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Spatio-temporal analysis of aerosol concentration over Saudi Arabia using satellite remote sensing techniques

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Abstract

Aerosols are a principal factor in altering climatic dynamics both at regional and global scales. Saudi Arabia is highly affected by aerosols particulates mainly due to the frequent sand and dust storm events in the region. In this context, this study examined Moderate Resolution Imaging Spectroradiometer (MODIS) Deep Blue (DB) Aerosol Optical Depth (AOD) variability both from Terra and Aqua satellites and its relationship with temperature for the period 2002-2007.A comparison between Terra and Aqua DB AOD products were also made in this study. The annual mean AOD analysis based on Terra and Aqua showed a decreasing and increasing trend respectively. Results of the study also showed that the temperature had a strong correlation with Terra DB AOD (r =0.79) than Aqua DB AOD (r =0.68). Overall, DB algorithm was found to be well enough for the assessment of aerosol variability to be conducted over Saudi Arabia.

Keywords: aerosol, aqua, deep blue algorithm, MODIS, temperature, terra

Introduction

Atmospheric aerosols such as dust, tobacco smoke, pollen, volcanic dust, mist, fog, sea salts, oceanic sulphates, industrial sulphates, anthropogenic aerosols, pollen, soot (Black carbon), organic particles and some toxic pollutants are emitted from an extensive assortment of anthropogenic and natural activities (Gupta et al., 2013). Aerosols play vital role in the Earth's atmospheric system by affecting the incoming solar radiation through scattering and absorption (Hsu et al., 2006). In addition, atmospheric aerosols can also change the cloud properties thus creating various environmental and climatic changes over a particular region (Khan et al., 2013). Besides impacts on solar radiation budgets, aerosols are reported to have some severe impacts on human health by influencing the air quality (King et al., 1999; Chu et al., 2003; Grousset et al., 2003). Monitoring aerosols variability is therefore, of great concern to understand the aerosol-atmosphere interactions and changing climatic patterns as well as to mitigate its disastrous impacts on human well being. However, assessment of aerosol climatology is one of the challenging tasks mainly due to the diversity of aerosol types, identification, source regions and short time existence in the atmosphere (Levy et al., 2005; Hsu et al., 2004; Haywood & Bougher, 2000). In this regard, the importance of remote sensing for aerosol monitoring has increased due to the availability of continuous data records within due course of time (Misra et al., 2015). The satellite based retrieval of aerosol optical properties over arid and semiarid regions of the world has been increased during the last few decades particularly from Moderate Resolution Imaging Spectroradiometer (MODIS) and SeaWiFS (Hsu et al., 2006; Misra et al., 2015; Tanre et al., 1997; Tripathi et al., 2005). Due to the large spatial coverage and repeat cycle, these satellites can provide much detailed information regarding aerosol properties which is otherwise difficult to obtain via traditional measurement methods (Chu et al., 2003). Transport of aerosol loadings from one place to another can be done by various means and among them dust and dust storms have the major contribution (Khan et al., 2013). Saudi Arabia is one of the biggest regions in Arabian Peninsula which receive high concentrations of aerosols mainly due to dust storms from various geographical sources (Khan et al., 2013). Unfortunately, due to the scanty of traditional aerosol measurements, the region is lacking in the accurate and up to date aerosol monitoring.

In view of the above, the present research has been designed to study the Aerosol Optical Depth variability using Deep Blue algorithm and its association with temperature over Saudi Arabia for the period 2002-2007. For this study, MODIS Deep Blue (DB) AOD data product was used from Terra and Aqua satellites. This study has three main objectives. The first objective is aimed to understand the spatial distributions of AOD based on the Deep Blue aerosol products from Terra-MODIS and Aqua-MODIS satellites. The second objective is to assess the temporal variations of AOD over Saudi Arabia. Finally, the third objective is to understand the AOD relationship with temperature.

Materials

In this research, the study area is Saudi Arabia as shown in Figure 1. The area is mostly covered by desert which produce large amount of aerosols. In addition, Saudi Arabia is significantly dominated by sand and dust storms and mineral dust aerosols (Shalaby et al., 2015). Saudi Arabia is surrounded by the Strait of Hormuz and the Gulf of Oman on the east, the Arabian Gulf on the northeast, the Arabian Sea on the southeast and south, the Gulf of Aden on the south and Red Sea which is located on the southwest and west. These areas are considered as the salt deposits coastal areas. The high surface reflectance causes difficulties for satellite based remote sensing retrieval of aerosol over the Saudi Arabia (Shalaby et al., 2015).

