

Article

Types, Indications and Impact Evaluation of Sand and Dust Storms Trajectories in the Arabian Gulf

Ali Al-Dousari ^{1,*}, Domenico Doronzo ² and Modi Ahmed ¹

¹ Environment and Life Sciences Research Center, Kuwait Institute for Scientific Research (KISR), P.O. Box: 24885, Safat, Kuwait City 13109, Kuwait; mmahmed@kISR.edu.kw

² Institute of Earth Sciences “Jaume Almera”, Consejo Superior de Investigaciones Científicas (CSIC), Barcelona 08028, Spain; domenico-doronzo@libero.it

* Correspondence: adousari@kISR.edu.kw

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Abstract: Dust is a common weather phenomenon in the Arabian Gulf, which has severely affected economy and health. Sand and dust storms (SDS) trajectories in the Arabian Gulf were temporally and spatially monitored from March 2000 to March 2017. Eight major SDS trajectories were detected from satellite images. The dust storms trajectories were categorized according to shape and size into three main types with 12 subtypes in the region. The annual transported dust amount into the Arabian Gulf was estimated by 89.1 million metric tons, which is about 10,330 metric tons per cubic kilometer of water volume. In comparison to other seas and oceans, the amount of dust deposited into the Arabian Gulf water body volume is the highest. Dust deposited in the coastal regions within the Arabian Gulf are originated from Mesopotamian Flood Plain (MFP), Ahwaz (HZ), Ahwar (HR) and Baluchistan Desert (BSH) and characterized by physical parameters and composition. Such physical characterization of the trajectories of SDS, and of the properties of particles transported in the Arabian Gulf can be helpful to assess and mitigate the environmental impact of future similar events.

Keywords: aeolian; dust; aerosol; sand storm; dust storm; trajectories; Arabian Gulf

1. Introduction

Sand and dust storms (SDS) are considered to be most common phenomena in the Arabian Gulf regions [1]. Dust is a part of, and a key player in, the earth’s ecological systems [2–4]. Dust events can be meteorologically categorized into four types depending on visibility, namely: suspended dust, dust storms and haze [5]. The Arabian Gulf is surrounded by desert ecosystem characterized by active aeolian conditions [6,7]. Land degradation and extended drought periods act as a major activator of SDS in deserts [8]. There are substantial amounts of dust grains that may be driven thousands of kilometers from their origin [9], and it has been valued that aeolian dust derived from soil erosion gives annually around 500 million tons of particulates into the atmosphere [10]. Up to two billion tons of dust blows into the atmosphere in a single year within major SDS trajectories [11]. Frequent occurrences of SDS in the Arabian Gulf cause an acute environmental problem that can affect the health, safety and economic well-being of society [12]. The SDS passing over the Arabian Gulf is considered to be the major sources of sediments [13]. There are major SDS trajectory areas in northern Arabian Gulf were identified, namely; Mesopotamian Flood Plain (MFP), Western Desert-Iraq (WD), Nafud Desert (NFD), Ahwar (HR) and Ahwaz (HZ) [14]. Another interesting aspect is the possible effects of draining the Ahwar marshland which acts later as a new source area for dust [15]. Empty Quarter (EQ), Nafud [16] and Baluchistan (BSH) [17] deserts act as major sources of SDS within southern Arabian Gulf region. Quartz-poor fine sediment is a characteristic of soil sediments in MFP, HR, HZ, and BSH, while quartz-rich coarse sediment found in WD, NFD and EQ [18,19].

The reduction of the adverse impact of SDS in the Arabian Gulf environment requires a full understanding of dust phenomena both physically and mineralogically, toward improvement in future effective control measures. Thus, it is essential for global and regional aspects to put appropriate classification for SDS trajectories and their indications.

Therefore, the aim of this study is to establish a suitable classification for SDS trajectories focusing on its indications in the Arabian Gulf by passing through chemical and physical characteristics of some deposited dust samples on areas within a pathway of these SDS trajectories. The physical characterization of SDS trajectories, and of their particle properties, as provided here with an integrated approach, can be helpful to mitigating the impact of future similar events in the environment (agriculture, infrastructures and air quality).

2. Materials and Methods

Four methods were used in this study to characterize SDS in the Arabian Gulf:

