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Ashraf Farahat
King Fahd University of Petroleum & Minerals

Hesham el-Askary
Chapman University, elaskary@chapman.edu

A. Umran Dogan
University of Iowa

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Aerosols Size Distribution Characteristics and Role of Precipitation during Dust Storm Formation over Saudi Arabia

Ashraf Farahat[1,2], Hesham El-Askary[3,4,5*], A. Umran Dogan[6,7]

[1] *Department of Prep Year Physics, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabi*
[2] *Department of Physics, Faculty of Science, Moharam Beek, Alexandria University, Alexandria 21522, Egypt*
[3] *Schmid College of Science and Technology, Chapman University, CA 92866, USA*
[4] *Center of Excellence in Earth Systems Modeling and Observations, Chapman University, CA 92866, USA*
[5] *Department of Environmental Science, Faculty of Science, Moharam Beek, Alexandria University, Alexandria 21522, Egypt*
[6] *Chemical and Biochemical Engineering Department, University of Iowa, Iowa 52242, USA*
[7] *Center for Global and Regional Environmental Research (CGRER), University of Iowa, Iowa 52242, USA*

ABSTRACT

Kingdom of Saudi Arabia and the Gulf region are frequently exposed to major dust storms and anthropogenic emissions from rapidly growing industrial activities that affect aerosols optical and physical characteristics. This paper integrates observations from space-borne sensors namely MODIS and CALIPSO, together with AERONET ground observations to examine eight years aerosols characteristics during the (March–May) season of 2003 to 2010 over Saudi Arabia. Aerosol analysis from the interdependent data assessment show comparable aerosols characteristics over the eight year period with higher aerosols mean optical depths over enhanced dust load region, (46–50°E, 25–29°N), during March–May of 2009 and 2010. The mean angstrom exponent during March–May 2003 to 2008 was found ~17% higher than the same period during 2009. The major dust storm on March 9 and 10, 2009 could have an effect on the coarse mode particles increment during 2009. Over the eight years the highest angstrom exponent was observed on 2004 suggesting dominance of fine-mode particles, whereas a declination in the angstrom exponent values is observed during 2005, 2006, 2007, and 2008. The aerosols size distribution measured by sunphotometer indicates a maximum value of ~47% higher in 2009 compared to 2010 suggesting the domination of coarse mode particles in 2009. Using the CALIPSO volume depolarization ratio, a possible mixing of anthropogenic aerosols with dust was observed during March–May of 2009 and 2010 featured by coarse particles domination and high percentage of fine particles during 2009. The effect of precipitation prior to dust storms on dust loading was investigated. Our observation suggests a possible impact of the varying precipitation rate prior to dust storms outbreak and the actual dust loading during dust events.

Keywords: Atmospheric aerosols; Remote Sensing; AERONET; Dust; Pollution.

INTRODUCTION

The Kingdom of Saudi Arabia (KSA) occupies nearly 80% of the Arabian Peninsula (AP) with an area of 2,149,690 km^2 (Fig. 1). KSA is located in the sub-tropical belt between (17°N–30°N) and (36°E–55°E), characterized mostly as arid/semiarid land with desert climate except in the Jizan region near the west coast (Shmida 1985; Edgell 2006). Hence, sand storms of different magnitudes may occur throughout the year in the KSA although mainly in cooler months (September–February) and can last for hours or days according to the prevailing meteorology (Awad and Mashat, 2013; Awad *et al.*, 2014). Occasionally they may occur during the hot season (March–October) with a high occurrence frequency during the spring season (March–May) (Farahat, 2016). The amount of the rainfall a region receives is significant in determining the dust emissions over that region (Prospero *et al.*, 2002). In the case of the KSA, rainfall is low and irregular with an annual average rainfall of 92 mm except for the Jizan region as it usually receives about 300 mm of rainfall between October and March. Moreover, the maximum annual rainfall over the KSA occurs over two areas; the first is the east of the central KSA (Hail, Qassim, Hafr Al Baten, Qaisoma, Riyadh, and Dhahran) and the second is the SW region (Taif, Baha, Khamis Mushed, Abha, and Jizan) (Alamodi *et al.*, 2008). On the other hand, the lowest rainfall values occur over the

* Corresponding author.
E-mail address: elaskary@chapman.edu

Fig. 1. Location map of the Kingdom of Saudi Arabia and neighboring countries.

north and NW areas. Rainfall scarcity and warm temperature during the winter months create favorable meteorological conditions for spring sand storms as it affects soil moisture and makes sand particles become loosely held due to arid conditions. They could also produce strong pressure gradients, which cause an increase in wind velocity over wide areas. Although the KSA is characterized by a considerably harsh climate with high spatial and temporal variability it received much lesser attention as compared to North African countries neighboring the Mediterranean over the past four decades (El-Askary 2006; El-Askary *et al.*, 2009; Prasad *et al.*, 2010; Marey *et al.*, 2010, 2011; Gerasopoulos *et al.*, 2011; Kaskaoutis *et al.*, 2012, Aboel Fetouh *et al.*, 2013). It is noteworthy that both the Red Sea at the KSA west coast and the Arabian Gulf at the east coast moderate the desert temperature and also contributes to a relative humidity of more than 60% that produces hot mist during the day and fog at night. Yet, the NW Shamal wind blowing over the country several times a year mostly during the spring and the summer creates strong sandstorms that affect air and ground traffic as well as daily life activities in the KSA (Saeed *et al.*, 2014). Moreover, the two relative positions of a high-pressure system that prevails over the Mediterranean region in conjunction with the low-pressure system over the southern part of Iran are mainly responsible for characterizing the synoptic systems associated with the Shamal dust storms over the KSA (Awad *et al.*, 2014).

