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Study of aerosol optical properties in the Middle East during 2013

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Abstract

Aerosols affect the earth's atmospheric radiative fluxes via direct, semi-direct, and indirect mechanisms. Aerosols also are one of the main sources of uncertainty in climate models. In the Middle East, in addition to climate effects, various problems such as reduced visibility, human health hazards, and air pollution are caused by aerosols. Studying the optical and physical properties of aerosols on local and global scales helps reduce the uncertainties in climate forcing. In this study, aerosol optical properties, including Aerosol Optical Depth (AOD), Angstrom Exponent (AE), ASYmmetry parameter (ASY), Single Scattering Albedo (SSA), and phase function were analyzed. These properties were investigated over five sites in the Middle East during 2013 using the Aerosol Robotic NETwork (AERONET) data. The results revealed an inverse relationship between AOD and AE in all sites. A high AOD value and a low AE value were detected in spring and summer in all studied sites, suggestive of coarse mode dust particles. ASY initially decreased due to the dominance of absorbing type aerosols in the visible spectrum with the increase in wavelength. Afterwards, ASY increased with the increase in wavelength in the infrared region due to the dominance of the coarse mode particles. In most sites, SSA increased, particularly in spring and summer, with the increase in the wavelength because of the dominance of desert dust. In spring and summer, the phase function was high over all sites. High phase functions associated with small scattering angles were caused by the coarse mode particles.

Keywords: AERONET; Middle East; Aerosol Optical Depth; Angstrom Exponent; Asymmetry parameter

1. Introduction

An aerosol is defined as a colloidal system of solid or liquid particles in the atmosphere. Various types of aerosol have been classified based on its physical form and the manner of its generation (Kokhanovsky, 1997). Aerosols are a major source of uncertainty in climate models (Hansen *et al*., 1997; McCormick and Ludwig, 1967). They may further cause a variety of problems such as reduced visibility which is a major issue. Among other environmental impacts consist of reduced soil fertility and damage to crops (Zoljoodi *et al*., 2013). Aerosols also influence radiative processes and climate: directly by backscattering and absorbing solar radiation (McCormick and Ludwig, 1967), semi-directly via changes in atmospheric temperature structure and evaporation rate of cloud droplets (Hansen *et al*., 1997; Koren *et al*., 2004), and indirectly through affecting the optical properties of clouds (Liou and Ou, 1989).

In the Middle East, there exist many problems associated with high concentrations of atmospheric aerosols (Jacob, 1999; Sportisse, 2007). Anthropogenic aerosols are mainly restricted to urban-industrial areas, but dust exists almost everywhere (Gharibzadeh *et al*., 2017a. 2017b; Masoumi *et al*., 2013). Over the past two decades, due to droughts, dust storms have increased in the Middle East. The frequency and severity of these storms increase with the passage of time (Hamidi *et al*., 2013). The increased effects of aerosols in the Middle East and the many ensuing problems have made it necessary to conduct detailed and comprehensive studies. In this regard, some studies have been carried out in the Middle East. Some research has been done to investigate the optical and physical properties of aerosols (Mishra *et al.*, 2012; Alam *et al.*, 2014; Bangalath *et al.*, 2015; Bibi *et al.*, 2016a) over different sites in the Middle East.

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There are also studies examining the optical properties of aerosols by means of remote sensing techniques (Alam *et al.*, 2011; Masoumi *et al.*, 2013; Bayat *et al.*, 2013; Khoshsima *et al.*, 2014; Sabetghadam *et al.*, 2014) and radiative effects of aerosols (Alam *et al.*, 2012; Gharibzadeh *et al.* 2017.a; Gharibzadeh *et al.* 2017.b) over different sites.

The present study of aerosol optical characteristics such as Aerosol Optical Depth (AOD), Angstrom Exponent (AE), ASYmmetry parameter (ASY), Single Scattering Albedo (SSA), and Phase function, provides important information over five locations in the Middle East using the AErosol RObotic NETwork (AERONET) data sets. The current research will also fill a geographic gap in our present knowledge regarding the importance of atmospheric aerosols because several Middle Eastern sites pertaining to different countries were simultaneously studied.

2. Materials and Methods

2.1. Site description

In the Middle East, there are some AERONET sites; Five AERONET sites were selected, which the required data were available for 2013.

IASBS is a research institute in Zanjan, northwest of Iran (36.70 N, 48.50 E, and 1800 m above sea surface). The area has moist springs and winters, hot and dry summers, and cold winters. Anthropogenic aerosols and dust are dominant in the atmosphere of Zanjan in winter and summer, respectively (Bayat *et al*., 2013; Gharibzadeh *et al*., 2018b; Masoumi *et al*., 2013).

