The Use of Aerosol Optical Properties in Identification of Dust Sources in Iraq

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Abstract. In recent years, dust events in Iraq become very frequent due to its emission from active local dust sources or transportation from abroad. This study aims to identify dust sources in Iraq for the period (1st January, 2005 to 31 December, 2016) using mean of monthly mean of the aerosol optical properties including Deep Blue Aerosol Optical Depth(DB-AOD), Deep Blue Angstrom Exponent(DB-AE) and UV Positive Absorption Aerosol Index(AAI) acquired from space borne instruments including MODerate resolution Imaging Spectroradiometer (MODIS) for both Aqua and Terra, Multiangle Imaging SpectroRadiometer (MISR) and Ozone Monitoring Instrument (OMI), considering the dust aerosols having values of AOD>0.5, AE<0.5 and AAI>0.7 based on the predefined thresholds. The results show that Al-Jazira and the southern region of Iraq considered as significant dust sources most of the year, with the absence of active dust sources in December, January, October and November. While spring and summer months show many active dust sources in the Alluvial plain, western plateau, southern and southeastern parts of Iraq with high AOD, low AE and high AAI especially in April, May, June and July. MISR/AOD shows lower values of MODIS-DB in Iraq along months of the years, which could be due to the insufficient coverage over dust regional sources compared to MODIS.

Keywords. Absorbing Aerosol Index, Aerosol optical depth, Angstrom Exponent, Dust, MISR, MODIS.

1. Introduction
Airborne dust is considered as a natural source of atmospheric particulate matter causing respiratory diseases, and reducing the visibility which can affect the transportation sector. As for weather and climate, dust also play a substantial role in the microphysics of clouds, atmospheric chemistry and the radiative balance of earth and the air temperature by absorbing and scattering of radiation. Depending on dust particle size, shape and density, dust can be lifted directly from the surface by aerodynamic entrainment, while large soil particles have to undergo creeping and saltation to be released over arid regions, and the emitted dust depends on the wind speed at the surface, some soil characteristics such as soil texture and moisture [1].

Mineral dust can be generated by volcanic processes and fine-grained rocks, while most of it resulted from the reduction of coarse particles due to physical and chemical mechanisms, and fine-grained rocks [2].
Dust is emitted from arid soils of the Earth mostly located in the so-called ‘dust belt’, that extend from North Africa, through the Middle East, Central and South Asia to China [3]. Dust has two main sources: Natural and Anthropogenic. Natural sources account for 75% of emissions and they primarily include arid and semi-arid deserts, dry lake beds and ephemeral channels [4], while anthropogenic sources account for 25% and they are associated with land use, were the largest proportion is observed in the Mesopotamian region and Saudi Arabia [5].