1. Remote sensing methodology as it is effective tool for monitoring dust storms and aerosol layers trajectories. This is valid especially for regional scales. Brightness measurements from NOAA/AVHRR- LAC (Local Area Coverage) and GAC (Global Area Coverage) archives, Terra/Aqua MODIS (The moderate-resolution imaging spectroradiometer) and TOMS (The Total Ozone Mapping Spectrometer) aerosol images of dust phenomena are good operational middle resolution indicator over the cloudless Arabia Gulf region. Low resolution meteorological images were used from METEOSAT are supporting the real time synoptic view of major dust storms over the Region. Old SeaWifs image archive (LAC and GAC) is additional support for delineation of dust trajectories in early 2000th. Analysis of true-color composition of three bands MODIS 1(645 nm), 4(555 nm) and 3(469 nm) gave excellent opportunity for relatively high resolution of intensive dust jets over the Arabian Gulf and the Gulf of Oman. The collected images from these satellite data related to SDS days (using visibility and wind direction) were used in tracing major trajectories. SDS images were also collected from these satellites NASA web sites such as (<http://earthobservatory.nasa.gov/NaturalHazards/event>), (<http://visibleearth.nasa.gov>) and (<http://modis.gsfc.nasa.gov>).
2. Dust fallout was monitored using a modified dust trap with 20 cm aperture and fixed at 240 cm above ground level and filled with marbles following the design by Al-Dousari and Al-Awadhi [14] (Figure 1) modified from Reheis [20] and Al-Awadhi [21] dust trap. There were 40 dust traps installed within coastal and terrestrial areas (20 traps for each) in Kuwait at the northern part of Arabian Gulf (Figure 2). The samples were monthly collected between 1 January 2011 and 31 October 2011 from all dust traps.
3. Deposited dust was also collected from smooth surfaces on building at 5 m or more above ground level within major paths of SDS in the Arabian Gulf region. This sampling method were also used to cover surrounding global and regional areas to identify the dust properties in the Arabian Gulf in relation to other samples that include south Ahwar-Iraq, Manama-Bahrain, Riyadh and Walamen-south Arabia, Dubai and Ain-UAE and Cairo-Egypt.
4. All collected samples (from both above methods) were analyzed to detect the physical and mineralogical properties of dust using the following techniques:
 - a. Scanning electron microscope (SEM) and the Brunauer, Emmett, and Teller (BET) surface area were used to analyze all collected samples in the second method, in addition to terrestrial and coastal areas samples from Kuwait. The BET-surface area is stated as values for a particular weight of loose particles concerning meter square per gram ($\text{m}^2 \text{g}^{-1}$) measured via isotherm plot diagrams of volume against pressure and using the BET equation was devised [22].

- b. Dust fallout particle size percentages for 20 samples collected during 10 months from desert and coastal areas within Kuwait (January to October) were determined using Shumadzu, SA-CP3 Centrifugal Particle Analyzer.
- c. The whole components of the dust samples collected from the Arabian Gulf region in addition to March, June, September and December samples from desert and coastal dust traps in Kuwait were softly milled and analyzed using Philips PW-1830 X-ray diffraction (XRD) to semi-quantitative analysis.

These methods allow for the establishing of a decent classification for SDS trajectories in the Arabian Gulf, highlighting dust physical and chemical properties within these trajectories.

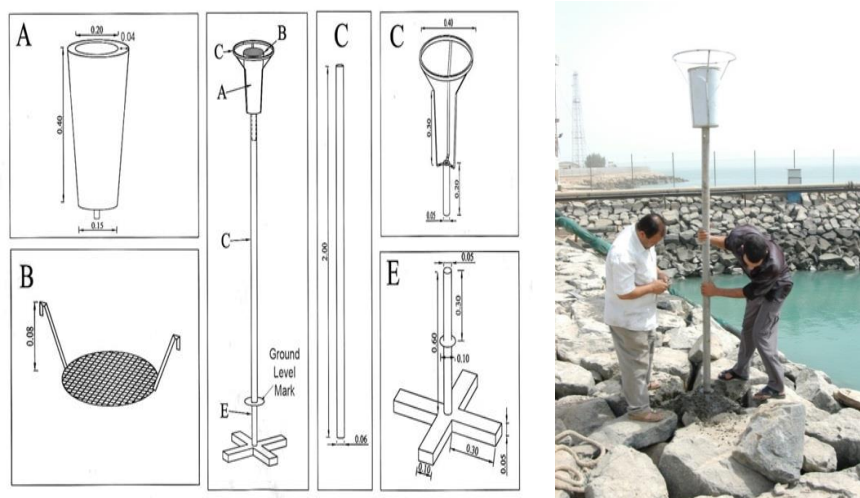


Figure 1. Dust trap design (left) and photo (right) in coastal area of Kuwait.

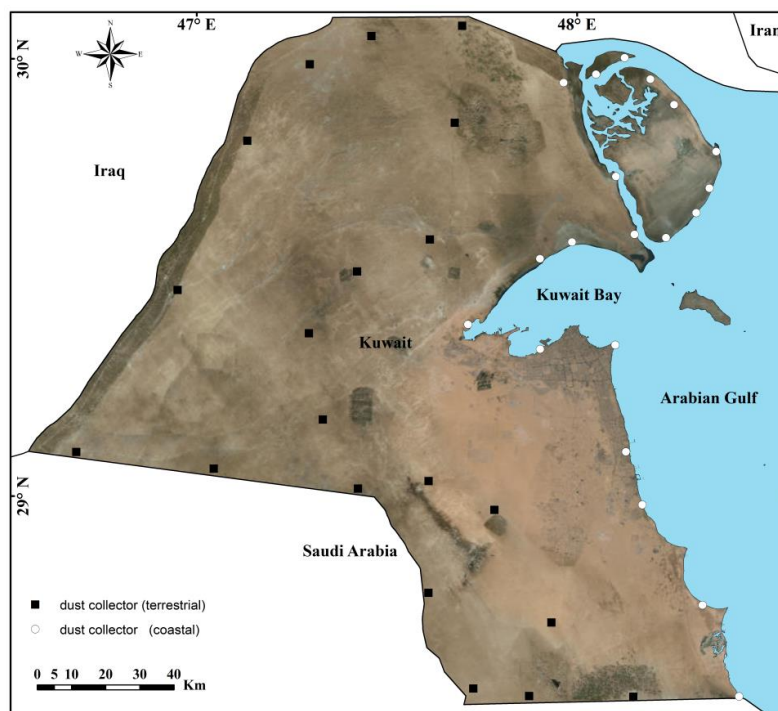


Figure 2. Dust traps locations in terrestrial and coastal areas of Kuwait at northern Arabian Gulf.