It was concluded that naturally and manmade induced aerosol emissions play a non-trivial role in affecting the KSA air quality and dynamics as well as the local climate resulting from radiation budget modifications (Farahat *et al.*, 2015).

Aerosols particles are classified based on their size, shape and chemical composition, upon which, meteorologists and climatologists refer to aerosols as ultrafine, fine, or coarse mode particles. Key aerosols include different chemical compositions like dust, sulfate, sea salt, black carbon and organic carbon; however, aerosols usually mix to form complex mixtures of different aerosol particles. For example, it is common for black carbon to coat dust, creating hybrid particles.

In the KSA scenario, naturally induced particles are mainly due to dust storms and sea salt, whereas the rapidly growing number of vehicles, excessive construction activities, marine transportation in the Arabian Gulf, and the Red Sea and water desalination plants, and power plants contributes to the anthropogenic emissions. Sulfate aerosols forms by the reaction of sulfur dioxide produced by fossil fuel combustion with water vapor. Among the drawbacks of the prevailing dust storms is the continuous mixing of these aerosols, with pollutants and heavy toxic materials and transferring from one part to another across the country. Such transportation and mixing scenarios contributes to the significantly changing weather conditions and aerosols characteristics after dust related events. For example, after the major March 10–11, 2009 dust event in the KSA, changes in atmospheric emissivity and Aerosol Optical Depth (AOD) were reported together with the air pressure and humidity increment accompanied by a change wind speed and wind

direction (Maghrabi *et al.*, 2011). On another incident, The Moderate Resolution Imaging Spectroradiometer (MODIS) AOD values were found to be 4–5 times higher over the KSA and the Arabian Gulf during the March 2012 massive dust storm (Alam *et al*., 2014). Similar work and observations has been carried out in different parts of Asia (Agarwal *et al.*, 2007; El-Askary *et al.*, 2015; Park *et al.*, 2015). For instance, in Shanghai, the proportions of As, Pb, and Se were 2.4, 0.8, and 5.5 times the normal values after a dust storm in March 2010 (Guoshun *et al.*, 2011). Yet in Beijing, the April 2000 sand storm increased the airborne particles by 27 times (Ning and Polenske, 2008). During dust storm events (2001–2005), the maximum AOD shows increase from ~1 to ~2.4 and the aerosol size distribution shows increase in radius from 1.71 to 2.24 µm over India (Prasad and Singh, 2007). In South Korea, during 2004, Anmyeon exhibits the highest concentration of fine particles where the volume size distribution (VSD) peaked at 0.1 µm, yet a variation of the VSD over Seoul was observed for dust storm occurring on 21 March, 2002 with a substantial increase in the concentration of the coarse particles at 2.9 µm (Park *et al.*, 2015). Several studies highlighted the relationship between sandstorm and general health problem mainly respiratory ones over different locations (Carbone *et al.*, 2011; Dogan, 2012; Sprigg *et al.*, 2014; Vukovic *et al.*, 2014).

In this paper, ground based Aerosol Robotic Network (AERONET) measurements are integrated with space-borne sensors, MODIS and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), observations to analyze aerosols' characteristics during the spring season (March to May) of (2003–2010) over the KSA. It is widely known that, small dust events frequently occur during the year in the KSA; however, the Shamal wind results from strong northwest winds blow through Turkey and Iraq into the Arabian Gulf is strongest during the Spring-Summer season and have a major impact on stimulating major dust event during March–May period. Notaro *et al.* (2013) concluded that Saudi Arabian dust activity is greatest during February–June, with a mid-winter peak along the southern coast of the Red Sea based on a backward trajectory analysis for 2005–2013. The CALIPSO backscattering measurements were used to derive volume depolarization ratios (VDR) during March to May of 2009 and 2010, where massive dust storms blew up and caused a widespread of heavy atmospheric dust load over the KSA. During the same period of 2010, an opaque dust plume ~100 km in width extended from KSA across eastern Kuwait into Iran (Pilewskie and Valero, 1992). A possible role of remarkably low rainfall in the suppressed dust activity is investigated and presented in this work.

DATA SOURCES

We employ aerosol products retrieved using MODIS Deep Blue algorithm, which retrieves global aerosol information over bright-reflecting land surfaces, such as deserts where the standard MODIS AOD algorithm does not work (Hsu *et al.*, 2004). The MODIS Level 2 data are averaged over a grid to represent aerosols loading at a spatial resolution of a 10 × 10 km. Data from another space-borne sensor CALIPSO is utilized in this study. The CALIPSO two - wavelength and depolarization profiles provide global vertically resolved data on aerosol distribution, extinction coefficient, hydration state, and discrimination of particles' size and shape. Backscattering depolarization data from CALIPSO at 532 nm are also used to discriminate dust from other types of aerosols (Murayama *et al.*, 2001; Sassen *et al.*, 2003; Vaughan *et al.*, 2009). We use Level 2–5 km aerosol and cloud profile data products including 532 nm Column Optical Depth and Volume Depolarization Ratio Statistics. Along with satellite observations, we use Level 2.0 ground measurements of aerosols properties from the Solar Village, AERONET, located at 24°54′25″N and 46°23′49″E, altitude of 764 m.