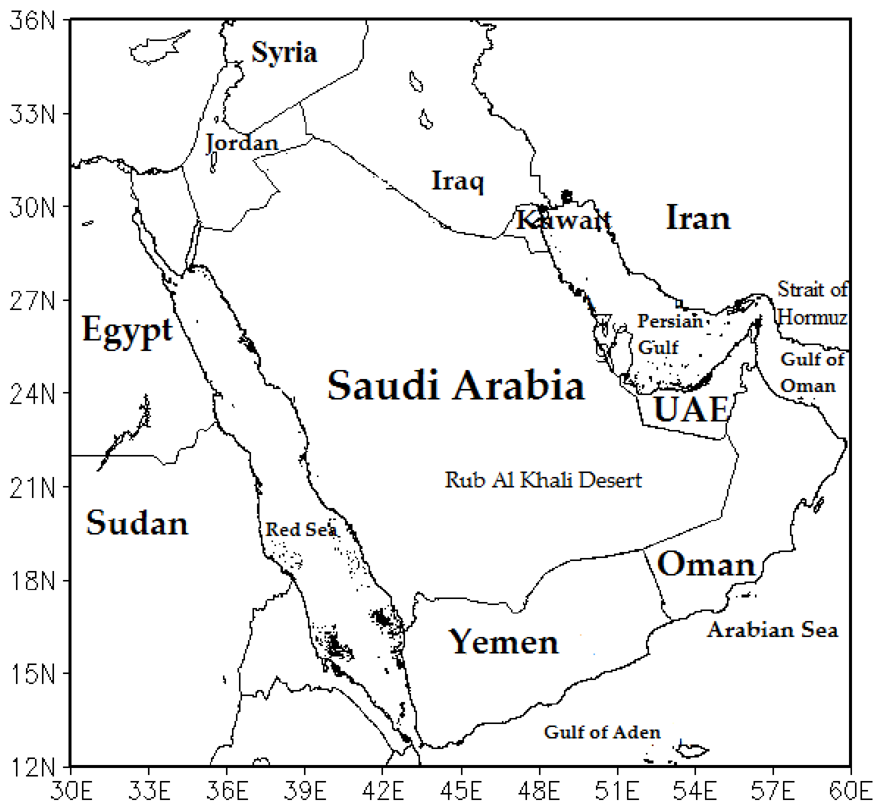


Figure 1. *Geographical location of Saudi Arabia*

MODIS is onboard both on Terra and Aqua satellites. The Terra was launched in 1999 whereas the Aqua was launched in 2002. These two satellites are the sun-synchronous polar orbital satellites. Terra passes at morning i.e.10.30AM and Aqua at afternoon i.e. 01.30 PM local times (Sharif et al., 2015). Both Terra and Aqua are polar orbiting satellites however Terra satellite is orbiting the earth from north to south while Aqua passes from south to north. MODIS has 36 spectral bands with a spatial resolutions of 250m for bands (1-2), 500m for bands (3-7) and 1km for bands (8-36). The temporal resolution or revisit cycle of the instrument is 1-2 days (Ichoku et al., 2004; Alam et al., 2010). The spectral resolution of MODIS spectral bands ranges from 620nm to 14.385 µm (Sharif et al., 2015). MODIS DB AOD Level 3 collection 5.1 data is available from 2000 to 2007 for Terra and 2002 to present for Aqua satellite with spatial resolution 1^0 x 1^0. For this study, we have used Level 3 MODIS DB AOD product at 550nm from Terra and Aqua satellite. The monthly MODIS DB AOD Level 3 collection 5.1 products were downloaded from NASA DACC website http://disc.sci.gsfc.nasa.gov/giovanni.

Modern Era Retrospective-Analysis for Research and Applications (MERRA)isdesigned by NASA's Global Modeling and Assimilation Office to monitor climate background. Data from MERRA is generated with Goddard Earth Observing System (GEOS) atmospheric model and data assimilation system (DAS). MERRA is still working with satellites and provides climatic datasets from 1979 to the present (Climate data guide, 2014). In this study, the surface skin temperature (K)is used to know the potential influences of meteorological conditions on aerosols over Saudi Arabia. The monthly surface skin temperature (K) data was downloaded from the NASA DACC from the following website link: http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=mairs_monthly.

