Long term (2003-2019) Spatial-Temporal Variation of Aerosol Optical Depth over Tibetan Plateau

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ABSTRACT

The present study aims to explore the aerosol optical depth- an index of air quality, using the satellite observations over Tibetan Plateau (TP). The study is significant as the plateau exerts strong thermal forcing over Asian monsoon region. The atmospheric and hydrological cycle of the plateau has been changed over the years due to climate change effect. As the aerosols are one of the major component of climate change of any region the present study explores the variation of aerosol optical depth over the TP. Long term (2003-2019) Aqua and Terra MODIS Collection 6.1 Combined Deep Blue (DB) and Dark Target (DT) AOD observations are analyzed to study the seasonal variation of AOD over Tibetan Plateau. The AOD values are found the highest in pre-monsoon season over TP.

Keywords: *Air quality, Aerosol Optical Depth, Seasonal variation, Asian monsoon, and Tibetan Plateau.*

1. Introduction

The Tibetan Plateau (TP) known as the third pole of the world, impacts the weather, climate and lives not only in South and East Asia but also in the world (Yu et al. 2021, Wu et al. 2016, Kang et al. 2019). The studies conducted in the past indicate that clouds and radiations in regions such as Arctic and TP are sensitive to the variations of aerosols (Garrat and Zhao 2006) over the region. As the aerosols can absorb and scatter solar radiation and can also modify the cloud properties, especially when absorbing aerosols such as black carbon (BC) falls on the snow at the surface; they can play an important role in the weather and climate system of the TP. The increased number of absorbing aerosols such as dust and black carbon over TP may lead to positive temperature tropospheric anomaly over TP and adjacent region of south, causing the advance and enhancement of the Indian summer monsoon. It has been reported that shrinkage of glaciers and snow over TP is due to presence of aerosols at the region (Kang et al. 2019). It is found that the aerosols have more dominant influence than meteorological conditions on ice cloud properties over TP (Liu et al. 2019).

A number of studies have been conducted to analyze the aerosol characteristics over TP (Wan et al. 2015, Zhao et al. 2013, Du et al. 2015). Both the ground-based observations and satellite products have been analyzed to study the seasonal variations in aerosol properties over TP (Shen et al. 2015). However, an analysis of long-term trends in the variation of aerosol properties over TP is required for the guidelines to develop environmental policies.

A scientific climatologically database on aerosol properties at 550 nm from the passive MODIS sensor is utilized in the present study to analyze the variation of aerosols over TP. The main focus of the study is to analyze the long term (Jan 2003-December 2019) variation of aerosol optical depth (AOD) at 550 nm and extinction Angstrom exponent (EAE) over TP. The paper also presents seasonal, interannual and spatial variations in AOD over TP. The study is divided into different sections. The next section discusses the dataset and methodology used in the study. The variation of AOD over TP is discussed in Section 3 and conclusions are given in Section 4.

2. Dataset and Methodology

The Moderate Resolution Imaging Spectroradiometer (MODIS) has been flying in the polar orbit of Terra (morning descending direction) and Aqua (afternoon ascending direction) satellites of National Aeronautics and Space Administration

