Dust Storms and Its Benefits to the Marine Life of the Arabian Gulf

Waleed Hamza

Abstract As a major source of atmospheric dust, the Arabian Peninsula contributes significantly to the nutrients supply for the marine ecosystem of the Arabian Gulf. It does this via dust deposited across the Gulf basin, mainly during the frequent local dust storm events. In addition to dust deposition, it appears that the Gulf ecosystem receives additional nutrients, especially Fe, P, and N, from other sources, such as upwelling of deep waters and recycling of old nutrients as well as through the discharge of sewage and salts from desalination plants. With an estimate of total average dust flux of 6.385 gm m^{-2} day^{-1}, for an average of 33 days per year, it is expected that the entire Gulf area (240,000 km^2) receives roughly 5.5×10^6 tons of dust per year, assuming 10% uniform deposition. The release of nutrients from the dust, e.g., by dissolution, within the marine ecosystem, depends on several factors, beginning with atmospheric photochemical reactions, acid rain dissolution, and microbial mineralization and recycling. Although dust storms contribute positively to the richness and diversity of living marine organisms in the Arabian Gulf, they also have a negative side. The dust may transport and release undesirable toxic metals that potentially inhibit algal growth and cause human respiratory diseases via inhalation of PM10 and PM2.5 particles. The dust also negatively affects agriculture and exacerbates desertification. It promotes the appearance of harmful algae blooms (HAB) that are responsible for massive fish kills and interruptions to the operations of desalination plants. Further studies on nutrients recycling, assimilation, and its pathways through the different trophic levels of the Gulf ecosystem are necessary to understand and quantify the net contribution of dust storms to the nutrient balance.

Keywords Arabian Gulf · Dust deposition · Nutrients recycling · Ecosystem responses

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W. Hamza (✉)
Department of Biology, College of Science, United Arab Emirates University, Al Ain, UAE
e-mail: w.hamza@uaeu.ac.ae

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1 Introduction

During the last few decades, interest in investigating the contribution of Sahara dust to marine productivity has increased considerably, especially where signs of marked increase of productivity have been noticed after dust storms precipitation, even under normally oligotrophic conditions, such as in the southeastern Mediterranean and the north Atlantic regions. A major aim of these studies has been the identification of the source of the dust and the path traveled from dust source to sink. Recent studies assisted by new technology (e.g., METEOSAT) have highlighted the Bodele Depression between Tibesti and Lake Chad as an important dust source region, together with a large swathe of territory covering portions of Mauritania, Mali, and southern Algeria (Herrmann et al. 1999; Prospero et al. 2002; Barkan et al. 2004; Mahowald et al. 2005). Other recent studies were concerned with the mineralogical composition and the major element characteristics in the atmospheric dust, as well as the effects of its deposition on both terrestrial and marine ecosystems. These studies have recognized atmospheric deposition of Sahara dust as a potential provider of trace elements of continental origin to marine areas. Of particular interest are the inputs of elements such as nitrogen (N), phosphorus (P), and iron (Fe), which are essential elements for the biological growth of marine living organisms (Prospero 1996; Paerl 1997; Guerzoni et al. 1999; Markaki et al. 2003; Jickells et al. 2005; Hamza 2008; Sunda 2012). The potential role of atmospheric deposition on the oceanic productivity is expected to be particularly important for oligotrophic oceanic areas (Herut et al. 1999; Migon et al. 2001; Ridame and Guieu 2002, Lekunberri et al. 2010; Guieu et al. 2014). It has been estimated that the leachable fluxes of inorganic phosphorus and inorganic nitrogen (dry + wet) can support between ~15 and ~70%, respectively, of new production in the southeastern Mediterranean, effective only following dust events.

Apart from classical nutrients such as nitrogen compounds (NO_3, NO_2, and NH_4) and phosphorus in the form of orthophosphate (PO_4), many researchers consider iron (Fe) to be the main stimulator of aquatic productivity. Martin et al. (1994) hypothesized that adding iron to water bodies rich in nutrients, but low in chlorophyll content, would significantly boost primary productivity. Many large-scale iron-fertilization experiments have been carried out to test this hypothesis, and indeed a positive relation between dissolved-iron input into the ocean and planktonic blooms can be demonstrated (de Baar et al. 2005; Boyd et al. 2007). Although these studies have focused on quantifying the nutritive contribution of Sahara dust to marine productivity, their results are based on theoretical calculations and satellite image approximations. Previous studies have not measured the nutritive contribution in situ nor have they explained how these elements can be quantified within a natural ecosystem food web. Furthermore, these studies were restricted to particular areas, such as the northern Atlantic and Mediterranean regions.

Previous studies have barely touched upon other regions with high dust storms intensities, such as the Arabian Peninsula, despite their role as major sources of dust (Goudie and Middleton 2001; Miller et al. 2008; Hamza et al. 2011; Sissakian et al.

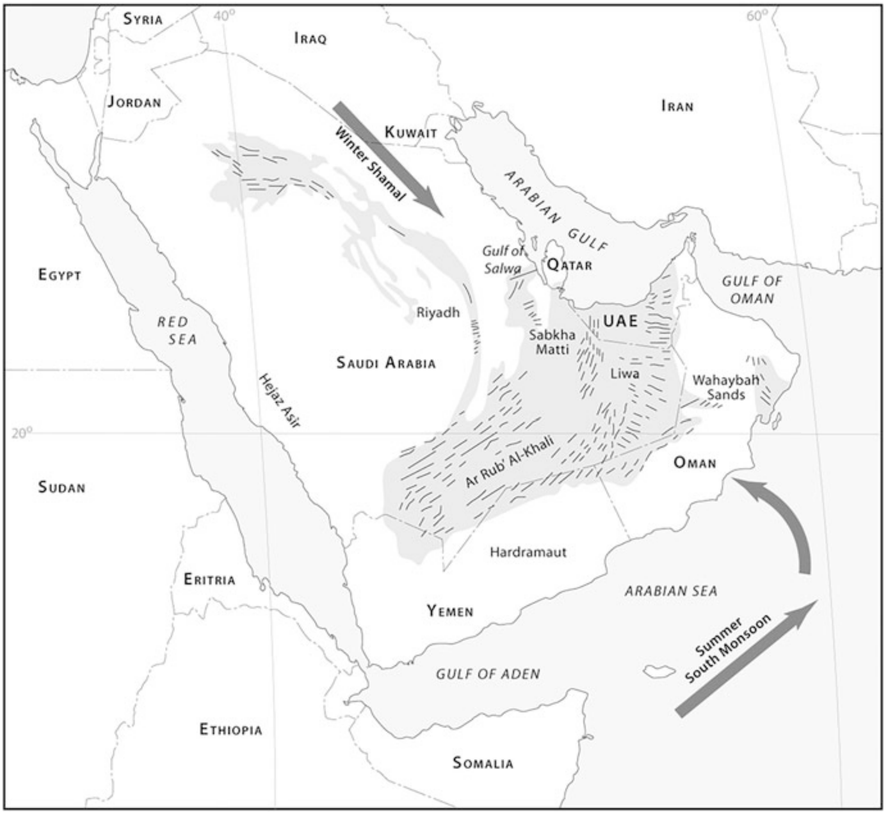

Fig. 1 Map of the major seasonal wind trajectories blown over the Arabian Peninsula [modified from Glennie (2005)]

