Quaternary International 429 (2017) 86–99

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Aeolian dust deposition in the southern Aral Sea region (Uzbekistan): Ground-based monitoring results from the LUCA project

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ARTICLE INFO

Article history:
Available online 1 April 2016

Keywords:
Dust deposition
Central Asia
Aral Kum
Monitoring
Deposition dynamics

ABSTRACT

As larger parts of the former Aral Sea have been desiccated, more (and harmful) dust storms (DS) and dust deposition (DD) occur more frequently in the surrounding area. Due to the prevalent wind directions, the southern Aral Sea region is affected stronger by these DS and DD as other areas around the former Aral Sea. The densely populated study area belongs to the autonomous republic of Karakalpakstan and the autonomous oblast (district) Khorezm within the Republic of Uzbekistan. For improving the knowledge about the spatial and temporal distribution of DD in the study region, seven sampling stations of the Uzbek meteorological survey have been equipped with passive deposition samplers between 2003 and 2012. The monthly amount of dust, the grain sizes, the mineralogical and chemical composition were determined and in several cases individual dust storm events were analyzed as well. Although the monthly average dust deposition was relatively low (598.4 kg/ha), the peak deposition during dust storms was up to 160 times higher than this average. While the seasonal DD rate was increasing from spring to fall, the health related threshold excess showed the highest intensity during spring and summer. At most stations the grain size composition of the dust samples (85–90% are silt and clay dominated) was very similar to the composition of the near surface soils. The stations Muynak and Jaslyk, representing dust originating from the Aral Kum, are characterized by dust rich in HCO_3, SO_4 and Ca. Among the trace elements, heavy metals were analyzed because of their health-affecting potential. The total heavy metal concentrations in the southern Aral Sea region are relatively low compared to the results from other parts of Uzbekistan. Zinc showed the greatest dominance close to the Aral Kum, while chromium on the other hand increased its percentage with a growing distance to the former Aral Sea. The spatial and temporal dynamics of the dust deposition as well as the distribution of heavy metals indicate a further need for ground based research for the improvement of the database and a better understanding of the dust mobilization, transport and deposition mechanisms in the Aral Kum and the southern Aral Sea region.

1. Introduction

The aeolian transport of small particles is a natural phenomenon which occurs worldwide. In arid regions the mobilization, transport and deposition are of particular importance as they can cause manifold ecological and economic problems and can lead to severe dust storms (Gomes and Gillette, 1993; Goossens et al., 2001; Sun and Zhao, 2008).

Dust transported and deposited in arid regions can contribute to the soil salinization (Popov, 1998) and impair the photosynthetic efficiency (Razakov and Kosnazarov, 1996; Usmanov 1998). Dust entrained in the air can affect the respiratory systems of humans and lifestock (Taylor, 2002; Orlovsky et al., 2004; Ochmann and Nowak, 2009; Gao and Washington, 2010). The damages caused by aeolian dust are amplified wherever excessive anthropogenic activities impair the natural ecosystems (Griffin et al., 2001; Sivakumar 2007; Ginoux et al., 2012; D'Odorico et al., 2013). Large scale desertification and human-made soil erosion increase the amount of mobilized dust while the contamination of the source regions (e.g. with heavy metals, fertilizers or pesticides) can result in toxic or saline dust (Phillips, 1999; Youlin et al., 2001; Field

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http://dx.doi.org/10.1016/j.quaint.2015.12.103

et al., 2010). The most symbolic example for the dramatic effects of unsustainable anthropogenic activities has become known as the Aral Sea syndrome (Opp, 2007; Opp and Groll, 2009), the largest human-made ecological disaster (Saiko and Zonn, 2000). The Aral Sea basin has been used for oasis farming for several millennia, but until the 20th century the land use did not lead to a significant flow reduction of the Aral Sea tributaries, as the crop, irrigation, and water management were well adapted to the arid climate (Matley, 1970). During the Czarist, and later and more importantly the Soviet period the irrigated area expanded exponentially (+40.6% between 1918 and 1960; +216.9% between 1918 and 2008; 3.44 million ha in 1950, 7.86 ha in 1990 and 10.00 million ha in 2000; Opp, 2007) as the Aral Sea basin became the major cotton producer for the Soviet Union (Matley, 1970). A vast irrigation network was created in the early 20th century in order to support this agricultural growth, mainly in the Fergana and Zarafshan valley, the lower Amu-Darya, Murgab, and Tedzhen rivers (Matley, 1970; Opp, 2007). Cotton became the most important crop cultivated during the second half of the 20th century (16.9% of the irrigated area in 1918; 48.9% in 1960) and since the independence of the Central Asian states it is an important economic factor for this region. However, the expansion of this cash crop farming comes at the expense of a very high water demand of the cotton plants in the arid climate of the Aral Sea basin has led to an unsustainable increase of the water consumption for irrigation purposes (+41.2% between 1918 and 1960; +106% between 1918 and 2008). A dynamic population growth (+129% between 1918 and 1960; +660% between 1918 and 2008) and the industrial proliferation of the 20th century have further increased the water demand. The result of this development is the overexploitation of the available water resources provided by the two large streams of the Aral Sea basin – Amu-Darya and Syr-Darya (Dukhovny and de Schutter, 2011; Gaybullaev et al., 2012a, b; Groll et al., 2015; Karthe et al., 2015). Prime examples for this are the Kara Kum Canal, which even though its construction has not been completed and it does not reach its planned destination, diverts one third of the river flow of the Amu-Darya, or the Zarafshan river, which does no longer reach the Amu-Darya as more than the available water resources are consumed by the irrigation farming in the Samarkand, Navoi and Bukhara provinces in Uzbekistan (Groll et al., 2015). Overall, more than 94 km^3 of water are diverted from the rivers in the Aral Sea basin annually (ZOI Environmental Network, 2010), which drastically decreases the inflow into the Aral Sea. By 2008 almost 90% of the lake's water volume and 74.3% of its former surface area were lost (Dukhovny, 2008; www.cawater-info.net, 2011). The once fourth-largest inland lake of the world desiccated into three fragments of which only the northern part (the "Small Aral") is considered to be savable (Fig. 1). Of the two southern parts, only the western (deeper) lake remains as a permanent water body, while the larger but shallower eastern part has been transformed into a desert called Aral Kum, covering almost 54,000 km^2.