KAUST Campus is located in Thuwal, west of Saudi Arabia (22.30 N, 39.10 E, and 11.2 m above sea surface). This rural region, located near the sea coast, has a desert climate with very low rainfall.

Masdar Institute is in Masdar city, The United Arab Emirates (24.44 N, 54.62 E, and 4 m above sea surface). This city has a desert climate with moderate winters but humid and hot summers (Beegum *et al*., 2016).

Mezaira is in Mezaira, a city located in the vicinity of Abu Dhabi, south of The United Arab Emirates (23.15 N, 53.78 E, and 204 m above sea surface). This region has a sub-tropical climate such that it has humid and hot conditions in summer months and remains warm in winters.

Solar Village is located 50 km from Riyadh, Saudi Arabia (24.91 N, 46.40 E, and 764 m above sea surface). Winters and springs are rather wet while summers are dry and hot. Wind speed and dust events increase in springs (Sabbah and Hasan, 2008).

The locations and descriptions of the five mentioned AERONET sites are shown in Figure 1 and Table 1, respectively.

Fig. 1. Location of five AERONET sites in the Middle East (IASBS, KAUST Campus, Masdar Institute, Mezaira and Solar Village) marked with green circles

Table 1. Description about five AERONET sites in the Middle East (IASBS, KAUST Campus, Masdar Institute, Mezaira and Solar Village)

Site name	Geographical coordinates	country	Altitude	climate	Urban/ rural
IASBS	36.70 N, 48.50 E	Iran	1800 m	Moist springs and winters, hot and dry summers and cold winters	Urban
KAUST Campus	22.30 N, 39.10 E	Saudi Arabia	11.2 m	Desert climate with very low rainfall, located near the sea coast	Rural
Masdar Institute	24.44 N, 54.62 E	United Arab Emirates	4 m	Desert climate with moderate winters, humid and hot summers	Urban
Mezaira	23.15 N, 53.78 E	United Arab Emirates	204 m	Sub-tropical climate, humid and hot summers and warm winters	Urban
Solar Village	24.91 N, 46.40 E	Saudi Arabia	764 m	Winters and springs are rather wet, summers are dry and hot	Rural

2.2. AERONET data

The AERONET program is a federation of ground-based remote sensing aerosol networks. The program provides a continuous and long-term database related to aerosol microphysical, optical, and radiative properties. AOD data are computed for three data quality levels: Level 1.0 (unscreened), Level 1.5 (cloud-screened) and Level 2.0 (cloud screened and quality-assured). For AOD, the uncertainty in retrieval under cloud-free conditions is less than ±0.01 at wavelengths higher than 0.44 nm and less than ±0.02 at shorter wavelengths; however, the uncertainty for the retrieval of sky radiance measurements are less than ±0.05 (Dubovik *et al*., 2000). In the current study, the aerosol optical properties were analyzed during 2013 because the AERONET data pertaining to all sites were only available simultaneously for 2013.

2.3. CALIPSO data

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite provides an enhanced view of clouds and aerosols and the role they play in climate, earth's weather, and air quality. Passive visible and infrared sensors were combined by an active Lidar's instrument to provide data on the structure and properties of thin clouds and aerosols over the globe (Winker *et al*., 2007). Aerosol subtype profiles retrieved from CALIPSO were utilized in this study. Uncertainties improved from 10% to 5% in CALIPSO version 3 data products.