2013). The Arabian Peninsula is one of the largest desert areas in the world, characterized by regional dune fields, arid conditions, and monsoon winds. Dust storms over the area are triggered by strong monsoon winds during spring and summer seasons (March–August). During these events the characteristics and transport paths of the airborne sand particles vary according to wind strength and wind directions. Substantial quantities of the storm sand loads are carried over the Arabian Gulf basin and the Gulf of Oman (Fig. 1). An important factor, during these events, is the intensive rain periods that develop, despite warm conditions (35–45 °C), wherein sand particles act as nuclei for condensation of evaporated water. These precipitations are responsible for the wet deposition of high quantities of dry dust suspended in the atmosphere over the aquatic bodies of the Arabian Gulf and the Gulf of Oman (Foda et al. 1985). Recent publications on the productivity of the Arabian Gulf ecosystem have indicated that the basin is very productive and highly diversified (Hamza and Munawar 2009), despite the limited nutrients it receives from land sources and intermittent river discharges into its basin (Reynolds 1993).

These findings support the hypothesis that dust deposition may be a major nutrient contributor, capable of sustaining the ecosystem productivity of the Arabian Gulf and the linked Oman Gulf basin.

2 Dust Storms over the Arabian Gulf

2.1 Data Collection and Analyses Results

Collective studies involving dust storm deposition across the entire the Arabian Gulf within a single research project between the Gulf countries are absent. However, scientists from the region in collaboration with international researchers have carried out different studies in various locations in separate years within the past decade. In their study, Miller et al. (2008) intensively studied dust storms over the southeastern Arabian Peninsula in the summer of 2004 by means of a large assortment of satellite, radar, lidar, and meteorological station network observations. The aim of their study was to understand and interpret dust storm evolution and out flow interactions. Their results were limited to the period August–September, 2004, and to the United Arab Emirates (UAE) territory and were analyzed quantitatively to conclude that the storm fronts in the studied period produced 15 min mean wind speed increases of 10 ms^{-1}, pressure rises of 2 mb, humidity increases of 15%, and temperature drops of 7 °C. By computing the dust events of 15 days within the studied period, they found that there were occasions when enhanced dust storm activity could account for a significant component of regional transportable aerosol mass up to one-third over the 1000 × 1000 km domain.

In another study, Sissakian et al. (2013) investigated the sand and dust storm events in Iraq with the aim of distinguishing regional from local sand and dust events. Their study mainly depended on an overview of meteorological data at different locations in Iraq from 1951 until 1990, though they did not link it with other parameters. However, they concluded that regional sand and dust events extend outwards from Iraq territory in different directions, but usually cover Syria and cross towards Kuwait and Saudi Arabia and/or towards the Arabian Gulf.

On the other hand, numerical modeling of dust storms in the Arabian Peninsula ws performed by Prakash et al. (2015) to simulate 1 of the 15–20 dust storms that occur annually in the studied area. The storm occurred from 18 to 20 March 2012. The results showed that a southward propagating cold front caused the storm, and the associated winds activated dust dispersal in river valleys of the lower Tigris and Euphrates in Iraq, the coastal areas in Kuwait, Iran and the United Arab Emirates, and the Rub al Khali, An Nafud, and Ad-Dahna deserts. The model results estimated the total amount of dust generated by the storm to reach 94 million tons (Mt). Approximately 78% of this dust was deposited within the calculation area. The Arabian Sea and the Arabian Gulf received 5.3 Mt. The authors indicated that dust particles bring nutrients to the marine ecosystems; however they were not able to estimate its contribution to the nutrient balance of the Arabian Gulf.

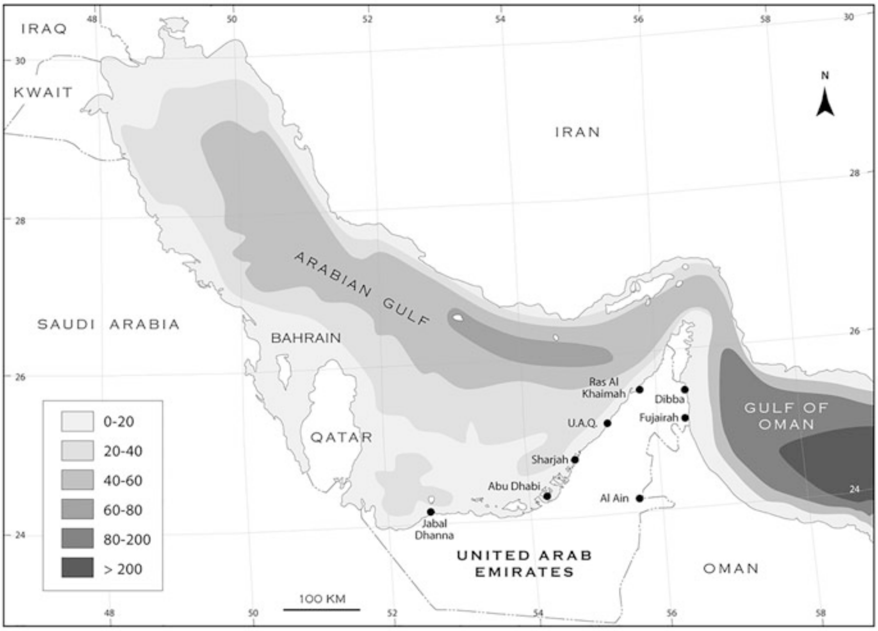

Fig. 2 Map of the Arabian Gulf, indicating the sampling stations (•) along the UAE coast (modified from Hamza et al. (2011)]

A more comprehensive study that involved a 1-year dust sampling program from eight sampling stations distributed along the coastal area of UAE and Oman (Fig. 2) was completed in 2009 (Hamza et al. 2011). The study made use of historical meteorological data (2004–2008) and satellite imagery with the aim of quantifying levels of dust deposition over the coastal areas of UAE, during a 1-year period, and to characterize the deposited dust particles mineralogically and determine their trace metals content. The study also involved collection of ground samples from the major sand dunes in the Al Rub Al Khali (Empty Quarter area), which is located in the eastern part of Saudi Arabia, bordering the southern area of the UAE, close to Al Ain City. The mineralogy of the sand dune sediments was compared to that of the dust samples collected from coastal stations. Dry or wet dust samples were collected at coastal stations each 15 days by an automatic Andresen dry and wet acid rain sampler (Fig. 3). In the event of a dust storm, samples were taken immediately after the end of the storm.

The results of the aforementioned study have led to the development of a “dust storm intensity index” based on horizontal visibility rather than wind velocity. When wind velocity is strong, sand and dust particles are transported by the wind, but with minimum reduction in wind velocity, the sand particles are deposited rapidly, while fine particles remain suspended and transported to farther distances, even with moderate wind. The horizontal visibility may not improve, even after the wind has ceased, because finest particles remain suspended in the air, to be later deposited as

Fig. 3 An Automatic Andresen dry and wet acid rain sampler installed at a coastal station of UAE

an aerosol attached to water condensate. The intensity index ranges in value from 1 to 4. An index equal to 1 refers to horizontal visibility of 0 to 499 m, while index $x = 4$ categorizes a storm with horizontal visibility ranging from 1500 to 2000 m (Hamza et al. 2011). Comparison of historical meteorological data and dust storm events during 2004–2008 with those of 2009 in Abu Dhabi (UAE) area shows an intensification of dust storms during 2008 and 2009 relative to previous years (Fig. 4).