The desiccation of the Aral Sea is in its dimensions a spectacular manifest of human ambitions, but it has repercussions reaching much further than just the loss of water, as the irrigation farming not only consumed vast amounts of this precious resource, but also created highly polluted drainage water, which was returned to the large streams and finally dumped into the Aral Sea. For instance, 29,000 t of pesticides were used in Karakalpakstan between 1980 and 1992 (72 kg/ha compared to 1.6 kg/ha used in the US and 4 kg/ha used in Russia during that time period; Ataniyazova, 2003). As a result fertilizers (e.g. Ammonium nitrate fertilizer, Ammonium chloride fertilizer, Ammonium sulphate fertilizer, Nitrogen phosphorus fertilizer, Potassium chloride fertilizer; FAO, 2003), pesticides (e.g. DDT, phosalone, toxaphene and lindane) accumulated in the Aral Sea as well as salts which were leached from the salinized irrigated fields (Micklin, 1988; Zetterström, 1999; O'Hara et al., 2000; Whish-Wilson, 2002). Heavy metals (e.g. nickel, lead, mercury and zinc, vanadium, copper, cadmium and chromium), radioactive matter and oil products from the upstream ore mining and processing, industrial and urban waste water have added to the pollution of the Aral Sea (Wiggs et al., 2003a; Kulmatov and Soliev, 2009; Kulmatov and Hojamberdiev, 2010a; Groll et al., 2015). The continued input of pollutants and the reduced water inflow led to an accelerated increase of the water salinity (10.2 g/l in 1947; 90 g/l in 2002). Once the saturation point was reached, the pollutants accumulated in the sea sediments (Létolle et al., 2005). Today, a salt layer of at least 0.5 m thickness covers large parts of the Aral Sea bed. As those salty deposits were exposed by the receding water, the aeolian processes, namely erosion, started remobilizing the chemical compounds contained in those sediments (Micklin, 1988; Orlovsky and Orlovsky, 2001; Spivak et al., 2012). Estimates put the amount of salty (and potentially polluted) dust blown out of the dry sea bed between 43 and 75 10^6 t per year (Micklin, 1988; Saiko and Zonn, 2000) which characterizes the Aral Kum as one of the most important dust sources worldwide (Shi and Zhao, 2003). Based on sporadically conducted remote sensing analyses, the amount of dust originating in the Aral Kum and the main directions of its transport are known on a regional scale. However, there is still much uncertainty about the when and where of the dust deposition and about the chemical properties of the dust and its effects on the arable land on the human health (Orlovsky et al., 2004; Dukhovny, 2008). In order to provide ground based dust deposition monitoring in the Aral Sea basin, two research projects – CALTER (Long Term Ecological Research Program for Monitoring Aeolian Soil Erosion in Central Asia; 2006–2010; funded by the European Research Council; Groll et al., 2013) and LUCA (Land Use and Human Welfare in Central Asia; 2010–2013; funded by the Volkswagen Foundation) – had been initiated with the following objectives:

- Analysis of the spatial and temporal characteristics of the dust and sand deposition in the southern Aral Sea region;
- Analysis of the connections between the dust deposition dynamic and meteorological parameters;
- Analysis of the mineralogical and chemical characteristics of the deposited material;
- Comparison of the dust characteristics with local soil characteristics and an estimation of the effect of deposited dust on the arable land.

2. Regional setting

The dust monitoring research has been carried out in the southern Aral Sea region and covers the two autonomous regions Karakalpakstan and Khorezm as well as the Navoi Province (Fig. 2). This research area is characterized by an arid climate with long and dry summers. The annual precipitation rate is below 150 mm and the average air temperature is above 10 °C (Indoitu et al., 2012). Due to the flat topography of the Turan Lowland and the sparse vegetation cover, high wind speeds are very common as well. The research area spans approximately 500 km from west to east and 400 km from north to south and is adjacent to four major source areas for aeolian dust – the Kyzyl Kum ("red desert") to the northeast, the Kara Kum ("black desert") to the south, the Ustyurt Plateau to the west and the newly formed Aral Kum to the north.

The typical soils in the arid regions of Central Asia are Regosols, Calcisols and Solonchaks, which are prone to aeolian erosion and can be characterized by high salt concentrations, due to their origin as marine deposits in the former Cenozoic Sea (Opp, 2005; Scheffer and Schachtschabel, 2010). The less arid steppe regions on the other

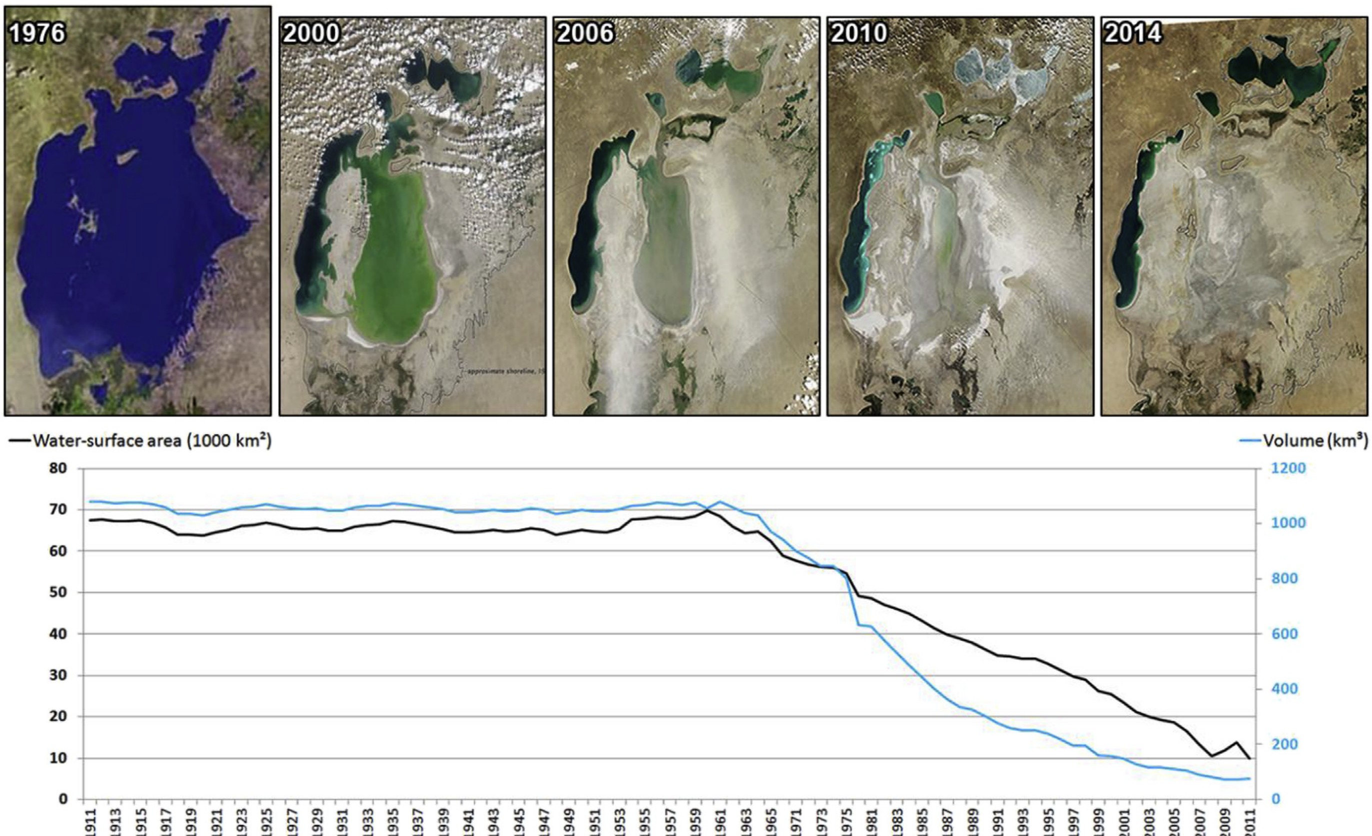

Fig. 1. Desiccation of the Aral Sea between 1976 and 2014 and water surface and volume data between 1911 and 2011 (www.visibleearth.nasa.gov, 2014, data: Nachtnebel, 2007; www.legos.obs-mips.fr, 2015).

hand are characterized by Chernozem, Kastanozem, and Solonetz soils, which are also highly erodible (Scheffer and Schachtschabel, 2010).

Seven meteorological stations were chosen for the dust monitoring and the collection of meteorological data – Muynak, Jaslyk and Takhiatash in Karakalpakstan, Beruniy, Urgench and Yangibazar in Khorezm and Buzubay in Navoi (Fig. 2). This regional focus on the southern Aral Sea region was based on the results from previous studies and long-term observations in the frame of other research projects in Khorezm, which had identified the dominance of northern winds and thus a mainly southern vector for the dust transport from the Aral Kum (Fig. 3; Romanov 1961, Orlovsky and Orlovsky, 2001; Orlovsky et al., 2005; Bennion et al., 2007; Galayeva and Idrissova, 2009; Kovalevskaya et al., 2009; Micklin, 2010; Wang et al., 2010; Groll et al., 2013). This allowed detailed analysis of the impact of the Aral Kum on the river delta and the floodplains in the lower Amu-Darya catchment which are densely populated and intensively used for agricultural purposes.

