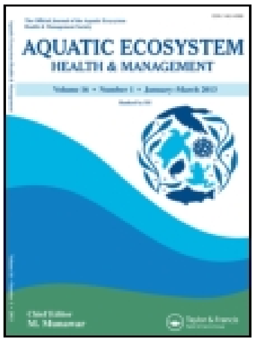

Aquatic Ecosystem Health & Management

ISSN: 1463-4988 (Print) 1539-4077 (Online) Journal homepage: https://www.tandfonline.com/loi/uaem20

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To cite this article: Waleed Hamza , Mohamed Rizk Enan , Huda Al-Hassini , Jan-Berend Stuut & Dirk de-Beer (2011) Dust storms over the Arabian Gulf: a possible indicator of climate changes consequences, Aquatic Ecosystem Health & Management, 14:3, 260-268, DOI: 10.1080/14634988.2011.601274

To link to this article: https://doi.org/10.1080/14634988.2011.601274

Dust storms over the Arabian Gulf: a possible indicator of climate changes consequences

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Dust storm frequencies and strengths were monitored during 2009 at various locations along the coast of the United Arab Emirates (UAE), as representative sites of the Arabian Gulf marine environment. The results have been compared with a pre-2009 five-year data set. Mineralogical components of dust samples collected during the 2009 study period were analyzed using both X-ray diffraction (XRD) and X-ray Fluorescence (XRF) techniques. The comparison of the 2009 and pre-2009 data revealed a shift in the characteristics of dust storms in the Arabian Gulf, which may constitute a sensitive indicator of climate change affecting the region. The range of mineral compositions of the collected dust samples is consistent with temporally and spatially variable dust sources, associated with changing wind patterns over the Arabian Gulf. From a positive perspective, the dust may deliver mineralogical nutrients enhancing microbial productivity in the marine ecosystem. Increasing productivity and liberation of iron from sediments will lead to an increase of Dimethyl Sulfide (DMS) in the atmosphere, which by oxidation will scatter solar radiation effectively with a consequent decrease in global temperature as a climate feedback.

Keywords: dust precipitation, storm trajectories, Arabian Peninsula, marine ecosystem

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Introduction

Global climate change and its consequences are currently pre-eminent topics of international research, covering a range of environmental sciences. The models of climate change are complex and require not only long term meteorological datasets, but also model links to biogeochemical cycles in order to verify and quantify the predicted changes (Turner et al., 2004; Jickells et al., 2005). Due to the disparate and incomplete datasets forming the basis of global numerical climate models, assumptions, constants, and extrapolations, as well as other mathematical techniques, are used to support these models. For these reasons the models are still a far cry from adequately describing the earth system. Dust storm activity is an important and largely unknown variable within global circulation models (Jickells et al., 2005; Miller et al., 2006). However, it is too complex at this stage to be formally incorporated into the models via formulae describing the initiation of the storms, their trajectories, variability and regional distributions of dust deposition. During the last two decades there have been several studies

Aquatic Ecosystem Health & Management, 14(3):260–268, 2011. Copyright © 2011 AEHMS. ISSN: 1463-4988 print / 1539-4077 online
DOI: 10.1080/14634988.2011.601274

concerned with the mineralogy and major chemical element compositions of atmospheric dust, and its effects on terrestrial and marine ecosystems. These studies recognized the contributing role of desert dust to the abundances of trace elements of continental origin in 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). The relationship between deposition of atmospheric dust and marine productivity is regarded as potentially significant for oligotrophic oceanic areas (Migon et al., 2001; Herut et al., 2002; Ridame and Guieu, 2002). These latter studies focused on quantifying the nutritive effects of dust deposition on marine productivity. However, they were specific to areas such as the north Atlantic and Mediterranean regions, and disregarded the Arabia Peninsula despite its ranking amongst the major sources of dust storms (Zender, 2003; Hamza, 2008; Hamza and Munawar, 2009). There is a shortage of data on the characteristic properties of dust derived from the Arabian Peninsula, its contribution to the earth system in general, and to the Arabian Gulf in particular. The Arabian Peninsula is one of the largest desert areas in the world, being characterized by arid conditions, monsoon winds and consequently large areas of sand dunes. The strong monsoon winds during spring and summer seasons (March–August) promote dust storms over the Gulf area. The size and composition of the sand particles and the pathways of particle transport during the monsoons vary according to wind direction and strength. In any case, substantial quantities of storm-carried dust are deposited within the Arabian Gulf basin, or pass over it. Despite existing warm temperatures (35–45°C), intensive rainy periods may develop when windblown sand/dust particles act as nuclei for condensation of water vapor. These rainstorms are responsible for the wet deposition of large quantities of the dust suspended in the atmosphere during this period over the Arabian Gulf basin. Recent publications on the productivity of the Arabian Gulf marine ecosystem indicate that the basin is very productive and highly diversified (Khan et al., 2002, Munawar et al., 2007; Hamza and Munawar, 2009), despite the limited amounts of nutrients received from land sources and the unsustainable river discharges into its basin (Reynolds, 1993). These observations find explanations in the hypothesis that dust storms are providing the additional nutrients needed to sustain the ecosystem productivity of the Arabian Gulf. The United Arab Emirates (UAE), one of the Arabian Peninsula countries, has a long coastal area (up to 700 km) that borders the Arabian Gulf and the Gulf of Oman. Dust storms affect the atmosphere above the UAE during several months of the year. The present study was designed to address the need for information on dust storm frequency; mineralogy, sources, deposition and bioactive effects of atmospheric dust in the Arabian Gulf basin area. It compares data on dust storm frequency and strength along the coastal area of UAE during 2009, with similar data from the 5 years prior to 2009. This study also presents information on dust mineralogy during both dry and wet seasons, and discusses this data in terms of the various source areas of the dust, and how the dust may be beneficial to marine productivity of the Arabian Gulf ecosystem. Lastly, it aims to highlight the importance of the Arabian Peninsula as a major source of the dust storms relevant to global climate concerns.