RESULTS AND DISCUSSION

Aerosol Physical Characteristics Analysis over the KSA during the Period 2003–2010

We used AOD and Angstrom Exponent observations to determine the aerosol physical characteristics during the spring season (March–May), well known for dust activity in the KSA; however, the varying intensity of these dust events is not necessarily known over the years. As shown by MODIS Aqua Deep Blue AOD during (2003–2010) Figs. 2(a)–2(h) the dust loading is clear over different parts of the KSA and at different abundance. The overall aerosols distribution pattern is comparable between all periods; however, with much intensified dust distribution near the eastern province of the KSA (46–50°E, 25–29°N), at the Arabian Gulf and near Kuwaiti-Iraqi borders during (March–May) of 2008 to 2010. It is clear that the mean optical depths over the enhanced dust load region (46–50°E, 25–29°N) during (March–May) 2003 is as low as 0.34 as compared to 0.56 in 2008 and 0.48 during the same period of 2009 and 2010. This can be attributed to the known synoptic pattern over the KSA that consists of northern and south-eastern high-pressure systems associated with low-pressure systems over Iran and the southern regions of the Arabian Peninsula (Awad *et al.*, 2014). Such varying seasonal component over the eight years period suggests that aerosols of different origin, source and grain size distribution have compiled a clear mixing scenario over the region of interest. This work has been further corroborated by studying the Angstrom exponent (spectral dependence of aerosol optical depth with the wavelength of incident light) observations and the corresponding AOD values over the Eastern Province region within the same period, since it showed the highest aerosol activity, in order to highlight the origin of these aerosols. Such analysis resulted in the identification of specific days that can be classified as dusty versus pollutants dominated and others with a mixed scenario (El-Askary *et al.*, 2009) as shown in Table 1. The Goddard Chemistry Aerosol Radiation and Transport (GOCART) model (Chin *et al.*, 2000) outputs were obtained to determine the possible sources and sea salt AOD over the KSA during March–May 2003–2010. Fig. 3 shows that monthly average sea salt contribution is insignificant over the KSA during the study period.

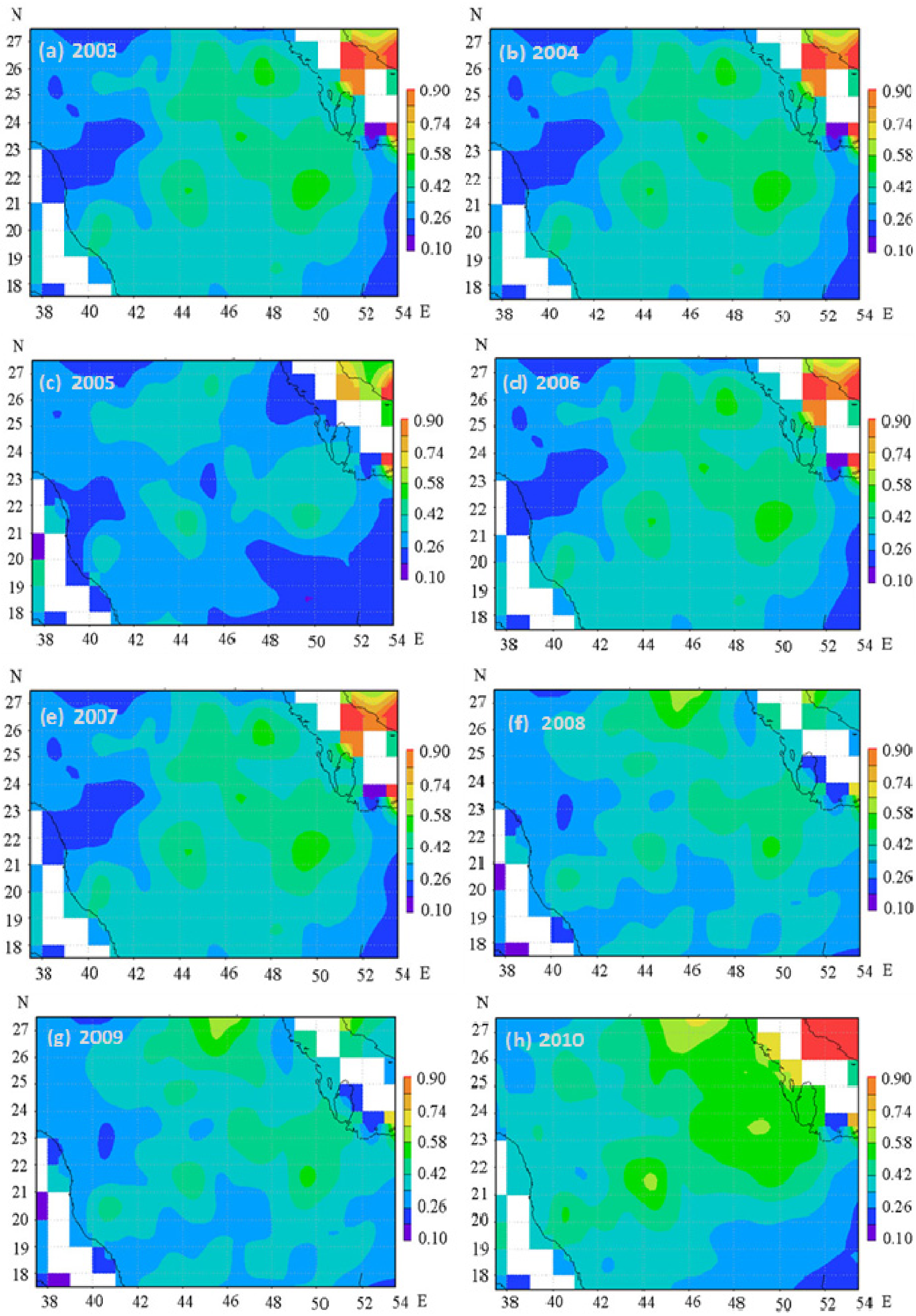


Fig. 2. MODIS Aqua aerosol optical depth (AOD) from Deep Blue aerosol products over Saudi Arabia during March–May of 2003–2010.

Table 1. Characterization of the aerosol types over KSA (36–55°E, 17–30°N), for selected dates where the bold days represent great variations associated with the specified atmospheric scenario using MODIS Aqua Deep Blue AOD during Mar–May of 2003–2010.