X-ray diffractometry (XRD), used for mineralogical analysis of the dust source samples (Al Rub Al Khali dunes), shows differences in mineral content between these dunes and the coastal dust samples during both summer and winter seasons (Tables 1 and 2). This points to the influences of anthropogenic emissions and the photochemical properties of the atmosphere (Shahsavani et al. 2012) on dust particle composition.

During the summer months of this study, the rate of dust deposition ranged between 2.65 and 21.31 gm m^{-2} day^{-1} with an average of 9.34 gm m^{-2} day^{-1}. During rainy months, the rate of dust deposition ranged between 1.34 and 7.61 gm m^{-2} day^{-1} with an average of 3.43 gm m^{-2} day^{-1}. On annual bases, this data yielded an overall estimate of daily deposition of 6.386 gm m^{-2} assuming an average of 33 days of dust storms per year for the entire Gulf area (240,000 km^2). This amounts to roughly 5.5×10^6 tons of dust per year being deposited on the Gulf

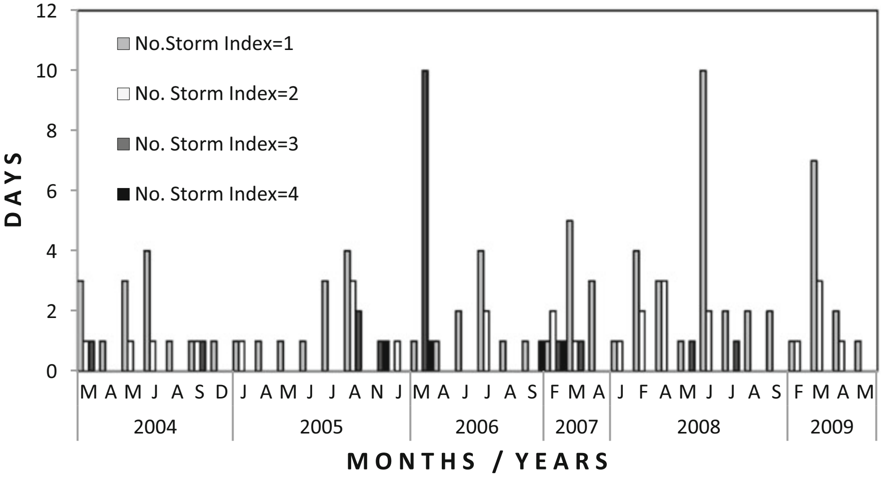

Fig. 4 Dust Storms strength indices and its frequencies over Abu-Dhabi coastal area during the period 2004–2009 [modified from Hamza et al. (2011)]

waters, assuming a 10% uniform deposition. This is quite similar to the 5.3 Mt. estimates by Prakash et al. (2015) for the same area.

XRF analyses of the dust for chemical elements of major interest in fertility of the Gulf water (iron, phosphorus, and nitrogen) show that iron content is lower in desert dune samples (average 3.12%) than in coastal dust samples collected during both summer and winter seasons (averages 10.96% and 8.45%, respectively). Phosphorus was virtually undetectable (0%) in the dune sand samples SS1 and SS2 (Table 3), while considerable amounts were detected in both summer and winter seasons in coastal dust samples (average 0.34 mg l^{-1}). Nitrogen as nitrate NO_3 was also detected in some coastal samples during dust storms that occurred in winter months. Other trace elements such as aluminum (Al) and sulfur (S) show higher values in coastal dust samples than to the inland dune samples (Tables 3 and 4). These findings confirm the availability of nutritive elements within the atmospheric dust deposited over the marine environment of the Arabian Gulf, mainly during dust storms. More recent and similar studies conducted within the region during the period 2014–2016 (unpublished data) have produced similar results.

2.2 *Dust Fertilization of the Arabian Gulf Marine Ecosystem*

Previous studies have concluded that the Arabian Gulf is very productive and has a high level of biodiversity (Hamza and Munawar 2009). Figure 5 shows the relations between sea-bottom type and fishing grounds in the Arabian Gulf.

Table 1 XRD-Mineralogical analysis of dust samples collected from the different stations along the UAE coastal area during summer months (May and August, 2009)

		XRD results (passive dry dust)		
Site	Date	Major mineral(s)	Subordinate mineral (s)	Minor mineral(s)
Abu Dhabi	05/09	Quartz (SiO_2), Calcite ($CaCO_3$)	Plagioclase ($CaAl_2Si_2O_8$)	Dolomite ($CaMg(CO_3)_2$)
	08/09	Quartz (SiO_2), Calcite ($CaCO_3$)	–	Plagioclase ($CaAl_2Si_2O_8$), Dolomite ($CaMg(CO_3)_2$), Clay Minerals, Serpentine ($Mg_3Si_2O_5(OH)_4$
Fujairah	05/09	Quartz (SiO_2), Calcite ($CaCO_3$)	Plagioclase ($CaAl_2Si_2O_8$), Amphibole($Ca_2(Mg, Fe)_5Si_8O_{22}(OH)_2$)	Serpentine ($Mg_3Si_2O_5(OH)_4$, Talc ($Mg_3Si_4O_{10}(OH)_2$
	08/09	Quartz (SiO_2), Calcite ($CaCO_3$)	Plagioclase ($CaAl_2Si_2O_8$)	Serpentine ($Mg_3Si_2O_5(OH)_4$, Dolomite ($CaMg(CO_3)_2$), Amphibole ($Ca_2(Mg, Fe)_5Si_8O_{22}(OH)_2$), High Magnesium Calcite ($CaMg\ (CO_3)$), Olivine? ($(Mg, Fe)_2SiO_4$)
Dibba	05/09	Pyroxene ($CaMg(Si, Al)_2O_6$),	–	Plagioclase ($CaAl_2Si_2O_8$), Talc ($Mg_3Si_4O_{10}(OH)_2$
	08/09	Pyroxene ($CaMg(Si, Al)_2O_6$), Feldspar	–	Serpentine ($Mg_3Si_2O_5(OH)_4$, Dolomite ($CaMg(CO_3)_2$)
U.A.Q	08/09	Quartz (SiO_2)	Calcite ($CaCO_3$)	Dolomite ($CaMg(CO_3)_2$)
Jebel Al-Dhanna	05/09	Quartz (SiO_2), Aragonite ($CaCO_3$)	Plagioclase ($CaAl_2Si_2O_8$)	Dolomite ($CaMg(CO_3)_2$), Hematite (Fe_2O_3)
	08/09	Quartz (SiO_2), Calcite ($CaCO_3$)	Dolomite ($CaMg\ (CO_3)_2$), Plagioclase ($CaAl_2Si_2O_8$)	Serpentine ($Mg_3Si_2O_5(OH)_4$, Pyroxene ($CaMg(Si, Al)_2O_6$), Gypsum ($CaSO_4 2H_2O$), Halite ($NaCl$), Hematite (Fe_2O_3)
SS1*		Quartz (SiO_2)	Calcite ($CaCO_3$)	Plagioclase ($CaAl_2Si_2O_8$), Dolomite ($CaMg(CO_3)_2$), Clay Minerals, Serpentine ($Mg_3Si_2O_5(OH)_4$
SS2*		Quartz (SiO_2), Calcite ($CaCO_3$)	–	Plagioclase ($CaAl_2Si_2O_8$), Dolomite ($CaMg(CO_3)_2$), Clay Minerals