Material and Methods

Meteorological data acquisition

Detailed historical and updated meteorological data (wind components, wind raising sand frequencies, and horizontal visibility) for the coastal areas of the United Arab Emirates (UAE), during the periods 2004–2009, have been obtained from the UAE- National Center of Meteorology and Seismology (NCMS). The obtained data sets pertain to the main meteorological stations situated along these coastal areas of UAE. Due to the large volume of data, and in order to avoid redundancy of the results obtained from the different stations, we have chosen to present the data analyses from the Abu Dhabi meteorological station as the representative site. The station is selected on the basis of its central location on the UAE coast (Figure 1). Information on the frequency and duration of sand storms was extracted from the Abu Dhabi data. The data was also analyzed to investigate the strength of dust storms, based on horizontal visibility measurements and their relations to the wind speed. The results obtained for the year 2009 were then compared with results obtained from the previous five years (i.e. 2004–2008). During the study period (January–December, 2009), METEOSAT, AQUA-images over UAE territory were obtained

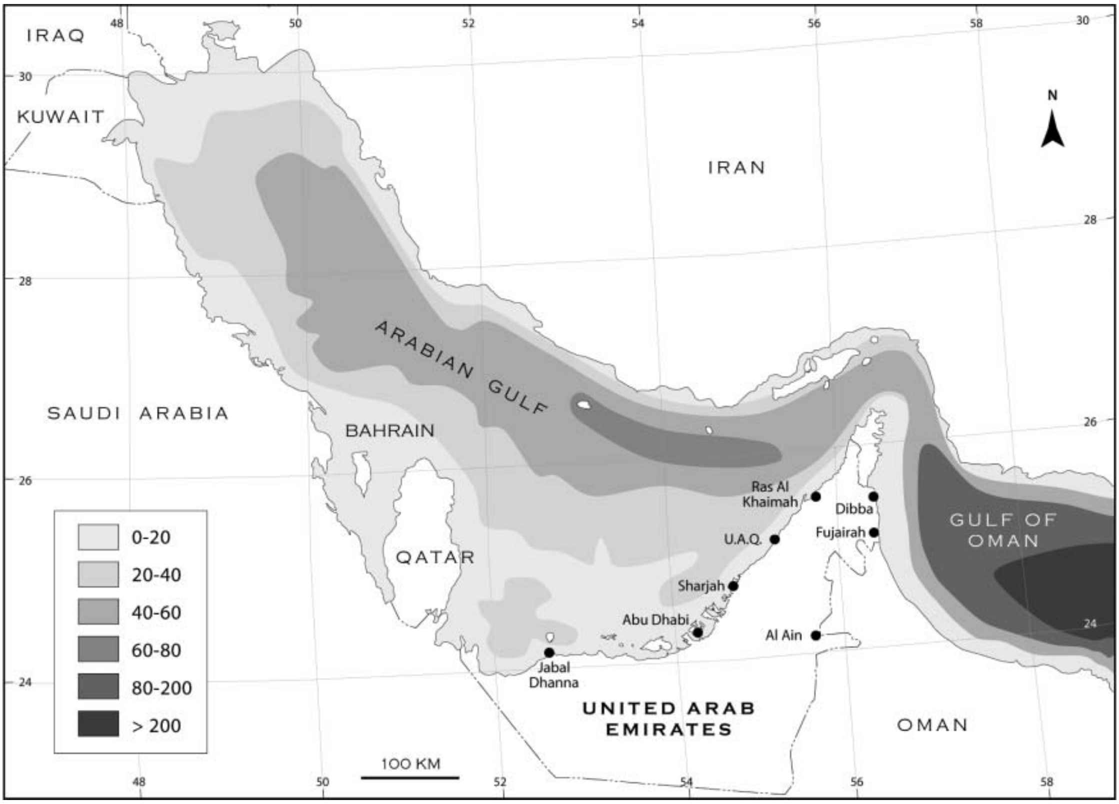

Figure 1. Map of the Arabian Gulf, indicating the sampling stations (●) along the UAE coast.

via AERONET in order to verify the atmospheric conditions and the intensities of sand storms.