MODIS Deep Blue (DB) algorithm is used to retrieve aerosol properties over brightly reflecting surfaces. Blue wavelength in the electromagnetic spectrum provides low surface reflectance, which builds it probable to extract expected aerosol information (Hsu et al., 2006). The key steps in MODIS based DB algorithm are: (1) Rayleigh correction is used for terrain elevation which measure the reflectance variation because of the inequalities in the surface pressures; (2) the clear and cloudy pixels are separated based on the reflectance at 412nm, and absorbing aerosol index (i.e. ratio of 412 and 490nm) is used to differentiate thick dust from cirrus cloud; (3) the surface reflectance is estimated at 412, 470 and 650nm wavelengths using 0.10 x 0.10 grid from clear-scene database of surface reflectivity that is based on its geolocation; and finally (4) the surface reflectance is measured by satellite which later compared with the resultant values in the look up table, which provides the aerosol optical depth and single scattering albedo using maximum likelihood method.

Methodology

We have downloaded Level-3 MODIS DB AOD monthly mean products at 550nm over Saudi Arabia. The data product was in Net CDF (NC) format. Afterward, these monthly mean products were converted into annual mean AOD climatology based on mean method in GrADS as shown in figure 2.In addition, we have also used some statistical methods which include mean, standard deviation, correlation coefficient and linear regression method to analyse the data. These methods are explained briefly as follows:

The study used Mean method to calculate annual mean AOD from monthly AOD data. The mean (also called an average) is obtained by dividing the sum of all the numbers by the entire numbers (Wilks, 2006). It is calculated using equation 1 as:

$$\text{Mean} = \frac{\text{Sum of all numbers}}{\text{total number}}$$

$$\bar{X} = \frac{\sum_{i=1}^{i=n} x_i}{n} \quad (1)$$

Where $\bar{X}$ is defined as mean,X_i is defined as the individual numbers for a given seti= 1, 2, 3... n and n is the total numbers.

The study used standard deviation method to calculate the annual and monthly variations of AOD. Standard deviation describes that how much the entire data set is closer with the mean value (Wilks, 2006). Equation 2 is used to calculate the standard deviation and is given as:

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i - \bar{X})^2} \qquad (2)$$

Where, $\bar{X}$ is defined as mean,X_i is defined as the individual numbers for a given set i= 1, 2, 3... n and n is the total numbers.

The study used Pearson correlation coefficient method to find out the relationship of AOD with time period and temperature. It is a statistical analysis that can be applied to find out the relationship between two variables. It is defined by r and ranging from -1 to 1. If the correlation coefficient r is nearest to -1, it indicatesthat the variables are anti-correlated. Whereas if the correlation coefficient r is nearest to 1, it indicates that the variables are positively correlated. Moreover, if the value of r is deviated from these values and come close to zero, it indicates that the variables are leastcorrelated and eventually are uncorrelated. The Pearson correlation equationis given as (Wilks, 2006):

$$r = \frac{\frac{1}{n-1}\sum_{i=1}^{n}(X_i-\bar{X})(Y_i-\bar{Y})}{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i-\bar{X})^2}\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(Y_i-\bar{Y})^2}} \qquad (3)$$

Where, $\bar{X}$and $\bar{Y}$is defined as mean,$X_i$and $Y_i$is defined as the individual numbers for a given set i= 1, 2, 3... n and n is the total numbers.

The study used linear regression method to calculate the aerosol trend and it's significance. Linear regression method is used to make a relationship between two variables by fitting a linear equation. Whereas, one variable is considered to be an explanatory or independent variable and the other is considered to be a dependent variable (Wilks, 2006). Linear regression method approximates the model by constructing a linear equation.

$$Y = mx + c \qquad (4)$$

Where, Y is the regression equation, x is independent variable, m is the slope which means change of Y per unit change of x and c is constant or offset or intercept.