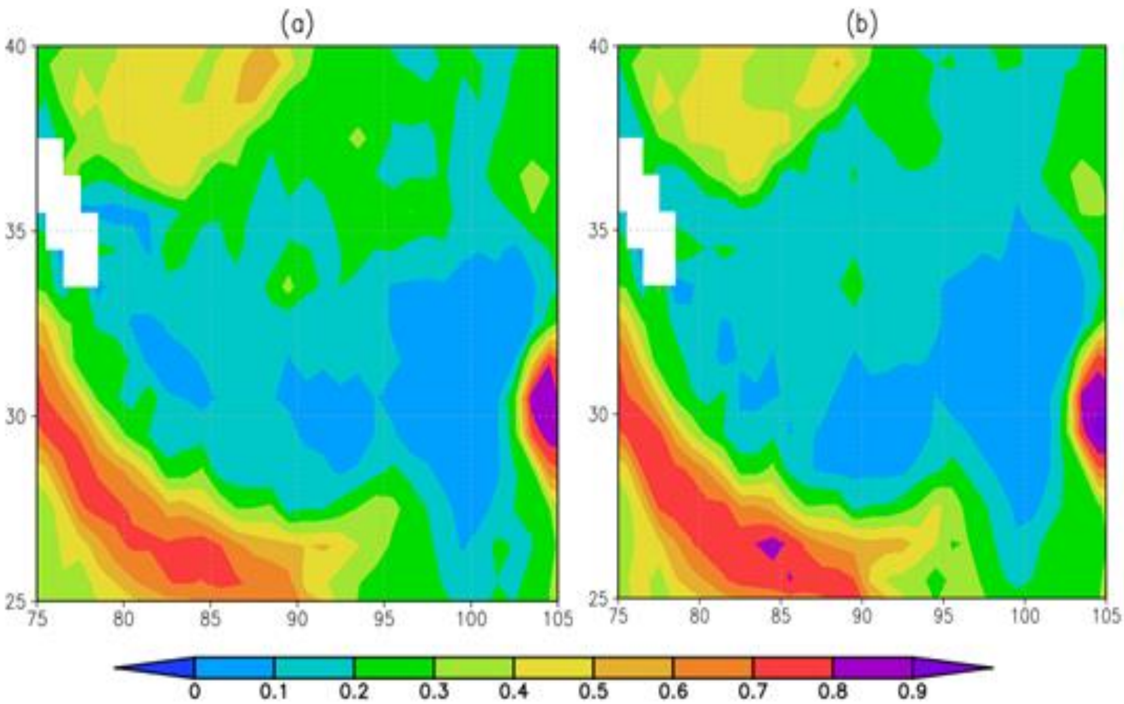

Figure 1: Time Averaged (2003-2019) values of MODIS AOD from (a) Aqua and (b) Terra Satellite.

(NASA) since 1999 and 2002 respectively in order to monitor the important climate properties, including aerosols. MODIS has a wide spectral range from 0.4 to 14.5 µm in 36 spectral bands or channels, swath of 2330 km and the fine spatial resolution. The combination of all these features leads to many algorithms for retrieving aerosol information from MODIS.

The MODIS data are generally processed into different levels from Level 1 (radiances or brightness temperatures that have been geo-located), to Level 2 (derived geophysical data products at the same resolution and location as the Level 1 data), to Level 3 (variables mapped onto uniform space-time grid scale) (King et al 2003). The MODIS atmospheric data products are available for public access. In this study, both the Terra and Aqua MODIS version 6.1 Deep Blue (DB) and Dark Target (DT) combined AOD product at 550 nm and aerosol extinction Angstrom exponent (EAE) with a spatial resolution of 1 degree is utilized from 2003-2019. The combined DT and DB AOD product at 550 nm merges the products from the two algorithms based on the statistics of normalized difference vegetation index (NDVI). The DT AOD are used for NDVI >0.3 and DB AOD are used for NDVI <0.2 and the mean of both is used for 0.2 ≤NDVI≤0.3. The TP is located in Asia (27-45^0 N, 70-105^0 E) t an elevation of more than 4000 m above mean sea level. The AOD product is averaged over the grid box (27.5 -37.5^0 N, 80.0 -100.0^0E) to analyze to the spatial and temporal variation over TP.

3. Temporal and Spatial Variation of MODIS AOD over TP

3.1 Variation of AOD (550 nm) from Aqua and Terra over TP during 2003-2019

Figure 1 shows the AOD at 550 nm time averaged for 2003-2019 from Aqua and Terra. High values > 0.5 are observed over northwest area around Taklamakan desert and northern parts of Tibetan plateau from both the satellites with higher values in Aqua than Terra. Figure 2 presents the spatial distribution of AOD in four seasons – Pre-Monsoon (March-May), Monsoon (June-August), Post-Monsoon (September-November) and Winter (December-February). High values of AOD are observed over northern parts of TP in all the seasons. However, the highest values (0.7-0.9) are observed in pre-monsoon season (Figure 2a) and lowest (0.1-0.3) in post monsoon (Figure 2c) and winter (Figure 2d) season over this region. In pre-monsoon season, the AODs in the northern TP are high due to the occurrence of frequent dust storms