3. Material and methods

Passive deposition samplers were used for the analysis of the spatial and temporal distribution of the aeolian processes. The sampler design was kept deliberately simple in order to ensure long-term endurance and maintainability under field conditions in remote areas and consisted of a plastic tray (diameter 23 cm), filled with a plastic foil (to prevent losses caused by the sparse precipitation) and artificial grass, as the dust and sand sink. Samplers of the same design had been used successfully in Central Asia by various research groups (O'Hara et al., 2000; Tolkacheva, 2000; Wiggs et al., 2003a, b; Orlovsky et al., 2004). The samplers were mounted on poles of 3 m height and carefully emptied on a monthly basis. In selected stations the dust sampling began in 2003, while the majority of the stations were integrated into the monitoring program in 2006. The dust sampling in the southern Aral Sea region continued until the end of 2012.

The collected samples were analyzed in laboratories in Tashkent (Uzbekistan) and Marburg (Germany) for the following parameters:

- Sample mass using a precision scale with an accuracy of 0.0001 g;
- Grain size distribution by means of microscopic grain size counting in four representative subsamples per sample with an accuracy of 0.00063 mm (Groll et al., 2013);
- Mineralogical composition using X-ray diffraction with standard deviation of less than 1% (Debye and Scherrer, 1916);
- Elemental composition using the wavelength dispersive X-ray fluorescence with a sensitivity of more than 50 cps per μg/g and a standard deviation of less than 0.5% (WDXRF; Glocker and Schreiber, 1928) and the heavy metal composition using flame atomic absorption spectrometry with a maximum resolution of 50–250 ng/ml (Beaty and Kerber, 1993).

In addition to the collected dust, soil samples in three clearly distinguishable depths (at the surface, in 5–10 cm depth and in 25–30 cm depth), were collected in 2011 at six of the seven stations as well as on the dry bottom of the Aral Sea and analyzed using the same methods applied to the dust samples, allowing a comparison of dust and soils from the same station as well as an estimation of

Fig. 2. Research area and dust sampling stations (base map: UN, 2004, modified).

the impact that the dust has on the topsoils. All near surface soil samples were identified as “arenic” (sand-dominated). They could be characterized by light yellowish, partly cross-bedded sandy, weakly coherent material with very low (or no) organic content.

Each station also provided meteorological data, including the average monthly air temperature, monthly precipitation sums, daily wind speed and direction data as well as information about the occurrence and duration of dust storms. All laboratory and meteorological data were then statistically analyzed and interpreted with consideration of additional (literature and database) data.

4. Results and discussion

For this study, a total of 321 dust samples have been collected. The average dust deposition across all samples was 598.4 kg/ha*month while the median was 37.6 kg/ha*month. This shows that the majority of dust samples, and thus the majority of months, were characterized by low deposition intensity while only a few samples showed the impact of dust storm events with a very high dust deposition intensity. The maximum deposition had been registered at the station Buzubay in September of 2009, when during 14 h 1870 kg/ha were deposited, an amount that is 160 times higher than the average across all samples, more than 2500 times higher than the median and 2 times the deposition intensity recorded during the second largest dust storm event recorded during this study (station: Jaslyk; month: July 2009; dust deposition: 21.6 kg/ha during a 20 min dust storm event). Both of these exceptional dust storm events occurred in 2009 and from the ten months with the highest dust deposition rate 50% are from that year (followed by 2007 with 40% and 2008 with 10%). These vast differences between individual months and years also show in the annual averages of the dust deposition (Fig. 4). 2009 was a year characterized by a very strong dust deposition with an average dust deposition intensity of more than 2770 kg/ha*month. This is 6 times higher than the average of all years, 8 times higher than the median and 17 times higher than the average of all years except 2009 (156.6 kg/ha*month).

Loking only at the average deposition rates does only reveal one part of the picture, as strong singular events can have a major influence on the averages, so that they not always reflect the actual impact of the aeolian transport of dust on a region. In order to estimate the severeness of the dust deposition, a health related threshold was used to indicate the potential harmfulness of the dust deposition activity in a certain region or period. The threshold used in this study was derived from the German clean air act (TA

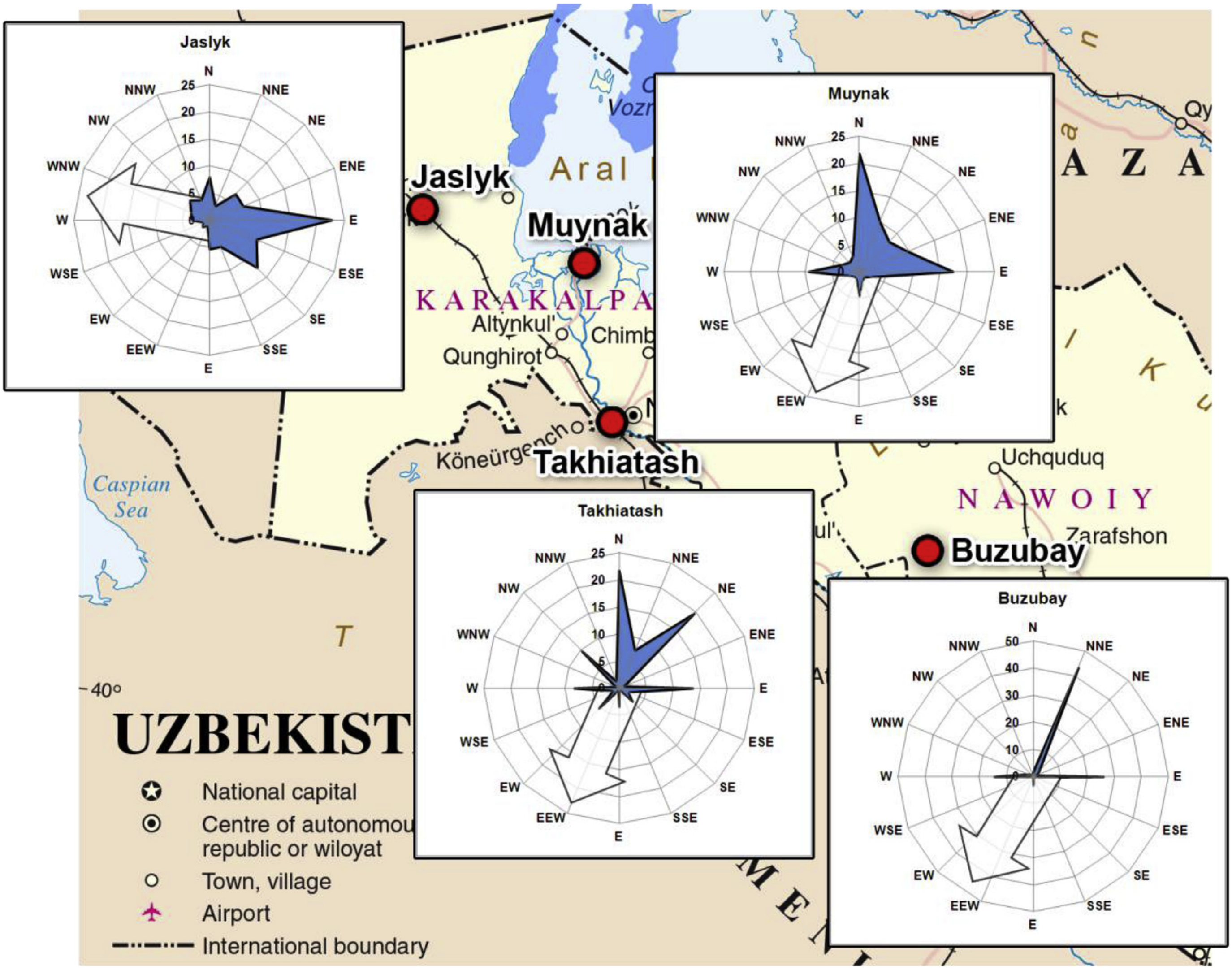

Fig. 3. Wind directions (in %) and resulting dominant wind direction for four stations in the southern Aral Sea region (based on daily data for January 2009 to December 2011; base map: UN, 2004, modified).