Date	AE	AOD
Pollution		
2 May 2003	1.01	0.69
23 Sep 2003	1.18	0.29
18 April 2004	1.02	0.69
19 Apr 2005	1.81	0.49
7 Mar 2006	**1.81**	**0.25**
9 Sep 2008	1.81	0.37
3 Jan 2009	1.81	0.49
15 Mar 2009	**1.22**	**0.35**
14 Feb 2010	1.23	0.27
30 Apr 2010	**1.81**	**0.51**
Dust		
18 May 2003	**0.54**	**0.64**
5 Aug 2003	0.49	0.71
4 Aug 2008	0.48	0.57
17 Aug 2009	0.48	0.67
19 Jul 2010	0.49	0.70
11 Aug 2010	0.47	0.59
Mixed		
19 Jan 2003	0.66	0.19
5 Mar 2003	**0.61**	**0.39**
4 Apr 2004	**0.61**	**0.30**
4 Apr 2005	**0.63**	**0.31**
27 Apr 2006	**0.63**	**0.28**
7 Apr 2007	**0.61**	**0.29**
23 Jan 2008	0.83	0.18
24 Apr 2008	**0.51**	**0.51**
14 Jan 2009	0.62	0.27
25 May 2009	**0.60**	**0.33**
3 Mar2010	**0.61**	**0.25**
28 Sep 2010	0.63	0.27
Clean		
6 Jan 2003	0.87	0.09
2 Jan 2005	0.80	0.08
3 Oct 2005	0.81	0.07
29 Dec 2009	0.73	0.10
5 Jan 2010	0.67	0.10
9 Jan 2010	0.87	0.10

The annual AOD during the years 2004 and 2005 showed the lowest values, where the Angstrom exponent was the highest, suggesting a dominant pollution episode during these two years (Fig. 4). Precipitation values peaked during the same years suggesting that pollutants would enhance precipitation as confirmed over different regions (El-Askary *et al.*, 2009). Furthermore, Fig. 5(a) shows the angstrom exponent measurements over the KSA during (March–May) of 2003 to 2010 confirmed the above observation. It was found that 2004 and 2005 showed an intense abundance of fine particles with large count of angstrom exponent between 0.8–1.0. On the other hand, 2009 and 2010 are dominated with mixed-mode aerosols with angstrom exponent between 0.4 and 0.8. The mean angstrom exponent during (March–May) (2003–2008) is 0.68 compared to a lower value of 0.56 during 2009 and 0.62 during 2010. For instance, in 2004, ~13% of the particles have an angstrom exponent of less than 0.6, compared to ~52% in 2009 and ~37% in 2010. During March–May 2003 to 2008 ~29% of the particles have an angstrom exponent less than 0.6. Angstrom exponent measurements of 0.2–0.6 are ~32% lower during March–May 2003–2008 compared to the same period on 2009, while measurements of > 0.6–1.2 are ~20% lower during 2009 compared to 2003–2008. Therefore, it is quite evident that the major dust storm on March 9 and 10, 2009 could have had an effect on coarse mode aerosols increment during 2009 (Fig. 5(b)).

In the solar spectrum, the exponent is a good indicator of the size range of the atmospheric particles responsible for the AOD loadings. For instance, exponent > 1 when fine mode (submicron) aerosols are dominant, while exponent < 1 for aerosols dominated by coarse or supermicron particles. In fact, the spectral variation/dependence of the exponent can provide further information about the aerosol-size distribution (King *et al.*, 1978; Nakajima *et al.*, 1986; Kaufman, 1993; Eck *et al.*, 1999; O'Neill *et al.*, 2003; Schuster *et al.*, 2006).

While examining the mean (March–May) AOD over the eight-year period of (2003–2010) using Aqua MODIS Deep Blue, we found a lower AOD during 2010 over the KSA as compared to 2008 and 2009. However, the rise in the AOD during 2009 is not significant (~16%) compared to 2010 and (~14%) compared to the mean value for March–May 2003–2008 (Fig. 2). The observed drop during 2010 in the dust loading is also suggested by the high value of angstrom exponent (0.62) in 2010 compared to (0.56) in 2009 (Fig. 2). Over an eight year period of 2003 to 2010, the highest angstrom exponent was observed in 2004 (0.79) suggesting dominance of fine-mode particles, whereas a declination in the angstrom exponent values is observed as 0.76, 0.69, 0.62, and 0.54 during 2005, 2006, 2007, and 2008, respectively. Using data from the Global Precipitation Climatology Project, the mean precipitation rate over the KSA during December–February of 2003–2010 is found to be (~12.12 mm). However, the KSA received the highest rainfall during 2005 with January marked with a significant increase of (~25.35 mm) (Fig. 4). The mean precipitation during December 2008–February of 2009 is low (~4.69 mm) compared to (~10.27 mm) during 2010. The remarkably low rainfall (~4.89 mm) in February 2009 may have enhanced dust emission over arid regions during the March 9–10, 2009 major dust storm over the KSA. However, the rainfall during December 2009–February 2010 is ~2 times higher than the same period of 2008– 2009 and this might have impacted the lower mean AOD values reported during (March–May) of 2010. It is clear that enhanced precipitation prior to dust storms season could have minimized dust storms formation. For example, the high precipitation rate from December 2003 to February 2004 and from December 2004 to February 2005 resulted in no significant dust activities reported during March–late May of 2004 and 2005 over the KSA (Fig. 4).