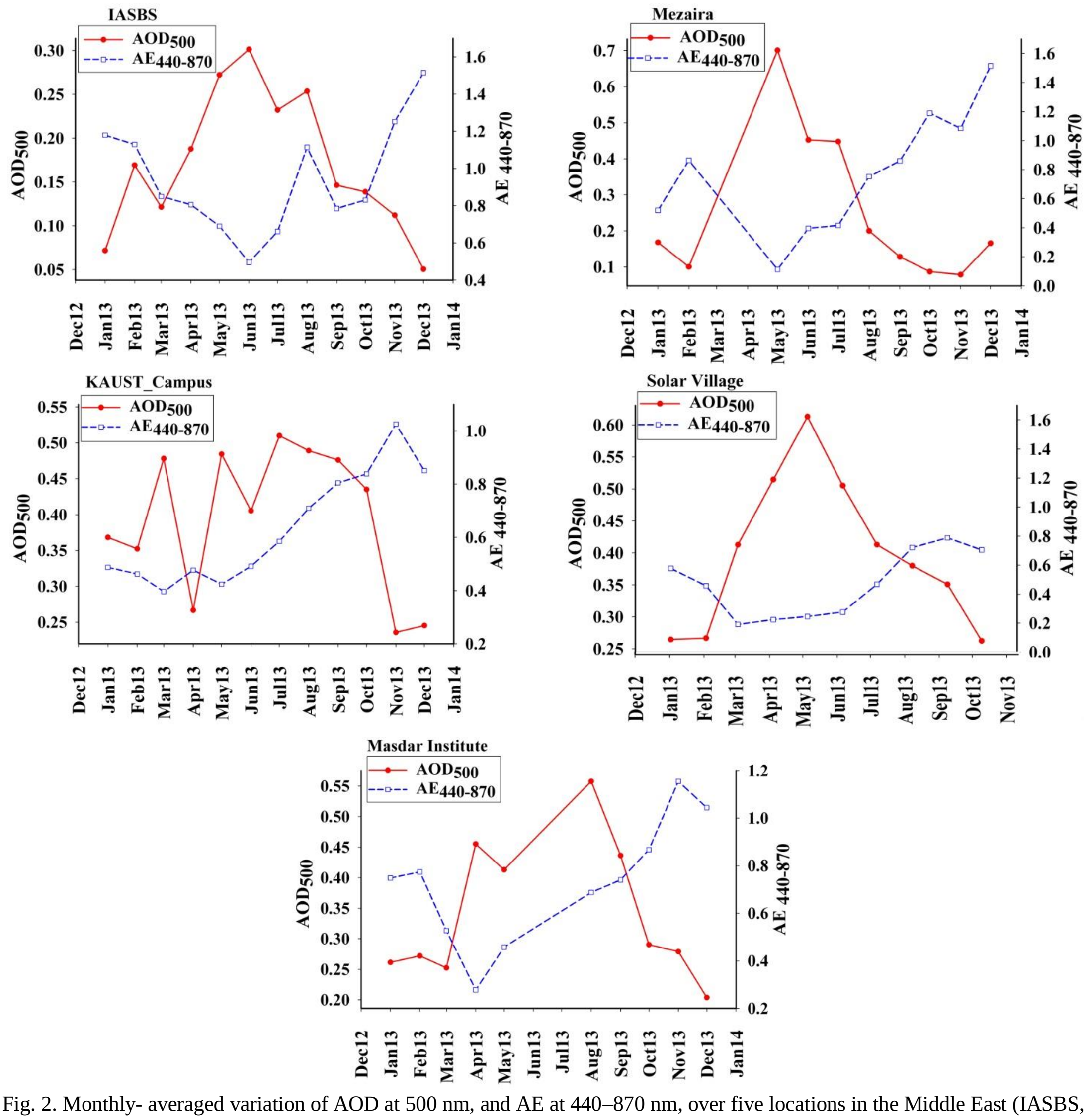


Fig. 2. Monthly- averaged variation of AOD at 500 nm, and AE at 440–870 nm, over five locations in the Middle East (IASBS, KAUST Campus, Masdar Institute, Mezaira and Solar Village) in 2013

3. Results and Discussion

3.1. AOD and AE

AOD represents the amount of solar radiations absorbed or scattered by aerosols. It is a measure of the total column extinction of radiations transmitted due to atmospheric aerosols (Holben *et al*., 2008). Wavelength dependence of the AOD determines AE, a good indicator of aerosol particle size demonstrated by the Angstrom relationship (Angstrom, 1964) given as:

$$\tau_a(\lambda) = \beta\lambda^{-\alpha} \quad (1)$$

where $\tau_a(\lambda)$ is AOD at wavelength λ, β is the turbidity coefficient indicating aerosol loading in the atmosphere, and α is AE. Figure 2 shows the monthly variation of AOD_{500} nm and AE $_{(440\text{-}870\ nm)}$ over the five studied sites in the Middle East in 2013.