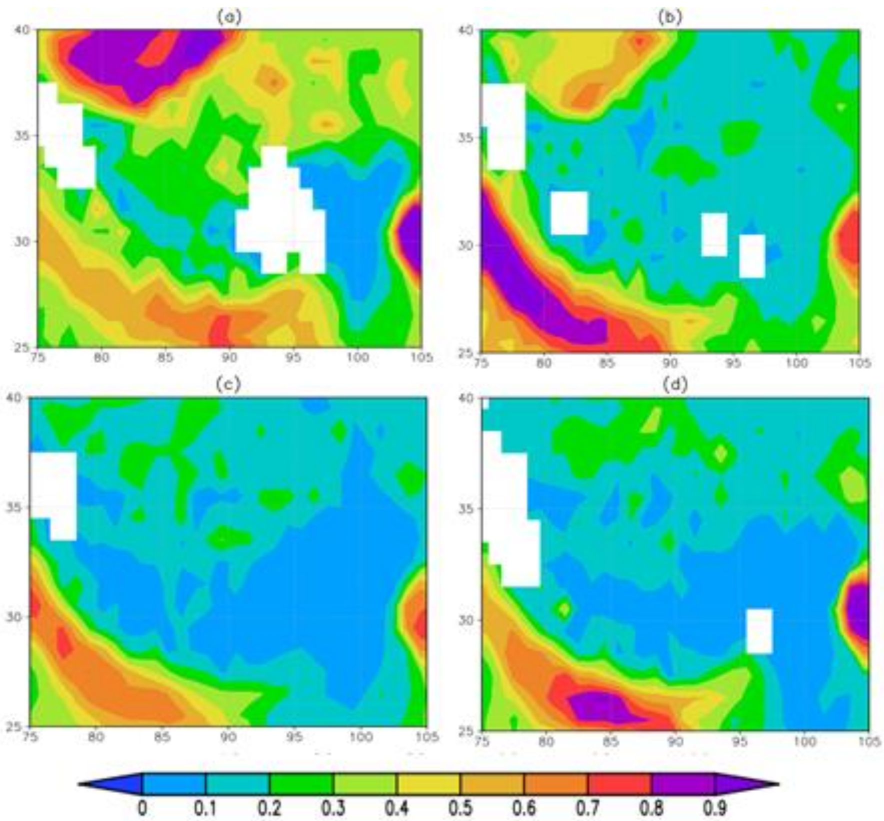

Figure 2: Spatial Distribution of 16-year averaged MODIS AOD (Aqua) at 550 nm for (a) Pre-Monsoon (b) Monsoon (c) Post-Monsoon and (d) Winter Season.

during the season and dust may also be transported from the adjacent Taklimakan and Qaidam desert. The AOD values exceed 0.6 in the eastern TP regions (east of 90 deg E).

The values of AOD in monsoon season are close to 0.3 in eastern TP region (Figure 2b), indicating rare occurrence of dust storm in this season. The values are still high close to 0.5 in northern part of the plateau. The AOD values are decreasing from north to south.

The values of AOD in post monsoon (Figure 2c) and winter season (Figure 2d) are close to 0.1 for most of the parts. However, the values are still higher over the northern parts of the plateau.

The values of AODs in pre-monsoon are controlled by local dust storms and the transportation of dust aerosols originated from the Taklimakan desert is one of the most important factor that determines the inter annual variation of AODs over the TP in monsoon season. Huang et al (2007) showed that dust aerosols originated in Taklimakan desert in summer (June-September) may accumulate over northern slopes of plateau. Xia et al. (2008) concluded that a positive correlation occurs between AOD over TP and Taklimakan desert during summer. The low values in winter and post monsoon season may be due to the fact that no significant source of aerosols occurs over TP during both of these seasons.