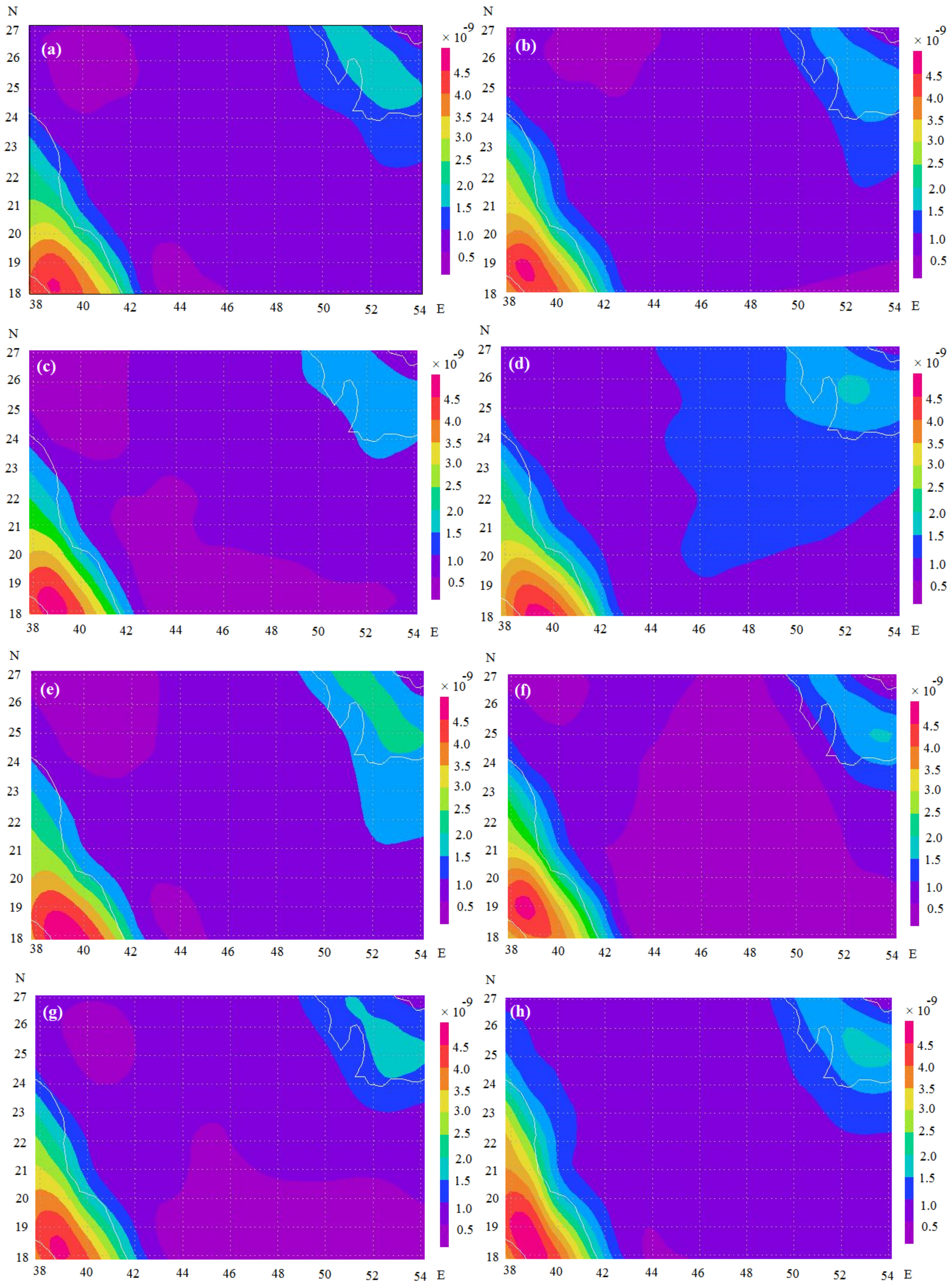


Fig. 3. GOCART model outputs of sea salt AOD during March–May 2003–2010.

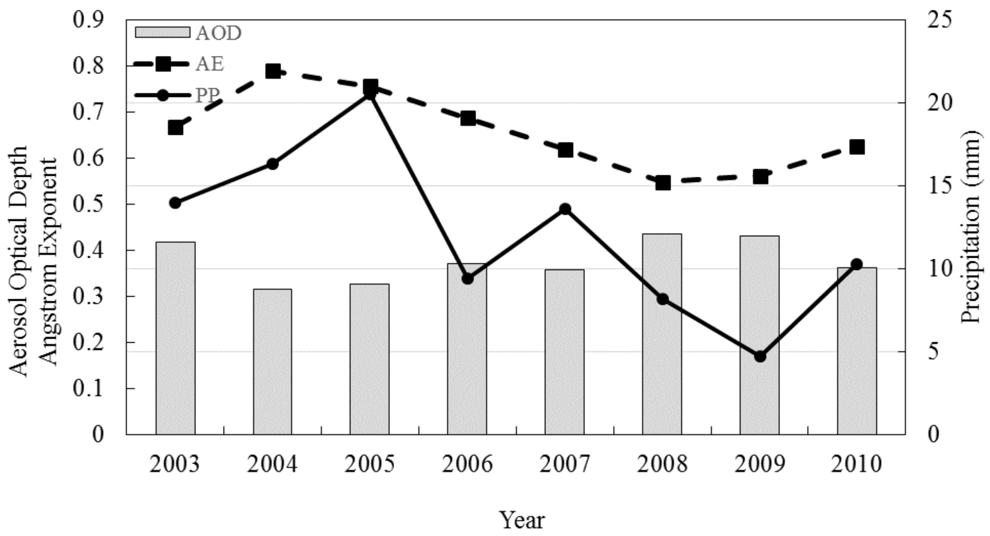
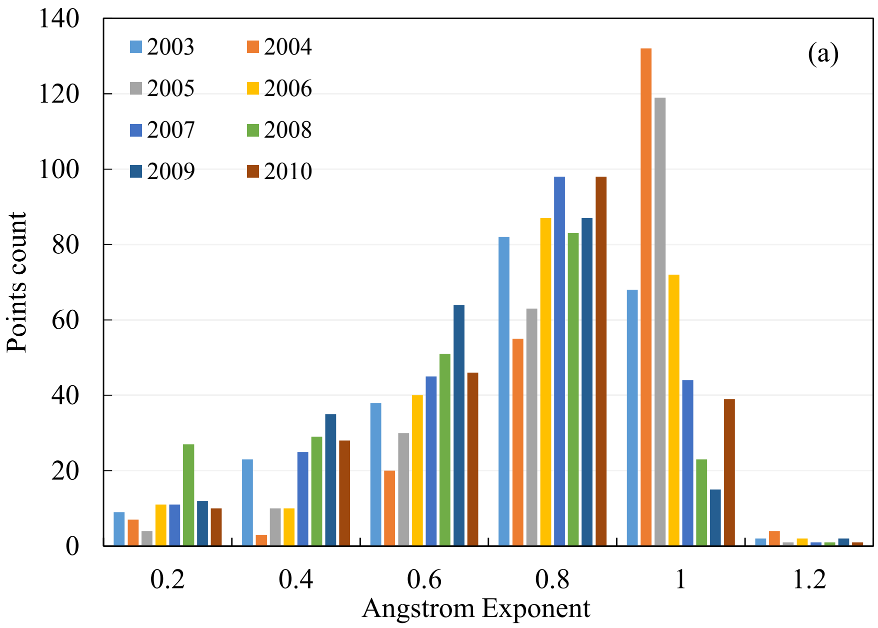


