Seasonal Aerosol Optical Depth (AOD) Variability Using Satellite Data and its Comparison over Saudi Arabia for the Period 2002–2013

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ABSTRACT

This study analyzes the spatiotemporal variations of seasonal Moderate Resolution Imaging Spectroradiometer (MODIS) Deep Blue (DB) AOD at 550 nm from the Aqua satellite over Saudi Arabia for the period 2002–2013. Satellite retrieved AOD is also compared with AERONET AOD over the Solar Village and KAUST station. The result of the seasonal AOD spatial distribution shows that the peak AOD value of 0.6 is observed over Hafr Al Batin, Riyadh, and the Rub Al Khali desert during spring, whereas the Gizan area shows the peak AOD during summer. In contrast, the autumn shows the peak AOD value of 0.5 over Dhahran and in the proximity of Jeddah, whereas Hafr Al Batin, Al Khafji, Al Jubail, and the Rub Al Khali desert show the peak AOD value of 0.4 in winter. Regression analysis shows the AOD increasing trends during spring, summer, and autumn (except for winter) over the entire Saudi Arabia. Over the Solar Village, the AOD increasing trends are also noted during spring and summer, whereas autumn and winter display the AOD decreasing trends. The AOD increasing trends are displayed in all seasons over KAUST. Hence, the AOD increasing/decreasing trends indicate that the number of dust storms either increases or decreases over these regions. Over the Solar Village, the correlation values for MODIS DB AOD versus AERONET AOD are 0.77 (spring), 0.62 (summer), 0.65 (autumn), and 0.75 (winter). Likewise, over KAUST, the correlation values for the same pairing are 0.85 (spring), 0.71 (summer), 0.81 (autumn), and 0.89 (winter). The incorrect aerosol model selection and imperfect surface reflectance calculation are responsible for reducing the correlation. Therefore, this study recommends that the DB algorithm can be used effectively to detect AOD over Saudi Arabia, which will further help to improve the MODIS DB AOD product utilizing the next version of the algorithm.

Keywords: Aerosol; MODIS DB Algorithm; Regression; AERONET.

INTRODUCTION

Aerosols are the mixture of tiny solid and liquid suspended particles in the atmosphere. They form after different physical and chemical processes of natural dust, volcanic dust, mist, fog, sea salts, oceanic sulfates, urban/industrial sulfates, anthropogenic aerosols, pollen, soot (back carbon), organic particles, and some toxic pollutants (Gupta et al., 2013; Pawar et al., 2015). The current research on this issue mainly focuses on the role of aerosol in the Earth's climate system (Misra et al., 2015; Kolhe et al., 2016). Aerosols attenuate the incoming solar radiation that reaches the Earth's surface by absorbing and scattering the radiation (Haywood andRamawamy, 1998; Hatzianastassiou et al., 2007; Pawar et al., 2015; Kolhe et al., 2016). Atmospheric aerosols can cause climate change through their direct, indirect, and semi-direct effects on the radiative energy budget of the Earth-Atmosphere system (Papadimas et al., 2008; Pawar et al., 2015; Kolhe et al., 2016). However, the quantification of these effects is very difficult because the aerosol physical, chemical, and optical properties are highly variable in space and time, due to their short atmospheric lifetime and to inhomogeneous emission. According to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007), aerosols have been perceived as the principal constituents of global climate change in the last two decades because they play a decisive role in transferring the solar and thermal radiation in the atmosphere (Kosmopoulos et al., 2008). Moreover, aerosols have a significant impact on the solar radiation budget, hydrological cycle, precipitation, and human health (Charlson et al., 1992; Ramanathan et al., 2001; Lohmann and Feichter, 2005; Kosmopoulos et al., 2008). Kaskaoustis et al. (2007) stated that numerous types of aerosols have the different impression of the degree and sign of aerosol radiative forcing. For example, black carbon aerosols have significantly added to global warming (Jacobson, 2001; Penner et al., 2003), increased rainfall over the southern areas, and simultaneous drought conditions over the northern areas of China (Menon et al., 2002; Sarkar et

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al., 2006). Dust particles alter the transport of the short-wave and long-wave radiation through the atmosphere by absorption and scattering processes (Otto et al., 2007), which produce heat in the atmosphere (Haywood et al., 2001). In addition, the environmental ecosystems and human livelihoods are significantly affected by aerosols (Smart et al., 2011). Air quality and public health are also affected due to the boreal forest fire and biomass burning aerosols (Torres et al., 2002).