3.2 Time Series of AOD (550 nm) and EAE over TP during 2003-2019

The monthly spatial mean of AOD over TP is shown in Figure 3. The seasonal variation in AOD is distinct and characterized by a peak (Figure 3a). An increase in values of AOD is observed from January to May and a gradual decrease is observed in the following months (Table 1.). The monthly AOD ranges from 0.07-0.45. The seasonal mean AOD are highest (0.37) in pre-monsoon season and lowest (0.09) in winter season. The monthly AOD departure from 16-year mean is shown in Figure 3b. The solid line represents the 9-points smooth of the time series. The monthly percentage departures from their 16 -year mean value lie between -50% and +30%. For the years 2003, 2007, 2010, 2011, 2014, 2018 the AODs are smaller than multiyear

Table 1. Monthly Mean (µ) Aqua AoD and Standard Deviation (σ) over TP.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
µ	0.14	0.21	0.30	0.37	0.32	0.25	0.20	0.17	0.12	0.14	0.12	0.09
σ	0.03	0.03	0.04	0.03	0.04	0.04	0.03	0.02	0.01	0.02	0.01	0.02

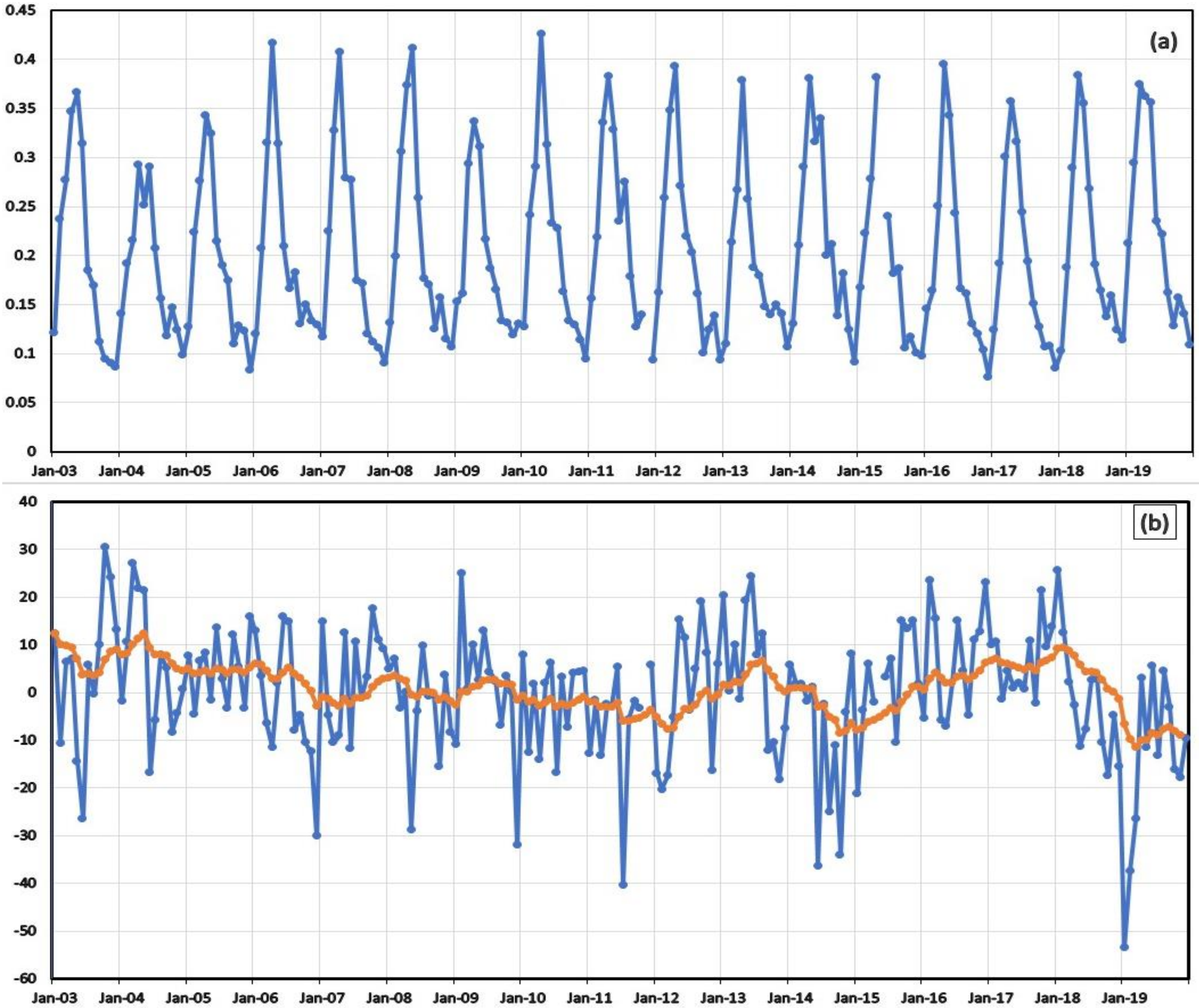

Figure 3: Area Averaged (27.5-37.5 deg N, 80-100 deg E) (a) AOD at 550 nm and (b) Monthly percentage departure of AOD from 16 year average.

averages whereas for the years 2004, 2005, 2006, 2008, 2009, 2012, 2013, 2015, 2016 and 2019 the AODs are higher than multiyear averages.