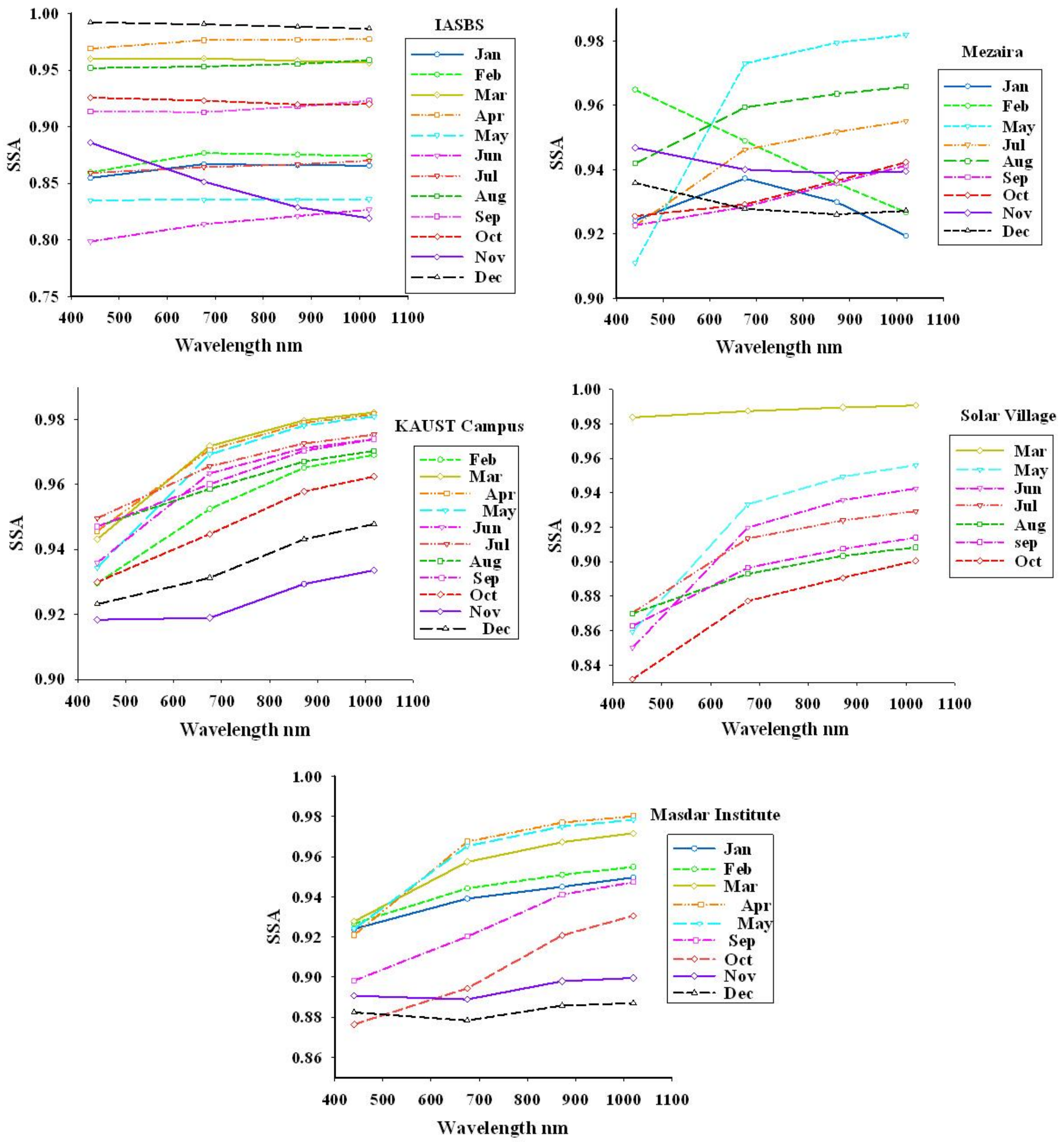


Fig. 3. Spectral variation of monthly-averaged SSA over five locations (IASBS, KAUST Campus, Masdar Institute, Mezaira and Solar Village) in the Middle East in 2013

In several sites (IASABS, KAUST Campus, and Masdar Institute), maximum AOD values were detected in summer while in others (Mezaira and Solar Village), they occurred in spring. This can be attributed to the dominance of dust particles during spring and summer because of high temperatures and dry conditions. The annual average values of AOD were 0.17 (IASABS), 0.40 (KAUST Campus), 0.34 (Masdar Institute), 0.26 (Mezaira), and 0.40 (Solar Village). The reason for the occurrence of maximum AOD in spring and summer is the dry conditions and high temperature in these seasons, generating heat and lifting loose materials from the soil due to greater wind speeds (Alam *et al*., 2014). Reverse relationships were observed between AOD and AE in all sites. An inverse relationship was further found between high AOD values and low AE values in spring and summer due to the presence of coarse mode particles, indicative of dust storms in these seasons. A comparable inverse relationship has already been reported between AOD and AE in a number of locations (Alam *et al*., 2011; Gharibzadeh *et al*., 2017b; Singh *et al*., 2005; Srivastava *et al*., 2015).