Dust sampling

In this study, dust samples were collected by a number of methods, from the coastal areas of the UAE at the same locations as the five main meteorological stations of the NCMS. These five sampling stations are at (1) Jebel Al-Dhanna (Dhanna), (2) Abu Dhabi, (3) Um Al-Quwain (UAQ), (4) Dibba and (5) Fujirah (Figure 1). At each sample location an Automatic Andresen dry and wet acid rain sampler was installed. The sampler was used to collect dry dust in dry weather and wet dust with rain water during precipitation. The cover lid between the two (dry and wet) collection buckets was activated via a highly sensitive electrical rain sensor. The samplers were installed at the research centers belonging to the Ministry of Water and Environment, and environmental departments belonging to the Abu Dhabi Oil Company (ADCO). Dust samples were regularly collected each 15 days, unless there were dust storms (either dry or wet). During dust storm periods the samples were collected separately and labeled to indicate the precise time and date of the storm event. The dust background fraction was determined by collecting the dust deposited on a flat surface covered by glass beads mounted on a funnel and erected 6 m above the ground, according to the method described by Kouvarakis et al. (2001). The sampling apparatus was exposed to the atmosphere for a period of 1 to 2 weeks during calm periods, when no sand storms were detected. This procedure enabled the quantification of the aerosol background content of dust particles. For the wet dust, i.e. the dust deposited during rain events, samples were collected as mentioned above on an event basis. The rain water was immediately filtered through a 0.45 um diameter membrane filter and refrigerated prior to analysis (Kubilay et al., 2000). The collected dust samples were also stored in a frozen state for later mineralogical analysis.

Dust analysis

After weighing each sample of dust, an analysis of the sample was made using one or more of the following: spectroscopic analysis by XRF, or by XRD using an X-Ray diffractometer (Model Philips PW/1480) and wavelength depressive X-ray fluorescence spectroscopy (WRXRF). These analyses were performed in the Geology Department laboratories of the UAE University. The analyses were carried out on a representative fraction of each sample, according to the protocol of the analytical techniques. The XRD was used to identify the main mineralogical components of the dust samples, while the XRF provided an estimate the major elemental compositions of the samples. Other fractions (500 mg) of the dry dust samples underwent leaching experiments by autoclaving the dust with filtered sea water. After autoclaving, the resulting sea water filtrates were extracted and analyzed to detect leached inorganic elements. Nitrogen (N), phosphorus (P) and Iron (Fe) concentrations were specifically measured in the autoclaved sea water extracts. The filtered rain water samples were also analyzed for inorganic components. These analyses were carried out using Inductively Coupled Plasma (ICP) on instrument at the Central Laboratory Unit of UAE University. In order to identify the source areas of the airborne dust, samples of surface dust were also collected from the "Empty Quarter area." This is the largest mobilized sand dune area of the region (also known in the literature as the 'Rub Al-Khali') and is located in the eastern part of Saudi Arabia bordering the southern areas of the UAE. The surface dust samples were treated analytically in the same way as the dry dust storm samples collected from the coast. A comparison was then made of the mineralogical compositions of the Rub Al-Khali and dust storm samples.

Data presentation

A representative subset of data from dust storm samples (both dry and wet events) collected at the above mentioned stations is presented in this paper. The analytical results for dry dust storm events of May and August, 2009; and wet dust storms of January–February and March 2009 have been selected.

Results

The available meteorological information on dust storms events for the period 2004–2009 may be utilized to explore the relations between horizontal visibility and wind speed during dust storm events. A negative correlation between these two variables was found, but is not significant, at r = −0.206 (Figure 2*). Therefore, instead of using a direct correlation of these two variables, it is preferable to develop a dust storm strength index, relevant to the Arabian Gulf coastal area, which is based on horizontal visibility alone. This index has both qualitative and quantitative scales of horizontal visibility (Table 1), ranging between 1 and 4, where 1 is the strongest storm (0–500 m) and 4 is the weakest (1500–2000 m). The index is applied when wind-disturbed dust reduces horizontal visibility to below 2000 meters. When wind events have horizontal visibility greater than 2000 meters the index is not applicable. Comparison of the record of dust storms during 2004–2008 with that of 2009, in the Abu Dhabi area, indicates an intensification of dust storms during 2008 and 2009, relative to previous years. A shift in storm occurrence toward winter months (January–March) was observed mainly during 2009 (Figure 3). During the hotter months of 2009, a series of storms occurred in the period May–August, with wind velocities ranging between 11 and 30 knots. However, the visibility records of these events were above 3000 m, reflecting the large size of the dust particles and their brief period of suspension. These findings are supported by satellite images downloaded from AERONET through the NCMS interactive website. Examples of these images representing summer and winter periods are shown in Figure 4. The main winds blowing over the Arabian Gulf were identified as the southwest monsoon wind in summer and the northwest wind in winter (also known as the 'Shamal' wind) (Figure 5). Statistical analysis of dust storms data sets of the Abu Dhabi area, for the entire study period (2004 to 2009), indicated that the main prevailing wind was from the NW, with the exception of 2008, when wind from the SE quadrant was dominant. Winds from the SW were also responsible for dust

Table 1. Indices of dust storm strengths based on visibility.