Figure 4 shows the monthly variation of AOD over TP for the period 2003-2019. High values > 0.2 and close to 0.4 are observed in the month of March, April and May whereas values less than 0.15 are observed during October, November, December, January and February. Figure 5 gives the seasonal and inter-annual variation of AOD over TP. It is clear that highest values of AOD are observed in pre-monsoon season and lowest in post- monsoon season.

Figure 6 gives the time series of EAE over TP from 2003-2019. It shows that values of EAE decreases during the pre-monsoon season to 0.9 from the values higher than 1.0 in remaining seasons for

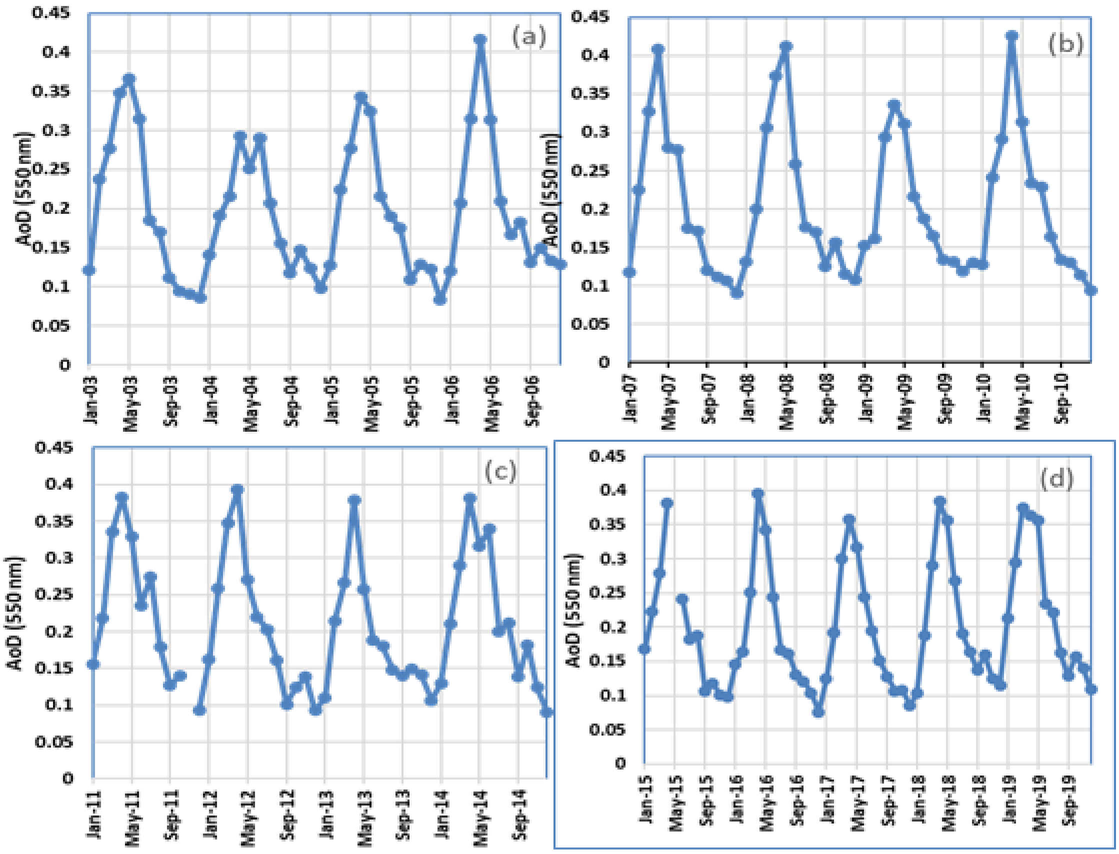

Figure 4: Monthly Variation of AOD over TP from 2003-2019.