3.2. Single scattering albedo

SSA is defined as the ratio of scattering efficiency to the total extinction efficiency (Seinfeld and Pandis, 1998). SSA is 0 and 1 for the totally absorbing and scattering types of aerosol, respectively. Figure 3 shows the monthly average of SSA values at 440, 675, 870, and 1020 nm for the five sites in 2013.

In most sites (KAUST Campus, Masdar Institute, Mezaira, and Solar Village), SSA increased with the increase in wavelength, signifying a comparative increase in the scattering nature of particles, such as desert dust, with larger sizes, especially in spring and summer. As previously reported by Srivastava *et al*. (2011), during summer, SSA significantly increased in most sites when the dust aerosols were dominant over Middle East due to high temperatures and dry conditions. However, over IASBS, SSA showed an insignificant dependence on wavelength and SSA variation was nearly flat due to the presence of mixed (dust and anthropogenic) aerosols (Alam *et al*., 2011). The low SSA values in winter were caused by the presence of urban/industrial absorbing aerosols (Bhaskar *et al*., 2015).

3.3. Asymmetry parameter

ASY represents a preferred direction in scattering, and it is an important component in determining the radiative forcing calculations. ASY is -1 for completely backward scattering and 1 if scattering is completely in the forward direction (Seinfeld and Pandis, 1998). Figure 4 shows the spectral variations of ASY monthly average over the five studied sites in the Middle East in 2013.

The ASY was observed to be wavelength-dependent. In the visible spectrum, it was reduced in the beginning with the increase in wavelength due to the dominance of anthropogenic absorbing aerosols. Afterwards, with the increase in wavelength in the infrared region, the ASY increased due to the dominance of the coarse mode dust particles (Alam *et al*., 2011). In all sites, the maximum values of ASY were observed in spring and summer. Srivastava *et al*. (2015) and Alam *et al*. (2012) observed the same types of results over various cities of India and Pakistan. Srivastava *et al*. (2015) detected high ASY values in dusty days.

3.4. Phase function

Phase function is the angular distribution of the light intensity scattered by a particle at a given wavelength. In other words, it is the scattered intensity at a particular angle relative to the incident beam which describes how much light is scattered in each direction (Seinfeld and Pandis, 1998). Figure 5 shows the variations of the monthly average of phase function versus the scattering angle over five locations in the Middle East during 2013.

The maximum values of phase function occurred in forward scattering angles (zero angles): 409 (June), 323 (June), 337 (September), 437 (May), and 457 (July) over IASABS, KAUST Campus, Masdar Institute, Mezaira, and Solar Village, respectively. The phase function had its highest values in spring and summer over all sites. Coarse mode particles often cause higher phase functions at small scattering angles. At angles between 0-10 degrees, the phase function was uniformly reduced. Moreover, lower values of phase function at angles higher than 10 were due to the presence of fine mode particles (Bibi *et al*., 2016b). At larger angles, phase function remained almost constant. Kokhanovsky (1997) reported that the most stable phase function of aerosols occurred around a scattering angle of 150 degrees.