West Asia including Arabian Peninsula, Syria, Iraq and Iran has been recognized as one of the most important primary sources of dust [5], and Iraq includes the most important sources located in the alluvial plain that affecting the countries of the region in general, in addition to their impact on the Iraq itself, which can be also affected by dust sources in the Syrian Desert. The simplest approach to estimating dust sources in West Asia is by using in-situ observations of visibility acquired from SYNOP and METAR reports [6]. As for example, [7] studied the spatial and temporal characteristics of dust storms in the Middle East by analyzing the visibility reduction in that region, and found that in summer seasons dust storms occurred in Syria, northeast of Iraq, Iran, south of the Arabian Peninsula and the gulf more frequently, and in the main in spring they occurred in Syria, west of Iraq, north of Arabian Peninsula, the gulf and some other regions [7]. But this approach is not sufficient due to the limited coverage of observations sites in dust source regions such as the Middle East, therefor, the need for another approach has become necessary and it is the use of satellite data images and remote sensing techniques. Prospero et al. [3] used TOMS imagery (Total Ozone Mapping Spectrometer) to present a global map of dust sources in which they identified global dust belt which associated with topographic depressions [3]. In addition to the use of TOMS, Hickey and Goudie [8] used MODIS data and they found additional sources comprising Sistan basin and Tokar Delta located in the Middle East and South-West Asia respectively associated with silt load carried by the rivers and winds over regions that undergoing a dry and hot summer [8]. [9] identified the source regions of dust storms in Iraq by using the Aerosols Index, and found that the source of dust is in the northern part of the western plateau, and the southern area overlooking the Arabian Gulf. [5] presented a global-scale high resolution mapping of sources based on estimations of dust optical depth acquired from Moderate Resolution Imaging Spectroradiometer (MODIS) Deep Blue, connected to other data sets such as land use, showed that the highest frequency of dust is along the border of Syria and Iraq regions, with the highest and most widespread FoO (frequency of occurrence) of DOD > 0.1 of higher than 20% is over most of Mesopotamia, and that the source of dust in the Tigris- Euphrates basin is almost natural, while in Saudi Arabia, Syria and Iran it is anthropogenic. [10] used a combination of remote-sensing techniques, hybrid single particle Lagrangian integrated trajectory (HYSPLIT), and some other data related to the area of study such as wind speed, soil-texture and land cover, and they identified the main sources of dust that exported to the west parts of Iran: The area between the Tigris and Euphrates rivers in Iraq and Rub’ Al Khali desert (Empty Quarter) in Saudi Arabia. [11] analyzed aerosol optical properties at near UV and Visible wavelengths in order to identify the dust hotspot sources over Iraq and surrounding region during the study period (January 2005-December 2014). Results show that Basra, Nasiriya, east of Muthanna and Diwaniya provinces at south of Iraq and Ninawa, Salahaddin and north of Anbar provinces at north west of Iraq, Kuwait and northeast of Saudi Arabia are considered as the hotspot of dust in spring and summer months, with higher probability of occurrence of dust storm and rising dust over the stations located in the middle and south of Iraq than at the north, and high probability of suspended dust over the stations of Mosul, Baghdad and Nasiriya,[12] compared AOD from both MODIS-Aqua and sky radiometer measurements and found that MODIS-Aqua presented encouraging estimations of AOD; and he used (HYSPLIT) model to classify the types and origins of aerosol sources in Baghdad, and he found that about 28% of air masses in winter are loaded with dust from local sources or from the borders between Iraq and Saudi Arabia, while air masses with about (62% and 56%) during spring and summer respectively, are loaded with dust originated from the border region between Jordan and Saudi Arabia in spring, and from Syrian steppe and the Iraqi western desert in summer, with less occurrence of dust events in Autumn. He also studied the seasonal behavior of aerosols using MODIS- AOD, AE, and
OMI-AI for eight years and found that the fine mode aerosols are dominated in spring and summer months, whereas in winter and autumn, the coarse mode has the predomination.

This work aims to identify the sources of dust in Iraq by using Space-borne Observations Data for the following parameters: UV Positive Absorbing Aerosol Index (AAI) from OMI, Deep Blue Angström exponent from MODIS Aqua and Terra (DB-AE), Deep Blue Aerosol optical depth from MODIS Aqua and Terra (DB-AOD) and Aerosol optical depth from MISR (AOD) as a mean of monthly mean for the period (1st January, 2005 to 31 December, 2016).

2. The Study Area
Iraq lies in southwestern Asia to the northwest of the Arabian Gulf, and its climate which is affected by its location is characterized by sub-tropical, continental, arid to semi-arid climate, its winter season is loaded with precipitation between November to April and almost dry and hot summer, with a mean average temperature of about (10.8/31.7) °C and total precipitation of (3.3/0) mm/day in winter months (December to February) and summer months (June to August) respectively. It is worth to mention that Iraq was one of the countries that experienced one of the most severe drought cases in the world within (1999-2002) [13]. The soils in Iraq have two main types which are silt and clay with a diameter smaller than 70μm, and thus it can be easily lifted and transported by the wind [14]. Moreover, the new projects of dam construction on Tigris and Euphrates rivers have a negative effect on the soil water content, and hence decreases the threshold friction velocity required for dust uplifting [15]. Due to all the above reasons, dust activities have intensified in the Mesopotamian area in recent years and this makes Iraq prone to dust storms. Thus it is important to map the distribution of atmospheric dust sources in Iraq.