Index	Visibility (m)
1	499–0
2	500–999
3	1000–1499
4	1500–2000

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*Figures 2–6 and Tables 2–6 can be found at http://www.aehms.org/Journal_14_3_Hamza_Appendix.html.

storms during 2005 and 2009, while in 2007 winds from the NE and SE were the main agents of dust storms (Figure 6a). Although no significant differences were found in wind speed values for 2009, compared with the period 2004–2006, substantially different values were found for 2007 and 2008 (Figure 6b). This was reflected in the significant variances $n = 376$ $p = 0.007$ in visibility records between the different wind directions, for the entire study period (Figure 6c). For the coastal samples there were sharp differences in terms of the quantities of dust deposited during the dry and wet storm periods. During the dry months of May and August the rate of dust deposition ranged between 2.65 g m^{-2} day^{-1} and 21.31 g m^{-2} day^{-1} with an average of 9.34 g m^{-2} day^{-1}. During the rainy months, the rate of dust deposition ranged between 1.34 g m^{-2} day^{-1} and 7.61 g m^{-2} day^{-1} (on a dry dust basis) with an average of 3.43 g $m^{-2}day^{-1}$. Calculations show that dust storms over the UAE coastal area had an average frequency of 33 days per year, with intensities estimated using visibility indices. XRD analysis of dry dust samples collected from the five sampling stations (Jebel Al-Dhanna, Abu Dhabi, Um Al-Quwain, Dibba and Fujirah), revealed differences in the main mineral concentrations, not only at the seasonal level, but also from month to month in a single season. Some coastal dust samples were markedly similar in composition to surface dust (dust source) samples collected from the Empty Quarter (Table 2). For example, the dry dust samples collected during May and August, 2009 from Jebel Al-Dhanna, Abu-Dhabi, Fujirah and UAQ had similar major mineral composition to the Rub Al-Khali source samples, though concentrations of minor minerals departed from this trend. Samples collected from Dibba during the same periods were strikingly different in both major and minor mineral concentrations to the Rub Al-Khali samples. Wet samples collected during January–March 2009, from all stations apart from Abu Dhabi and UAQ, showed mineralogical compositions different to those of the Rub Al-Khali samples. The Abu Dhabi and UAQ samples in the latter period showed differences only in the minor mineral concentrations to the Rub Al-Khali samples (Table 3). XRF analysis of dust samples for the elements N, P and Fe showed distinct differences in wt% for these elements amongst samples collected from the different locations, and between samples collected during dry and wet months. These variations (Tables 4 and 5) corroborated the XRD results on the mineralogical differences between samples. The percentage of P in the analyzed dust was 0% in Jebel Al-Dhanna and Fujirah samples collected in May. Similar results for P were obtained from UAQ samples collected during August (Table 4). Iron was present in high percentages in all samples collected during both May and August, with concentrations ranging from 2.11% to 18.5%, and an average of 10.96% (Table 4). In contrast, dust samples collected during the months January–March from rain water after dust storms showed lower percentages of Fe, with values ranging from 5.9% to 11%, and an average of 8.45% (Table 5). Unlike the coastal dust storm samples, the Rub Al-Khali source samples had low percentages of Fe, with an average of 3.12%, and 0% for P. ICP analyses of sea water after autoclaving with dry dust fractions showed higher concentrations of some elements compared with the initial sea water composition. This was the case for Al, Fe, Mn, and P, though the factor of increase differed between sampling locations (Table 6). The ICP analyses of the filtered rain water collected during dust storms in January–March, showed high nitrogen concentrations as nitrate (range 1.3–36.7 NO_3 mg l^{-1}). Considerable concentrations of dissolved phosphate (average 0.034 mg l^{-1}) and iron (average 0.03 mg l^{-1}) were also detected in some samples, as shown in (Table 6).

