

# More than a Decade of Observations of Dust Properties near Source and Transport Regions in the Vicinity of Kuwait City using NASA's CALIPSO Satellite Measurements

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**Abstract** The lidar on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission, makes robust measurements of dust and has generated a length of record that is significant both seasonally and inter-annually. We exploit this record to determine a multi-year climatology of the properties of Middle Eastern dust in the vicinity of Kuwait City. In particular seasonal optical depths of dust gridded in accordance with the Level 3 data products protocol between 2006 and 2015. The data are screened using standard CALIPSO quality assurance flags, cloud aerosol discrimination (CAD) scores, overlying features and layer properties. CALIPSO is collaboration between NASA and Centre National d'Études Spatiales (CNES), was launched in April 2006 to provide vertically resolved measurements of cloud and aerosol distributions. The primary instrument on the CALIPSO satellite is the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), a near-nadir viewing two-wavelength polarization-sensitive instrument. In addition to CALIPSO, we use the AErosol RObotic NETwork (AERONET) sites in the region to identify extreme dust events such as Sand and Dust Storms (SDS). The lidar measurements of the vertical location of the layers along with predominant prevailing wind vectors will enable identification of dust sources and inform mitigation solutions for extreme SDS.

## 1 Introduction

CALIPSO is collaboration between NASA, the US Space Agency and Centre National d'Études Spatiales (CNES), the Space Agency of France. It was launched in April 2006 to provide vertically resolved measurements of cloud and aerosol distributions [14; 15]. The primary instrument on the CALIPSO satellite is the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), a near-nadir viewing two-wavelength polarization-sensitive instrument. CALIOP is particularly well suited to the identification and observation of mineral dust due to its sensitivity to non-spherical particles which is manifested in the depolarization measurements. A depolarized profile is returned when light interacts with a non-spherical particle [8; 4; 10; 11; 3; 12; 1; 2]. Arabian Desert dust shows depolarizations of 28-35% [7] with typical values of 30% during dust storms. CALIPSO uses a 20% threshold for to identify pure dust particles and a 7.5% threshold for polluted dust particles[9].

Mineral dust affects the Earth's radiative balance and its distribution and has important consequences in both past, current and future climate systems. Dust directly forces the radiative balance by absorbing and scattering radiation, and indirectly by acting as cloud condensation nuclei and ice nuclei. It also alters the atmospheric heating profiles in such a way that it impacts cloud distributions. Dust also has a significant effect on air quality near source regions and can lead to hazardous particulate matter concentrations in populated regions during dust storms. These conditions also lead to significant visibility degradation that affects both ground and air transportation and severely impacts the welfare of the affected populations. To effectively study dust and its impact, a global distribution of dust and its vertical resolution is needed. An instrument that provides such data

is a Light Detection and Ranging (LIDAR) profiler based on a free flying orbiter. The CALIOP instrument on the CALIPSO satellite is just such an instrument.

Lidar is a powerful tool for studying the vertical distribution of aerosols and clouds in the atmosphere. The deployment of CALIPSO has enabled vertically resolved measurements of dust and provides significant insights into properties of Saharan and Asian dust aerosols. CALIOP is designed to acquire vertical profiles of elastic backscatter at two wavelengths (1064 nm and 532 nm) from a near nadir-viewing geometry during both day and night phases of the orbit. In addition to the total backscatter at the two wavelengths, CALIOP also provides profiles of linear depolarization at 532 nm. Accurate aerosol and cloud heights and retrievals of extinction coefficient profiles are derived from the total backscatter measurements [13]. The depolarization measurements enable the discrimination between ice clouds and water clouds [5] and the identification of non-spherical aerosol particles [6]. Additional information, such as estimates of particle size for the purpose of discriminating between clouds and aerosols, are obtained from the ratios of the signals obtained at the two wavelengths. On April 28, 2006, the CALIPSO satellite was launched into a low earth sun-synchronous orbit at a 705-km altitude, and an inclination of 98.2 degrees. CALIPSO's measurements of dust properties are robust and the length of the record is significant both seasonally and inter-annually.