Luft; BMU, 2002) and is, based on extensive clinical research on the effect of dust on the human respiratory system, set at 0.35 g/m^2 and day over an extended period of time (or 10.5 g/m^2*month). Based on this threshold the percentage of samples (=months) exceeding this value have been calculated and the results can also be found in Fig. 4. And this data draws a quite different (and complementary) picture about the impact of the aeolian dust deposition in the southern Aral Sea region. Between 2003 and 2012 the number of months with potentially harmful dust deposition intensity has increased from well below 25% (7% in 2003, 22% in 2004) to 54% in 2011. Even though there is variability between years, the dust deposition intensity in recent years has reached a level where every second to third month poses a potential health risk for the local population.

The dust deposition in the southern Aral Sea region not only shows an annual, but also a seasonal and monthly variability as can be seen in Fig. 5. The month with the highest average dust deposition was September (2913 kg/ha*month), followed by July (1488 kg/ha*month). All other months showed much lower deposition rates (62–174 kg/ha*month). This shows the importance of high impact dust storm events, as the analysis of the health related threshold excess rates revealed that the highest health risk occurred during February (44% of all samples), followed by April (38%) and a more general high during the summer months (33% in June and 34% in July). On a seasonal level the disparities between the average dust deposition and the percentage of threshold excess are even more obvious. Fall is characterized by the highest average dust deposition (1310 kg/ha*month) but also by the lowest percentage of months exceeding the health related deposition threshold (22%). During spring and summer on the other hand less dust is deposited (101 and 611 kg/ha*month), but this deposition is more consistent, so that the threshold is exceeded during more months (26% and 32%).

This characteristic dust deposition clearly distinguishes the southern Aral Sea region from other regions in Central Asia, which have been analyzed using the same methodology during the same period (Groll et al., 2013). This becomes also obvious when all the dust samples are categorized based on their deposition rate (Fig. 6) and compared to samples from Eastern Uzbekistan, Kazakhstan and Turkmenistan. The dust deposition in the southern Aral Sea region is much more intense (median: 37.6 kg/ha*month; threshold excess: 26.8%) than in Eastern Uzbekistan (where no large dust

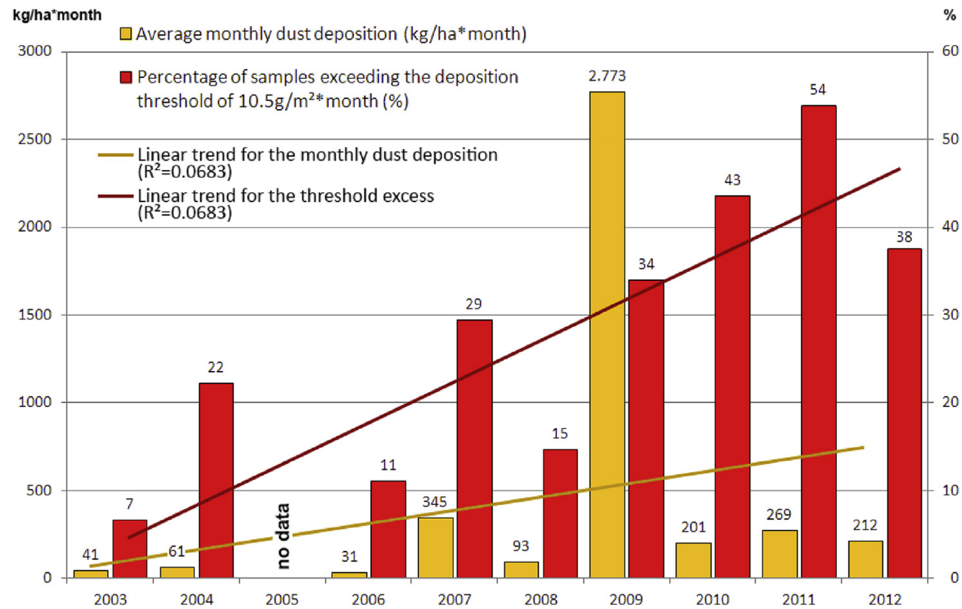

Fig. 4. Interannual dynamic of the dust deposition (in kg/ha*month) and the health related threshold excess (in % of samples).