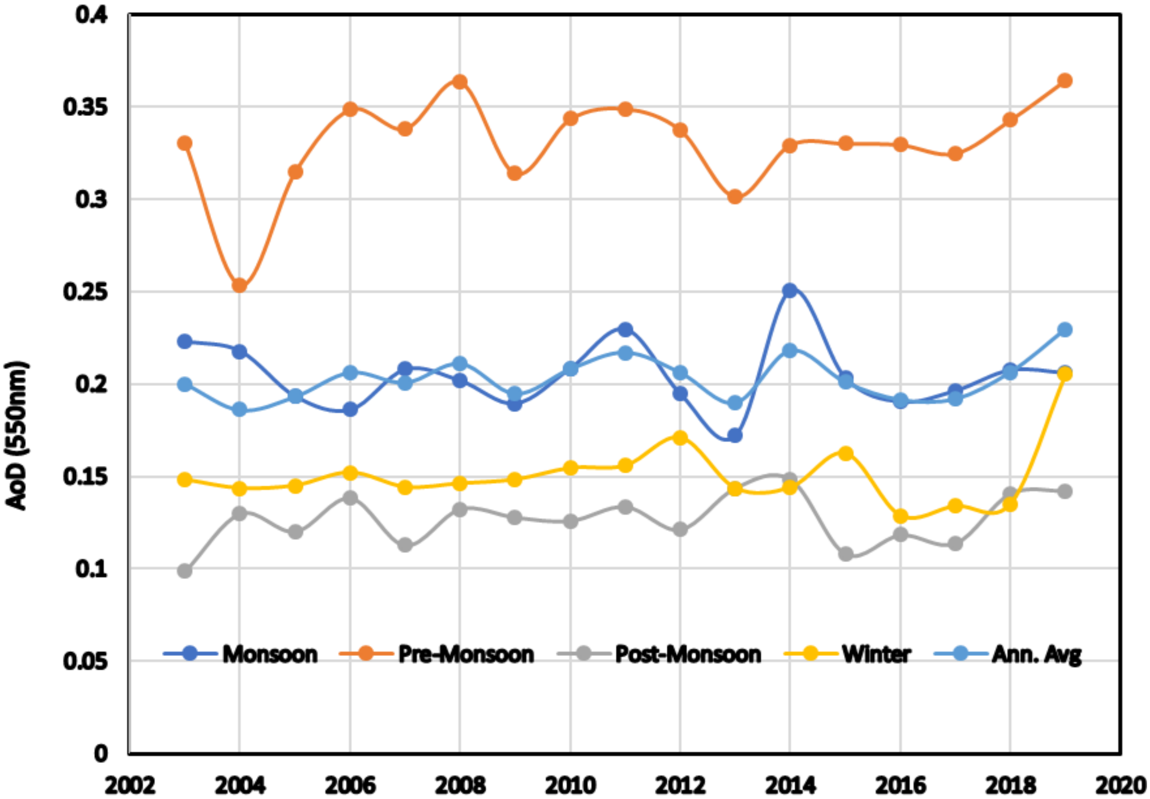

Figure 5: Seasonal and Inter Annual variation of area averaged AOD over TP.