3. Results and Discussion

3.1. Dust Regional Trajectories

The SDS sizes and shapes within main trajectories are predominantly controlled by two main factors; topography and the wind (speed and direction). SDS trajectories can be classified in the region in reference to size and shape into three forms (Figure 3), namely,

1. Extensive (SDS averaged width more than 300 km),
 - a. Contains 6 subtypes (Agglomerated–Dense, Agglomerated–Dispersed, Wavy, Hook–Single head, Hook–Multiple heads, and Spiral),
2. Intermediate (width 300–100 km),
 - a. Contains 3 subtypes (Straight, Curved and Hook), and
3. Small (width less than 100 km) SDS.
 - a. Contains 3 subtypes (Needle like, Arrow shape-straight, and Arrow shape-curved).

In this study, the main SDS trajectories were identified, and satellite derived data were used to delineate temporal and spatial variations in their emission intensities (Figure 4). Eight major SDS trajectories were detected from these satellite images originating from:

1. The Mesopotamian Flood Plain (MEP),
2. The western desert of Iraq (WD),
3. Ahwar marshes (HR),
4. Nafud Desert (NFD)
5. Ahwaz-Iran (HZ)
6. Empty Quarter Desert (EQ) and
7. Bandar Lenga (BLG), Iran.
8. Hurmuz (HRZ)

Some of these eight SDS trajectories were also identified by other investigators [23–27]. Major SDS trajectories are initiated in southern Iraq [25]. Therefore, WD, MFP, HR, BLG and HZ are the most active sources of SDS trajectories in the Arabian Gulf region during the period from January to October. The EQ and NFD are mostly energetic trajectories during February, March, May, July, August, September and October (Figure 4a).

Among the three major types, there are 12 subtypes of SDS trajectories. The extensive SDS in the northern part of the Arabian Gulf is dominantly originated from the MFP or the WD or the HZ or the EQ desert or by a combination of multiple sources.

The Arabian Gulf total area is around 226,000 km² with 900 km long and width 56–338 km as width range [28] with 7000 to 8400 km³ as a total water volume [29]. There are more SDS trajectories in northern Arabian Gulf in comparison to the southern portion (Figure 4b). The northern parts of Arabian Gulf receive annually about 373 t km⁻² of deposited dust. The number of SDS days and annual average within northern Arabian Gulf are about five times more in comparison to the south (Table 1). The amount of fallen dust into the Arabian Gulf originated from the eight major trajectories represents the highest in the world (about 10,330 metric tons of dust for each cubic kilometer volume of water) (Table 2).