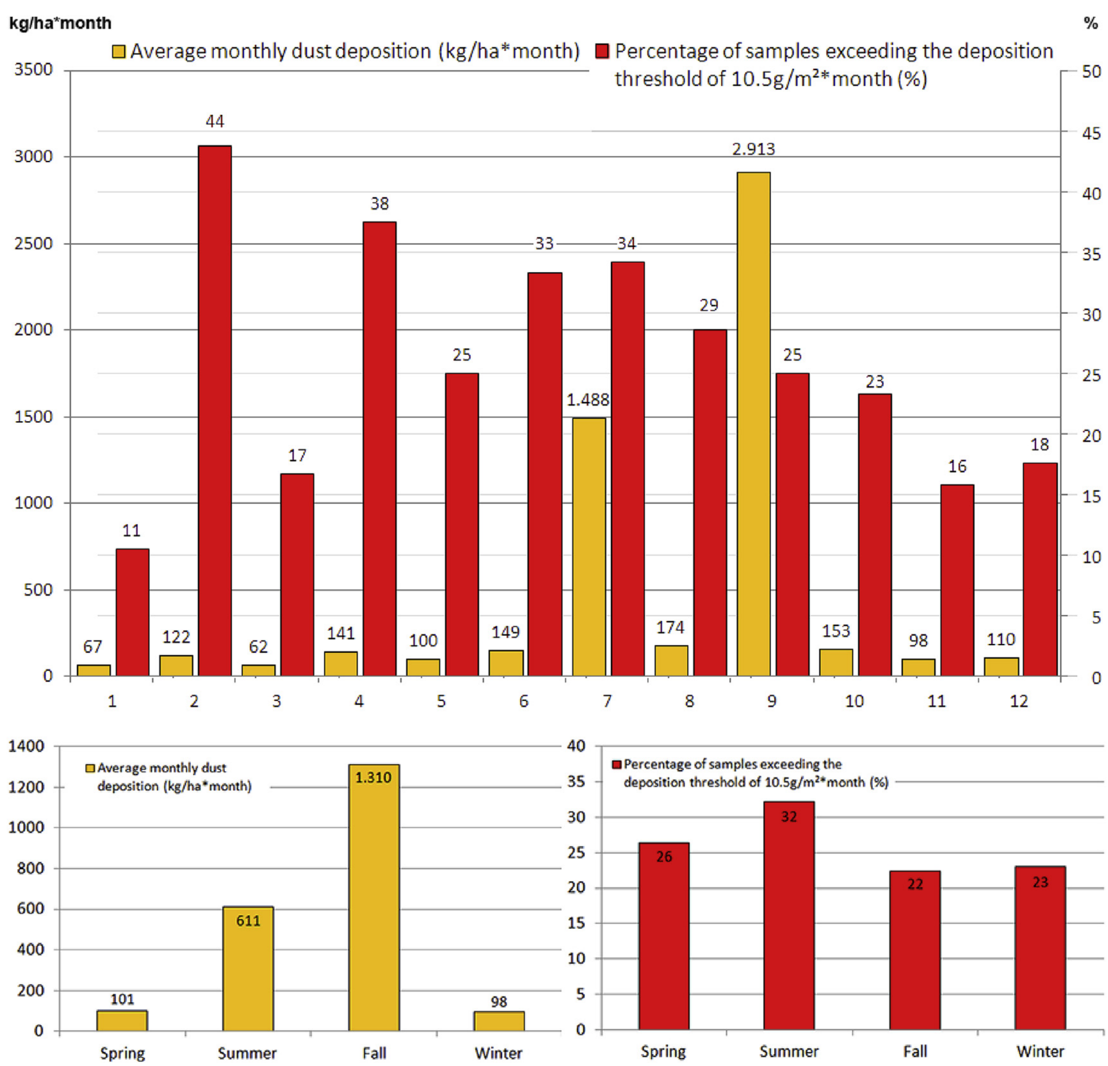

Fig. 5. Monthly and seasonal dynamic of the dust deposition (in kg/ha*month) and the health related threshold excess (in % of samples).

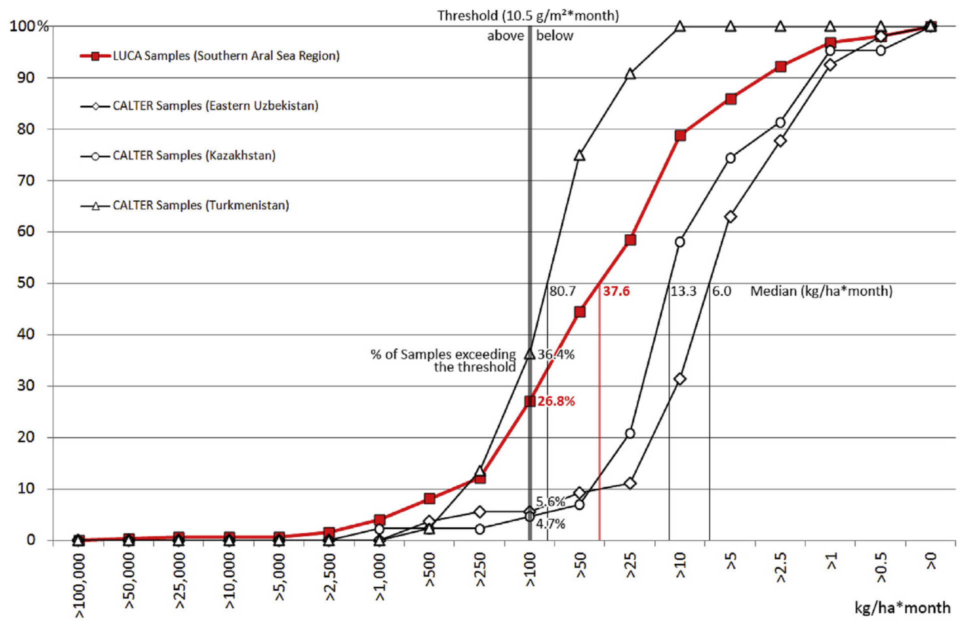

Fig. 6. Cumulative frequency of the dust deposition rates (in kg/ha*month) of the stations in the southern Aral Sea region (LUCA samples) in comparison to samples from Kazakhstan, Turkmenistan and Eastern Uzbekistan (data from the CALTER project, Groll et al., 2013).

source is nearby; median: 6.0 kg/ha*month; threshold excess: 5.6%) and in Kazakhstan (which lies North of both the Aral Kum and the Kyzyl Kum and thus not in the man vector of the aeolian dust transport; median: 13.3 kg/ha*month; threshold excess: 4.7%), but less intense than in Turkmenistan (median: 80.7 kg/ha*month; threshold excess: 36.4%), which is affected by the Aral Kum and by the Kara Kum.

The analysis of the cumulative frequency of dust deposition categories is not only interesting for the comparison of different regions, but also for highlighting the differences between individual stations (Fig. 7). Buzubay and Beruniy, both located near the Kyzyl Kum (compare Fig. 2), were characterized by a very high median of the dust deposition (617.8 kg/ha*month and 164.0 kg/ha*month), followed by Jaslyk and Muynak, located near the Aral Kum (101.4 kg/ha*month and 72.5 kg/ha*month). The stations which were farthest away from either of those two dust sources (Kyzyl Kum and Aral Kum) showed a less intense dust deposition activity with medians of 15.7 kg/ha*month in Yangibazar and Urgench and 20.5 kg/ha*month in Takhiatash. The dust deposition variability between individual stations becomes even more obvious for the percentage of samples (=months) exceeding the health related deposition threshold. These results range from 4% in Takhiatash, signaling that there was no significant dust related health risk near that station, to 86.7% in Buzubay, which means that there was a significant dust related health risk near the Kyzyl Kum during the vast majority of sampled months. At the stations near

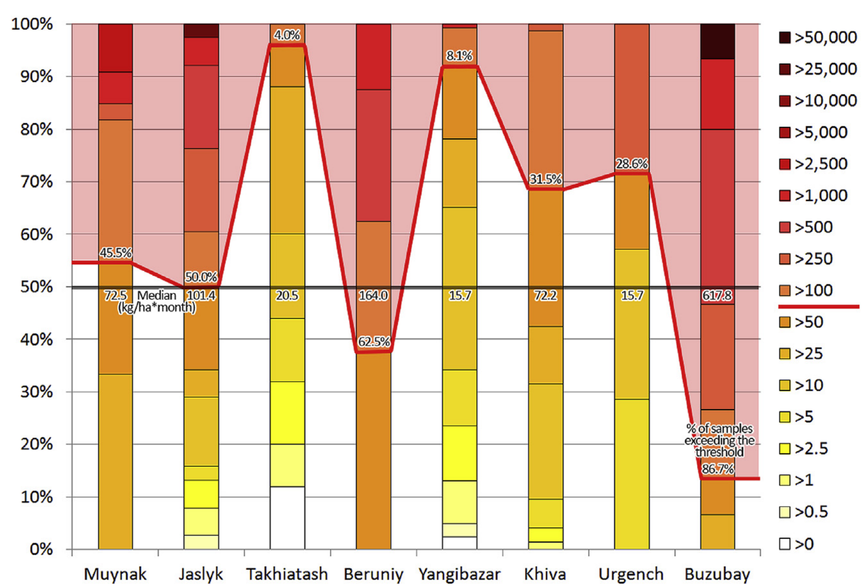

Fig. 7. Cumulative frequency of the dust deposition rates (in kg/ha*month) and percentage of threshold excess at the stations in the southern Aral Sea region.

the Aral Kum almost every second month (50.0% in Jaslyk and 45.5% in Muynak) had to be considered a health risk, showing the impact of the newly formed desert.

The deposition intensity is a crucial parameter for the assessment of the impact of the aeolian transport of material from the Aral Kum and other source regions, but it is not the only one. The second parameter of importance is the grain size distribution of the deposited material. The grain size distribution is influenced by both the wind speed and the distance from the source region. Larger and thus heavier grains (medium sand and larger – >0.2 mm diameter) require a larger force in order to be set into and kept in motion (O'Hara et al., 2000; Zepp, 2004; Wu et al., 2006; Goudie, 2009; McKnight and Hess, 2009; Semenov 2011). They can only be mobilized during strong wind events and even then there preferred mode of transportation is a saltation near the earth surface. They are thus limited to a short-distance transport. Finer grains (fine sand, silt and clay – <0.2 mm) will be transported over much larger distances and thus represent the long-distance part of the deposition. These smaller grains are of particular importance for the health impact, as they are more likely to enter the respiratory system. Fig. 8 shows the grain size distribution for the dust collected at six stations in the southern Aral Sea region. These results are contrasted by the grain size distribution in three different soil layers at those stations as well as in the dry bottom of the Aral Sea.