Fig. 4. Average monthly Deep Blue Aqua MODIS AOD (vertical bars), Angstrom Exponent (dashed line) during March–May from 2003 to 2010 over the Kingdom of Saudi Arabia, and precipitation during December– February from 2003–2010 (solid line).



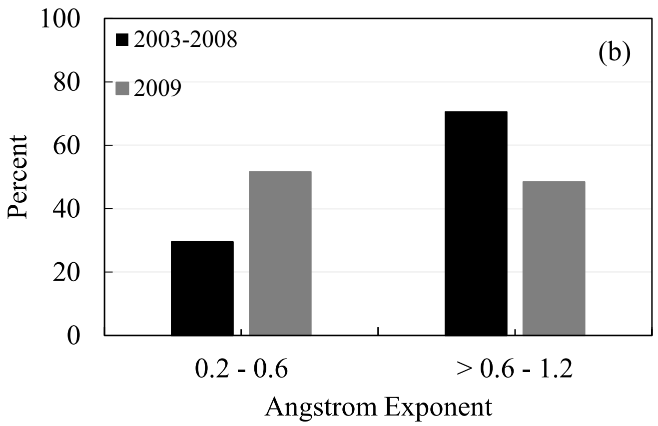
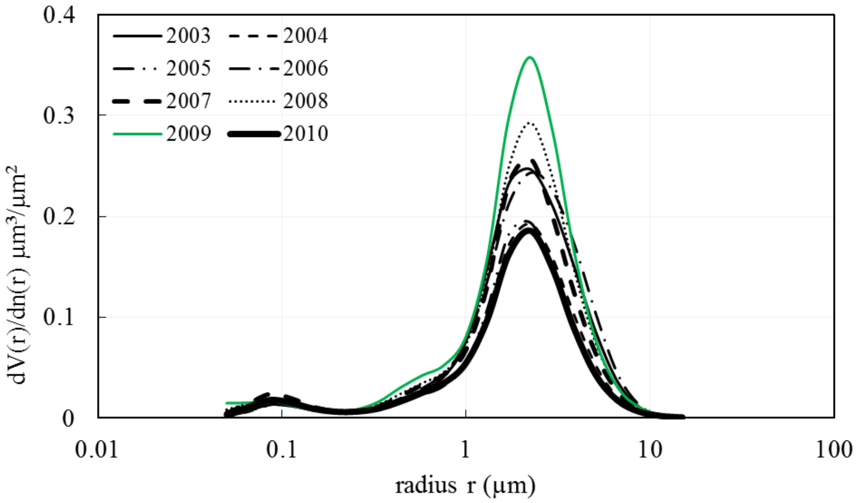


Fig. 5. a) Angstrom exponent during March–May of 2003 to 2010 over Saudi Arabia, b) (0.2–0.6) and (> 0.6–1.2) Angstrom exponent percentage during March–May 2003–2008 and 2009.

Grain Size Distribution Analysis over the KSA during the Period 2003–2010

In this section, we investigate the variation of the volume size distributions (VSD) as a function of the particle geometric mean radius for the KSA aerosols using the AERONET data from the Solar Village located ~450 km from dust loading zone (46–50°E, 25–29°N) at the East Province of the KSA, during the spring season of the period 2003 to 2010. The VSD helps understanding local aerosol properties and variation (Yang and Wenig, 2009; Park *et al*., 2015). Fig. 6(a) displays a bi-modal log-normal variation of the VSD (*dV*/*d*ln*R*) with a high magnitude of coarse mode peaking during the years 2006 to 2009 as compared to the other years. The year 2009 has the highest concentration of coarse particles at the Solar Village due to the dust storm of 9, 10 March, 2009. The VSD peaks to 0.36 $\mu m^3\ \mu m^{-2}$ at ~3 µm geometric mean radius with less significant contribution for the fine particles fraction. The substantial increase in the coarse particles concentrations at ~3 µm dominated the aerosol loadings during 2009 as a result from the major dust events over the KSA during that year. The overall fine particles concentration is minimal yet, the year 2010 over Solar Village exhibits the highest concentration of fine particles where the VSD peaks at 0.1 µm with a loading of 0.19 $\mu m^3\ \mu m^{-2}$. Fig. 6(b) on the other hand shows the daily plot of the VSD for March 7, 9, 11, and 12 where the loading jumped to > 1 on March 11 with a higher dominancy at coarse mode fraction as a result of the dust outbreak in the previous two days and a significant drop and shift on the following day owed to excess deposition.