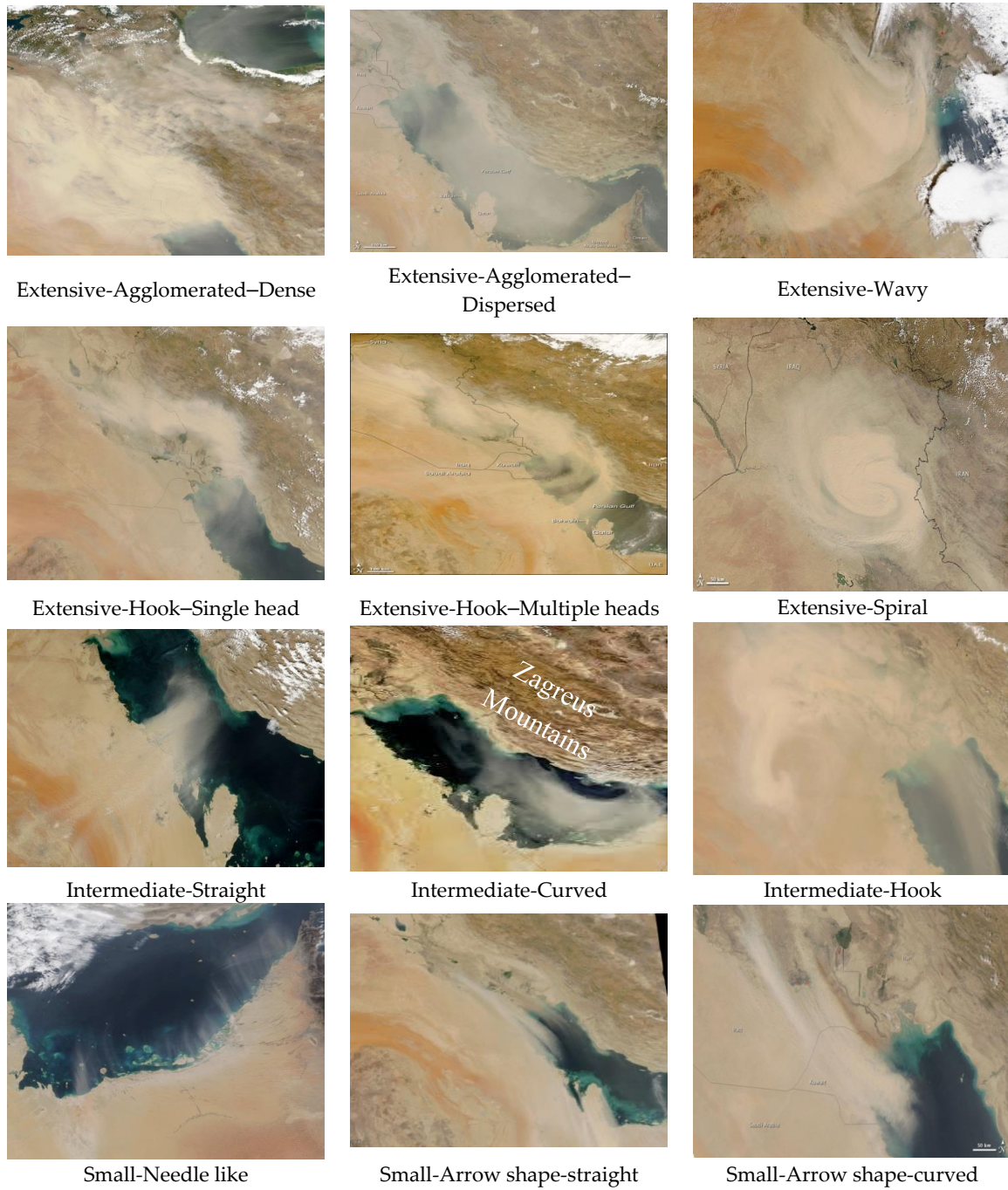


Figure 3. Classification index of sand and dust storms (SDS) trajectories in the Arabian Gulf observed by MODIS images (3 major types and 12 sub types).

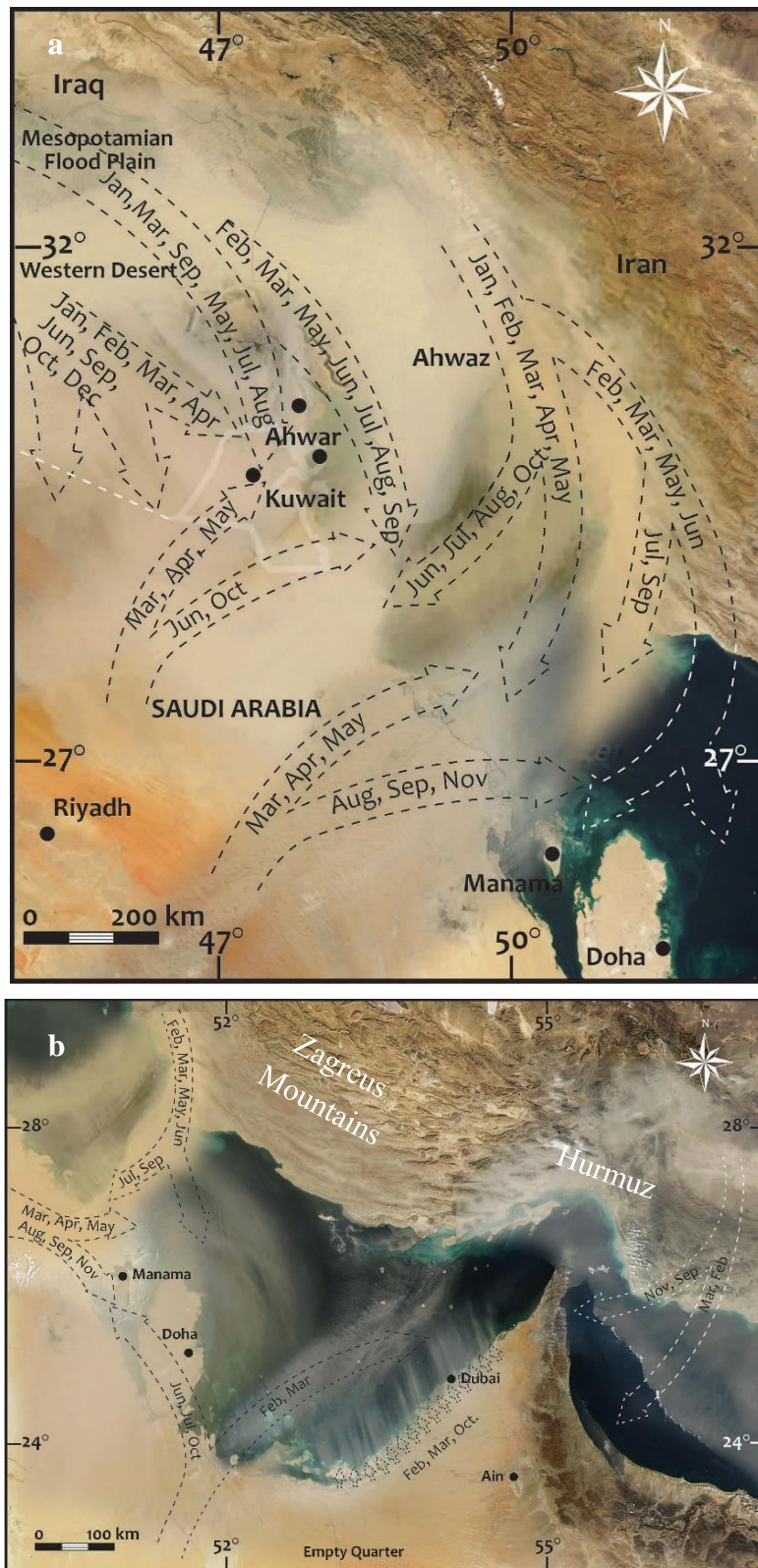


Figure 4. Spatial and temporal distribution for multiple dominant SDS trajectories (2000–2017) superimposed images in northern (a) and southern (b) parts of the Arabian Gulf with sampling sites (dark dot).

Table 1. The average number of SDS days in the Arabian Gulf.