SS1* = Source Sample 1, SS2* = Source Sample 2 [modified from Hamza et al. (2011)]

Table 2 XRD-Mineralogical analysis of dust samples collected from the different stations along the UAE coastal area during winter months (January–March 2009)

		XRD of wet samples		
Site	Date (mm/yy)	Major mineral(s)	Subordinate mineral(s)	Minor mineral(s)
U.A.Q	01/09	Calcite ($CaCO_3$)	Tale ($Mg_3Si_4O_{10}(OH)$)	Plagioclase ($CaAl_2Si_2O_8$), Dolomite ($CaMg(CO_3)_2$), Serpentine ($Mg_3Si_2O_5(OH)_4$, Clay Minerals
	03/09	Pyroxene	–	Iron Oxides
Abu Dhabi	03/09	Calcite ($CaCO_3$), Quartz (SiO_2)	Plagioclase ($CaAl_2Si_2O_8$), Dolomite ($CaMg(CO_3)_2$)	Clay Minerals, Iron Oxides, Serpentine ($Mg_3Si_2O_5(OH)_4$, Talc ($Mg_3Si_4O_{10}(OH)_2$
Dibba	03/09	Pyroxene	Olivine (Mg, Fe, Silicate)	–
Fujairah	02/09	Plagioclase ($CaAl_2Si_2O_8$), Calcite ($CaCO_3$), Quartz (SiO_2)	–	Serpentine ($Mg_3Si_2O_5(OH)_4$, Clay Minerals

Modified from Hamza et al. (2011)

This figure clearly illustrates that the waters above the sandy bottom in the Arabian Gulf are characterized by highest levels of primary productivity, while those above fine-grained bottoms are poor in marine life. One probable reason for the sandy sediments correlating with high primary productivity is that these seafloor sands are likely to have been derived from windblown sands, especially in the southern area of the Gulf, as shown in Fig. 1. The area of high marine productivity is clearly identifiable in satellite images of the region (Fig. 6).

The hypothesis that high primary productivity in the Arabian Gulf is strongly related to the dust, and the metals and nutrients it carries, has never been confirmed by direct field measurements or in experimental findings. However, laboratory experimental results have shown that there is an enrichment of *Chlorella vulgaris* cultures after having been exposed to elements leached from dust released into distilled water by autoclaving dust samples collected along the Arabian Gulf coastal area during dust storms. The growth rate of the cultures increased by about 50% compared to control cultures (Hamza 2008). These bioassay studies were recently repeated based on dust samples collected from other locations along the coastal areas of the UAE, including comparison with dust samples collected from inland areas during the same period. The results were apparently contradictory (unpublished data) as explained below. The enrichment of the *Chlorella* cultures with similar amounts of leached elements from dust of both locations (coastal and inland) boosted culture growth in the first 10 days, compared to the control. The leached elements from the inland dust samples were efficient in maintaining high growth rates for >25 days, compared to the control; however, the leached elements from the coastal samples were not able to support the same continuity of growth of the

Table 3 XRF-elemental analysis (%) of dust samples collected from the different stations along the UAE coastal area during summer months (May and August, 2009)

Location	Abu Dhabi		J. Al-Dhanna		Dibba		Fujairah		U.A.Q		SS1*	SS2*
Date (mm/yy)	05/09	08/09	05/09	08/09	05/09	08/09	05/09	08/09	05/09	08/09		
Si	33.64	31	16.2	22.6	21.7	27.2	29.8	27.2	–	28.5	57.8	37.35
Ca	48.2	51.2	71.7	38.1	46.2	40.7	39.23	36.96	–	35.75	28	51.2
Al	5.39	4.92	2.37	7.25	5.47	6.45	8.25	8.25	–	5.01	3.43	2.6
Mg	4.3	4.44	2	4.52	9.88	10.5	8.03	8.39	–	3.2	3.12	2.17
Fe	5.37	5.23	2.11	10.2	10.9	9.6	13.4	13.4	–	18.5	3.14	3.1
Cl	0.341	0.285	1.68	4.04	1.76	1.32	1.16	2.25	–	1.93	0	0.11
S	0.24	0.44	0.598	7.01	2.05	2.48	0.985	1.63	–	3.85	0.764	0
Sr	0.184	0.185	1.97	0.135	0.154	0	0	0.19	–	0	0.132	1.4
K	2.33	2.18	1.26	2.99	1.71	1.57	1.23	1.16	–	3.26	0.114	0.17
Na	0	0	0	3	0	0	0	0	–	0	3.49	1.9
P	0	0.146	0.125	0.197	0.218	0.206	0.565	0.565	–	0	0	0

SS1* = Source Sample 1, SS2* = Source Sample 2 [modified from Hamza et al. (2011)]

Table 4 XRF-Mineralogical analysis (%) of rain filtered dust samples collected from the different stations along the UAE coastal area during winter months (January–March, 2009)

Location	Abu Dhabi	U.A.Q		Dibba	Fujairah
Date	03/09	01/09	03/09	03/09	02/09
Si	22.6	30	28.2	31.9	42.3
Ca	56.3	42.03	37.9	34	21.1
Al	4.1	7.66	8.13	9.27	12.2
Mg	4.0	5.09	7.68	8.88	9.16
Fe	9.29	5.9	9.55	11	6.54
Cl	0.936	0.471	0.193	0.323	0.109
Na	0.0	1.3	0.0	0.0	2.54
S	0.13	1.12	0.273	0.128	0.38
Zn	0.0	2.2	3.74	1.44	2.78
Zr	0.0	0.124	0.073	0.062	0.08
Sr	0.287	0.0	0.0	0.0	0.0
K	2.21	2.9	2.63	2.79	2.49
Cu	0.0	0.0	1.36	0.0	0.0
Ni	0.0	0.0	0.0	0.0	0.175
P	0.148	1.2	0.273	0.179	0.118

Modified from Hamza et al. (2011)

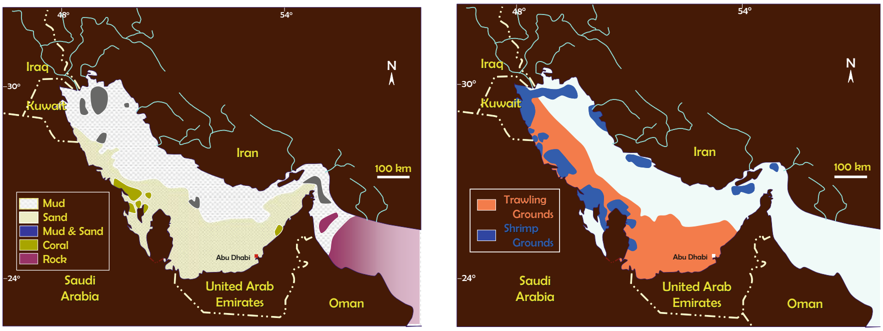

Fig. 5 Relations between bottom type (Left) and Fishing Grounds (Right) in the Arabian Gulf [modified from Al-Majed et al. (2000, pp. 29, 88)]

cultures. The analyses of the leached elements show concentrations of aluminum and sulfur in the coastal samples are almost 5 times higher than in the inland samples. To make sense of these observations, we suggest that, although trace elements are important to the growth of phytoplankton, an excess of them may inhibit the growth of some, if not all, phytoplankton species. It is also confirmed that the dust quality and its composition can vary significantly, depending on its original sources and on the atmospheric components through which it passes.