The soil data shows for all but one station (Beruniy) a higher percentage of smaller grain size particles near the soil surface while the percentage of larger grains is much smaller near the surface (Fig. 8). More interesting, however, is the comparison of the soil data from the meteorological stations and the dry bottom of the Aral Sea (Aral Kum). In the southern Aral Sea region, the topsoils contain almost 90% of silt and clay (88.7% in Takhiatash, 88.5% in Jaslyk, 85.8% in Urgench), the average across all meteorological stations was 75.6%. The soil samples from the Aral Kum on the other

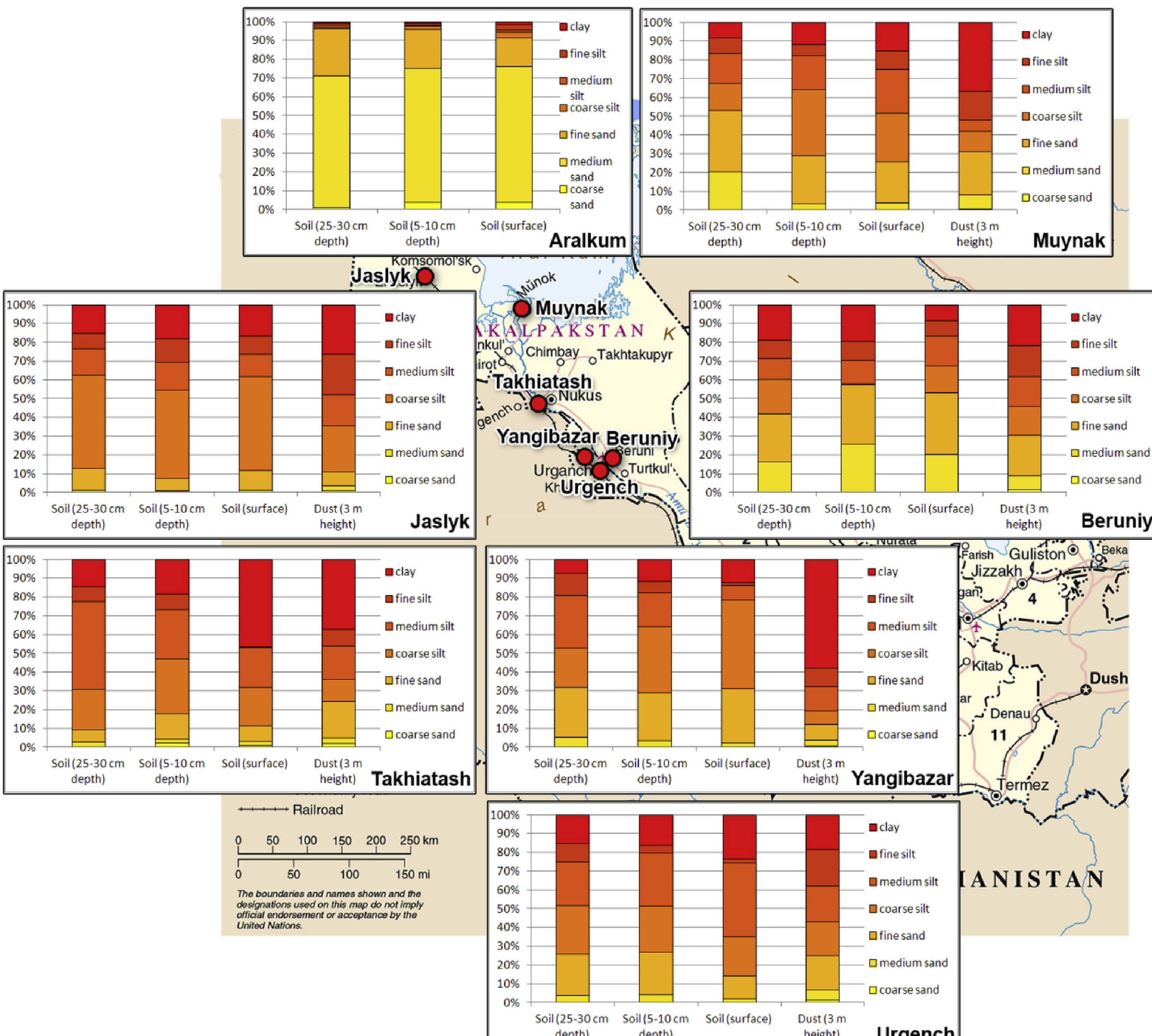

Fig. 8. Grain size composition for the dust and soil samples from seven stations in the southern Aral Sea region.

hand only contained 2.2% of silt and clay at the soil surface (and even less in deeper layers).

The differences between the dust and soil samples are less pronounced and at most stations the grain size composition of the dust samples was very similar to the composition of the soils. The dust collected at Yangibazar is the exception, with the highest percentage of clay (58.2%) found in any dust or soil sample. As for the dust deposition rates, the grain size distribution varies greatly between individual stations, stressing the influence of local characteristics and the importance of a long-term and multi-station dust monitoring system.

As the mobilization of grains of different size classes is related to the wind speed and the wind speed (maximum and average) is also a parameter influencing the overall dust deposition rate, the monthly dust deposition and the average grain size per month are related as well. As can be seen in Fig. 9, this relation is not as straightforward as could be expected (higher deposition rates = larger average grain size, Goudie and Middleton, 2006). The data rather suggests that low deposition rates are related to larger average grain sizes (Fig. 9A). A closer analysis (clustering the data into four deposition rate groups and displaying the results on a logarithmic scale, Fig. 9B) however does not confirm this inverted relation of the two parameters. All four datasets show a wide spread of average grain diameters and the averages for each group are very similar (0.037 mm–0.062 mm) and do not follow any significant trend. This suggests, that the grain size composition of the dust samples is not controlled by the dust deposition intensity (and thus the wind speed), but that other factors like the local land use or the availability of source material for the short distance transport also play an important role. A further investigation of this interesting relation between dust deposition, grain size composition and local and meteorological parameters could deepen our understanding of the dust deposition processes and their controlling factors.

Besides the amount and frequency of the dust deposition and the grain sizes of the deposited material, its chemical composition is also of interest for the evaluation of the overall impact of the aeolian dust transport originating from the Aral Kum and other