Cities	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
Kuwait	17	0.9	1.2	1.1	3.3	3.7	4.4	4.5	1.9	0.6	1.4	0.3	1.1	21
Riyadh	5	2.2	4.4	5.6	10	6.2	8.4	5.2	2.2	1.2	0.6	1.8	1.0	49
Bahrain	33	0.1	0.3	0.5	0.6	0.5	1.4	1.5	0.2	0.3	0.0	0.1	0.1	5.6
Doha	15	0.4	0.5	0.7	0.7	0.4	1.7	1.4	0.4	0.4	0.3	0.4	0.1	7.6
Abu-Dhabi	6	0.4	0.3	0.6	0.1	0.4	0.4	0.7	0.0	0.0	0.0	0.2	0.7	3.9

Table 2. The annual fallen dust in major water bodies in the world.

Ocean/Sea	Total Area (km ²)	Annual Dust (t km ⁻²)	Location-Political Region (Reference)	Annual Dust to Total Sea Area (Million Tons) *	Annual Dust in Water Volume (t km ⁻³) **
Arabian Gulf	226,000	373	Kuwait (present study)	89	10,330
		76	Um Qasr-Iraq [12]		
		194	Khur Zubir [12]		
Arabian Sea	3,862,000	392	Nufud [30]	344	33
		89	Oman [31]		
Red Sea	938,000	57	Negev Desert [32]	53	1.33
Mediterranean Sea	2,500,000	155	Tripolli-Libya [33]	185	49
		10	Crete-Greece [34]		
		114	Agadir-Morocco [35]		
		145	Sidi Afni-Morocco [35]		
Atlantic Ocean	106,400,000	175	Tan Tan-Morocco [35]	13,324	38
		111	Smara-Morocco [35] Itguity-Morocco [35]		
		40	Morocco [35]		
		52	Layoune-Morocco [35]		
		219	Boujdour-Morocco [35]		
191	Dakhla-Mauritania [35]				
		80	Noudhibou-Mauritania [35]		

* Calculated by multiplying the average annual amount of deposited dust with total area of water body; ** Calculated by dividing the average amount of deposited dust with water body volume.

3.2. Particle Size Characteristics

The sedimentological significance of the distribution between bedload and suspended load lies in the distance are carried by wind [36]. Two main mud size fractions of dust were identified; these are: short (diameter ranges between 20–63 μm) and long (diameter less than 20 μm) term suspended particles [36]. In addition to local dust source areas that comparatively produce coarse dust particles greater than 63 μm particle size diameters. The average mud (silt and clay) percentages represent 76%, while the mean percentages for sand particles are 24% from the whole collected dust samples in this study area. The particle size percentages are varying between those collected in the open desert (Kuwait, Nufud, and Ain) and others in the coastal areas (Bahrain, Dubai and Kuwait). The clay percentages are much more in dust within coastal areas (21%) (Table 3). Dust from coastal areas is negatively skewed, trimodal with dominance of clay, coarse and fine silt size fractions showing slight seasonal variations (Figure 5a). The trimodality of the distribution curves for dust samples within coastal areas indicated multiple sources (Figure 5b). On the other hand, open desert dust samples are negatively skewed and unimodal.

A closer view of dust particles using scanning electron microscope confirms that dust in desert areas contains loose, sub angular and dominantly composed of quartz particles (Figure 6a). In contrast, coastal dust contains consolidated angular particles with more carbonates and evaporites compared to desert dust (Figure 6b). The collected dust sampled show different chemical and physical properties.

Table 3. Particle size percentages of fallen dust in the Arabian Gulf and surrounding areas.

Location	Sand	V. C. Silt *	C. Silt *	M. Silt *	F. Silt *	V. F. Silt *	Clay
Desert dust around the Arabian Gulf							
Walameen-Saudi	40	8	21	15	11	2	4
Ain, UAE	97	0	1	1	1	1	0
Kuwait desert	37	22	18	14	7	2	0
Coastal dust around the Arabian Gulf							
Ahwar, Iraq	3	12	20	25	15	5	20
Kuwait coast	12	10	20	11	13	5	28
Bahrain	12	10	20	11	13	5	28
Dubai, Emirate	17	3	14	24	23	10	8
Mean (Desert)	58	10	13	10	6	2	1
Mean (Coastal)	11	9	19	18	16	6	21

* V. C. Silt: Very coarse silt; C. Silt: coarse silt; M. Silt: Medium silt; V. F. Silt: Very fine silt.