The AOD usually changes with respect to time and space, changing the cloud properties, and precipitation processes. Some researchers have reported that the indirect impacts of the AOD spatial and temporal patterns are monitored based on the satellite observations at both regional and global-scales (Nakajima et al., 2001; Kaufman et al., 2005; Matheson et al., 2005). Satellite remote sensing is used as an important instrument for observing the global aerosol budget and the relative effects on climate (Penner et al., 1992; Tripathi et al., 2005). In addition, Kosmopoulos et al. (2008) reported that satellite remote sensing usually provides aerosol properties and its spatial distribution with a complete and synoptic mapping of a large area in a single image. In light of the above, it can be concluded that satellite remote sensing identifies seasonal, regional, and global spatial patterns of aerosol loading and its properties. In understanding the effect of aerosols on human health and the Earth's climate system, a consistent AOD observation is needed both at regional and global scales.

Ground-truth AOD is measured based on automatic permanent monitoring stations or exclusive software. For example, the AOD is routinely measured using ground-based stations that provide AOD point data over certain areas of Asia, Australia, urban areas of Europe, and the USA. In this regard, AERONET (Holben et al., 1998) has been developed for providing simultaneous satellite remote sensing and ground-based measurement of the AOD point data. Within the last 10 to 15 years, the satellite remote sensing has undergone major developments. For example, Chu et al. (2003) and Wang and Christopher (2003) reported that MODIS satellite data have significant potential for mapping the AOD attributes and distribution, as well as for determining the indirect measurement of particulate matter. Liu et al. (2007) reported that MISR satellite data could also be used in the same manner as the MODIS data application. Satellite data have been used to observe the AOD loading and its characteristics on local and global scales because ground-based measurements have limited coverage over many areas in the world (Gupta et al., 2008).

In Asia, the amounts of aerosol are significantly rising over all the industrialized and urbanized areas due to increasing populations, rapid urbanization, changing land use, increased mobile traffic, industrialization, and various types of pollution (Alam et al., 2011). In India, several studies reported that the AOD trends are increasing due to increased anthropogenic activity levels. For example, the AOD was found to be higher in summer than in winter season over the Indo-Gangetic Plain (Prasad et al., 2007). Likewise, the AOD was found to be higher in summer and lower in winter over different cities of Pakistan (Alam et al., 2010). Moreover, Ranjan et al. (2007) reported that the AOD was found to be lower in winter and higher in summer over Rajkot, due to the high wind speeds that drive dust particles. Dey et al. (2005) reported that industrial and urban-based AOD have added more than 75% of the observed AOD in winter and post-monsoon seasons, while the natural AOD added 60% of the total AOD in pre-monsoon season and during monsoon. Ali et al. (2015) also reported that the correlation between Aqua MODIS and AERONET AOD over Dhaka, Bangladesh showed a better correlation in pre-monsoon and monsoon seasons than in autumn and winter seasons. Tripathi et al. (2005) reported that the correlation between MODIS and AERONET AOD during the pre-monsoon and monsoon seasons was approximately equal to that in the post-monsoon and winter seasons over Kanpur for the year 2004. There are limited studies available on satellite based AOD over Saudi Arabia. For example, the AOD climatology based on the satellite remote sensing data has been studied over different Provinces of Saudi Arabia (Farahat et al., 2015). Sabbah and Hasan (2008) studied the ground-based measurements of aerosol optical depth over the Solar Village, Saudi Arabia.

The present investigation has been designed to study the seasonal AOD variability and its comparison with ground-based AERONET AOD data over Saudi Arabia for the period 2002–2013. For this, the study uses the MODIS DB AOD product from the Aqua satellite and AERONET AOD from the Solar Village and KAUST station. The study has been undertaken based on three main objectives. The first is to calculate the seasonal AOD spatial distributions over Saudi Arabia. The second is aimed to assess the AOD temporal variations and frequency distribution over the entire Saudi Arabia, the Solar Village, and KAUST. The third is intended to compare the satellite retrieved AOD with AERONET AOD over the Solar Village and KAUST station.