(a)



(b)

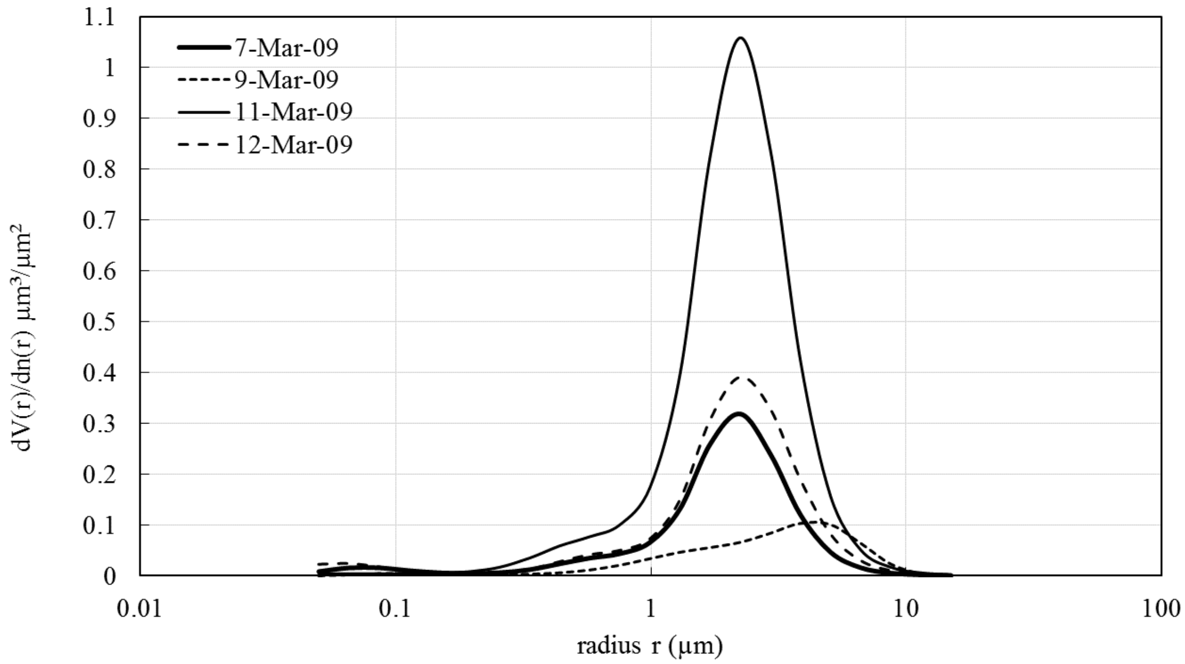


Fig. 6. a) Variation of aerosol volume size distribution of AERONET station at solar village during March-May of 2003–2010 for N = 69, b) Daily average variation of aerosol volume size distribution of AERONET station at solar village during March 7, 9, 11 and 12, 2009 for N = 1. N is the number of days used.

To further exploit aerosols characteristics during major dust events CALIPSO data are compiled over the KSA on daily basis at (36–55°E, 17–30°N) during March–May of 2009 and 2010. The mean AOD profile from CALISPSO indicates similar aerosol loading during the two years (Fig. 7). The mean AOD profile (not shown in the figure) shows that dust loading during March 2009 is ~15% less than March 2010, dust loading in April 2010 decreased to ~23% of its value during April 2009; while May 2009 dust loading is ~13% less than May 2010. In addition to the CALIPSO AOD latitudinal profile, we also use the CALIPSO backscattering measurements to derive volume depolarization ratios (VDR) (Liu *et al.*, 2008) during the two dust events in 2009 and 2010 (Fig. 7). The VDR as a ratio between the perpendicular and parallel component of the attenuated backscattering signal is used here to distinguish the physical properties of aerosols (spherical and non-spherical). Higher VDR values suggest greater amount of non-spherical particles like dust as compared to smoke and pollution aerosols results in small VDR values. The mean VDR values are 1.31 and 1.32 during March–May of 2009 and 2010, respectively. The unexpected close to similar VDR values during 2009 and 2010 can be attributed to the dust outbreak on March 4, 2010 and to the clear mixed scenarios observed over Saudi Arabia as shown from Table 1.

It is also noteworthy the big difference in the AOD values of 2009 versus 2010 suggests a bigger mixing scenarios as mentioned above. To further investigate the aerosols' physical properties, the mean aerosols latitudinal VDR values were grouped in three different bins to overcome the aerosols mixing (Figs. 8(a) and 8(b)). In March–May of 2009 ~4.9% of the particles have VDR values between 0.2 and 0.4; 22.3% are between 0.4 and 0.6, and about 72.0% of the aerosols particles have VDR values > 0.6. The corresponding VDR values during March–May of 2010 are 2.8, 15.7, and 81.5%, respectively. This suggests a significant contribution of dust aerosols during 2009 and 2010. The moderately high VDR values (between 0.2–0.6) suggesting the existence of anthropogenic particles mixing with the dust. The moderately high VDR values are found be higher during 2009 than in 2010.

CONCLUSIONS

The mean AOD during the spring season (March–May) for the years 2003–2010 showed high aerosol abundance as expected due to combined natural and anthropogenic sources. AOD during recent years exhibits higher values as compared to early years owed to possible higher pollution scenarios as evidenced from the Angstrom exponent values. The drop in dust loading in 2010 is observed as suggested by the higher angstrom exponent value (0.62) in 2010 compared to (0.56) in 2009. Therefore, pollution has been contributing lately to the mixed scenarios as compared to natural aerosols. The size distribution showed coarser particles dominance during 2009 as compared to 2010 suggesting a role for the March 9 and 10 major blown dust storms, hence affecting the air quality over the KSA. The significant anthropogenic emissions, mainly from oil and cement industry, and from significant urban areas composed of a significant amount of carbonaceous aerosols, sulfate, and nitrate favor the existence of hazy conditions over the KSA during the most of the year. During the spring season from March onwards the high-land temperatures over the majority of the KSA favors the convection and uplift of dust aerosols forming dust storms that affects the region.

