variations of AOD and Ångström Exponent (AE), and identification of aerosol types were investigated by Kumar et al. (2015) over the urban-coastal site, Durban in SA. Recently, there was a study on aerosol (also using handheld measurements) over nineteen domestic (local towns) locations in SA to determine the air quality using multiple platforms (Hersey et al., 2015). In addition, a ground-based AOD climatology obtained from Precision Filter Radiometer (PFR) sun photometer was presented for Cape Point, South Africa by Nyeki et al. (2015) during 2008–2013.

The present study is undertaken using Collection 5.1 (C051) MODIS-Terra (T), MODIS-Aqua (A), MISR, and OMI-derived Ultra-Violet Aerosol Index (UVAI) data to compare aerosol loading over a hinterland and a coastland areas in SA for the 2004–2013 period. First, the validation was carried out using MODIS-T, MODIS-A, and MISR satellite aerosol products with ground-based sun photometer (part of AERONET) measurements. Later, we have proceeded to see the performance of MODIS-T and MODIS-A satellites in these two distinct terrains based on monthly and seasonal datasets. Further, we estimated the long-term seasonal and annual trends and changes (in %) for the 10-year data derived from these satellites, followed by inter-annual variations in the derived aerosol characteristics over two sites in SA. Finally, using UVAI data obtained from OMI, we explored the aerosol absorption property for the two distinct locations in terms of inter-annual and seasonal changes for a period of 9 years between 2005 and 2013, because OMI–UVAI product is available online from October 2004. A short overview of the contents of the paper is as follows. In Section 2, descriptions of observation sites, instrument details and datasets obtained from different satellites, and method used for the estimation of statistical trends are elaborated. The results obtained with a detailed analysis are elucidated in Section 3 and the important conclusions drawn are presented in Section 4.

2. Satellite data and method

2.1. Study regions

South Africa (SA), is bounded between the latitudes 22–36°S and 16–34°E longitudes, being burdened by almost all major types of aerosols produced from both natural and anthropogenic activities. It is characterized by a subtropical climate with warm wet summers and dry winters. SA, which has plenty of industries and mining sectors, is the most industrialized country in the continent. These human activities make SA one of the most important regions for anthropogenic aerosol study in the globe, which contributes several types of aerosols (Piketh et al., 1999). Further, the dust-blown aerosols from the arid/semi-arid regions of SA and its neighboring countries, along with the marine aerosol induced from the surrounding oceans (the Atlantic and Indian Oceans), is another main component of natural aerosols (Piketh et al., 1999; Freimen and Piketh, 2003).

The geographical locations of the present two study regions are shown in Fig. 1. Skukuza (SKZ; 24.99°S, 31.58°E) is a rural agricultural region in the Mpumalanga province of SA with an area of 4.98 km^2 and a population of 1599 (as per 2011 census of SA). It receives an annual rainfall of ~353 mm, with a huge amount of rains (~60%) occurring during the summer. The minimum and maximum temperatures range from 24.5 °C in July to 31.7 °C in January. Richards Bay (RBAY; 28.8°S, 32.1°E) is a coastal town located in the KwaZulu-Natal province of SA, which is about 180 km from the urban-industrial and coastal city, Durban. It covers a total land area of 142.78 km^2 and with a population of 57,387 (as per 2011 census of SA). It receives an annual rainfall of ~1228 mm and attaining its highest temperature in the month of January/February (25.2 °C), with an annual mean temperature of 21.5 °C. The detailed regional meteorological conditions for the specific time periods measured at several locations of SA provided by the South African Weather Service (SAWS) using an automatic weather station can be found in the recent works of previous researchers (Queface et al., 2011; Kumar et al., 2013, 2014, 2015; Hersey et al., 2015 and references therein). For the seasonal analysis, four seasons considered are summer (December, January, February; DJF), autumn (March, April, May; MAM); winter (June, July, August; JJA) and spring seasons (September, October, November; SON).

2.2. The MODIS sensor

The MODIS instrument, as part of the NASA's Earth Observing System (EOS) mission, which has been flying aboard Terra since

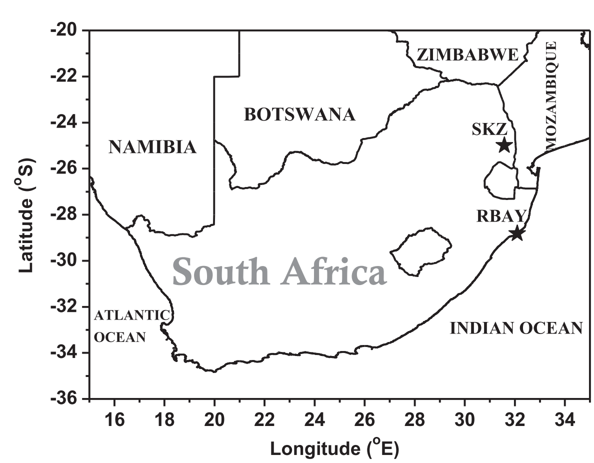

Fig. 1. Geographical map showing the locations of Skukuza (SKZ) and Richards Bay (RBAY) in South Africa with its bordering countries and Oceans.