Iraq is characterized by its different terrain regions, where the mountains are located in the north and north-east of it on the borders with Turkey and Iran respectively, the desert region to the west and south-west of it. The center and south of Iraq is characterized by a low elevation areas representing the alluvial plain and valleys[14]. Thus Iraq can be divided according to the topography into four main areas as shown in Fig.1: Al-Jazira located in the north-western part of Iraqi – Syrian borders; Mesopotamian Alluvial Plain between the Tigris and Euphrates rivers which located in the central to the south-eastern regions of Iraq; The western Plateau in the western part of Iraq; and The upland area in the north and northeast of Iraq as shown in Figure (1). This classification will be considered in interpreting the results of this study.
3. DATA AND METHODOLOGY

According to the dust optical properties, many techniques were used based on some retrieving products acquired from ground-based and space-borne remote sensing instruments. The Ground-based instruments such as sun photometers provide a time series of observations with highly temporal and spectral resolutions continuously, but the spatial resolution is limited to be around the monitoring site only [16]. To increase spatial coverage, highly sophisticated and accurate space-borne instruments are used such as the MODerate resolution Imaging Spectroradiometer (MODIS), Multiangle Imaging SpectroRadiometer (MISR), and Ozone Monitoring Instrument (OMI).

3.1. Aerosol Optical Properties

The relationship between light and aerosols is complicated and depends on a number of aerosols properties (i.e. particle size, refractive index, morphology) as well as the wavelength of the incident light, in which the beam of radiation would encountered attenuation processes (scattering and absorption) while passing within a layer containing atmospheric aerosols, and in order to have a clear perception about the amount of aerosols load, some aerosol properties were used related to attenuation processes. The measure of distributed aerosols in a total atmospheric vertical column extending from the surface to the top of the atmosphere that causing light extinction is defined as Aerosol Optical Depth (AOD), that can be measured by AERONET sun photometers or Lidar, satellite retrieval data or it can be calculated by numerical models. The wavelength value of AOD is often used to be around 550nm because it is close to the wavelength of the maximum intensity of the solar spectrum and many devices can measure attenuation at this value [17].

The Angstrom wavelength exponent (represented as AE or $\alpha$) is a commonly used parameter to illustrate the wavelength dependence of AOD. It can be expressed by Angstrom’s equation [18]:

$$\text{AOD}(\lambda) \sim \lambda^{-\alpha}$$

The Angstrom wavelength exponent is used to obtain basic information on the aerosol size distribution in the solar spectrum. It is inversely proportional to average size of aerosols were smaller particle refers to larger values of the exponent. Thus, it is considered as an indirect measurement of the aerosol size in a given column of air [6].

For clear (Rayleigh) and non-clear atmosphere (containing aerosols), the wavelength dependency on back scattered Ultra-violet radiation is different, which can be expressed by Aerosol Index (AI) for Ozone Monitoring Instrument (OMI) as [19]:

$$\text{AI} = 100 \log_{10} \left( \frac{I_{360}^{\text{OMI}}}{I_{360}^{\text{Calc}}} \right)$$

Where $I_{360}^{\text{OMI}}$ is the OMI measured radiance at 360 nm and $I_{360}^{\text{Calc}}$ is the OMI calculated radiance at 360 nm for a clear atmosphere, and the difference between both radiances infer to the types of aerosols as it will be shown later.

3.2. MODIS, MISR AND OZONE MONITORING INSTRUMENTS

The Moderate Resolution Imaging Spectroradiometer (MODIS) is an instrument aboard the Terra and Aqua satellites, scanning and viewing the Earth’s surface every (1-2) days entirely, It’s detectors acquiring data in 36 spectral bands with different spatial resolutions, and it has different algorithms associated to aerosols (over land and ocean) [20].