The low precipitation rate during December 2008–February 2009 and December 2009 to February 2010 enhanced the strong dust activities on March 2009. Dust plumes appeared as translucent beige blurs over the KSA. On March 2010, an opaque dust plume with 100 km in width extended from the KSA across eastern Kuwait into Iran. This study integrated observations from MODIS, CALIPSO, and data from the GOCART to shed some light on the aerosols' characterization over the KSA. Taking into consideration, the frequent dust storms, unprecedented infrastructure activities, overusing governmental subsidized energy, water desalination, heavy traffic in large cities, and

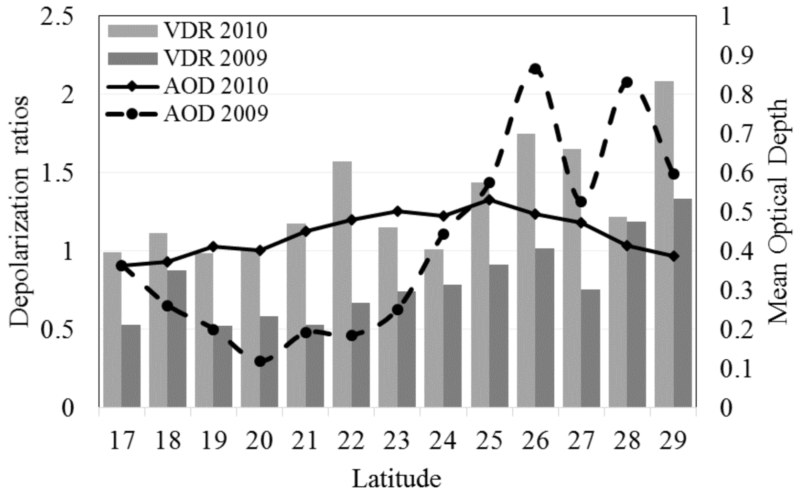
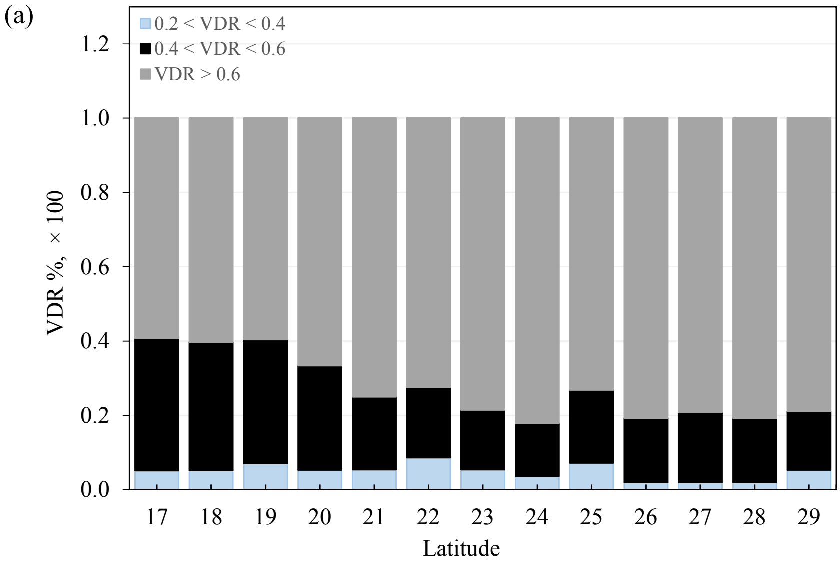


Fig. 7. Mean aerosol optical depth (AOD) and volume depolarization ratio (VDR) over Saudi Arabia during March–May 2009 and 2010.



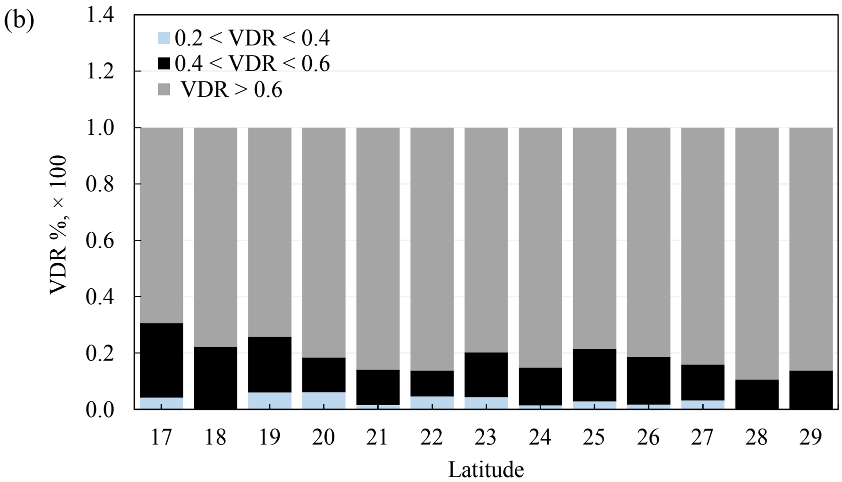


Fig. 8. Mean volume depolarization ratio separated in three bins based indicated by different colors in the vertical bars a) March–May 2009, b) March–May 2010.

cement plants, it is very important to monitor dust aerosols over the KSA. It is also important to understand the spatial and temporal distribution using satellite and ground station as it affects the hydrological cycle and the radiation budget by intercepting sunlight.

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