This leads to a further hypothesis that dust storms may help or hinder primary productivity of marine environment depending on the quantity and the quality of

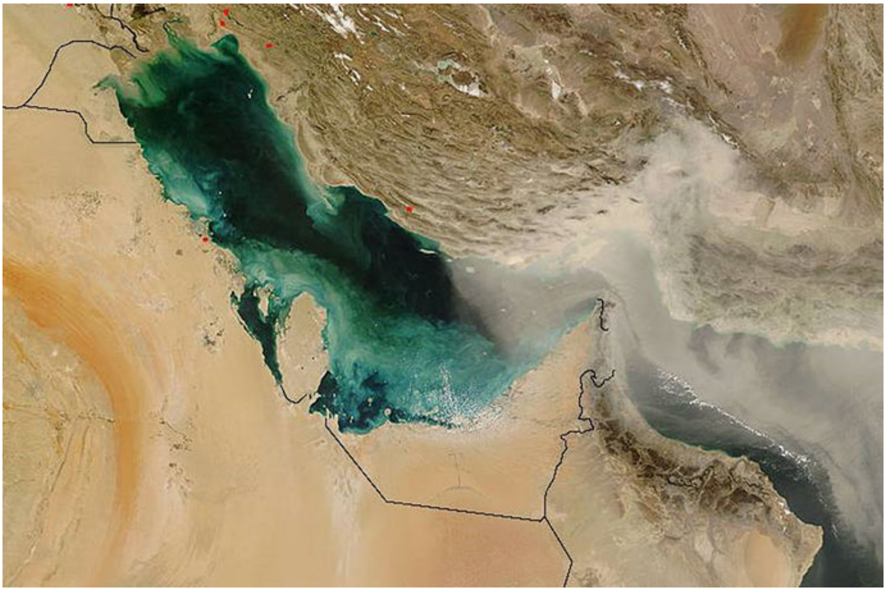

Fig. 6 Satellite image of the region showing high amounts of chlorophyll in the Gulf (turquoise colors) as evidence for high primary productivity. In addition, suspended Aeolian dust (light-brown colors, best visible above water) is present in the atmosphere. Image courtesy of NASA's earth observatory

both stimulator and inhibitor elements they transport and deposit. Here it is important to consider both photochemical, diagenetic, and microbial roles in reducing, synthesizing, and recycling such elements within the marine ecosystem. It has been mentioned that metals and nutrients (especially phosphate) are only released in the period between deposition of the sediments and exposure to early diagenetic processes, e.g., anoxic conditions, that leading to metal reduction. Metal reduction may be biologically driven or occur abiotically with sulfide. The consequence of these reductive processes is an increased solubility of the metals and associated phosphates. Upon transport to the photic zone, these compounds are available for primary production, the base of the food chain for the entire ecosystem. Sandy sediments have a lower organic content than fine-grained sediments but are increasingly recognized as the more biologically active. This is because transport is facilitated by the coarse grain-size and the high porosity, allowing advective transport of the sands by currents, tides, and waves (Huettel et al. 1996, 1998; de Baar et al. 2005). Metals reduced in coarse-grained sediments indeed quickly reach the sediment surface (Huettel et al. 1998). It has been shown that not only dissolved substances are very rapidly exchanged between water column and the sediments, but also that particulate matter is efficiently filtered from the seawater by coarse sediments (Rusch and Huettel 2000). The enhanced release of nutrients and metals could well explain the observed high primary production rates of sandy intertidal flats of the Arabian Gulf (Billerbeck et al. 2007).

Still, the importance of microbial activities in the ecosystem cannot be easily estimated. Marine microbial primary production normally exceeds, or is of the same order of magnitude as, that of the higher plants (Fuhrman and Azam 1980; Cahoon 1999; Dubinsky and Berman-Frank 2001; Jassby et al. 2002; van Beusekom 2005; Spilmont et al. 2006). Microbial phototrophs can very quickly respond to nutrient changes. It has been reported that in shallow coastal waters, benthic productivity exceeds pelagic productivity, depending on the light penetration (Cahoon 1999). In the Arabian Gulf, benthic photosynthesis will be dominant over pelagic productivity. Rates of primary productivities are not necessarily coupled to high nutrient levels in the environment. The availability of nutrients for the phototrophs is also important. The ecological cycle must be considered, including the release of nutrients from decaying biomass, where the mineralization process is controlled by a large diversity of microbial processes, leading to an almost complete degradation into CO_2, nutrients, and trace elements. Biomass penetrates rapidly into permeable sediments, where it is degraded by aerobic and anaerobic processes (Rusch and Huettel 2000; Rasheed et al. 2003a, b; Billerbeck et al. 2007). The most rapid mineralization occurs with oxygen as the electron donor. In marine environments sulfate reduction can account for ca. 50% of the total mineralization; however, this process is much slower. Oxygen penetrates more easily into permeable sediments; thus mineralization rates are higher in sands than in muds. Moreover, nutrients, especially Fe, ammonium, and phosphate, bind strongly to clays, making them inaccessible to both benthic and pelagic phototrophs. Consequently, benthic productivity of sands is higher than of similarly illuminated muddy sediments in the same habitat. Obviously, primary production is at the base of the food chain, which explains why sand bottoms form more productive fishing areas. It is for this reason that the biogeochemistry of the sediments of the Arabian Gulf is the cornerstone of its ecosystem fertilization. Large parts of the nitrogen cycle are entirely driven by prokaryotes, e.g., nitrification, nitrogen fixation, and denitrification.

In the Arabian Gulf, dust may well be an important source for nutrients, especially phosphates and Fe. As phosphates bond well to oxidized iron, fertilization of the Gulf waters by dust involves a cycling through the sediments, so that only in places where Fe-oxides are reduced are Fe and phosphate available for assimilation. While it is essential to study the effects of experimental nutrient additions on the productivity, the effects of dust on the primary productivity can only be understood from the sum of the processes that make nutrients, including Fe, available in excess of the inhibitory effects of other parameters.

2.3 Impacts of Dust Fertilization on Health, Economy, and Biodiversity of the Arabian Gulf

There are negative consequences of dust storms to human health and agriculture, for example, the 1930–1940 dust storms were economically and environmentally disastrous to American and Canadian prairie lands, leaving millions of acres of farmland useless and displacing hundreds of thousands of agriculture workers (Gosh and Pal 2014). Moreover, fine particles known as PM 10, PM 2.5, and PM 1 are responsible for acute respiration problems that may lead to death for many people worldwide. In their study, Shahsavani et al. (2012) reported an increase of PM concentrations during a dust storm period of 5 days in July 2008 in the Ahvaz region of Iran, which was responsible for 1131 deaths and morbidity in 8157 cases. In contrast, aquatic ecologists view dust storms and their deposition as a source of enrichment to the marine ecosystems that supply nutrients sufficient to maintain sustainable productivity of the marine food web, especially in major fisheries.

