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Baseline

Atmospheric dry deposition of mineral dust to the Gulf of Aqaba, Red Sea: Rate and trace elements

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ABSTRACT

Atmospheric dry deposition to the Gulf of Aqaba (GoA) is particularly a significant source of trace elements. Amid desert regions, the Gulf receives high fluxes of mineral dust with an average rate of 34.68 g/m^2/year measured in 2012. Patterns of dry deposition showed seasonal fluxes with highest rates observed in summer and lowest in winter. The observed variations were attributed to wind direction, timing of deposition and sources of dust. The average dry fluxes of Al, Fe, Mn, Cr, Cd, Cu, Pb and Zn were 551, 440, 10.29, 1.42, 0.04, 0.68, 1.42 and 4.02 mg/m^2/year, respectively. While the dry deposition fluxes were enriched in Cd, Cu, Pb and Zn indicating their dominant anthropogenic sources, they appeared to be less influenced compared to the neighboring Mediterranean area and other industrial countries, but were similar to or slightly higher than those in remote areas. The enrichment values for Fe and Mn were low, consistent with their crustal origin. The fluxes of all elements suggested the impacts of both crustal (due to climate change) and anthropogenic sources became stronger in this region. The Sahara dust was probably a minor contributor to dry deposition in the GoA.

The Gulf of Aqaba (GoA) is a partially-enclosed basin which is located in an extremely arid region with negligible rainfall and virtually no surface runoff. It is surrounded by the Sinai and Negev Deserts to the west and by the Arabian Desert to the east. The Gulf's location amid desert regions makes it subject to intense and frequent dust storms, where a large fraction of the aerosols delivered to the Gulf is principally derived from adjacent arid lands (Chase et al., 2006). The GoA also receives long-range atmospheric dust from distant deserts (e.g.: Sahara dust (Abed et al., 2009)). In addition to the desert mineral dust, the GoA is influenced by air masses containing anthropogenic aerosols originating from Europe during most of the year (Kouvarakis et al., 2001). However, the source of dry deposition to the Gulf depends on the timing of deposition, where the GoA is affected by two different wind directions; the prevailing northerly and the southerly winter winds.

The atmospheric dry deposition to the Gulf is expected to increase due to the impacts of climate change. As aridity and potentially dust fluxes are expected to increase in the future (Tegen et al., 2004; Woodward et al., 2005), dust-dominated systems may become more common in this region. These aeolian fluxes to the GoA are likely to play a significant role in modifying the chemical composition of seawater. While dust deposition can stimulate the surface marine productivity by providing important nutrients (Dulac et al., 1996; Bergametti et al., 1992; Bishop et al., 2002; Jickells et al., 2005) especially in oligotrophic water (Duce et al., 2008) as that of the GoA (Levanon-Spanier et al., 1979; Batayneh et al., 2014), it may also contribute toxic elements and other contaminants which may affect the primary productivity and the marine biodiversity. The GoA has regular seasonal cycles of water mixing (during winter) and stratification (in summer). The impacts of airborne contaminants to the Gulf are likely to be significant during the summer stratification period, where metals, nutrients and phytoplankton are trapped in the euphotic zone (Mackey et al., 2007).

In the GoA, atmospheric dry deposition is the major external source of trace elements and is likely to exceed their supply from continental runoff input (Chase et al., 2011). This has led to the widespread realization of the importance of dust deposition, particularly the elements contained in the mineral dust. Although the GoA has been studied with regard to air pollutants and their impacts on the marine ecosystem, little information currently exists on the relative contribution of trace metals from atmospheric dry deposition to the Gulf.

This study is designed to quantify the atmospheric dry fluxes to the GoA with emphasis on the northeastern corner (Jordanian side of the GoA), and to investigate their relative contribution of trace metals. Furthermore, it compares the present results with those

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previously reported for the same region (and other coastal regions) to help provide a baseline for evaluating future changes of atmospheric fluxes in this region.

The GoA is the eastern segment of the V-shaped northern extension of the Red Sea (Fig. 1). It is about 180 km long with a maximum width of 25 km, decreasing to about 5 km at the northern tip. It extends from the Jordan shoreline in the north to the Strait of Tiran in the south. The surface water of the GoA is oligotrophic with a shallow but stable thermocline for most of the year, except during the winter, when winds drive convective mixing of deep (higher-nutrients) and surface waters. The water temperature in the upper 200 m varies from 20 °C in the winter to 26 °C in the summer. The high evaporation rate of seawater (365 cm/year), sparse rainfall and negligible runoff, result in high salinity (in the upper 200 m) ranging from 40.3‰ to 40.8‰ in the winter and from 40.5‰ to 46.6‰ in the summer (Badran and Foster, 1998; Manasrah et al., 2004, 2007; Al-Taani et al., 2014). Water lost to evaporation is primarily compensated by inflow in the upper 80 m of water from the Red Sea to the GoA (Murray et al., 1984).

The GoA hosts one of the most diverse coral communities in the world that are particularly susceptible to pollution including airborne dust. The susceptibility of GoA to pollution is due to its relatively small volume, the lack of significant wave activity and the low rate of water exchange between the GoA and the Red Sea. The average residence time of water in the Gulf ranges between one and three years (Klinker et al., 1976; Paldor and Anati, 1979; Hulings, 1979). The prevailing northerly wind, with an average speed of approximately 18–28 km/h and a maximum activity during the summer months, accounts for most of deposition events. However, the southerly wind patterns dominate during winter, may be initiated by Khamaseen wind blowing in the spring, are responsible for sand and dust storm events in southern Jordan and the adjacent regions (Abed et al., 2009). The Khamaseen winds mobilize dust from the interior of North Africa (Sahara desert) to the east and northeast over the eastern Mediterranean countries, including Jordan (Abed et al., 2009).