Discussion

To the authors' knowledge, the present study is the first of its kind for the Arabian Peninsula and Gulf basin. Similar studies dealing with quantitative data on dust storms in Asia almost exclusively focus on the Chinese territory and North Pacific (Ginoux et al., 2001; Zhang et al., 2003; Miller et al., 2004). As shown in Figure 1 the UAE coastal area extends beyond the Arabian Gulf to include parts of the Gulf of Oman. These two parts of the UAE coastline are not contiguous, but lay only about 40–50 km apart, and have both been investigated in this study using the sampling apparatus. The presence of the Oman Mountains separating the Fujirah-Dibba and UAQ stations presents the possibility of dust samples from the two coastlines having profoundly different mineralogical compositions, in addition to different rates of dust deposition for any individual storm period. The detailed 2004–2009 meteorological data from the Abu Dhabi station described in this contribution is representative for all of the data sets from the UAE coastal area in indicating insignificant correlations between wind speed and horizontal visibility. This result is to be expected if we consider wind speed as a factor capable of removing suspended dust. Under other conditions it may promote the suspension of dust in the atmosphere. In their studies, Ginoux et al. (2001); Zender et al. (2003); and Koren and Kaufman (2004) stated that the uplifting of dust particles can be expressed as a function of surface wind speed and surface dust dampness. However, it has been concluded that vegetation and other ground features also control dust dispersal (Moulin and Chiapello, 2004; Jickells et al., 2005). Our observations along the UAE coastal area were in accordance with both of these hypotheses. There has been rapid growth in tall building constructions along the UAE coastal areas during the last 30 years. These buildings act as complete or partial barriers to the transport of dust particles. It is for this reason that our index of dust storm strength was based only on horizontal visibility, with the index limited to visibility maxima of 2000 m or less. Visibility is always mentioned in scientific and meteorological reports (Sunnu et al., 2007), but, up to our knowledge, has not previously been considered as a measure of dust storm intensities. Horizontal visibility is introduced in this study as a new measurable variable which strongly correlates with wind direction along the UAE coastal area (Figure 6c). It appears that wind direction was an important factor controlling not only visibility level, but also composition and depositional rate of dust over the Arabian Gulf basin. Satellite images during February–March, 2009 showed high concentrations of dust blanketing the UAE coastal area and the Arabian Gulf basin (Figure 4), while lower concentrations were evident in the May–June images (Figure 4). This has also revealed the mineralogical composition of the source of the dust, and the temporal changes in composition of dust deposited in the marine environment of the Arabian Gulf. Major mineral compositions of desert sands worldwide show narrow variations, as quartz is the most common component of rocks (Goudie and Middleton, 2001). Depending on the bedrock source of dust, other minerals, such as calcite ($CaCO_3$), may also amount to major constituents. Subordinate and minor minerals identified in dust analyses may be important for identifying the bedrock source. Dust mineralogical variations result mainly from the geological or geochemical peculiarities of areas through which dust storms have passed. In their study, Callot et al. (2000) found that dust emissions from arid regions were influenced by surface features encountered in the source region. They identified some of these features as rocks, fluviatile deposits, sabkha deposits, clay deposits and sand dunes. One of the conclusions of our study is that differences in subordinate and minor mineral abundances between source area and coastal area dust samples were a result of dust passing over different surface features as it is transported from source to coast. Changes in seasonal wind directions at the coastal stations also result in dust arriving from different sources according to season. This was clearly demonstrated in our data (Tables 2 and 3), as shown by the differences between Abu Dhabi samples collected during summer and winter months. Examples of relevant surface features in and surrounding the UAE territory were the Abu Dhabi sabkha (Abed et al., 2008), the Empty Quarter sand dunes (Rub Al-Khali), and the Oman Mountains (Glennie et al., 1974). These features may also have contributed to the mineralogical composition of the deposited dust (Figure 6). Most previous studies on dust and aerosol deposition mainly addressed the chemical composition of the dust rather than its mineralogy. During the last few decades there have been many studies of the nutritive effects on oceanic productivity, contributed by the deposition of atmospheric dust in sea water (Talbot et al., 1986; Martin, 1990; Duce et al., 1991; Zhuang et al., 1992; Swap et al., 1996; Zohary and Robarts, 1998; Gruber and Sarmiento, 1997; Shinn et al., 2000; Kouvarakis et al., 2001; Markaki et al., 2003; Baker et al., 2003; Turner et al., 2004; Mills et al., 2004; Jickells et al., 2005; Sailot, 2006; Hamza, 2008). Chemical elements of major interest are iron, phosphorus and nitrogen, which are major nutrients influencing ocean productivity in iron-deficit waters. In our study, XRF analysis of source area dust and coastal dust samples collected in dry and wet weather conditions showed great variations in chemical composition (Tables 4 and 5). Silica and calcium were the major chemical elements in the samples, accounting for a combined 60–80 wt%. The higher 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 being picked up during dust storms. Zender et al. (2003) concluded that a model of heterogeneous erodibility may explain 15–20% more of the spatial structure of dust emissions than uniform erodibility in the Sahara and Arabia. They explained that dust emission "hot spots" exist in regions where accumulations of alluvial sediments were disturbed. The absence of detectible phosphorus (P) in the dust source area samples collected in our study correlated with the rock chemical analyses by Goudie and Middleton (2001). It is present, however, in the coastal dust samples up to a level of 0.5 wt%, implying that human activities (in this case phosphate additives to soil, and the increased erodibility of agriculturally disturbed soils) have influenced the mineralogical composition of the windblown dust. Our analyses of dust samples also showed high percentages of aluminum (Al), magnesium (Mg), and sulphur (S) in the coastal dust samples relative to source area dust samples. These elements are valuable nutrients for phytoplankton production in the marine environment if they exist in a soluble form. The solubility of iron compounds and other trace metals in the marine environment is known to be dependent on pH of sediments, in that the binding capacity of sediments decreases at acidic pH allowing mineral dissolution (Parekh et al., 2004; Jickells et al., 2005). Other studies point towards rain water as an effective leaching agent or solvent of minerals during precipitation over the ocean basins (Markaki et al., 2003). Hand et al. (2004) and Saliot (2006) suggested that photochemical reactions could be responsible for element solubility in the oceanic surface water micro-layer, which they considered as a micro-reactor, effectively sequestering and transforming selected materials brought to the interface from the ocean and the atmosphere by physical processes. Both rain water and photochemical reactions have the potential to be of great importance in dissolving elements carried by dust storms over the Arabian Gulf. Rain water in the Gulf area is scarce, however, mixing with high sulphur concentrations in the atmosphere, as a consequence of intensive sulfur rich oil production, may make the rain water acidic enough to dissolve other minerals such as iron-bearing ones. On the other hand, light intensity in the Arabian Peninsula as in other world desert areas is high enough to promote photochemical processes at the sea surface micro-layer. These conclusions, along with results obtained from rain water analyses and autoclaved rain water - dust experiments confirmed the significant contribution of elements such as nitrogen, phosphorus and iron, via dust storms, to the marine ecosystem of the Arabian Gulf. In their review, Jickells et al. (2005) noted that in some areas iron limitation may lead to High Nutrient Low Chlorophyll (HNLC) regions. It appeared that this was not applicable to the Arabian Gulf, where the recorded high productivity (Khan et al., 2002), reflected efficient assimilation of nutrients by primary producers. Despite the limited freshwater runoff from coastal areas into the Arabian Gulf (Hamza and Munawar, 2009), which replenishes $<10\%$ of the annual evaporation of its waters, the Arabian Gulf ecosystem appears to receive additional nutrients, especially Fe, P and N, from other sources. One of these extra sources could be the upwelling of waters charged with dissolved nutrients derived by recycling of marine sediments (Kampf and Sadrinasab, 2006). Another source is surely the annual dust and aerosol deposition onto its waters (Hamza, 2008). The present study confirmed this by estimating a total average dust flux of 6.385 g m^{-2} day^{-1}, for an average of 33 days per year. For the entire Gulf area (240,000 km^2), a rough estimate indicates about $5.5 * 10^6$ tons of dust per year is deposited on Gulf waters, assuming a 10% uniform deposition. This calculation probably underestimated the actual flux, since it was based on sampling stations distributed randomly along the UAE coastal area without a standard sampling methodology (Herut et al., 2002). Similar calculations could be performed for each nutrient element (e.g. Fe and P) based on wt% compositional data in the dust samples and concentration of these elements in fresh rain water, and sea water autoclaved with dust (Table 6). It has been estimated that the total atmospheric dust input into the oceans is about 450 Gigatons $year^{-1}$, with about 25% of this quantity being received by the Indian Ocean (Jickells et al., 2005).