A pertinent question is *how quickly does primary production increase upon dust deposition and what is the effect of dust on the composition and abundance of primary producers in the Arabian Gulf?* Although there is no definite calendar or numeric answer to this question, there are evidences and events that can help to reach a tentative estimate for forward modeling. In their study, Shahsavani et al. (2012) found that Saudi Arabia was the primary source of dust events in the region and that the Ahvaz region appeared to be influenced by similar dust storms during summer seasons. They also mentioned that the most severe recorded dust event occurred during summer 2008, which caused the closure of industrial and educational centers and led to thousands of hospital admissions for cardiovascular and respiratory ailments. They expressed concern that, despite its importance, these dust storms have not been studied, and questions remain about many aspects of this phenomenon. At the same year, 2008, patches of red water were first observed in the port of Dibba al Hassan on the east coast of UAE in late August (Zhao and Ghedira 2014). Nearly 2 months later (21–23 October, 2008), red tide blooms, and fish kills were observed in the same location (Fig. 7).

The bloom subsequently entered the Arabian Gulf through the Straits of Hormuz, spreading to coastal waters of the UAE, Qatar, and Iran. It also spread southwards along the east coast of UAE to Fujairah and thence to the south of Oman. The bloom was remarkable in its immensity, affecting more than 1200 km of coast line in the region and causing massive mortalities of wild and farmed fish, as well as extensive coral reef damage. Near Fujairah, UAE, the cell count of the dinoflagellate species (*Cochlodinium polykrikoides*) causing the event was 1.1–2.1 × 10^7 cells/L, recorded in October 2008 from surface waters (Zhao and Ghedira 2014; Richlen et al. 2010). In linking the two events in the Ahvaz region and the Arabian Gulf, it raises the possibility that the red tide phenomenon was a result of the dust storms that spread from the southeastern part of the Arabian Peninsula at the beginning of August. In fact, the study completed by Hamza et al. (2011), and the analyses of the historical meteorological parameters, confirms the expected direction of transport of the dust (Fig. 8a–c). Moreover, the developed storm intensity indices show that in 2008 the storm intensity was very high, with a visibility index ranging from levels 1 to 2 (Fig. 8a–c).

On the other hand, the first appearance of the reddened water was recorded off the east coast of UAE, i.e., in the waters of the Gulf of Oman. According to the dust storm scheme shown in Fig. 1, the dust carried over the Arabian Gulf during summer

Fig. 7 Fish kill phenomenon along the coastal area of UAE (Source; Etihad local daily Newspaper-in Arabic, March 2009)

was a result of the monsoon wind that crossed the Arabian Gulf and reached as far as the Iranian coastal area. The initiation of the red tide phenomenon in the Gulf of Oman in late August 2008 suggests that a portion of the windblown sand and dust was deposited on Omani waters at the beginning of the storm. The Omani Gulf has relatively greater water depth (Fig. 2) compared to the Arabian Gulf, and its coastal area is rich in coral reefs. On its sandy seafloor are nutrient mineralizations that enhance the algae blooms. The significance of these events is that it took as little as 2–3 weeks (15–21 days) for a red tide to develop following a dust storm that deposited sand and dust from the inland into the nearest water body (Gulf of Oman, in this case). The red tide phenomenon of August 2008 in the Gulf extended until August 2009 (Zhao and Ghedira 2014) and incurred much economic loss. It is interesting that the nutrient concentrations in the Gulf were able to support this bloom for such a long period, though with declining strength. Upwelling phenomenon is known to be a source of nutrients supply to the marine ecosystem in the Arabian Gulf. These are in addition to the discharge of high concentrations of nutrient salts from desalination plants, sewage treatment plants, and fertilizers industries.

The red tide phenomenon and the presence of Harmful Algae Blooms (HAB), in the Arabian Gulf, that has resulted from the discharge of ballast water from oil tankers in the Arabian Gulf are a persistent problem (Hamza 2006). These blooms are a burden on the economies of the Gulf countries, such as in 2008–2009, when they temporarily stopped desalination plant operations and fishing activities were suspended. The issue of algal blooms shows a negative side of the dust fertilization of the Arabian Gulf. The dominant feature of the Gulf marine environment is its rich

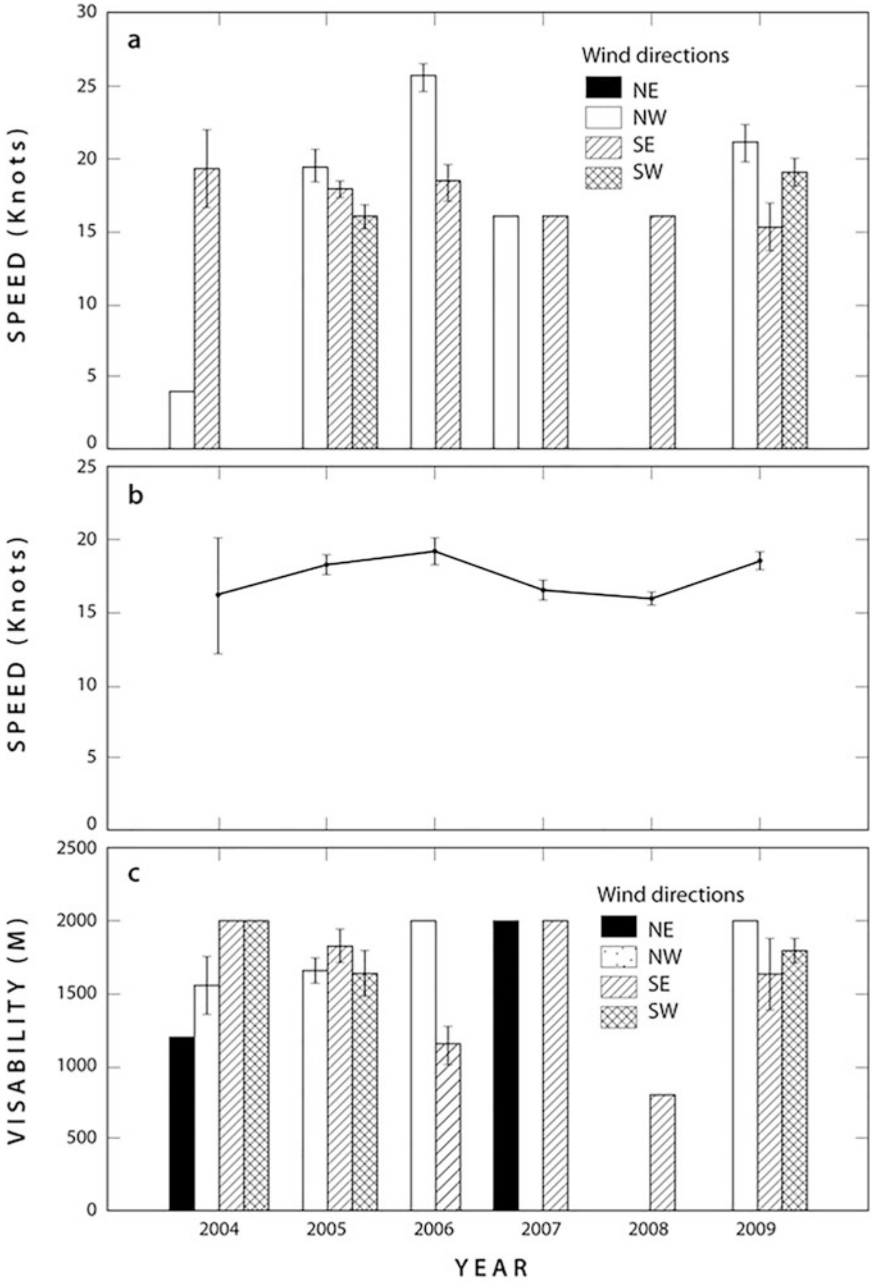

Fig. 8 (**a**–**c**) Results of Statistical ANOVA of wind speeds, directions and horizontal visibility during 2004–2009 [modified from Hamza et al. (2011)]