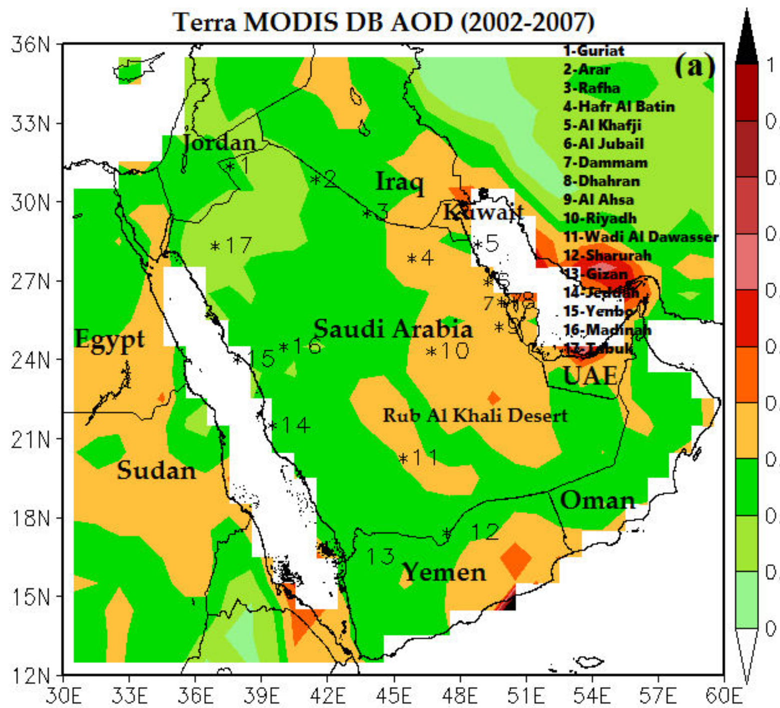
Result and discussion

The MODIS DB algorithm decreases the limitation of aerosol retrieval difficulty over bright reflecting surface (Hsu et al., 2006). Thus, DB algorithm has been used over Saudi Arabia which is mainly covered with desert to find out aerosols concentration. The spatial distribution of annual mean MODIS DB AOD at 550nm has been plotted for the period 2002-2007 from Terra and Aqua satellite. We have analyzed temporal variations of annual AOD, monthly mean AOD and yearly AOD over Saudi Arabia. Finally, AOD relationship with temperature has been studied over the study area.

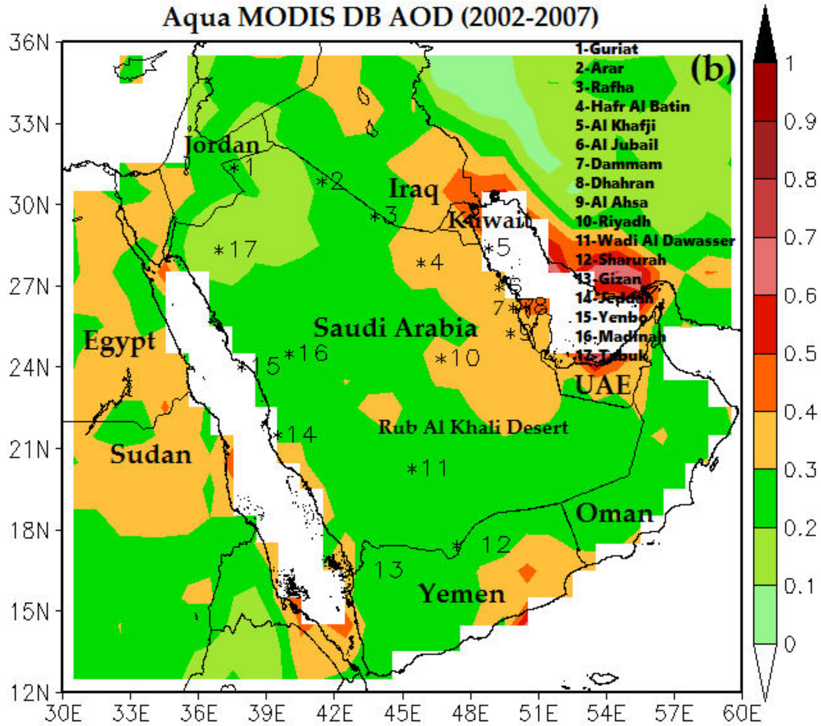
Figures 2a-b show the spatial distribution of annual mean MODIS DB AOD based on Terra and Aqua satellite for the period 2002-2007 over Saudi Arabia. For Terra satellite (Figure 2a) the highest AOD value, that is, 0.5 is observed over major part of Rub Al Khali desert, while various regions, for example Northeast, East and Southeast parts of Saudi Arabia over Hafr Al Batin, Al Jubail, Dammam, Dhahran, Al Ahsa, Riyadh, portion of Rub Al Khali desert and Wadi Al Dawasser have AOD value in the range of 0.4.