## 2 Middle Eastern Dust Distributions – Sources Surrounding Kuwait

For the purposes of this study, the middle eastern source regions are defined by the four areas in Figure 1 and the coordinates in Table 1.

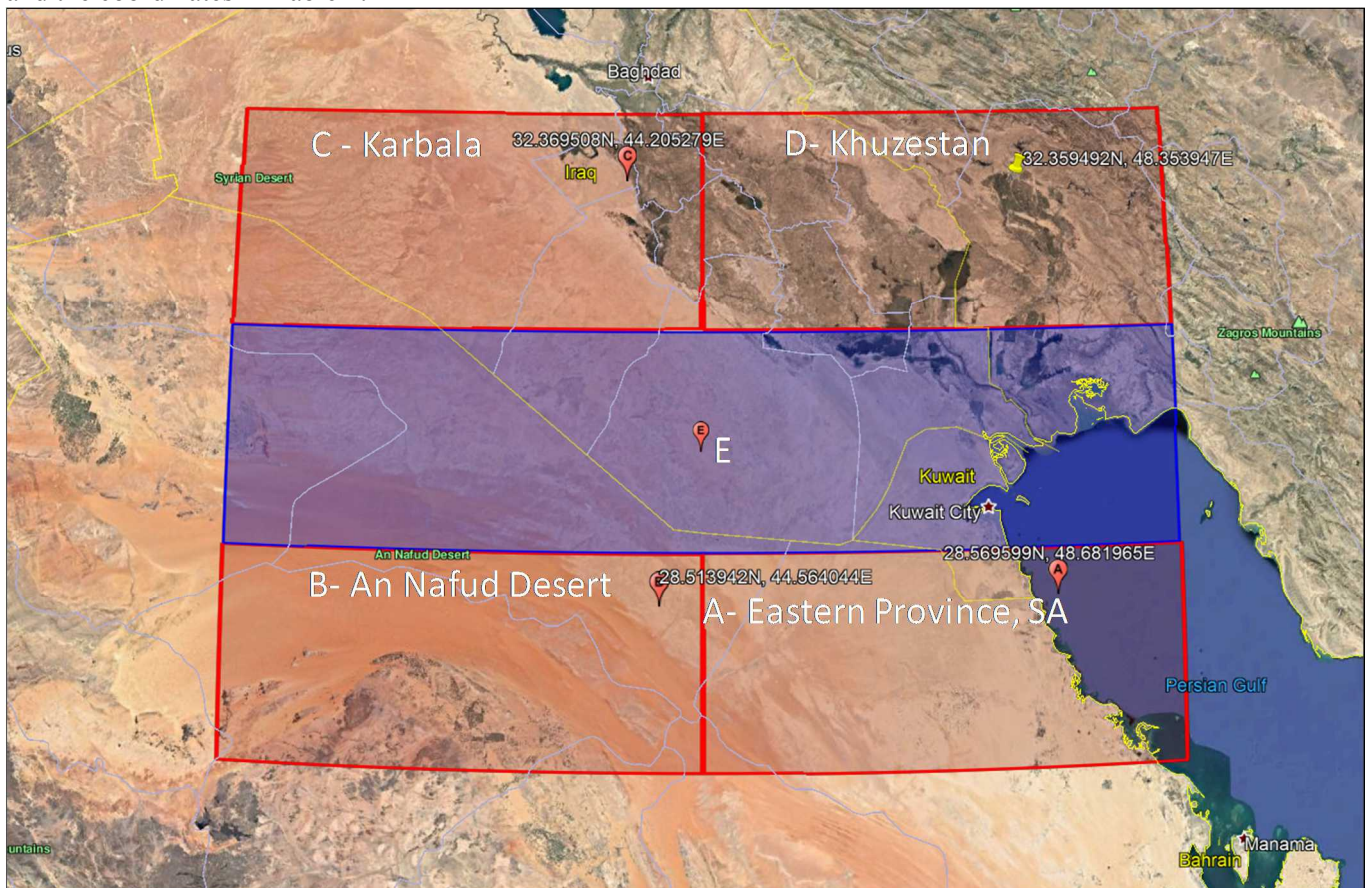


**Figure 1. Middle Eastern source regions considered in this study. The intermediate region E includes Kuwait city.**

### Region A. Eastern Province, Saudi Arabia

Figure 1 shows the AOD trends over the Eastern province of Saudi Arabia from 2006 to 2019. The largest AOD values were registered in the summer months of 2009-11. The maximum AOD's decrease to below 1 in

the years 2014-present. Large storms in this region can stretch roughly 500 kilometers (300 miles) across the peninsula. Large sand storms in this region are often fueled by strong northwesterly winds known as the shamal.