biodiversity and high productivity, which is in part owed to dust storm deposits and the consequent nutrient enrichment of its environment.

In conclusion, it appears that wind components are an important factor controlling not only visibility level but also composition and depositional rate of dust over the Arabian Gulf basin. Relevant surface features, mainly the Empty Quarter sand dunes (Rub Al-Khali) and the Oman Mountains, may contribute to the mineralogical composition of the deposited dust. The high iron (Fe) percentages in the coastal dust samples, relative to the source samples, could be a result of soil mineral particles of natural and agricultural areas raised up during the dust storms. Rainwater in the Gulf area is scarce; however, mixing with high sulfur concentrations in the atmosphere, due to the oil industry, may make it acidic enough to dissolve other minerals such as iron-bearing ones. Results obtained from rainwater analyses and autoclaved rainwater-dust laboratory experiments confirm the significant contribution of elements such as nitrogen, phosphorus, and iron, via dust storms, to the marine ecosystem of the Arabian Gulf. Furthermore, the Arabian Gulf ecosystem appears to receive additional nutrients, especially Fe, P, and N, from other sources, such as upwelling of deep waters and recycling of old nutrients and through the discharge of sewage and desalination plants. With an estimate of total average dust flux of 6.385 gm m^{-2} day^{-1}, for an average of 33 days per year, over the entire Gulf area (240,000 km^2), a rough estimate gives about 5.5×10^6 tons of dust per year deposited on Gulf waters, assuming a 10% uniform deposition. This calculation probably underestimates the actual flux. Dust storms make a positive contribution to the richness of diversity of living marine organisms in the Gulf; however, they also have a negative side, on human health (represented by respiratory system diseases), on agriculture (by increasing desertification), on marine life (promoting HABs leading to massive fish kills), and on water supplies (HAB interruptions to desalination plant operations). It is recommended that further studies be directed towards (1) investigation of the detailed dust nutrients pathways within the different trophic levels of the marine ecosystem of the Arabian Gulf; (2) the role of microbial communities in recycling nutritive elements, and (3) how some trace elements in dust deposits slow down and/or accelerate marine productivity.

References

Al-Majed N, Mohammadi H, Al-Ghadban A (2000) Regional report of the state of the marine environment. Regional organization for the protection of the marine environment (ROPME)

Barkan J, Kutiel H, Alpert P (2004) Climatology of dust sources in North Africa and the Arabian Peninsula, based on TOMS data. Indoor Built Environ 13(6):407–419

Billerbeck M, Røy H, Bosselmann K, Huettel M (2007) Benthic photosynthesis in submerged Wadden Sea intertidal flats. Estuar Coast Shelf Sci 71:704–716

Boyd PW, Jickells T, Law CS, Blain S, Boyle EA, Buesseler KO, Coale KH, Cullen JJ, de Baar HJW, Follows M, Harvey M, Lancelot C, Levasseur M, Owens NPJ, Pollard R, Rivkin RB, Sarmiento J, Schoemann V, Smetacek V, Takeda S, Tsuda A, Turner S, Watson AJ (2007)

Mesoscale Iron enrichment experiments 1993–2005: synthesis and future directions. Science 315:612–617

Cahoon LB (1999) The role of benthic microalgae in neritic ecosystems. Oceanogr Mar Biol Annu Rev 37:47–86

de Baar H, Boyd PW, Coale KH, Landry MR, Tsuda A, Asmmy P, Bakker DCE, Bozec Y, Barber RT, Brzezinski MA, Buesseler KO, Boyé M, Croot PL, Gervais F, Gorbunov MY, Harrison PJ, Hiscock WT, Laan P, Lancelot C, Law CS, Levasseur M, Marchetti A, Millero FJ, Nishioka J, Nojiri Y, van Oijen T, Riebesell U, Rijkenberg MJA, Saito H, Takeda S, Timmermans KR, Veldhuis MJW, Waite AM, Won C-S (2005) Synthesis of iron fertilization experiments: from the iron age in the age of enlightenment. J Geophys Res 110:24

Dubinsky Z, Berman- Frank I (2001) Primary production and population growth in photosynthesizing organisms in aquatic ecosystems. Aquat Sci 63:4–17

Foda MA, Khalaf FI, Al-Kadi AS (1985) Estimation of dust fallout rates in the northern Arabian gulf. Sedimentology 32:595–603

Fuhrman JA, Azam F (1980) Bacterioplankton secondary production estimates for coastal waters of British Columbia, Antarctica, and California. Appl Environ Microbiol 39:1085–1095

Glennie KW (2005) The desert of Southeast Arabia. Gulf Petrolink Publish (Manama-Bahrain kingdom)

Gosh T, Pal I (2014) Dust storms and its environmental implications. J Eng Comput Appl Sci 3 (4):30–37

Goudie AS, Middleton NJ (2001) Saharan dust storms: nature and consequences. Earth Sci Rev 56:179–204

Guerzoni S, Chester R, Dulac F, Herut B, Loye-Pilot MD, Measures C, Mignon C, Moulin C, Rossini P, Saydam C, Soudine A, Ziveri P (1999) The role of atmospheric deposition in the biogeochemistry of the Mediterranean Sea. Prog Oceanogr 44:147–190

Guieu C, Aumont O, Paytan A, Bopp L, Law CS, Mahowald N, Achterberg EP, Maranon E, Salihoglu B, Crise A, Wagner T, Herut B, Desboeufs K, Kanakidou M, Olgum N, Peters F, Pilido-Villena E, Tovar-Sanchez A, Volker C (2014) The significance of the episodic nature of atmospheric deposition to low nutrient low chlorophyll regions. Glob Biogeochem Cycles 28 (11):1179–1198

Hamza W (2006) Observations on transported exotic phytoplankton species to UAE coastal waters by gas tankers ballast water. J Egypt Ger Soc Zool 49(D):111–125

Hamza W (2008) Nutritive contribution of Sahara dust to aquatic environment productivity: a laboratory experimental approach. Proceedings (Verhandlungen Internationale Vereinigung für theoretische und angewandte Limnologie) 30:82–86

Hamza W, Munawar M (2009) Protecting and managing the Arabian Gulf: past, present and future. Aquat Ecosyst Health Manage 12(4):429–439