In addition, the AOD value in the range of 0.3 is observed in Northeast, Central, Southeast, South, Southwest, West, and Northwest areas of Saudi Arabia over Guriat, Arar, Rafha, Al Khafji, Sharurah, Rub Al Khali desert, Najran, Gizan, Abha, Bisha, Khamis Mushait, Jeddah, Makkah, Taif, Yenbo, Madinah and Hail (Figure 2a). The AOD value in the range of 0.2 is observed in Northern and Northwest part of Saudi Arabia over Tabuk (Figure 2a).

For Aqua satellite, the highest AOD value, that is, 0.4 is observed in Northeast and East parts of Saudi Arabia over Hafr Al Batin, Al Khafji, Al Jubail, Dammam, Dhahran, Al Ahsa, Riyadh, Rub Al Khali desert and Gizan (Figure 2b). Similarly, the AOD value in the range of 0.3 is observed in North, Central, Southeast, South, and Southwest parts of Saudi Arabia over Guriat, Arar, Rafha, Al Khafji, Rub Al Khali desert, Sharurah, Najran, Abha, Bisha, Khamis Mushait, Jeddah, Makkah, Taif, Yenbo, Madinah and Hail (Figure 2b). Finally, the AOD value in the range of 0.2 is observed in Northern and Northwestern part of Saudi Arabia over Tabuk (Figure 2b).



(a) Terra satellite



(b) Aqua satellite

Figure 2. *Annual mean spatial distribution of MODIS DB Aerosol Optical Depth (AOD) at 550 nm from Terra and Aqua satellite for the period 2002-2007 over Saudi Arabia*

In this section, Terra and Aqua MODIS DB AOD data areanalyzedover Saudi Arabia for the period 2002-2007. Figure 3 shows the inter-annual variability of aerosol which is calculated over Saudi Arabia. Distinctive maximum AOD was observed in 2003 (0.30) for Terra satellite while in 2006 (0.29) for Aqua satellite. In addition, the overall decreasing trend in AOD concentration is observed for Terra satellite (-0.00026y^{-1}) while increasing trend for Aqua satellite (0.007y^{-1}). Both the trends are however statistically insignificant at 95% confidence level.AOD was observed highly fluctuated in 2003 with a standard deviation value of 0.12(based on Terra satellite) while for Aqua satellite the values of standard deviation for the years 2003, 2005 and 2006 is 0.10.

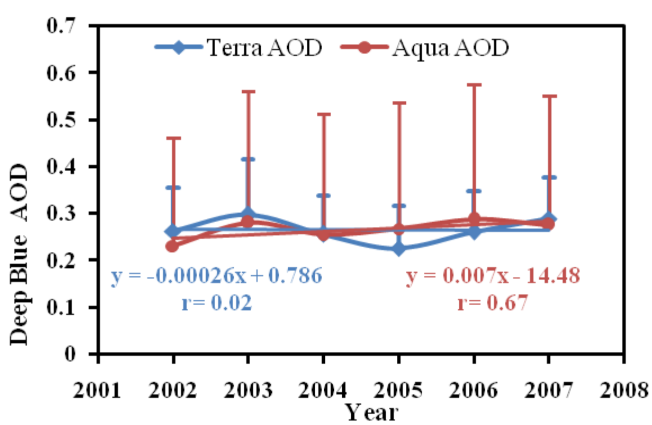


Figure 3. *The inter-annual variability in Deep Blue (DB) AOD at 550nm over Saudi Arabia for the period 2002-2007 from Terra and Aqua satellite. Where, the vertical bars indicate standard deviation of annual AOD*

In this section, monthly mean MODIS DB AOD data is analyzed over Saudi Arabia for the period 2002-2007 from Terra and Aqua satellite. Figure 4 shows the intra-annual variability of AOD which is calculated over Saudi Arabia. It has to be noted that the peak AOD value is observed in July (0.41) based on Terra satellite while for Aqua satellite, the peak AOD value is observed in June (0.44). Similarly, as evident from figure 4, the minimum AOD values for Aqua is observed for the month of January and November (0.17) and for Terra is observed for the month of November (0.15).The values of AOD from Aqua satellite has higher values for the months of February, March, April, May, June, October and November while lower for the months of July, August and September as compared to Terra satellite. However, for the months of January and December the values of AOD from both Terra and Aqua are more or less similar. In addition, the AOD variation from both the satellite system show increasing trend from the month of January to June and decreasing trend from the months of July to November.