Dust samples were collected in 2012 for different months to evaluate seasonal differences in dry deposition. The dust samples were obtained from three sites distributed along the Jordan GoA coast (Fig. 1) using three funnel-like stainless steel traps (0.5 m × 0.45 m) placed on the roof of a 20 m high building. The variations in particle size of dust depend on, among others, the height of collection, where the average diameter of the dust particle size decreases with increasing the height of collecting point (Rosen, 1964; Ahmed et al., 1987).

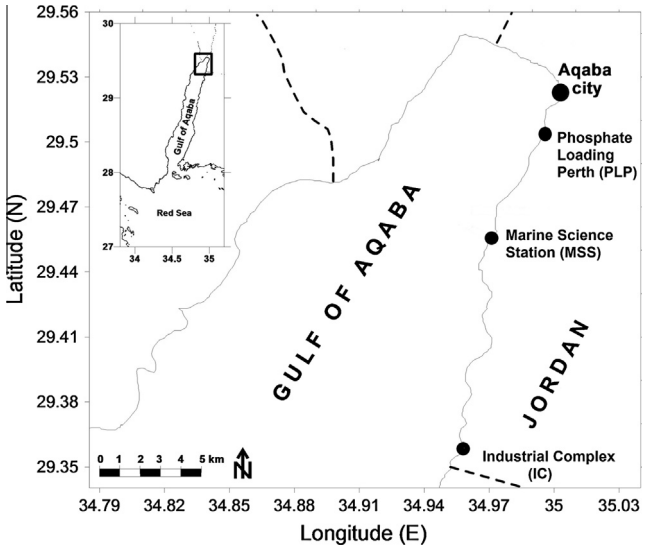

Fig. 1. Location map of the Gulf of Aqaba and the collection sites (PLB, MSS and IC).

The first trap was placed near the Phosphate Loading Berth (PLB), which is the southernmost portion of the main Aqaba port. The second trap was placed next to the Marine Science Station (MSS), which is a protected Marine Reserve area located about 5 km south of PLB. The third site was selected in the vicinity of the Industrial Complex (IC) about 16 km to the south of MSS.

Following samples collection, dust trapped samples were washed into a nylon bag using distilled water. Dust samples were filtered using What-man filter paper No. 41/5 cm, oven-dried at 55 °C, ground and homogenized. 0.2 g of dust sample was placed in a 100 ml polyethylene bottle and 4 ml of HCl (25%), 4 ml of HNO_3 (25%) and 2 ml of HF (40–48%) were added. The mixture was sonicated in water-bath at 70 °C for 2 h. Following 2 h, 50 ml of H_3BO_3 (39 g/l) was added to the solution and was re-sonicated until solution became clear. Then 40 ml of distilled water was added to obtain a 100 ml solution. The solution of the digested samples was analyzed for metal contents by Atomic Absorption Spectrophotometry (NOVA A300, Analytik Jena, Leybold, Germany).

The average dry deposition rates to the northeastern GoA in different seasonal period during 2012 are presented in Table 1. The seasonal flux variations in atmospheric deposition were apparent, with highest value observed in the summer months (60.05 mg/m^2/day) and lowest occurred in the winter season (3.70 mg/m^2/day). The average deposition rates in fall and spring seasons were 19.32 and 11.95 mg/m^2/day, respectively. The airborne dust fluxes in the summer account for about 63.21% of the total deposition rate observed during the study period, whereas the winter dust constitutes about 3.89% (Table 1). The total atmospheric inputs were estimated to be 95.01 mg/m^2/day.

The high fluxes of atmospheric deposition observed in the GoA are related to dust storms resulting in large contributions of mineral dust to the dry deposition. Dust storms in this desert region, frequently observed in the summer and triggered by the strong northerly winds, can mobilize large quantities of soil and transport particle-rich air masses toward the Gulf. As these dust-laden air masses are pushed up and over the GoA, larger particles are removed via gravitational settling such that the air mass becomes enriched in fine particles, and finally deposits particulates on the water surface. In addition to the southward winds, the prevailing dry conditions, during the summer months, accelerate dust emissions and bring the dust to its maximum activities.

While the surrounding deserts are potentially an important source of mineral dust to the Gulf, it is believed that the dry-lands located north of the GoA are particularly the major source, where much of that materials end up in downwind marine ecosystems of the Gulf. The GoA is located downwind in close proximity to the arid dust producing area of Wadi Araba (and other adjacent deserts), where the strong northerly winds blow over an extensive lands with high percent of fine material, that are delivered to the Gulf (Yusuf, 2007).

Although the dry deposition fluxes to the GoA showed temporal fluctuations, it is likely that the rate of deposition varies spatially. This is because the deposition events are dependent on the

Table 1
Seasonal deposition rates (mg/m^2/day) to the GoA in 2012.

Season	Deposition rate	Percent (%)
Spring	11.95	12.57
Summer	60.05	63.21
Fall	19.32	20.33
Winter	3.70	3.89
Total	95.01	100