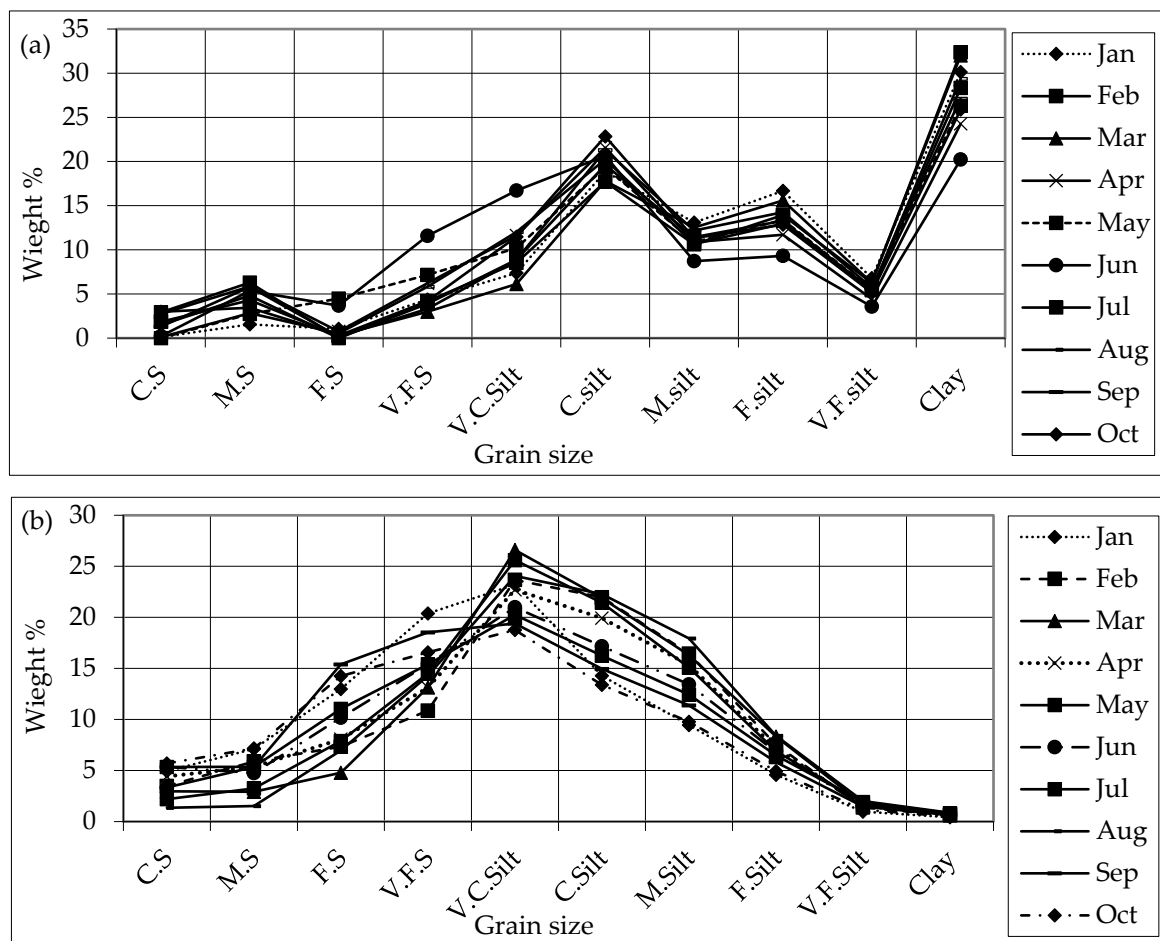


Figure 5. Dust fallout particle size percentages from January to October coastal (a) and desert (b) areas in Kuwait.