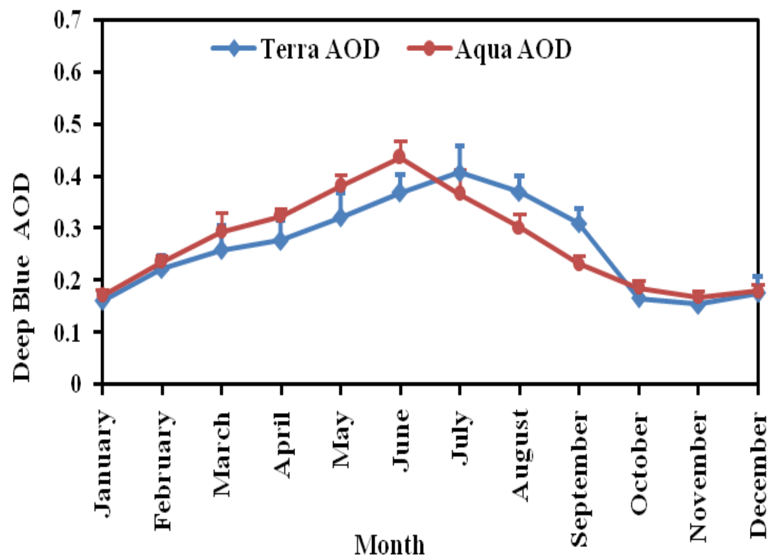


Figure 4. *The intra-annual variability in Deep Blue AOD over Saudi Arabia for the period 2002-2007 from Terra and Aqua satellite. Where, the vertical bars indicate standard deviation of annual AOD.*

In this section, annual MODIS DB AOD data was analyzed over Saudi Arabia for the period 2002-2007 from Terra and Aqua satellite. Figures 5a-f show the annually AOD variability which is calculated over Saudi Arabia. It is evident form Figure 5a that, in 2002, the minimum AOD value is observed in January (0.15) and peak in July (0.40) based on Terra satellite whereas for Aqua satellite, the minimum AOD value is observed in November (0.17) and peak AOD was observed in July (0.34).For the year 2003 (Figure 5b), the minimum AOD value is observed in January and October (0.16) and maximum in July (0.51) based on Terra satellite whereas for Aqua satellite, the minimum AOD value is observed in January (0.16) and peak in May and July (0.42). In year 2004 (Figure 5c), the minimum AOD value is observed in January (0.15) and peak in July (0.37) based on Terra satellite whereas for Aqua satellite, the minimum AOD value is observed in January (0.16) and peak in June (0.40).It is clear from figure 5d that for the year 2005 the minimum AOD value is observed in November (0.11) and peak in July (0.35) based on Terra satellite while for Aqua satellite, the minimum AOD value is observed in November and December (0.16) and peak in June (0.45).The results for the year 2006 are shown in figure 5e which indicate that the minimum AOD value is observed in January (0.15) and peak in July (0.40) based on Terra satellite while for Aqua satellite, the minimum AOD value is observed in November (0.17) and peak in June (0.47). Finally, for the year 2007 (Figure 5f), the minimum AOD value is observed in November (0.15) and peak in June (0.43) based on Terra satellite while for Aqua satellite, the minimum AOD value is observed in November (0.17) and peak in June (0.46).