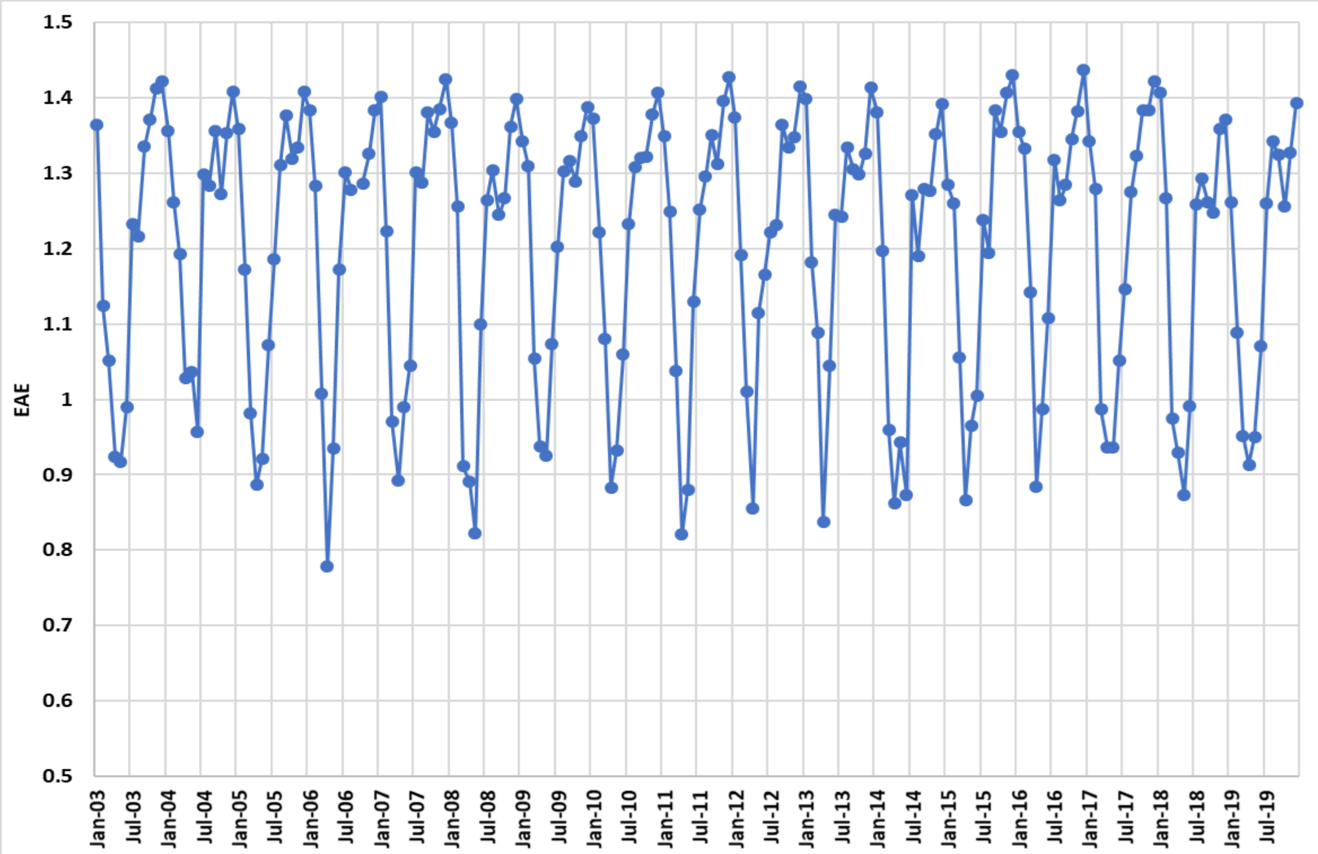

Figure 6: Time series of EAE for 2003-2019 over TP.

each year. The high values of EAE (≥1.0) over the region suggest the presence of smoke aerosol and the lower values (~0.8-0.9) indicate the occurrence of coarse aerosols such as dust.

4. Summary

The seasonal variation of AOD is studied over TP for 16 years using MODIS Aqua and Terra products from January 2003-December 2019. The AODs from Aqua satellite are found higher than Terra satellite values. The main findings of this study are as follows:

(a) On an annual scale, the AODs are highest in pre-monsoon season and lowest in post monsoon season. The values of AODs are found higher than annual average in some years.

(b) The AOD values are found higher over northern parts of plateau in all the seasons and throughout the year.

(c) The AOD values over TP show distinct seasonal variation. The seasonal mean AODs for pre-monsoon season is 0.37 which is twice that observed in winter season.

(d) The frequent occurrence of dust storms in pre-monsoon season may lead to higher values of AOD in this season.

(e) The values of AOD show much difference over the years. This may be due to the fact that area averaged values are used in the study.

(f) This is a preliminary study and further study using other products may provide further insight into the affect of aerosols.

The study indicates the transportation of dust aerosols from adjacent regions which is a significant feature for attention of the scientific community. A more detailed analysis with the effects of aerosols on radiative budget will provide further insight for the aerosol properties and species present over the plateau. In addition, the long term numerical model simulation with satellite observations and ground based observations will be significant to study the aerosol properties over the region in future.

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