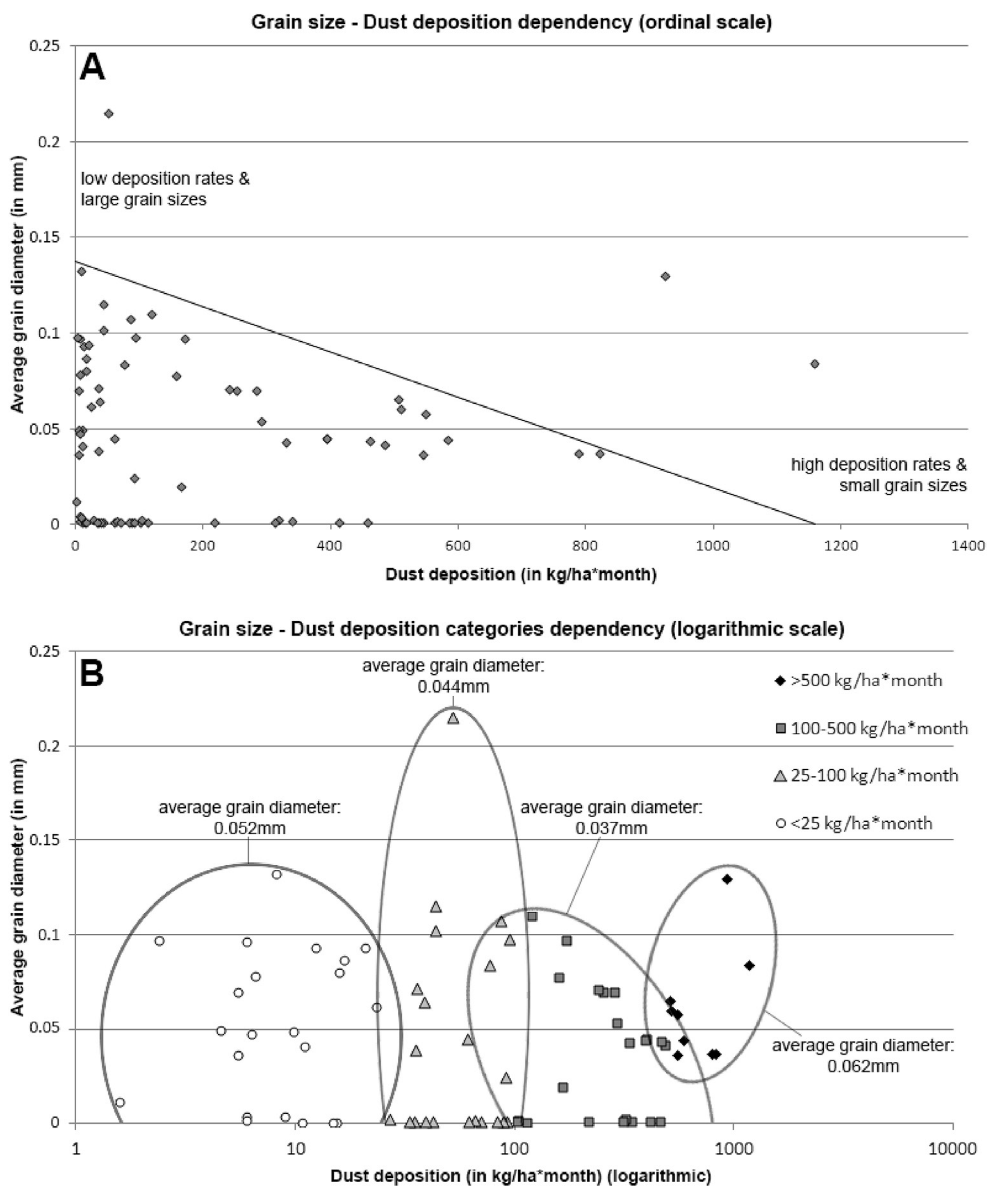

Fig. 9. Dependency of average grain size (in mm) and dust deposition (in kg/ha*month).

source regions. Fig. 10 shows the chemical composition of the dust collected at four stations in the research area. The results for Muynak and Jaslyk are very similar, representing dust originating from the Aral Kum. This dust is rich in HCO_3 (33–34%), SO_4 (23%) and Ca (15–17%). These three compounds constitute 72–73% of all the dust material collected at these two stations. Cl (11–14%) and Na (6–7%) are less frequent while other elements and compounds (K, NO_3, NH_4 and Mg) add up to only 8–9%. This chemical composition is characteristic for the sediments found in the Aral Sea, which are rich in hydrogen carbonate and gypsum (Khakimov, 1989; Razakov, 1999). The dust from the station in Buzubay shows are very different characteristic, which represents the central Kyzyl Kum as the source region of the dust. The material deposited here is dominated by HCO_3 (54%) while gypsum is much less important (Ca 12%; SO_4 14%). The concentrations of Cl (4%) is also much lower in Buzubay than in the stations near the Aral Kum, while the amounts of Ca (12%), Na (6%) and the rarer elements and compounds (K, NO_3, NH_4 and Mg) are comparable.

The chemical composition of the dust collected in Takhiatash is more even, with SO_4 as the strongest faction (26%), followed by HCO_3 (22%) and Cl (21%). Na and Mg were also detected more frequently, but the difference to the other stations was less pronounced. This dust is clearly distinguishable from the dust collected in Buzubay, even though both stations are near the Kyzyl Kum. However, as Takhiatash is near the western fringe of that desert and close to the Amu Darya, the source material is of a different geological and thus chemical characteristic (Khakimov, 1989; Gintzburger et al., 2003; Lioubimtseva, 2008). Unlike the dust collected in Buzubay, the dust from Takhiatash shows a stronger influence of short-distance aeolian deposition of material from the river terraces and by dust originating from the irrigated and salinized fields of the Takhiatash oasis.

In order to assess the toxicity of the dust originating from the Aral Kum, the concentration of several heavy metals was analyzed in the soil and dust samples. Fig. 11 shows the results of this analysis for the samples taken in the Aral Kum near Muynak and from six meteorological stations in the southern Aral Sea region.

The total heavy metal concentration in all soil samples is relatively low compared to the thresholds of the German law on soil protection (BBodSchG 1998), which has been used as a point of reference. However, there some characteristic differences between the sampling sites, especially with regard to the sampling depth. In 25–30 cm depth the Aral Kum soil samples were characterized by the highest concentration of heavy metals. Zinc clearly dominated the heavy metal spectrum with 123.0 ppb, followed by chromium (42.6 ppb), copper (30.0 ppb) and nickel (27.8 ppb). Closer to the soil surface all heavy metals, with the exception of arsenic (58%) and selenium (67.5%), showed a sharp decrease of their concentration by more than 85% and up to 89% (e.g. the zinc concentration dropped to 13.2 ppb in 5–10 cm depth). At the soil surface, however, all analyzed heavy metals showed higher concentrations again. This increase was not as dramatic as the difference between the 5–10 cm and 25–30 cm soil layers, but more varied. Zinc showed the highest increase (+152.5%), followed by cadmium (+120.0%) and lead (+108.8%), while selenium (+20.3%) and arsenic (+28.1%) showed the smallest increase. The higher heavy metal concentrations in the deeper layers of the Aral Kum soils seem to be the result of the sedimentation of material transported to the Aral Sea by the Amu-Darya. Due to the very low amounts of rainfall in this region, a vertical transport and enrichment of heavy