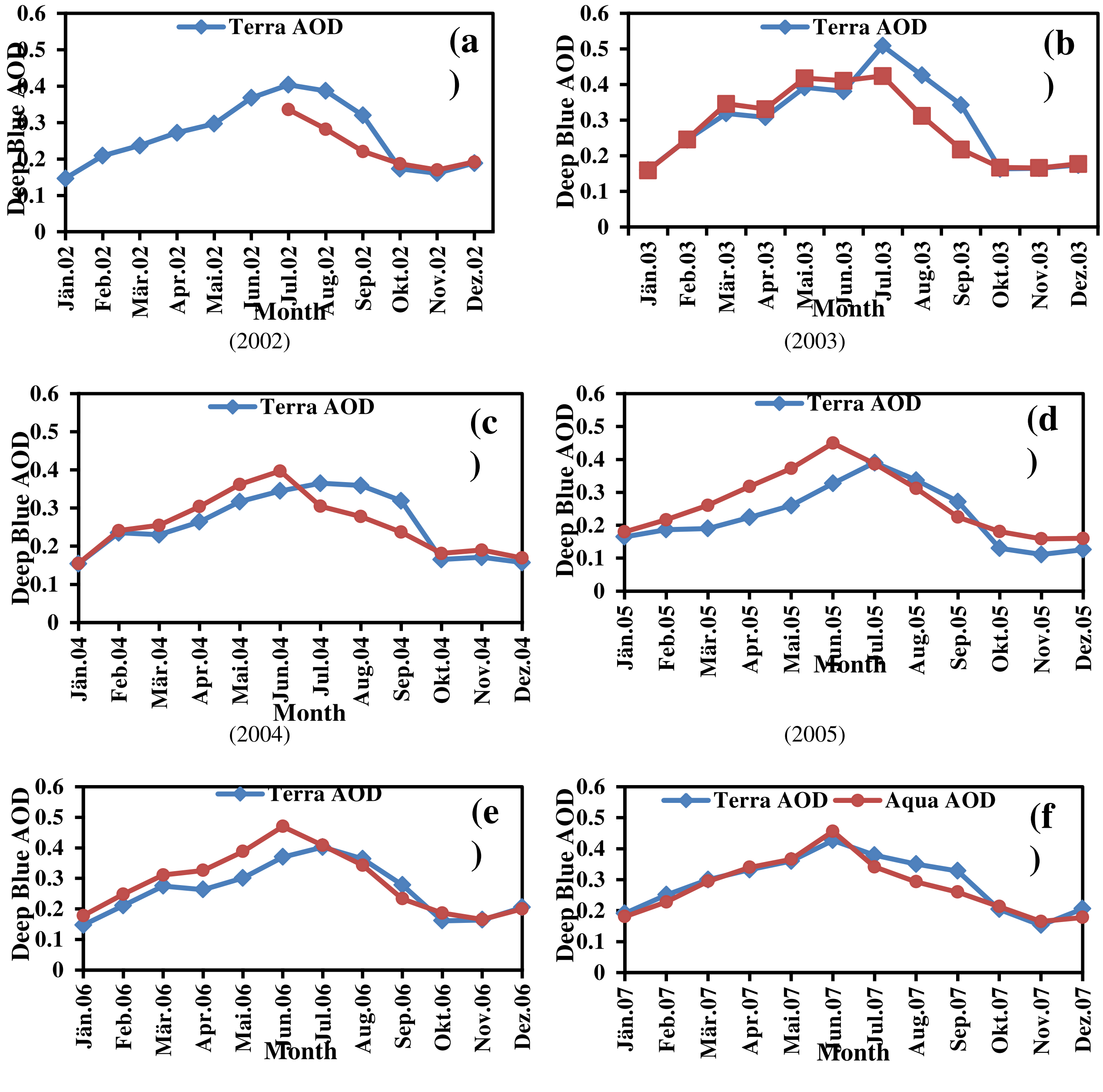


Figure 5. *Annually Deep Blue (DB) AOD variations for the period 2002-2007 over Saudi Arabia from Terra and Aqua satellite*

The aerosol variations are interlinked with meteorological parameters such as temperature, rainfall and relative humidity etc. In addition, meteorological conditions canal so affect aerosol by altering its composition and conduction path (Mamun et al., 2014). One significant metrological parameter i.e. temperature is analyzed over Saudi Arabia to understand the aerosol-temperature relationship. Figure 6 shows the inter-annual variations of Temperature and MODIS DB AOD over Saudi Arabia for the period 2002-2007. The Deep Blue AOD was used from Terra and Aqua satellite. It can be seen that both Temperature and AOD show good episodic variations during the study period. The temperature was found minimum in January and reached up its peak extend in July afterward temperature was gradually decreased and reached to it's lowest in December during the study period. Therefore, AOD from Terra and Aqua satellite reveals similar trend with Temperature.