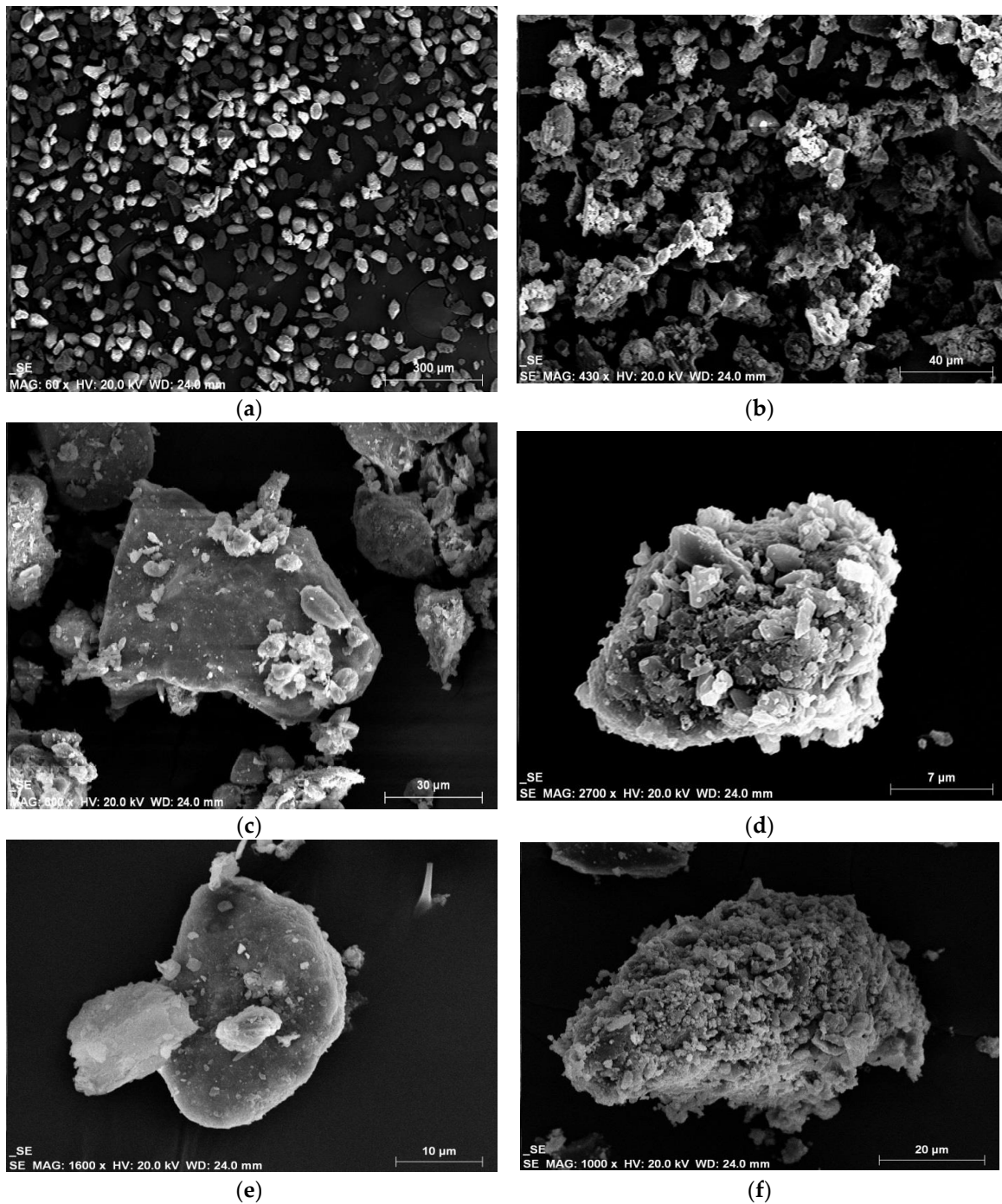


Figure 6. Scanning electron micrograph for dust particles from Rub al-Khali-Walameen (a), and coastal environment in Dubai (b), closer view of sub angular quartz particle from Rub al-Khali-Walameen carrying smaller adhering particles (c), coastal bassonite ($\text{CaSO}_4 \cdot 0.5\text{H}_2\text{O}$) (d) and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) particles from Dubai dust, and quartz particle from dust collected from Cairo carrying many adhering particles (f).

3.3. Mineralogical Analysis

The semi-quantitative results confirm that carbonates (38%) and quartz (34%) are the major components in the deposited dust samples within the study area. Feldspars are found in appreciable quantities (14% in average), while other minerals with lesser ratios (3%). Quartz percentages vary from 31% to 62% (Table 4). Commonly, due to the increase in aeolian activities during summer time, quartz percentages increase slightly with a drop in carbonates. Other minerals are mainly evaporites (bassonite, gypsum and anhydrite) increase toward coastal areas. The dust from Rub Al-Khali is dominantly quartz grains carrying on top of it adhering particles of feldspars, mica and carbonates (Figure 6c). The coastal dust samples such as Dubai show more carbonates and evaporites such as bassonite ($\text{CaSO}_4 \cdot 5\text{H}_2\text{O}$) (Figure 6d) and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) (Figure 6e). In contrast, dust particles from the Northern Desert of Africa composed of quartz with minute adhering particles of different minerals (Figure 6f).

Table 4. The XRD mineralogical semi-quantitative percentages of deposited dust in the coastal and open desert around the Arabian Gulf.

Sector	Area	Source	Quartz	Calcite	Dolomite	Carbonates	Feldspars	Clay	Others
Desert dust-Arabian Gulf									
Riyadh	Saudi	[37,38]	68	32	0	32	0	0	0
Walameen	Saudi	Present study	62	13	0	13	24	1	0
Doha	Qatar	Present study	48	21	7	28	24	0	0
Ain	Emirate	Present study	26	34	19	52	20	1	0
Desert	Kuwait	Present study	39	26	11	37	12	5	6
Coastal dust-Arabian Gulf									
Coastal	Kuwait	Present study	28	20	14	34	18	5	14
Ahwar	Iraq	Present study	36	30	11	42	8	5	9
Dubai	U.A.E	Present study	21	25	21	45	6	0	27
Manama	Bahrain	Present study	32	25	16	41	10	3	15
	Mean (Desert)		49	25	7	32	16	1	1
	Mean (Coastal)		29	25	16	41	11	3	16

3.4. BET Surface Area

BET surface area is a useful physical tool for determining the source areas of sediments [35]. The dust samples from the coastal areas which are dominantly affected by SDS trajectories from MFP, HZ, HR and BSH show notable variations when compared to the desert dust samples which mainly affected by trajectories from WD, NFD and EQ. The Ain dust surface area in mid of WQ shows low BET Surface area, while Kuwait coastal dust affected dominantly by MFP, HZ, HR trajectory shows the maximum values. The overall trend for upwind samples shows a slight decrease compared to downwind samples (Figure 7a). The BET surface area of dust particles varies with time with maximum values during October until March and lowest values during May (Figure 7b).