Conclusions

According to the present study, significant quantities of dust derived from the Arabian Peninsula form part of the annual dust input into the Indian Ocean directly and indirectly through water exchange with the Arabian Gulf. Increased photosynthetic activity in the Indian Ocean due to fertilization by dust nutrients from the Arabian Gulf and its adjacent water bodies may well be important in mitigating the increase in anthropogenic CO_2 in the atmosphere. Increasing productivity and liberation of iron from sediments leads to an increase of dimethyl sulphide (DMS) which can be released into the atmosphere by diffusion (Scarratt et al., 2007). It has been mentioned that oxidation of DMS forms an acidic sulphate aerosol that is able to scatter solar radiation effectively. A twofold increase in DMS fluxes produces a global temperature decrease of 1°C proving a potential climate feedback and link between the C, Fe and S cycles

(Bopp et al., 2003; Turner et al., 2004; Jickells, 2005). Research on global climate change must integrate earth system processes using detailed sub-models capable of quantifying natural interactions; and linking these sub-models in interactive ways. There is room for a more optimistic viewpoint in the quest for realistic answers to the questions about the consequences of climate changes. Results of model simulations should be based on realistic data; and an integrated effort by researchers to produce such data is paramount. The present study represents an attempt to fill gaps in datasets for dust deposition by introducing measured values from areas rarely investigated. It also highlights dust storms as a possible sensitive indicator of climate changes consequences.

Acknowledgements

The present study was supported by the Emirates Foundation project fund (UAE- EF #2008/053) in collaboration with Max-Planck Institute for Marine Microbiology (MPI-Bremen, Germany). The authors are grateful to the UAE-NCMS for supplying meteorological data and for the Ministry of Water and Environment of UAE as well as ADCO-Jebel Al-Dhanna Oil Farm for installing dust samplers and helping out in sample collection during the study period. A special thank to Ms Yolldes Idrizi (Laboratory specialist in Biology Department, Faculty of Science, UAE-University) for her valuable contribution to data harmonization and illustrations.