MATERIALS AND METHODS

Study Area

Saudi Arabia is by far the largest country in the Arabian Peninsula (Fig. 1). The Saudi Arabia coastlines, which encompass the Arabian Gulf in the east and the Red Sea in the west, provide globally and strategically significant shipping channels, particularly for crude oil, via the Arabian Gulf and the Suez Canal. The Saudi Arabia has borders with the United Arab Emirates (UAE), Oman, Yemen, Bahrain, Qatar, Kuwait, Iraq, and Jordan. Geographically, Saudi Arabia covers 2,217,949 km². The geography of Saudi Arabia is composed of desert, semi-desert, coastal plains, and mountain regions. The southern area of Saudi Arabia includes about 647,500 km² of desert (the Rub Al Khali desert/Empty Quarter). There are very few fertile land areas found in the alluvial deposits in the valley, basins, and oases. In addition, only less than one percent of the total region is suitable for agriculture. The country is composed of 13 provinces, with a total of 104 cities, including 20 large cities. According to the Saudi Arabia 2010 census report the total population is 27 million, including 8.4 million foreign residents (Royal Embassy of Saudi Arabia in Washington, DC).
The seasons of Saudi Arabia are classified based on the three months mean of meteorological parameters such as temperature and rainfall (AMS, 2001). Hence, the Saudi Arabia's seasons are classified into spring from March to May (MAM), summer from June to August (JJA), autumn from September to November (SON), and winter from December to February (DJF).

**MODIS AOD Data**

The Terra and Aqua satellites carry the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument. The Terra satellite was launched on December 18, 1999, flying northwardly over the equator at about 10:30 a.m. local time, while the Aqua satellite was launched on May 4, 2002, flying southwardly over the equator at about 1:30 p.m. local time. The time-gap between the Terra and Aqua satellites is generally less than three hours over the same area (Zhang et al., 2010). MODIS, the new generation Imaging Spectroradiometer contains 36 spectral channels that cover the wavelength range from (0.4–14.4) µm. All the spectral channels provide atmospheric, oceanic, and terrestrial information (Kim et al., 2003; Ichoku et al., 2004). In addition, MODIS has the three spatial resolutions of 250 m for 1 to 2 bands, 500 m for 3 to 7 bands, and 1 km for 8 to 36 bands respectively, and scanning-width of 2330 km (Kim et al., 2003; Ichoku et al., 2004; Alam et al., 2010; More et al., 2013). The temporal resolution of the MODIS Terra and Aqua satellites is 1–2 days. MODIS has daily, 8 days or 16 days merged images and products with various time-scales (Fozia et al., 2015). The numbers of climatic parameters are also retrieved based on the MODIS instrument with a spatial resolution of 5 km and 10 km (Alam et al., 2010, 2011, 2014; Balakrishnaiah et al., 2012). The global coverage of MODIS Terra and Aqua satellites are every one to two days, which are useful for sophisticating explanation in local, regional, and global distributions of some climatic parameters over the ocean and land.

The AOD is calculated based on the MODIS instrument with an error of ± 0.05 ± 0.02 AOD over the land and ± 0.03 ± 0.05 AOD over the ocean. MODIS AOD over the land is estimated based on the top of atmospheric reflectance at the 2.1 µm wavelength (band 7). On the other hand, Kaufman et al. (2002) reported that band 3 (470 µm) to band 7 (2.1 µm) are usually used to separate the fine and coarse particles from dust and sea-salt. The MODIS AOD retrieval algorithm has been updated for the correction of bias based on the earlier MODIS algorithm (Remer et al., 2005; Levy et al., 2007).