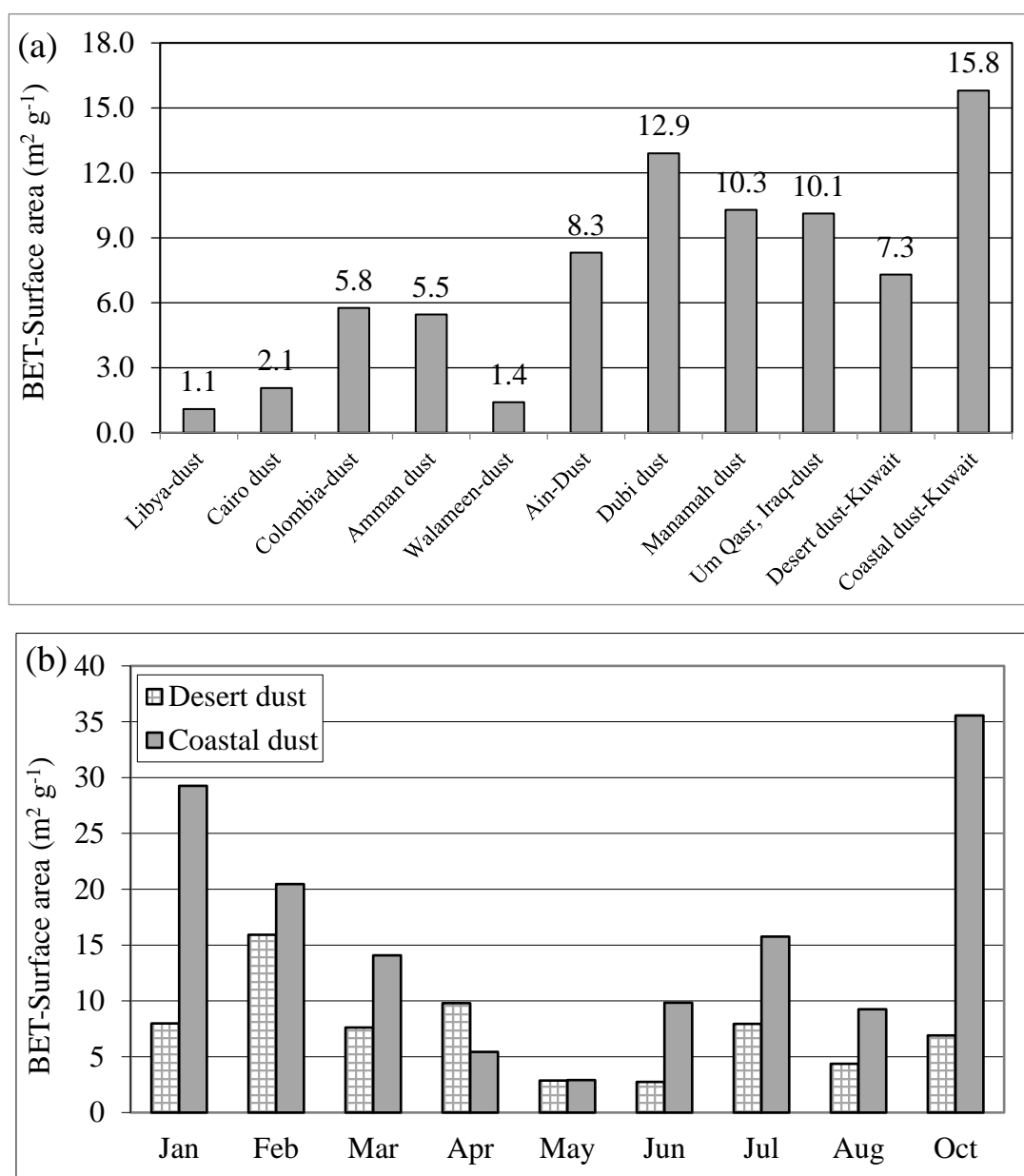


Figure 7. Spatial (a) and temporal (b) variations for Brunauer, Emmett, and Teller (BET)-Surface area values of collected from the desert and coastal dust samples in the Arabian Gulf compared to surrounding areas.

3.5. Summary

The fallen dust into the Arabian Gulf coastal regions are originated from MFP, HZ, HR and BSH and characterized by finer mean size fractions with trimodal particle size distribution, higher values of particles surface area and containing more carbonates and less quartz compared to dust deposited in terrestrial areas, which is dominantly originated from WD, NFD and EQ. Poor Quartz sediment are a characteristic of soil sediments in MFP, HR, HZ, and BSH areas, while quartz-rich coarse sediment found in WD, NFD and EQ [18,19]. Therefore, the physical and mineralogical properties of dust particles illustrate resemblances within coastal dust fallout samples in the Arabian Gulf, but with remarkable differences, if compared to deposited dust in terrestrial areas. In Kuwait at northern Arabian Gulf, the temperature data shows the overall positive rate of 4.7 degrees per century [39].

Regionally, a positive correlation was observed between annual and seasonal maximum temperature and dust storm frequency in Iran [40]. Therefore dust storms intensity and frequency in future decades are expected to be more. The hospital admissions in Iran [41] and Kuwait [42] for cardiovascular and respiratory diseases grew more with the increase in dust storms intensity and frequency in the Arabian Gulf and expected to rise in the future perspective. The socioeconomic effect of dust in Kuwait was noted in traffic accident rates, oil export loss due to close out of marine terminals, airlines delays and agricultural degradation [43]. Therefore, passive and active control measures should be applied in the region to minimize the negative effect of SDS.

4. Conclusions

The present study on SDS in the Arabian Gulf leads to the following conclusions:

- There are 8 major SDS trajectories were identified in the Arabian Gulf using satellite images and weather data.
- The dust storms trajectories were classified in accordance to shape and size into three major types namely, Extensive, Intermediate and Small dust storms with 12 subtypes in the region.
- The dust particles originated dominantly from SDS trajectories in WD, EQ and NFD are coarser, lower values of BET surface area, higher in quartz and low carbonate contents compared to dust from MFP, HZ, HR and BS.
- The very fine (V.F.S.) and fine (F.S.) sand grains (diameter above 0.063 mm) originate commonly from local sources representing around 58% of the average deposited dust ratios in desert areas, while it represents only 11% within coastal area of the Arabian Gulf.
- The deposited dust particles are fining towards the Arabian Gulf and getting coarser towards the desert areas.
- Quartz and carbonates are the main constituents of dust in the Arabian Gulf. Feldspars are found in considerable quantities, but it was observed that quartz percentages increases and carbonates decrease towards the desert area dust.
- Gypsum, anhydrite, bassanite and heavy minerals represent other minerals with 3% as minor components of dust.

The physical characterization of the trajectories of sand and dust storms in the Arabian Gulf, along with the mineralogical, grain size and BET analyses of the particles transported provide an integrated contribution toward indicating the environmental impact of such events, including the effect on agriculture, infrastructures and air quality. In particular, the grain size and mineralogical distribution of dust particles as a function of the different storm trajectories and source areas (from land to sea) are given here, with application to the Arabian Gulf. On the other hand, such integrated approach is applicable for characterizing sand and dust storms in other regions.

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