As over land, MODIS algorithm works when the ground has low reflectance such as dark vegetation. While over high reflectance areas such as arid and semi-arid regions, MODIS deep-blue algorithm is optimal due to the absorption at the blue region of the solar spectrum, the darker albedo at the blue region compared to the mid-visible and red region, and the small surface reflectance at (0.412 and 0.470 mm), which helps in dust discriminating among fine aerosols. The MODIS Deep-blue products were thus useful for our study of desert areas[21]. The MODIS Deep-blue products were thus useful for our study of desert areas.
The Multi-angle Imaging SpectroRadiometer (MISR) is an instrument aboard the Terra spacecraft uses algorithms of aerosol retrieval in order to acquire aerosol properties due to its special configuration of 36 channels with nine cameras working separately in four bands of the solar spectrum, in addition to the repeat time of observation that ranging between (3-4) per month over large deserts regions, which makes MISR to be able in determining the temporal resolution of strong dust events in those regions[22].

The OMI is the successor of the TOMS instruments, flies aboard the Earth Observing System (EOS)/Aura spacecraft orbits, working with 780 spectral bands of Ultra-violet (two UV sub-channels) and visible channels with a spatial resolution of (13x24) km at nadir, viewing the earth with a swath width of 2600 km, in which they provides a daily global coverage of aerosols such as ozone, tropospheric SO2 and NO2 [23]. UV aerosol index (AI) (also called Absorbing Aerosol index, AAI) is one of the OMI products derived from OMI aerosol near-UV (OMAERUV) retrieval algorithm that can be used as an indicator to distinguish between dust and biomass burning particles that are considered as absorbing aerosols from the clouds and other aerosols that has a weak absorbance, and it is used also in arid and semiarid regions due to their low reflectivity near UV while in the visible and near IR spectrum they have high reflectivity [24].

3.3. Identifying Dust Sources Techniques

In order to identify dust sources, dust aerosols should be discriminate among other types of aerosols emitted from natural and/or industrial sources in which they have specific optical properties, such as sea salt from oceanic sources and soot from fossil fuel and biomass burning [25]. Therefore, many studies used aerosols properties acquired from satellites such as MODIS and MISR, AERONET or retrieved from numerical models, but using one parameter is not sufficient to distinguish dust from other aerosols, and it is required to make some assumptions to discern dust from other aerosols. For that reason, Satellite sensors were modified and applied some new algorithms and new methods to improve the accuracy, which is variable depending on the sensors and the nature of the surface whether it is land or oceanic surfaces [26]. Some optical properties are used in common as an optical indicator of the atmospheric turbidity and can determine the size, type and amount of aerosols such as AOD corresponding to AE. For coarse mode aerosols that includes dust and sea salt particles, Angstrom Exponent AE would have values ≤ 1 which means that the extinction is the same for all the wavelengths, while for fine mode aerosols such as biomass burning aerosols and pollutants, AE would have values ≥ 1 as discussed in [26], [27] and [28]. For dust particles, AOD values would be higher compared to fine mode and oceanic aerosols with AOD < 0.15 [25]. If the air contains all types of aerosols simultaneously, the AE would have an intermediary values [29]. It seems that it is easy to use the relation of AOD-AE to discern dust from other aerosols, but in humid weather, fine mode aerosols such as sulphate can grow in size because of its hygroscopic nature and this will resulted in higher AOD and smaller AE [30], which leads to uncertain inference, therefore, Absorbing Aerosol index(AAI) were used to differentiate between the all types of aerosols, where Non-absorbing aerosols such as sulphate and oceanic aerosols have negative values, while absorbing aerosols biomass burning and desert dust aerosols have positive AAI values >0.7, and near to zero values for Clouds [19].