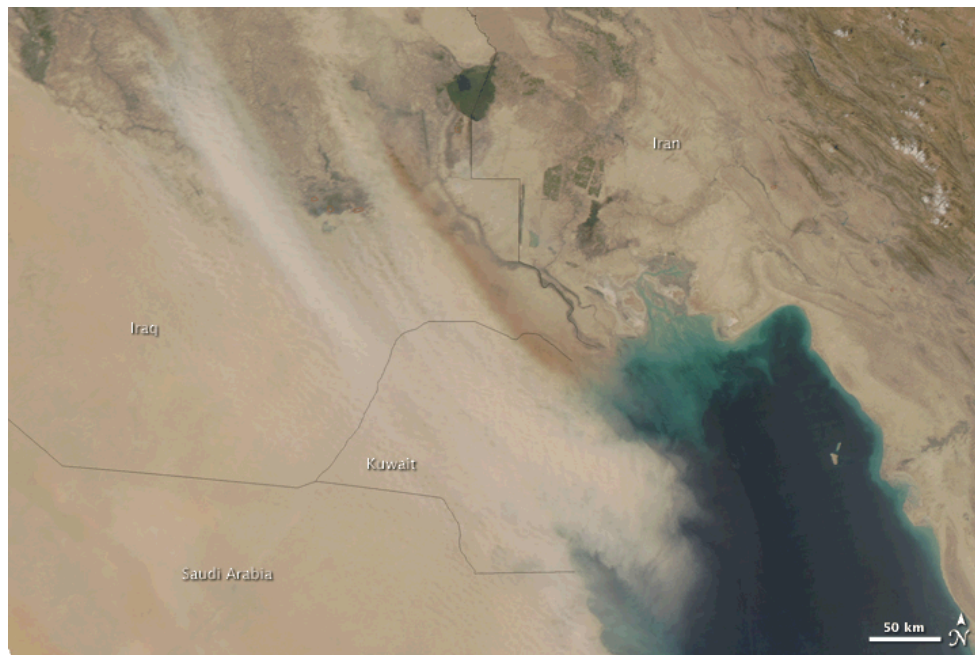


**Figure 2. Moderate Resolution Imaging Spectroradiometer (MODIS) August 15, 2009 image of ongoing drought contributing to the frequent and severe dust storms in the region. Note how the thick dust storm completely obscures part of the Gulf waters.**

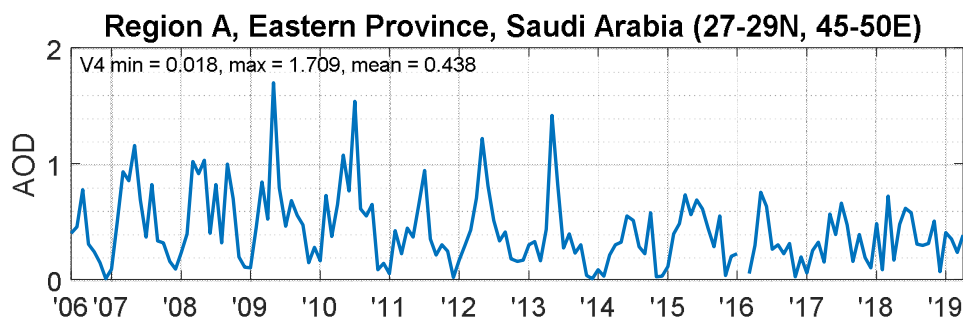


**Figure 3. Trends of the Aerosol Optical Depths for the Eastern Province from 2006-2019**

### **Region B. An Nafud Desert**

The Nafud is a desert region located in the north-central Saudi Arabia noted for strong winds which form large spectacular sand dunes that can reach heights of up to 30 meters. CALIPSO data shows that the total aerosol optical depth (AOD) of the dust has been decreasing since 2014. Without accurate measurements of particle size, it is not possible to conclusively predict that the impact on air quality in the region is also decreasing. This is because the AOD could decreasing because fewer large particles are present while the small particles that affect air quality may be unchanged or increasing.