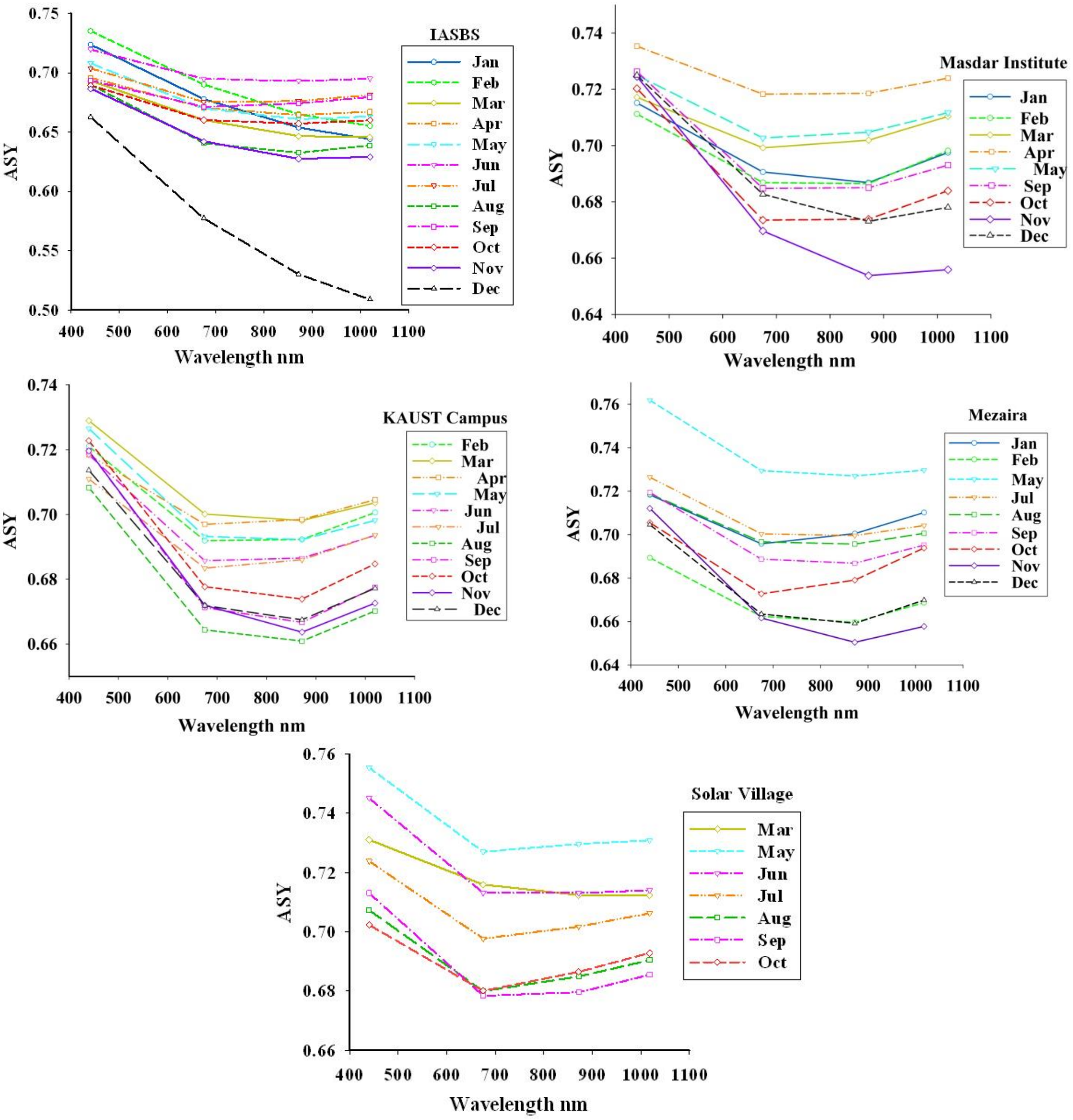


Fig. 4. Spectral variation of monthly-averaged ASY over five locations in the Middle East (IASBS, KAUST Campus, Masdar Institute, Mezaira and Solar Village) during 2013