In this study, combined optical properties were used including AOD-AE-AAI to identify dust sources in Iraq. In order to classify the aerosols, the selected threshold values of AOD550 , AE412-470 and AAI are based on many predefined thresholds discussed in details by [19], [31] and [16] considering the dust aerosols having values of AOD>0.5 and AE<0.5 and AAI>0.7. Those values were chosen in order to minimize the misjudgment of dust particles and absorbing aerosol. The data used in this study consists of space borne retrievals products for the domain extended from (26.5-39.5) N and (36.5-51.5) E as a mean of monthly mean for the period (1st January, 2005 to 31 December, 2016), including: MODIS Aerosol Optical Depth at 550 nm (Deep Blue, Land- only) (MOD08_M3 v6) monthly, Level 3 at 1°x 1° grid for both Aqua and Terra; MODIS Deep Blue Angstrom Exponent for land (0.412-0.47 micron): Mean of Daily Mean (MOD08_M3 v6) for both Aqua and Terra; MISR Aerosol Optical Depth at 555 nm (MIL3MAE) monthly, level 3 at 0.5°x0.5 grid which further resampled to 1°x 1° grid. All the above acquired data were retrieved from the NASA Giovanni site https://giovanni.sci.gsfc.nasa.gov/giovanni/.
In addition to UV Positive Absorbing Aerosol Index (AAI) from OMI at 1°x 1° grid http://www.temis.nl/airpollution/absaai/.[32].

4. Results and discussion
In December and January, MODIS DB-AOD (in both Aqua and Terra) show basically the same patterns with relatively low values all over the country (<0.5) suggesting no active dust sources is found in those months, while in February, a notable dust source is seen in Al-Jazira with AOD of moderate values ranging between (0.5-0.6) in Aqua image (higher than AOD values compared to December and January), but it was not seen in Terra, associated with low values of AE<0.5 and AAI>0.7 as shown in Fig. 2 and Fig. 3. This refers to an active dust source in this region which is quite compatible with the identified source region by [5]. As for MISR AOD, when it is compared to MODIS-DB, it shows lower values in Iraq for the three months, this could be due to the lower frequency of MISR observation above large desert regions (3 or 4 visits in a month) [22] which might be not enough to give a sufficient coverage over dust regional sources compared to MODIS [33].
In spring months, it can be noticed that the AOD values in both MODIS (Aqua & Terra) and MISR is higher than winter months, corresponds with low values of AE. As for March, Aqua image shows Al-Jazira region to appear again as active dust source, in which it have AOD>0.5, AE< 0.5 and AAI>0.7, while for Terra, another source region appeared in addition to the previous sources located in the south of Iraq having the same criteria of dust.

High values of AOD (0.5-1) corresponds with low AE and high AAI suggesting that the sources of dust extended more in April and May to include (Al-Jazira, western part of alluvial plain, parts of western Plateau and south of Iraq) according to Aqua image, with more extended area of the eastern part of the alluvial plain in Terra Image (near the Iraqi-Iranian borders started from longitude 45.5E). This refers to the activation of significant dust sources in spring, especially in April and May, as referred by [7] and [11]. Again, MODIS shows higher values in Iraq for the three months compared to MISR, as shown in Figure 4 and 5.
Figure 4. The Spatial distribution of DB-AOD, DB-AE from MODIS/Aqua, AOD from MISR and AAI from OMI as a mean of monthly mean for spring months (March, April, May) from (2005-2016).

Figure 5. The Spatial distribution of DB-AOD, DB-AE from MODIS/Terra, AOD from MISR and AAI from OMI as a mean of monthly mean for spring months (March, April, May) from (2005-2016).