Level 3 MODIS Deep Blue (DB) collection 5.1 AOD data products at 550 nm are available from March, 2000 to 2007 from the Terra satellite due to the known calibration issues, and from July, 2002 to present from the Aqua satellite. For that reason, the present study uses MODIS DB AOD products from the Aqua satellite for the period 2002 to 2013. The AOD products from the MODIS DB algorithm give significantly increased levels of accuracy and reliable AOD information over desert surfaces such as bright reflecting surfaces and snow or ice sheet areas (Hsu et al., 2004, 2006). MODIS Dark Target (DT) algorithm (Kaufman et al., 1997) is capable of locating and identifying the AOD information over vegetated land and soil surfaces. Due to Saudi Arabia being mostly covered by the desert surface, Level 3 MODIS DB AOD products at 550 nm, with a 1° × 1° degree spatial resolution are used. The MODIS DB AOD retrievals uncertainty is estimated as ± 0.05 ± 20% × AERONET AOD (Hsu et al., 2006; Huang et al., 2011; Shi et al., 2013). The daily and monthly basis Level 3 MODIS DB AOD data have been downloaded free of cost from the NASA GES DISC website, available online at http://giovanni.gsfc.nasa.gov/giovanni/. The study also uses Level 2 collection 5.1 MODIS DB AOD data from the Aqua satellite over the Solar Village and KAUST, Saudi Arabia. The data have been downloaded free of cost from the Multi-Sensor Aerosol Product Sampling System (MAPSS), NASA which is available online at (http://giovanni.sfc.nasa.gov/mapss/).
**AERONET AOD Data**

AERONET gives AOD data products based on measurements of direct solar radiation at different wavelengths, under cloud-free conditions, with low levels of uncertainty (~0.01–0.02), and high temporal resolution of approximately 15 minutes (Holben et al., 1998). The AERONET provides three levels of the AOD data: Level 1.0 (unscreened), Level 1.5 (cloud-screened), and Level 2.0 (quality assured) data (Holben et al., 1998). AERONET has been recognized as the standard source of the AOD due to the high quality of its data, its global range, and because it is free and straightforward to access. AERONET measured 500 nm AOD is converted to a 550 nm AOD using the Angström empirical formula such as AOD = β × λ² (More et al., 2013). AERONET AOD can also be used for comparison and bias correction of satellite measured AOD datasets (Ichoku et al., 2002; Zhang and Reid, 2006; Kahn et al., 2010; Levy et al., 2010; Hyer et al., 2011; Carboni et al., 2012; Sayer et al., 2012b; More et al., 2013). The present study uses Level 2 quality assured AERONET AOD data to compare the satellite AOD at 550 nm over the Solar Village, Riyadh and KAUST, Thuwal, Jeddah, Saudi Arabia. The data have been downloaded from MAPSS, NASA website http://giovanni.gsfc.nasa.gov/mapss. Table 1 designates the geographic information of Saudi Arabia AERONET sites.

**MODIS Deep Blue Algorithm**

MODIS DB algorithm is used to retrieve the AOD information over bright-reflecting surfaces such as desert areas. The blue channel is used since it provides low surface reflectance over the desert surface and it is possible to make the expected AOD information (Hsu et al., 2006). The major steps of the MODIS DB algorithm are following: (1) several radiances based on 412 nm (Band 8), 470 nm (Band 3), and 660 nm (Band 1) are used as input in DB algorithm for AOD estimation, (2) Rayleigh's correction is used for terrain elevation since terrain elevation has a relationship with pressure. It measures the variation of reflectance due to the inequalities in the surface pressures, (3) in the cloud screening step, the cloudy and clear pixels are detached based on the reflectance at 412 nm, and aerosol absorbing index (i.e., ratio of 412 nm and 470 nm) is applied to make a distinction from cirrus cloud, (4) surface reflectance is estimated based on the top of atmosphere (TOA) reflectance at 412 nm, 470 nm, and 660 nm wavelengths using a 0.1 latitude × 0.1 longitude grid from the clear-scene surface reflectivity database, based on its geolocation. Finally, the satellite-based surface reflectance is then compared with Radiative Transfer Model (RTM) based calculated values in the lookup table (LUT), which provides the AOD and single scattering albedo, using the maximum likelihood method.

**RESULTS AND DISCUSSION**

**Spatial Distribution of Seasonal Mean AOD**

In this study, the MODIS DB algorithm has been used to discover the AOD information over Saudi Arabia (i.e., mostly desert areas). It has been used because this algorithm diminishes the weakness of the AOD retrieval difficulty over bright-reflecting surfaces such as desert areas and snow or ice cover areas (Hsu et al., 2006). Furthermore, Misra et al. (2015) reported that the present MODIS DB is incapable of estimating the AOD information over water bodies. However, in this study we have analyzed the spatial distribution of seasonal mean AOD and its temporal variations based on the monthly MODIS DB AOD products at 550 nm. The AOD frequency distribution (Wilks, 2006), using daily MODIS DB AOD data at 550 nm over Saudi Arabia for the period 2002 to 2013 has also been included. Finally, the Aqua satellite retrieved MODIS DB AOD has been compared with ground-based AERONET measured AOD over the Solar Village and KAUST, Saudi Arabia. Fig. 2 shows the spatial distribution of the seasonal mean AOD over Saudi Arabia for the period 2002 to 2013.