References

Abed, R.M.M., Kohls, K., Schoon, R., Scherf, A.K., Schacht, M., Palinska; K.A., Hassani, H., Hamza, W., Rullkotter, J., Golubic, S., 2008. Lipid biomarkers, pigments and cyanobacterial diversity of microbial mats across intertidal flats of the arid coast of the Arabian Gulf (Abu-Dhabi, UAE). FEMS-Microbiol Ecol. 65, 449–462.

Baker, A.R., Kelly, S.D., Biswas, K.F., Witt, M., Jickells, T. D., 2003. Atmospheric deposition of nutrients to the Atlantic ocean, Geophys. Res. Lett., 30, 2296.

Bopp, L., Kohfeld, K.E., Le Quere, C., Aumont, O., 2003. Dust impact on marine biota and atmospheric CO during glacial periods, Paleoceanography 18, 1046.

Callot, Y., Marticorena, B., Bergametti, G., 2000. Geomorphologic approach for modeling the surface features of arid environments in a model of dust emissions: application to the Sahara desert. Geodinamica Acta 13, 245–270.

Duce, R., Liss, P.S, Merill, J.T, Atlas, E.L, Baut-menard, P., Hicks, B.B., Miller, J.M., Prospero, J.M., Arimoto, R., Church, T.M., Ellis, W., Galloway, J.N, Hansen, L., Jickells, T.D., Knap, A.H., Reinhardt, K.H, Schneider, B., Soudine, A., Tokos, J.J, Tsunogai, S., Wollast, R., Zhoult, M., 1991. The atmospheric input of trace species to the World Ocean, Global Biogeochem. Cycles 5(3), 193–259.

Ginoux, P., Chin, M., Tegen, I., Prospero, J., Holben, B., Dubovik, O., Lin, S-J., 2001. Sources and distributions of dust aerosols simulated with GOCART model. J. Geophys. Res. 106(D17), 20255–20273.

Glennie, K.W., 2005. *The Desert of Southeast Arabia*. Gulf Petrolink Publish, Manama, Kingdom of Bahrain.

Glennie, K.W., Boeuf, M.H.W. Hughes-Clarke, Moody-Stuart, M., Pilaar, W.F.H, Reinhardt, B.M., 1974. Geology of the Oman Mountains. Verh. K. Ned. Geol. Mijnbouwkd. Genoot. 31 (1974), 1–423.

Goudie, A.S., Middleton, N.J., 2001. Saharan dust storms: nature and consequences. Earth science reviews 56, 179–204.

Gruber, N., Sarmiento, J.L., 1997. Global patterns of marine nitrogen fixation and denitrification. Global Biogeochem. Cy. 11, 235–266.

Guerzoni, S., Chester, R., Dulac, F., Herut, B., Loye-Pilot, M.D., Measures, C., Mignon, C., Moulin, E., Rossini, P., Saydam, C., Soudine, A., Ziveri, P., 1999. The role of atmospheric deposition in the biogeochemistry of the Mediterranean Sea. Progress in Oceanography 44, 147–190.

Hamza, W., 2008. Nutritive contribution of Sahara dust to aquatic environment productivity: A laboratory experimental approach. Verh. Internat. Verein. Limnol. 30 (1), 82–86.

Hamza, W., Munawar, M., 2009. Protecting and Managing the Arabian Gulf: Past, present and future. Aquatic Ecosystem Health and Management 12 (4), 429–439.

Hand, J.L., Mahowald, N.M., Chen, Y., Siefert, R.L., Luo, C., Subramaniam, A., Fung, I., 2004. Estimates of atmospheric processed soluble iron from observations and a global mineral aerosol model: Biogeochemical implications. J. Geophys. Res. 109, D17205.

Herut, B., Collier, R., Krom, M.D., 2002. The role of dust in supplying nitrogen and phosphorus to the Southeast Mediterranean. Limnol. Oceanogr. 47(3), 870–878.

Jickells, T.D., An, Z.S., Andersen, K.K., Baker, A.R., Bergametti, G., Brooks, N., Cao, J.J., Boyed, P.W., Duce, R.A., Hunter, K.A., Kawahata, H., Kubilay, N., LaRoche, J., Liss, P.S., Mahowald, N., Prospero, J.M., Ridgwell, A.J., Tegen, I., Torres, R., 2005. Global Iron connections between desert dust, ocean biogeochemistry, and climate. Science 308, 67.

Kampf, J., Sadrinasab, M., 2006. The circulation of the Persian Gulf: a numerical study. Ocean Sci. 2, 27–41.

Khan, N.Y., Munawar, M., Price A.R.G., 2002. *The Gulf ecosystem: Health and sustainability*. Backhuys Publisher, Leiden, The Netherlands.

Koren, I., Kaufman Y.J., 2004. Direct wind measurements of Saharan dust events from Terra and Aqua satellites. Geophysical research letters 31, 1–4.

Kouvarakis, G., Mihalopoulos, N., Tselepides, T., Stavrakis, S., 2001. On the importance of atmospheric inputs of inorganic and nitrogen species on the productivity of the eastern Mediterranean Sea. Glob. Biogeochem. Cycles 15, 805–818.