Figures 6 and 7 shows a continuous series of active dust sources in Iraq, in which higher AOD (on both Aqua and Terra images) over the aforementioned zones is observed in June and July with low value of AE except the south-eastern part of Iraq (appeared in Terra Image), corresponds with high values of AAI>0.7, while for August, AOD and AE spatial patterns corresponds with AAI>0.7 refers to a limited
source region represents by Al-Jazira according to Aqua, while Terra suggesting another source area in the south of Iraq. In addition to that, it is notable that Terra images show higher values of AOD and lower values of AE, with the similar behavior of MISR/ AOD compared to MODIS.

Figure 6. The Spatial distribution of DB-AOD, DB-AE from MODIS/Aqua, AOD from MISR and AAI from OMI as a mean of monthly mean for summer months (June, July, August) from (2005-2016).

Figure 7. The Spatial distribution of DB-AOD, DB-AE from MODIS/Terra, AOD from MISR and AAI from OMI as a mean of monthly mean for summer months (June, July, August) from (2005-2016).

And finally in autumn, Fig. 8 and Fig. 9 show AOD spatial patterns with lower values of AOD compared to summer season, in which AOD reduced significantly, but a part of Al-Jazira region still having AOD>0.5 associated to low values of AE and AAI>0.7 in September (Aqua and Terra),
indicating that it still considered as significant and persist source region. MODIS shows higher values in Iraq for the months of autumn compared to MISR, as shown in Fig. 8 and Fig 9.

**Figure 8.** The Spatial distribution of DB-AOD, DB-AE from MODIS/Aqua, AOD from MISR and AAI from OMI as a mean of monthly mean for autumn months (September, October, November) from (2005 – 2016).

**Figure 9.** The Spatial distribution of DB-AOD, DB-AE from MODIS/Terra, AOD from and MISR and AAI from OMI as a mean of monthly mean for autumn months (September, October, November) from (2005 – 2016).

Table 1 summarizes the active source regions along the months of the years, representing five main source regions: Al-Iajira, The Alluvial Plain, the Western plateau, the south of Iraq (refers as S of Iraq) and finally the South east of Iraq (refers as SE of Iraq).
Table 1. The active dust sources in Iraq according to MODIS-DB (AOD,AE) and OMI( AAI) for the years (2005-2016).

|   | Aqua |   | Terra |   |
|---|------|---|-------|---|
|   | Al-Jazira | Alluvial Plain | Western plateau | S of Iraq | SE of Iraq | Al-Jazira | Alluvial Plain | Western Plateau | S of Iraq | SE of Iraq |
| Dec. | √ | | | | | | | | | |
| Jan. | | | | | | | | | | |
| Feb. | | | | | | | | | | |
| Mar. | | | | | | | | | | |
| Apr. | | | | | | | | | | |
| May | | | | | | | | | | |
| Jun. | | | | | | | | | | |
| Jul. | | | | | | | | | | |
| Aug. | | | | | | | | | | |
| Sep. | | | | | | | | | | |
| Oct. | | | | | | | | | | |
| Nov. | | | | | | | | | | |

5. Conclusion
The method of testing threshold values of AOD, AE and AAI was applied in order to identify dust sources in Iraq, and the results show that in winter months, there is no active dust source shown in both Aqua and Terra, except in February month, in which Aqua image shows an active dust source in Al-Jazira region. As for spring months, higher AOD, lower AE and higher AAI values are noticed compared to winter months, witnessed an activation of Al-Jazira source region in both Aqua & Terra, with new source in the south of Iraq in Terra, with the activation of all the main sources in April and May according to Terra except the south eastern source according to Aqua. The same active dust sources of April and May are seen in Jun and July for both Aqua and Terra, while in August, only Al-Jazira source was active according to Aqua, with another source in south-eastern of Iraq in Terra. While Autumn shows one active dust source in Al-Jazira in September for both Aqua and Terra with no active dust sources in October and November. This study also showed that Al-Jazira and the region in south of Iraq considered as significant dust sources most of the year. It is notable also to refer to the difference between MISR and MODIS-DB, were MISR shows lower values in Iraq for the three months, and this could be due to insufficient coverage over dust regional sources compared to MODIS.

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