In spring (MAM) season, the peak AOD value of 0.6 is observed over Hafr Al Batin, Riyadh, and the Rub Al Khali desert (Fig. 2(a)). The AOD value of 0.5 is detected in the northeastern, eastern, central, and southeastern regions of Saudi Arabia, over Rafha, Al Khafji, Al-Jubail, Dammam, Dhahran, Riyadh, Al Ahsa, near Makkah, and the Rub Al Khali desert. Similarly, the 0.4 AOD value is seen in the northern, southeastern, southern, western, and northwestern regions of Saudi Arabia, over Guriat, Arar, the Rub Al Khali desert, Wadi Al Dawasser, Giza, Jeddah, and Madinah. Finally, it is evident from Fig. 2(a) that the areas of Tabuk, the Rub Al Khali desert, and Sharurah display the minimum AOD value of 0.3.

In summer (JJA) season, the peak AOD value of 0.6 is observed over Gizan (Fig. 2(b)). The 0.5 AOD value is also seen in the northeastern, eastern, central, southeastern, and southwestern regions of Saudi Arabia, over Al Khafji, Dammam, Dhahran, Al Ahsa, Riyadh, the Rub Al Khali desert, Sharurah, Najran, and Abha (Fig. 2(b)). Similarly, the 0.4 AOD value is detected in the northeastern, central, southern, western, and northwestern regions of Saudi Arabia, over Hafr Al Batin, Al Jubail, the Rub Al Khali desert, Wadi Al Dawasser, Jeddah, Makkah, and Abha (Fig. 2(b)). Finally, it is evident from Fig. 2(b) that the minimum AOD value of 0.2 is seen in the northern and northwestern regions of Saudi Arabia in the vicinity of Tabuk and Guriat.

In autumn (SON) season, the peak AOD value of 0.5 is observed over Dhahran and in the proximity of Jeddah (Fig. 2(c)). The 0.4 AOD value is also detected in the

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Fig. 2. Spatial distributions of the seasonal mean MODIS DB AOD from the Aqua satellite over Saudi Arabia for the period 2002–2013. Panels (a), (b), (c), and (d) are for spring (MAM), summer (JJA), autumn (SON), and winter (DJF) seasons.

In winter (DJF) season, the peak 0.4 AOD value is observed over Hafr Al Batin, Al Khafji, Al Jubail, and the Rub Al Khali desert as shown in Fig. 2(d). In addition, the 0.3 AOD value is detected in the northern, northeastern, central, southeastern, southern, southwestern, western, and northwestern parts of Saudi Arabia, over Safiha, Al Ahsa, Riyadh, the Rub Al Khali desert, Wadi Al Dawasser, Sharurah, and Tabuk.

However, it has been reported by several earlier studies (Prospero et al., 2002; Washington et al., 2003; Goudie and Middleton, 2006) that the dust AODs are plentiful over the eastern parts of Saudi Arabia, as well as in the Rub Al Khali desert throughout the spring (MAM) and summer (JJA) seasons. In addition, Aher et al. (2014) which discusses AOD rise at KAUST Campus (Saudi Arabia) and Mezaira (UAE). Alharbi et al. (2013) reported that the AOD is unexpectedly increased over Dhahran is of an exceptionally high level as a result of frequent sand and dust events, in addition to the industrial activities in that region. Moreover, it has been related by Farahat et al. (2015) based on MODIS DB AOD at 550 nm data, that the AOD levels peak during spring season over the Rub Al Khali desert due to the frequent dust events. The authors also used OMI data to highlight excessive levels of air contamination over Dhahran. Sabbah and Hasan (2008) showed that the dust AODs are found to peak during spring over the Solar Village, central Saudi Arabia. Finally,
it is noted from Fig. 2 that the seasonal AOD has a noticeable impact on the different cities of Saudi Arabia, particularly in the northern, central, southern, southwestern, and eastern areas due to their geospatial locations (i.e., mostly covered by desert areas), heavy industrial and vehicular emission levels, and other anthropogenic activities. It is therefore concluded that the frequent sand and dust events and industrial activities explain the AOD variations over the different cities of Saudi Arabia.