Kubilay, N., Nickovic, S., Moulin, C., F. Dulac, F., 2000. An illustration of the transport and deposition of mineral dust onto the eastern Mediterranean. Atmospheric Environment 34, 1293–1303.

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, J.H., 1990. Glacial-interglacial CO2 change: The Iron hypothesis. Paleoceanography 5(1), 1–13.

Migon, C., Sadroni, V., Bethoux, J.P., 2001. Atmospheric input of anthropogenic phosphorus to the northwest Mediterranean under oligotrophic conditions. Mar. Environ. Res. 52, 413–426.

Miller, R.L., Perlwitz, J., Tegen, I., 2004. Modeling Arabian dust mobilization during the Asian summer monsoon: The effect of prescribed versus calculated SST. Geophys. Res. Lett. 31, L22214.

Miller, R.L., Cakmur, R.V., Perlwitz, J., Geogdzhayev, I.V., Ginoux, P., Koch, D., Kohfeld, K.E., Prigent, C., Ruedy, R., Schmidt, G.A., Tagen, I., 2006. Mineral dust aerosols in the NASA Goddard Institute for space sciences model E atmospheric general circulation model. J. Geophys. Res. 111. D06208.

Mills, M. M., Ridame, C., Davey, M., La Roche, J., Geider, R., 2004. Iron and phosphorus co-limit nitrogen fixation in the eastern tropical Northern Atlantic. Nature 429, 292–294.

Moulin, C., Chiapello, I., 2004. Evidence of the control of summer atmospheric transport of African dust over the atlantic by Sahel sources from TOMS satellites (1979-2000), Geophys. Res. Lett. 31, L02107. doi:10.1029/2003GL018931.

Munawar, M., Hamza, W., Krupp, F., Boer, B., Al-Ghais, S., 2007. The State of the Gulf ecosystem: Future and threats. Aquat. Ecosyst. Health Mgmt. 10 (3), 253–363.

Paerl, H.W., 1997. Coastal eutrophication and harmful algal blooms: Importance of atmospheric deposition and groundwater as “new” nitrogen and other nutrient sources. Limnol. Oceanogr. 42, 1154–1165.

Parekh, P., Follows, M.J., Boyle, E., 2004. Modeling the global ocean iron cycle, Global Biogeochem. Cycles, 18, GB1002.

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

Reynolds, M.R., 1993. Physical Oceanography of the Gulf, Strait of Hormuz, and Gulf of Oman- Results from the Mt. Mitchell Expedition. Marine Pollution Bulletin 27, 35–39.

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

Saliot, A., 2006. Biogeochemical processes in the ocean and at the ocean-atmosphere interface. J. Phys. IV France 139 (2006), 197–209.

Scarratt, M., Levasseur, M., Michaud, S., Roy, S., 2007. DMSP and DMS in the Northwest Atlantic: Late-summer distributions, production rates and sea-air fluxes. Aquatic Sciences-research across boundraries 69, 292–304.

Shinn, E.A., Smith G.W., Prospero J.M., Betzer P., Hayes M.L., V. Garrison Barber R.T., 2000. African dust and the demise of Caribbean coral reefs. Geophys. Res. Lett. 27, 3029–3043.

Sunnu, A., Afeti, G., Resch, F., 2007. *A long term experimental study of the Saharan dust presence in West Africa*. Elsevier, The Netherlands.

Swap, R., Ulanski, S., Cobbett, M., Garstang, M., 1996. Temporal and spatial characteristics of Saharan dust outbreaks. J. Geophys. Res. 101, 4205–4220.

Talbot, R.W., Harriss, R.C., Browell, E.V., Gregory, G.L., Sebasher, D.I., Beck, S.M., 1986. Distribution and geochemistry of aerosols in the temporal North Atlantic troposphere: relationship to Saharan dust. J. Geophys. Res. 91, 5173–5182.

Turner, S.M., Harvey, M. J., Law, C.S., Nightingale, P.D., Liss, P.S., 2004. Iron-induced changes in oceanic sulfur biogeochemistry. Geophys, Res. Lett. 31, L14307. doi: 10.1029/2004GL020296.

Zender, C.S., Newman, D., Torres, O., 2003. Spatial heterogeneity in Aeolian erodibility: uniform, topographic, geomorphic and hydrologic hypotheses. J. Geophys. Res., 108, 4543.

Zhang, X.Y., Gong, S.L., Zhao, T.L., Arimoto, R., Wang, Y.Q., Zhou, Z.J., 2003. Sources of Asian Dust and role of climate change versus desertification in Asian dust emission. Geophys. Res. Lett. 30, 2272. doi:10.1029/2003GL018206

Zhuang, G., Yi, Z., Duce, R. A., Brown, P.R., 1992. Links between iron and sulphur cycles suggested by detection of Fe(n) in remote marine aerosols. Nature 355, 537–539.

Zohary, T., Robarts R.D., 1998. Experimental study of microbial P-limitation in the eastern Mediterranean. Limnol. Oceanogr. 43, 387–395.