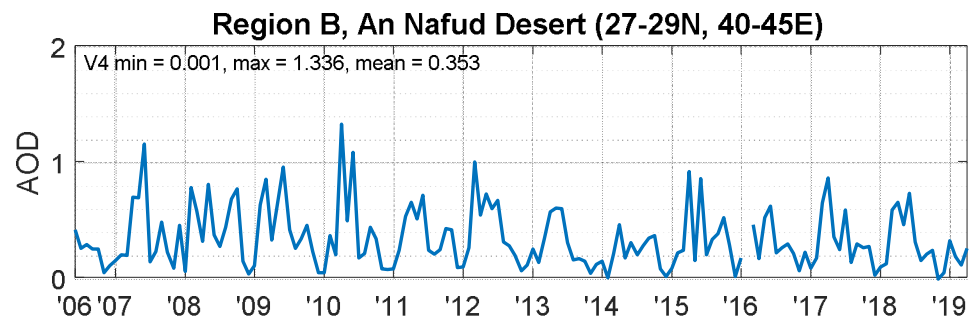


**Figure 4. Trends of the Aerosol Optical Depths for the An Nafud desert from 2006-2019**

**Region C – Karbala in Iraq**

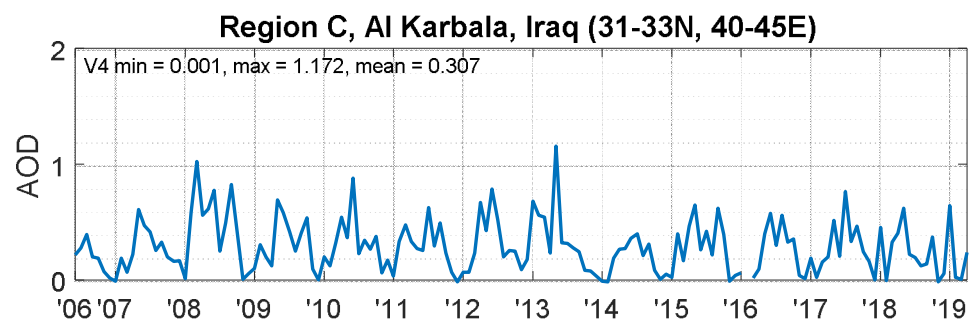


**Figure 5. Trends of the Aerosol Optical Depths for Karbala region from 2006-2019**

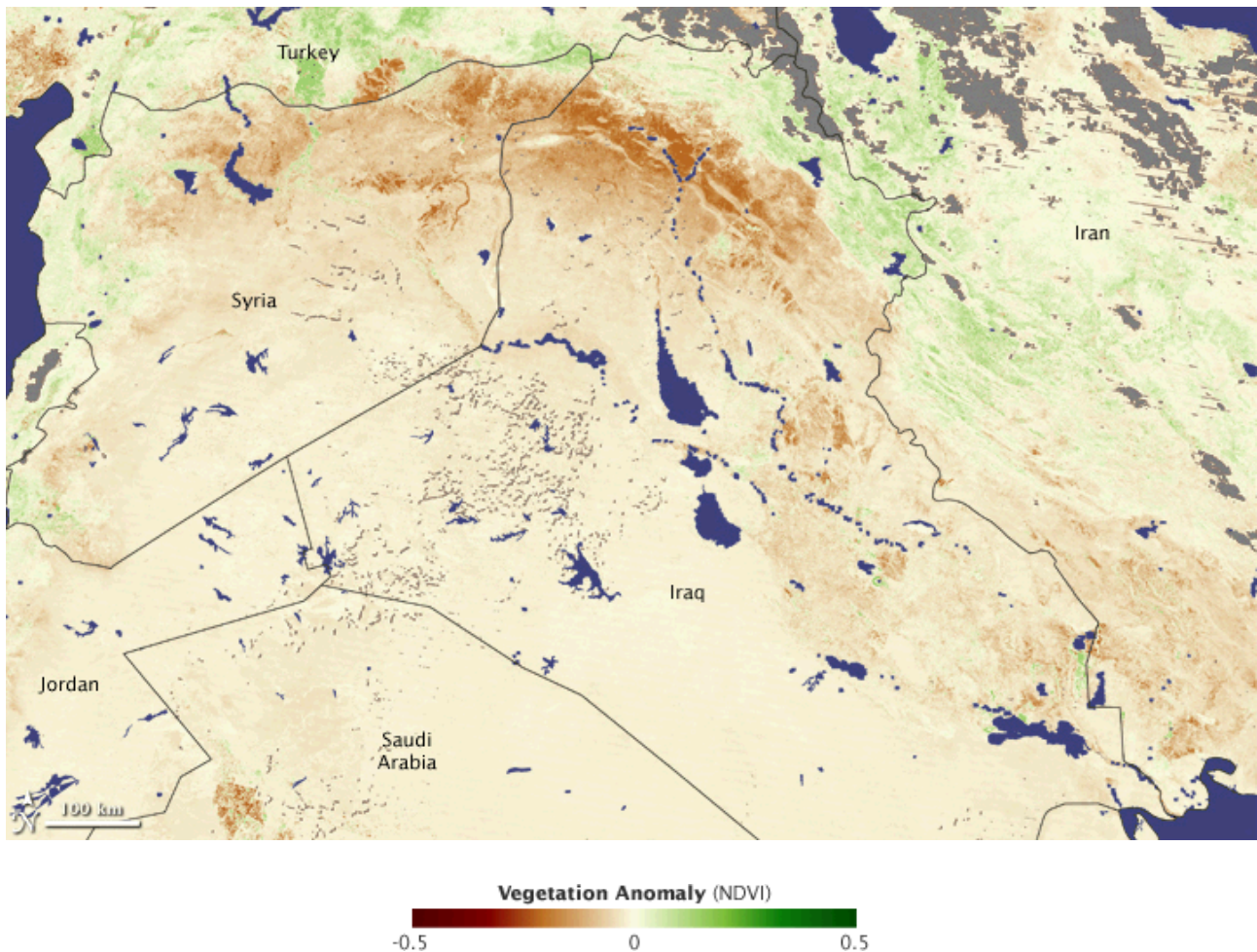


**Figure 6. Image reflecting the condition of plants growing throughout the region as observed by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite between April 7 and April 22, 2009. The brown hue denotes regions of extreme stress.**

Large parts of Iraq suffered a severe drought in the 2007-2008 growing season. The MODIS image of the normalized difference vegetation index (NDVI) in Figure XX shows severe plant stress in the Karbala region. This corresponds to increased dust AODs during this period shown in Figure XX. The drought continued into 2009. Areas that are brown show where plants were growing less than they did on average between 2000 and 2008. Green areas show better-than-average growth, and tan areas reflect average conditions.

#### **Region D- Khuzestan, Iran**

This region is also affected by the aforementioned drought that is manifested in large AOD values in the 2008-2009 period. Drought has increased the likelihood that shamal winds will produce a large dust storms, The airborne sand and dust can be transported long distances affecting the air quality of the region. Drought exposes the erodible material at the surface producing more spectacular dust storms once the winds are strong enough. For this region the maximum dust AODs (Figure XX) stabilized at less than 1.0 after the 2008-2009 drought season.