**Trend Analysis of the Seasonal AOD**

In this section, the inter-annual variability of the seasonal AOD is presented. Fig. 3 shows the inter-annual variability of the seasonal AOD obtained from the MODIS DB product at 550 nm from the Aqua satellite over the entire Saudi Arabia and two stations (the Solar Village and KAUST) for the period 2002–2013. A linear regression method (Wilks, 2006) is used to calculate slope, intercept, AOD trend, and significance. The mean AOD values of the individual season, which is calculated based on the yearly seasonal AOD values (displayed in Fig. 3) for the period 2002–2013 over the entire Saudi Arabia, the Solar Village, and KAUST. The distinctive maximum seasonal-mean AOD values are found in spring (0.37) rather than in summer (0.34), winter (0.22), and autumn (0.21) seasons over the entire Saudi Arabia (Fig. 3(a)). Similarly, the distinctive maximum seasonal-mean AOD values are found in spring (0.51) rather than in summer (0.46), autumn (0.29), and winter (0.27) seasons over the Solar Village (Fig. 3(b)). The distinctive maximum seasonal-mean AOD values are found in summer (0.36) rather than in spring (0.31), autumn (0.24), and winter (0.19) seasons over KAUST (Fig. 3(c)). It is evident from Fig. 3(a) that the increasing AOD trends are found in spring (0.006 y⁻¹) and autumn (0.001 y⁻¹) with 95% statistical insignificant (with the exclusion of the summer) from 2002 to 2013 indicating heavy dust aerosols. The AOD value in the range of 0.9 to 0.999 is found twice (in spring and summer), indicating heavy mixed aerosols (Fig. 4(a)). Similarly, it is evident from Fig. 4(b) that the AOD value from 1.00 to 1.50 is observed 55 times in spring, 17 times in summer, twice in autumn, and four times in winter over the Solar Village for the period 2002–2013, indicating heavy dust aerosols. The AOD value in the range of 0.9 to 0.999 is observed 29 times in spring, 13 times in summer, twice in autumn, and six times in winter, indicating heavy mixed aerosols (Fig. 4(b)). Finally, Fig. 4(c) shows that the AOD value of 1.00 to 1.50 is evident 17 times in spring, 10 times in summer, and four times in winter season over KAUST from 2002 to 2013, again indicating heavy dust aerosols. Moreover, the AOD value in the range of 0.9 to 0.999 is found eight times in spring, 20 times in summer, twice in autumn, and three times in winter season, indicating heavy mixed aerosols (Fig. 4(c)). More et al. (2013) also studied the frequency distribution of MODIS and AERONET measured AOD over a Tropical Urban City, Pune, India. They found that light and heavy aerosols are loaded during winter and pre-monsoon season respectively.

**Seasonal Comparison of Satellite-based MODIS DB AOD with AERONET AOD**

In this section, the MODIS DB AOD product from the Aqua satellite is compared with respect to ground truth AERONET measured AOD at 550 nm over two ground stations (the Solar Village and KAUST). A linear regression method (Wilks, 2006) is used in this study to calculate slope, intercept, and significance. The parameters of the regression line equation i.e., slope (m) and intercept (c) define the two information factors such as aerosol model and surface reflectance, which affect the quality of MODIS DB AOD retrievals (Chu et al., 2002; Xie et al., 2011; More et al., 2013; Misra et al., 2015). The slope (m) indicates the error that occurs due to the imperfect aerosol model assumption, while intercept (c) denotes the inaccurate surface reflectance estimation. The perfect matches between MODIS DB and AERONET AOD measurements are m = 1 and c = 0 respectively. The negative intercept indicates that the surface reflectance, pointing to a small amount of retrieved AOD values, has been overestimated. The positive intercept shows that the surface reflectance, pointing to a large amount of retrieved AOD, has been underestimated. Shi et al. (2011, 2013) use the Root Means Square Error (RMSE) method to discover the degree of error of the satellite-based AOD with respect to ground-based measurements AERONET AOD. The study also uses the mean absolute error (MAE) method to discover the mean error magnitude (Willmott and Matsuura, 2005). On the other hand, the Relative Mean Bias (RMB) method is used to calculate the estimation performance of the MODIS DB algorithm (Xie et al., 2011; Bilal et al., 2015). Here it is considered that the RMB value is equal to one indicates the normal estimation of the MODIS DB algorithm. The RMB value in excess of one indicates overestimation of the MODIS DB algorithm, and under-estimation if the RMB value is less than one.