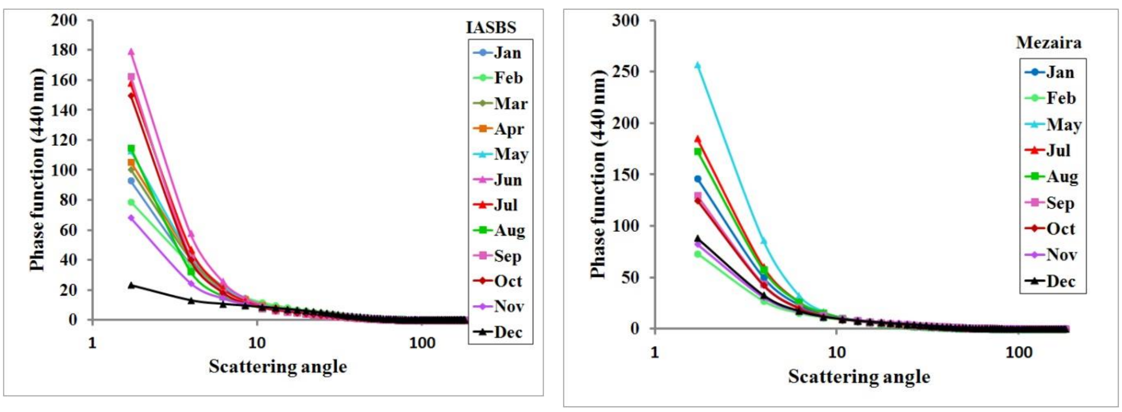
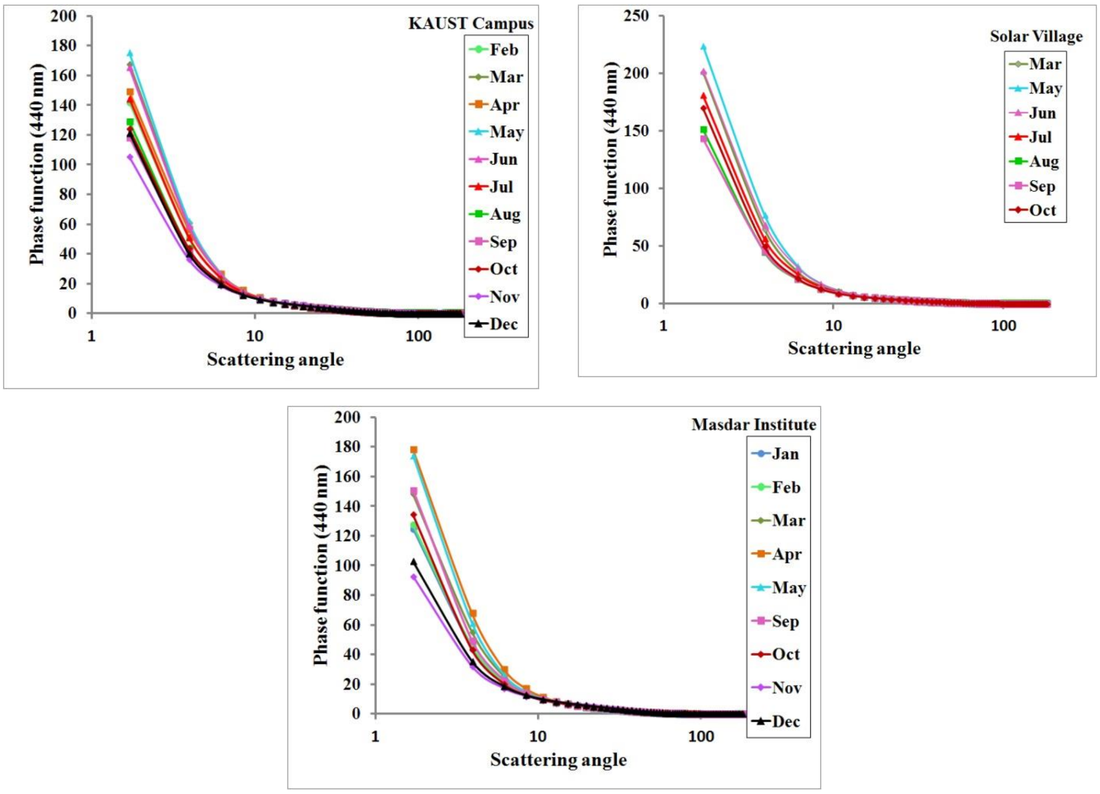


Fig. 5. Variation of monthly average of phase function over five locations (IASBS, KAUST Campus, Masdar Institute, Mezaira and Solar Village) in the Middle East in 2013



Continued Fig. 5. Variation of monthly average of phase function over five locations (IASBS, KAUST Campus, Masdar Institute, Mezaira and Solar Village) in the Middle East in 2013

3.5. CALIPSO Aerosol subtype profiles

CALIPSO measurements were employed to obtain the aerosol subtype profiles. Figure 6 shows the CALIPSO-retrieved subtype profiles. CALIPSO provided data on the dusty day of May 28th in the proximity of IASBS and Solar Village. On 29th May, there were also data in The United Arab Emirates Masdar Institute, –Mezaira, and the surrounding areas of KAUST Campus. The aerosol subtype profiles in the vicinity of IASBS, KAUST Campus, and Solar Village verified the dominance of dust and polluted dust. Furthermore, the aerosol subtype profile illustrated the dominance of dust in the vicinity of Mezaira and Masdar Institute. However, polluted continental and smoke can also exist in the region.

It is recommended that future work take into account more number of sites and study aerosol optical properties and radiative forcing over longer time periods, so that climatic effects can be more accurately studied.

5. Conclusions

Using AERONET data during 2013, aerosol optical properties were investigated over five sites in the Middle East. The data obtained from AERONET included AOD, AE, SSA, ASY, and phase function. The monthly averages of these aerosol properties were then studied. The following results can be extracted from this study.

In most months, an inverse relation existed between AOD and AE in all sites. Coarse mode particle and dust storms in spring and summer resulted in high AOD values and low AE values.

Initially, ASY decreased in the visible spectrum with the increase in wavelength due to the dominance of anthropogenic absorbing aerosol. Then, ASY increased with the increase in wavelength in the infrared region due to the dominance of dust.

In KAUST Campus, Masdar Institute, Mezaira, and Solar Village, SSA increased, especially in spring and summer, with the increase in wavelength because of the desert dust dominance.