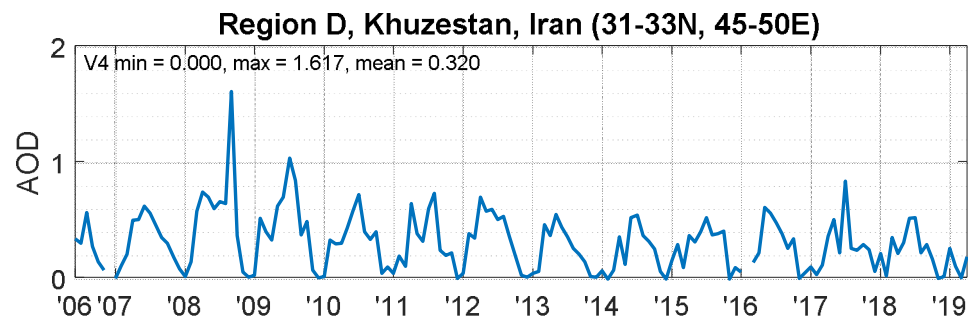


**Figure 7. Trends of the Aerosol Optical Depths for Khuzestan, Iran from 2006-2019**

Our region of interest for this study is the middle region spanning area between Khuzestan and Karbala to the north and Nafud and Eastern Province of SA to the south and including the city of Kuwait. The effects of the 2008-2009 droughts are clearly visible from the maximum dust AODs registered in 2008-2009 which slightly exceeded 1.0 and the minimum did not fall to zero for any month during this period. This shows that the strongest predictor of high AODs and therefore poor air quality is the drought condition.

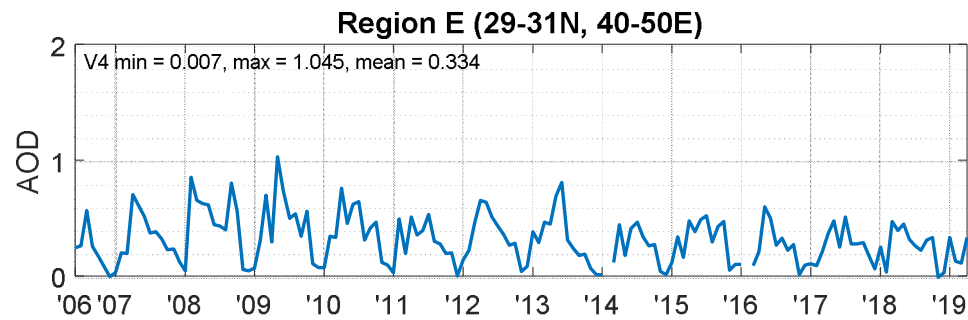


**Figure 8. Trends of the Aerosol Optical Depths for Region of Interest including Kuwait City from 2006-2019**

**Table 1. Source Regions of Middle Eastern Dust used in this Study**

| Region | Longitude, Latitude  | Level 3 data Longitude limits | Level 3 data Latitude limits | Mean AOD |
|--------|----------------------|-------------------------------|------------------------------|----------|
| A      | 48.681965, 28.569599 | 45E to 50E                    | 27N to 29N                   | 0.44     |
| B      | 44.564044, 28.513942 | 40E to 45E                    | 27N to 29N                   | 0.35     |
| C      | 44.205279, 32.369508 | 40E to 45E                    | 31N to 33N                   | 0.31     |
| D      | 48.353947, 32.359492 | 45E to 50E                    | 31N to 33N                   | 0.32     |
| E      | Intermediate Region  | 40E to 50E                    | 29N to 31N                   | 0.33     |

#### 4 Conclusion

Satellite based lidar (CALIPSO) and spectrometric (MODIS) measurements of Arabian dust optical properties near source regions and during transport have been used to study the effect of environmental changes on the dust reaching the region around Kuwait. Compared to African (Saharan) dust, Arabian dust has multiple sources. The source that has the highest AODs is the Eastern Province of Saudi Arabia, followed by the An Nafud desert. The authors recommend a rigorous transport study that is beyond the scope of this paper to pinpoint the most impactful source. The correlation between the Normalized Difference Vegetation Index (NDVI) and the AODs show that the dust generation is significantly amplified during the droughts. In particular, the 2008-2009 drought had a significant impact on the dust generation in two main regions – Karbala and Khuzestan. The lesson we can draw from this correlation is that increasing NDVI, i.e., reforestation has a direct impact on soil erosion and therefore the amount of suspended particles in the air. A plan involving satellite remote sensing and robust transport models to locate the most effective sites for planting can be used to develop an effective reforestation strategy.

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