Fig. 5 shows the seasonal comparison of the Aqua satellite
Fig. 3. The inter-annual variability of the seasonal AOD as calculated based on the MODIS DB AOD data from the Aqua satellite over the entire Saudi Arabia, the Solar Village, and KAUST for the period 2002‒2013. Panels (a), (b), and (c) are for the entire Saudi Arabia, the Solar Village, and KAUST.
Fig. 4. The seasonal AOD frequency distribution based on the MODIS DB daily AOD data from the Aqua satellite over the entire Saudi Arabia, the Solar Village, and KAUST for the period 2002–2013. Panels (a), (b), and (c) are for the entire Saudi Arabia, the Solar Village, and KAUST.

Fig. 5. The seasonal comparison of MODIS DB AOD from the Aqua satellite with ground truth AERONET measured AOD at 550 nm over the Solar Village, Saudi Arabia for the period 2002–2013. The blue line = regression line and red dash line = 1:1.

retrieved AOD based on the MODIS DB algorithm against ground truth AERONET measured AOD over the Solar Village station. The study uses the Level 2 data for the period 2002–2013. The slope values are found to vary in different seasons over the Solar Village, i.e., for spring \( m = 0.697 \), summer \( m = 0.662 \), autumn \( m = 0.723 \), and winter \( m = 0.658 \) as shown in Fig. 5. The study indicates the need for some corrections for aerosol model selection. In contrast, Fig. 5 shows the intercept values for different seasons, i.e., for spring \( c = 0.068 \), summer \( c = 0.101 \), autumn \( c = 0.044 \), and winter \( c = 0.049 \) over the Solar Village. The recorded intercept imply that there is much under-correction for surface reflectance in summer than in spring, autumn, and winter, due to the underestimation of the surface reflectance calculation. The correlation coefficient values are found to vary in different seasons over the Solar Village, i.e., for spring \( r = 0.77 \), summer \( r = 0.62 \), autumn \( r = 0.65 \), and winter \( r = 0.75 \) as shown in Fig. 5. Here, a much clearer correlation is evident in spring and winter than in summer and autumn. However, the correlations are found to be significant at 99.99% level for all seasons. The RMSE values are lower in autumn (RMSE = 0.11) than in spring (RMSE = 0.20), summer (RMSE = 0.22), and winter (RMSE = 0.12) as shown in Fig. 5. Likewise, it is noted from Fig. 5 that the MAE values are found to be lower in autumn (MAE = 0.07) than in spring (MAE = 0.15), summer (MAE = 0.17), and winter (MAE = 0.08). Finally, the RMB values are evident in spring (RMB = 0.85), summer (RMB = 0.90), autumn (RMB = 0.90), and winter (RMB = 0.89) as shown in Fig. 5. The relative mean biases imply that the MODIS DB algorithm has been underestimated to retrieve AOD in all seasons over the Solar Village.

Fig. 6 shows the seasonal comparison of the Aqua satellite retrieved AOD based on the MODIS DB algorithm against
Fig. 6. The seasonal comparison of MODIS DB AOD from the Aqua satellite with ground truth AERONET measured AOD at 550 nm over KAUST, Saudi Arabia for the period 2002–2013. The blue line = regression line and red dash line = 1:1.