In spring and summer, the phase function was high over all sites. High phase functions for small scattering angles were caused by the coarse mode particles. Phase function was uniformly reduced in angles between 0-10 degrees. Because of the presence of fine mode particles, the amounts of phase functions were low at angles larger than 10 degrees.

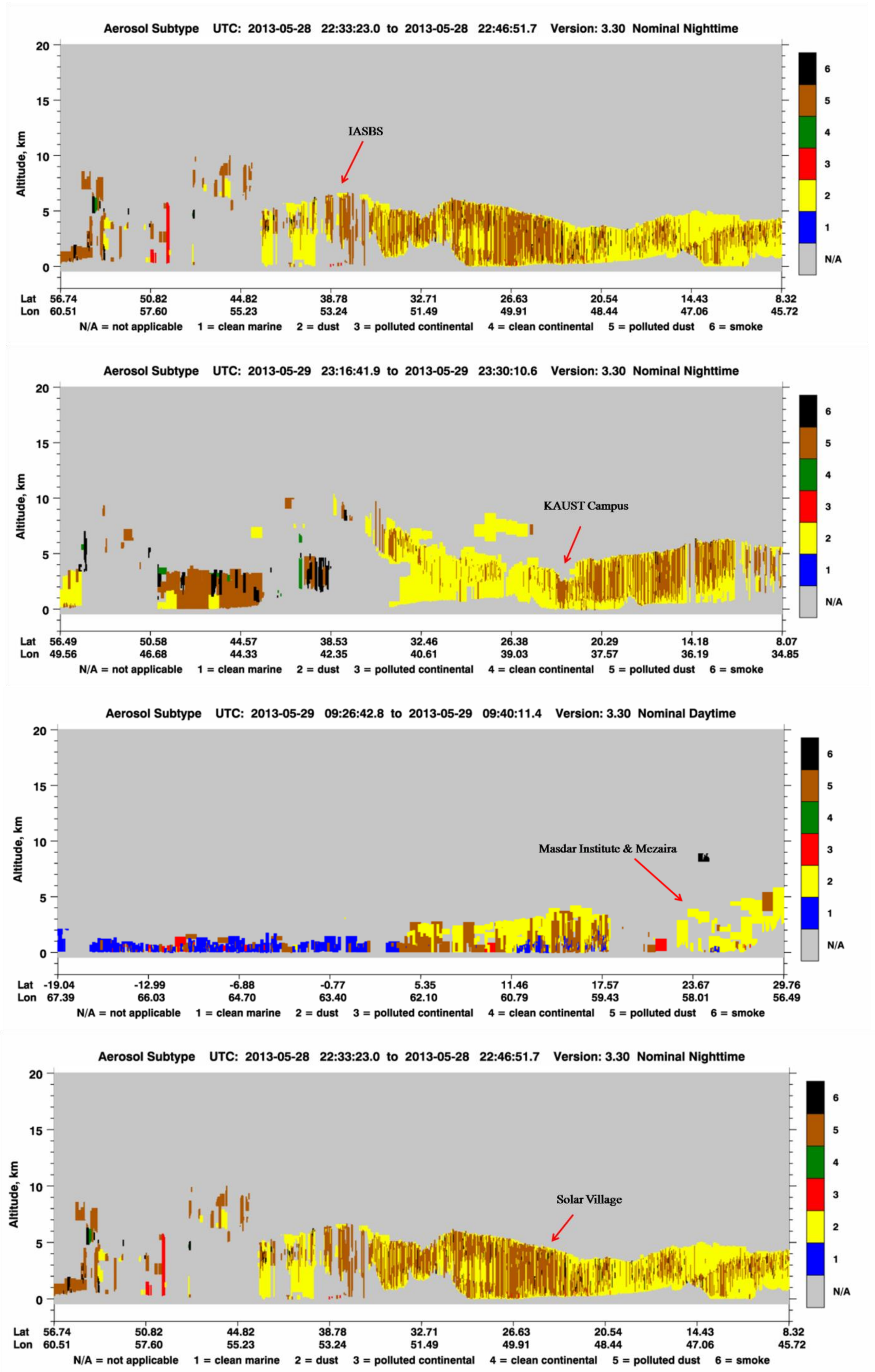


Fig. 6. Aerosol subtype profiles retrieved from CALIPSO over IASBS and Solar Village on 28th may 2013 and over Masdar Institute, Mezaira and KAUST_Campus on 29th may 2013

The aerosol subtype profiles retrieved from CALIPSO near IASBS, KAUST Campus and Solar Village, showed the dominance of dust and polluted dust; polluted continental and smoke and dust were dominant in the vicinity of Masdar Institute and Mezaira.

Acknowledgment

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