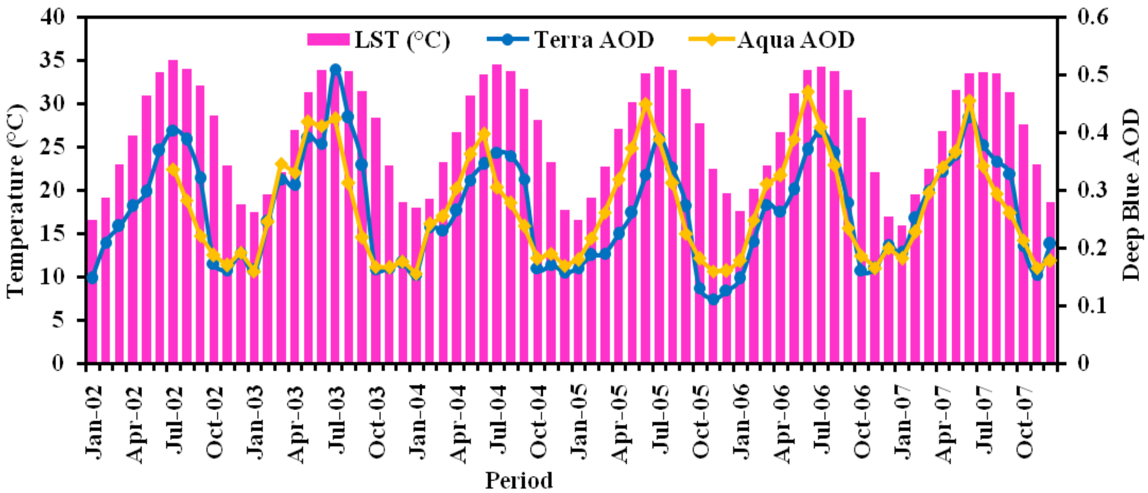


Figure 6. *Inter-annual variations of Temperature and AOD over Saudi Arabia for the period 2002-2007. Where, the Deep Blue AOD is used from Terra and Aqua satellite*

The correlation of AOD from Terra and Aqua satellite with temperature was also analyzed by scatter plot and is shown in Figure 7. The correlation between Terra AOD and temperature is r =0.79while between Aqua AOD and temperature is r =0.68. These analyses imply that temperature is significantly influenced aerosols and most important constituent for aerosol variability.

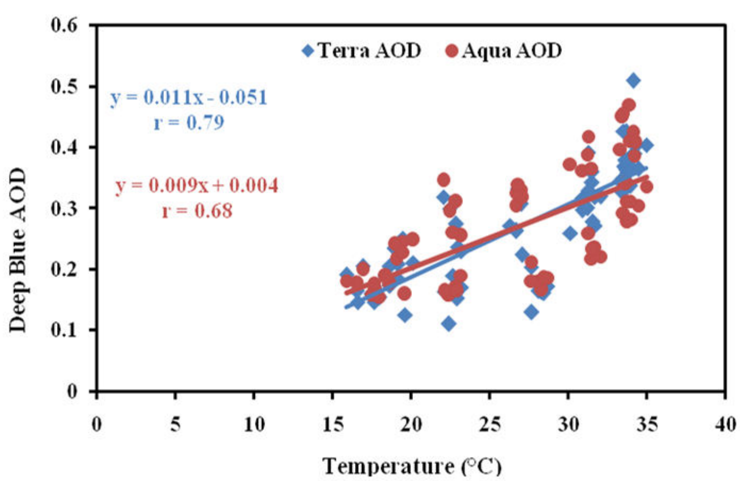


Figure 7. *Correlation between Temperature (^{0}C) and AOD from Terra and Aqua satellite for the period 2002-2007 over Saudi Arabia*

Conclusion

Deep Blue aerosol variability and its relationship with temperature over Saudi Arabia for the period 2002-2007 are presented in this paper. Level 3 MODIS DB AOD products from Terra and Aqua satellites at 550nm were used. Highest aerosols were observed over Rub-al-Khali desert based on DB AOD product of Terra satellite. The minimum aerosols were observed in Tabuk region based on DB AOD data from both Terra and Aqua satellites. Furthermore, annual mean AOD analysis from Terra and Aqua show decreasing and increasing trends of aerosols respectively over entire Saudi Arabia. Monthly mean AOD analysis based on Terra show high aerosols in July and minimum aerosols in November while Aqua based analysis reveal high aerosols in June and minimum aerosols in January and November. Strong correlation is found between aerosols and temperature which shows that the aerosols can have potential impacts on the climate of Saudi Arabia. Overall, the study revealed that Deep Blue algorithm is quite well enough to assess the aerosol properties over Saudi Arabia.

Acknowledgement

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