ground truth AERONET measured AOD over KAUST station. The study uses the Level 2 data for the period 2002–2013. The slope values are found to vary in different seasons over KAUST, i.e., for spring (m = 0.688), summer (m = 0.634), autumn (m = 0.958), and winter (m = 0.812) as shown in Fig. 6. The slope values show that aerosol model produces much better results in autumn than in spring, summer, and winter, indicating a need for some corrections for aerosol model selection. In contrast, intercept (c) values of 0.031, 0.037, –0.007, and 0.044 are found for spring, summer, autumn, and winter respectively (Fig. 6). The intercept values imply few under-corrections for surface reflectance in spring, summer, and winter due to the underestimation of the surface reflectance calculation. However, for the autumn, the intercept value implies slight over-correction for surface reflectance because of the overestimation of the surface reflectance calculation over KAUST. Varying correlation coefficient values are evident in different seasons, i.e., for spring r = 0.85, summer r = 0.71, autumn r = 0.81, and winter r = 0.89 over KAUST as shown in Fig. 6. Here, the very good correlations are seen in spring, autumn, and winter rather than in summer season. However, the correlations are 99.99% significant for all seasons. The RMSE values are lower in winter (RMSE = 0.06) than in spring (RMSE = 0.19), summer (RMSE = 0.21), and autumn (RMSE = 0.10) as shown in Fig. 6. Likewise, it is noted from Fig. 6 that the MAE are lower in winter (MAE = 0.05) than in spring (MAE = 0.15), summer (MAE = 0.16), and autumn (MAE = 0.08). Finally, varying RMB values are evident in different seasons, i.e. for spring (RMB = 0.76), summer (RMB = 0.72), autumn (RMB = 0.94), and winter (RMB = 1.01) as shown in Fig. 6. The relative mean biases indicate that the MODIS DB algorithm has been underestimated for retrieval of AOD in spring, summer, and autumn with the exception of winter. This has led to marginal overestimation over KAUST.
It must be noted that this is the first research report on seasonal MODIS DB AOD variability and its comparison with AERONET measured AOD over Saudi Arabia. The DB algorithm has been compared worldwide at different locations. Misra et al. (2015) compared collection 5.1 MODIS DB and DT retrieved AOD over Western India and found that the only error noted concerned the incorrect aerosol model assumption in all seasons. More et al. (2013) compared aerosol products from MODIS, AERONET, and MICROTOPS II Sunphotometer over a Tropical Urban City, Pune, India and found that MODIS is under-estimated to retrieve AOD in winter due to the inaccurate aerosol model selection and the imperfect surface reflectance calculation. Shi et al. (2013) also compared MODIS DB AOD collection 5.1 and reported that the accuracy of MODIS DB AOD is dependent on aerosol microphysics and surface albedo over the Arabian Peninsula and North Africa. Li et al. (2012) studied the comparisons between MODIS DT AOD (collection 4 and collection 5) and DB AOD over Northwest China and reported that 73.3% MODIS DB AOD retrieval falls within the possible error range of 30% over four sites in Xinjiang. Xie et al. (2011) also compared a collection of the 5 MODIS AOD products over China, based on CARSNET measurements AOD data. The authors reported that this MODIS DB is significantly underestimated.

CONCLUSIONS

The spatio-temporal distribution of the seasonal AOD (550 nm) over Saudi Arabia has been analyzed using the Aqua satellite based Level 3 MODIS DB product for the period 2002–2013. In addition, Level 2 DB AOD is compared with Level 2 ground-based AERONET AOD over the Solar Village and KAUST, Saudi Arabia. The findings of the current study are as follows:

- The seasonal AOD spatial distribution shows that the peak AOD value is observed over Hafr Al Batin, Riyadh, and the Rub Al Khali desert during spring, whereas it is only observed over the southwestern Giza during summer. On the other hand, the peak AOD is observed over Dhahran and in the proximity of Jeddah during autumn, whereas the winter displays the peak AOD over Hafr Al Batin, Al Khaifji, Al Jubail, and the Rub Al Khali desert.
- Except in winter, the AOD increasing trends are evident in spring, summer, and autumn over the entire Saudi Arabia. Over the Solar Village, the AOD increasing trends are also found in spring and summer, but not in autumn and winter. Over KAUST, the AOD increasing trends are observed in all seasons. The AOD increasing and decreasing trends are associated with increase and decrease in the number of dust events respectively.
- The seasonal correlations between MODIS DB AOD and AERONET AOD at the Solar Village station are 0.77 (spring), 0.62 (summer), 0.65 (autumn), and 0.75 (winter). While, the correlation values at KAUST are 0.85, 0.71, 0.81, and 0.89 in spring, summer, autumn, and winter respectively. The inaccurate aerosol model selection and imperfect surface reflectance calculation are the possible factors contributing to reducing the correlation between MODIS DB AOD and AERONET AOD over the Solar Village and KAUST. Therefore, this study suggests the Deep Blue algorithm identify the detailed features of the AOD information over Saudi Arabia.

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DISCLAIMER

The authors declare that this study does not make any reference to any companies or specific business products.

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