Hamza W, Enan MR, Al-Hassini H, Stuut JB, de Beer D (2011) Dust storms over the Arabian Gulf: a possible indicator of climate changes consequences. Aquat Ecosyst Health Manage 14 (3):260–268

Herrmann L, Stahr K, Jahn R (1999) The importance of source region identification and their properties for soil-derived dust: the case of Harmattan dust sources for eastern West Africa. Contrib Atmos Phys 72:141–150

Herut B, Krom MD, Pan G, Mortimer R (1999) Atmospheric input of nitrogen and phosphorus to the Southeast Mediterranean: sources, fluxes, and possible impact. Limnol Oceanogr 44:1683–1692

Huettel M, Ziebis W, Forster S (1996) Flow-induced uptake of particulate matter in permeable sediments. Limnol Oceanogr 41:309–322

Huettel M, Ziebis W, Forster S, Luther Iii GW (1998) Advective transport affecting metal and nutrient distributions and interfacial fluxes in permeable sediments. Geochim Cosmochim Acta 62:613–631

Jassby AD, Cloern JE, Cole BE (2002) Annual primary production: patterns and mechanisms of change in a nutrient rich tidal ecosystem. Limnol Oceanogr 47:698–712

Jickells TD, An ZS, Andersen KK, Baker AR, Bergametti G, Brooks N, Cao JJ, Boyed PW, Duce RA, Hunter KA, Kawahata H, Kubilay N, laRoche J, Liss PS, Mahowald N, Prospero JM, Ridgwell AJ, Tegen I, Torres R (2005) Global Iron connections between dessert dust, ocean biogeochemistry, and climate. Science 308(5718):67–71

Lekunberri I, Lefort T, Romero S, Vazquez-Dominguez E, Romero-Castillo C, Marrase C, Peters F, Weinbauer M, Gasol JM (2010) Effects of a dust storm deposition event on coastal marine microbial abundance and activity, bacterial community structure and ecosystem function. J Plankton Res 32(4):381–396

Mahowald NM, Baker AR, Bergametti G, Brooks N, Duce RA, Jickells TD, Kubilay N, Prospero JM, Tegen I (2005) Atmospheric global dust cycle and iron inputs to the ocean. Glob Biogeochem Cycles 19(4). https://doi.org/10.1007/s11426-010-4157-y

Markaki Z, Oikonomou K, Kocak M, Kouvarakis G, Chaniotaki A, Kubilay N, Mihalopoulos N (2003) Atmospheric deposition of inorganic phosphorus in the levantine basin, eastern mediterranean: spatial and temporal variability and its role in seawater productivity. Limnol Oceanogr 48(4):1557–1568

Martin JH, Coale KH, Johnson KS, Fitzwater SE, Gordon RM, Tanner SJ, Hunter CN, Elrod VA, Nowicki JL, Coley TL, Barber RT, Lindley S, Watson AJ, Van Scoy K, Law CS, Liddicoat MI, Ling R, Stanton T, Stockel J, Collins C, Anderson A, Bidigare R, Ondrusek M, Latasa M, Millero FJ, Lee K, Yao W, Zhang JZ, Friederich G, Sakamoto C, Chavez F, Buck K, Kolber Z, Greene R, Falkowski P, Chisholm SW, Hoge F, Swift R, Yungel J, Turner S, Nightingale P, Hatton A, Liss P, Tindale NW (1994) Testing the iron hypothesis in ecosystems of the equatorial Pacific Ocean. Nature 371:123–129

Migon C, Sadroni V, Bethoux JP (2001) Atmospheric input of anthropogenic phosphorus to the Northwest Mediterranean under oligotrophic conditions. Mar Environ Res 52:413–426

Miller SD, Kuciauskas AP, Liu M, Ji Q, Reid JS, Breed DW, Walker AL, Mandoos AA (2008) Haboob dust storms of the southern Arabian Peninsula. J Geophys Res Atmos 113(D1). https://doi.org/10.1029/2007JD008550

Paerl HW (1997) Coastal eutrophication and harmful algal blooms: importance of atmospheric deposition and ground-water as “new” nitrogen and other nutrient sources. Limnol Oceanogr 42:1154–1165

Prakash PJ, Stenchikov G, Kalenderski S, Osipov S, Bangalath H (2015) The impact of dust storms on the Arabian Peninsula and the Red Sea. Atmos Chem Phys 15(1):199–222

Prospero JM (1996) Saharan dust transport over the North Atlantic Ocean and Mediterranean: an overview. In: Guerzoni S, Chester R (eds) The impact of desert dust across the Mediterranean. Kluwer Academic Publishing, Dordrecht, pp 133–151

Prospero JM, Ginoux P, Torres O, Nicholson SE, Gill TE (2002) Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product. Rev Geophys 40(1):14723–14731

Rasheed M, Badran MI, Huettel M (2003a) Influence of sediment permeability and mineral composition on organic matter degradation in three sediments from the Gulf of Aqaba, Red Sea. Estuar Coast Shelf Sci 57:369–384

Rasheed M, Badran MI, Huettel M (2003b) Particulate matter filtration and seasonal nutrient dynamics in permeable carbonate and silicate sands of the Gulf of Aqaba, Red Sea. Coral Reefs 22:167–177

Reynolds MR (1993) Physical oceanography of the Gulf, strait of Hormuz, and Gulf of Oman—results from the Mt Mitchell expedition. Mar Pollut Bull 27:35–39

Richlen ML, Morton SL, Jamali EA, Rajan A, Anderson DM (2010) The catastrophic 2008-2009 red tide in the Arabian Gulf region, with observations on the identification and phylogeny of the fish-killing dinoflagellate *Cochlodinium polykrikoides*. Harmful Algae 9:163–172

Ridame C, Guieu C (2002) Saharan input of phosphate to the oligotrophic water of the open western Mediterranean Sea. Limnol Oceanogr 47:856–869

Rusch A, Huettel M (2000) Advective particle transport into permeable sediments-evidence from experiments in an intertidal sandflat. Limnol Oceanogr 45:525–533

Shahsavani A, Naddafi K, Haghighifard NJ, Mesdaghinia A, Yunesian M, Nabizadeh R, Arahami M, Sowlat MH, Yarahmadi M, Saki H, Alimohamadi M, Nazmara S, Motevalian SA, Goudarzi G (2012) The evaluation of PM 10, PM 2.5, and PM 1 concentrations during the Middle Eastern Dust (MED) events in Ahvaz, Iran, from April through September 2010. J Arid Environ 77:72–83

Sissakian VK, Al-Ansari N, Knutsson S (2013) Sand and dust storm events in Iraq. Nat Sci 5 (10):1084

Spilmont N, Davoult D, Migne A (2006) Benthic primary production during emersion: in situ measurements and potential primary production in the Seine estuary (English Channel, France). Mar Pollut Bull 53:49–55

Sunda WG (2012) Feedback interactions between trace metal nutrients and phytoplankton in the ocean. Front Microbiol 3:204

van Beusekom JEE (2005) A historic perspective on Wadden Sea eutrophication. Helgol Mar Res 59:45–55

Zhao J, Ghedira H (2014) Monitoring red tide with satellite imagery and numerical models: a case study in the Arabian Gulf. Mar Pollut Bull 79:305–313