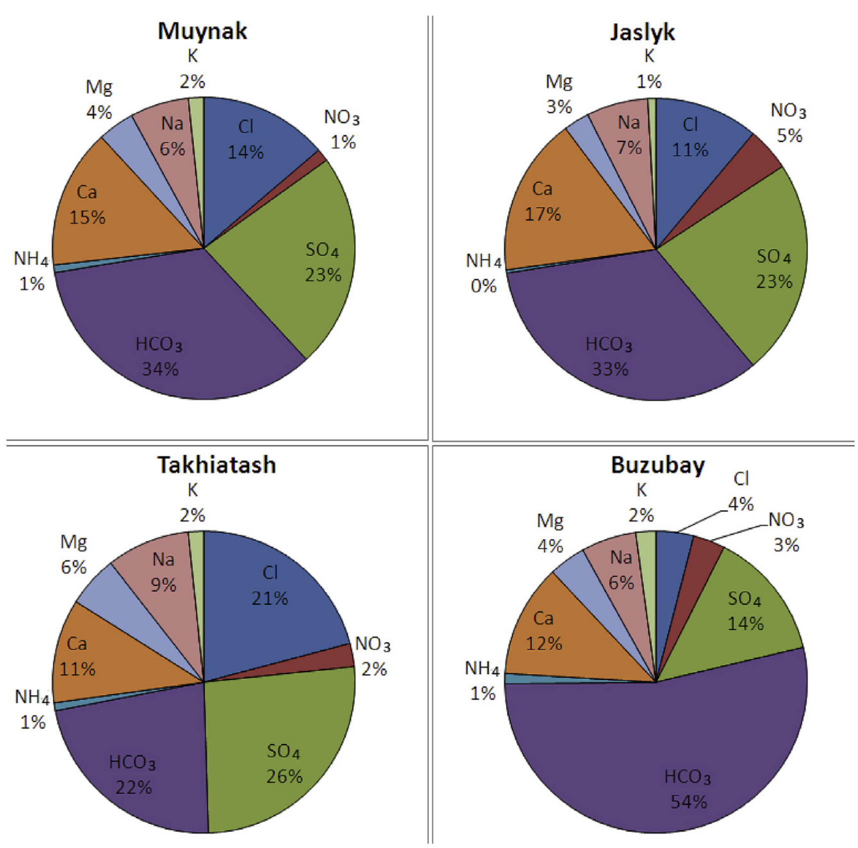

Fig. 10. Chemical composition of the dust samples from four stations in the southern Aral Sea region.

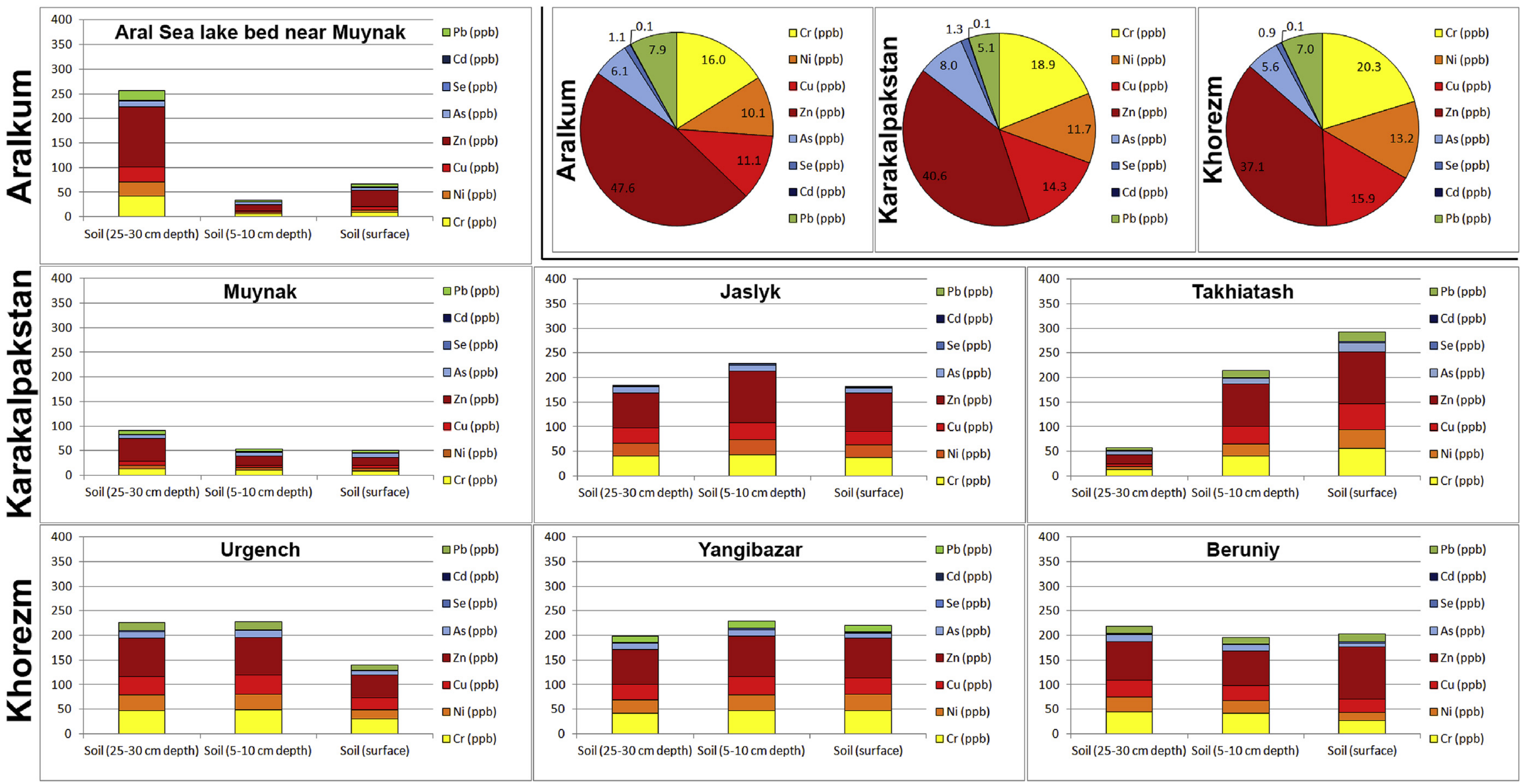

Fig. 11. Heavy metal concentrations in soil samples from the stations in the southern Aral Sea region.

metals in deeper layer can be excluded. Otherwise, snow melting and vertical transport of any element from the surface into deeper layers is possible, because the surface or near-surface aeolian sediments are often dominated by fine sand and lack any humic horizon. Thus, the higher heavy metal concentrations at the surface of the Aral Kum are most likely the result of the aeolian input of these pollutants after the desiccation of the lake. This means that considerable amounts of heavy metals are subject to aeolian transport in Central Asia.

The soil data from the meteorological stations shows a similar qualitative heavy metal composition than the data from the Aral Kum (Fig. 11), with zinc being the dominant heavy metal, followed by chromium, copper, and nickel. There are regional differences between the Aral Kum, Karakalpakstan and Khorezm, but they are outweighed by the similarities. Zinc showed the greatest dominance close to the Aral Kum (47.6% in the Aral Kum, 40.6% in Karakalpakstan and 37.1% in Khorezm), while chromium increased its percentage with a growing distance to the Aral Kum (16.0% in the Aral Kum, 18.9% in Karakalpakstan and 20.3% in Khorezm). Following the characteristics of the dust deposition intensity the difference between individual stations are even greater than the ones between regions, at least for the soil samples from Karakalpakstan, where the stations are spread out over a larger area. Muynak, being closest to the Aral Kum was characterized by the overall lowest heavy metal concentration (64.6 ppb), while Jaslyk and Takhiatash showed much higher values (197 ppb and 188 ppb).

Jaslyk shows a much higher heavy metal concentration in all analyzed soil layers than Muynak. Located on the Ustyurt Plateau, the direct anthropogenic influence at this station is negligible which leaves a higher natural concentration of heavy metals in the sediments (especially Oligocene clay, lime and sand stones as well as salty deposits in the eastern parts of the plateau) of the Cenozoic Sea as the main reason for these elevated concentrations. They are in fact comparable to the heavy metal characteristics of the lower soil layers in the Aral Sea bed, which was formed during the same geological period. Takhiatash is a good example of a strong local influence on the heavy metal characteristics. Located near the banks of the Amu Darya, the riverbank sediments are a major source of heavy metals (Kulmatov and Hojamberdiev, 2010b), which originate in the Pamir mountains and are transported downstream by the Amu Darya. Takhiatash is also a relatively large settlement with a population of approximately 65,000, which is much larger than the other sampling stations. Therefore, different sources or emissions by anthropogenic activities (e.g. the Takhiatash gas and oil power plant, which dates to 1961) can be considered as reasons for relatively higher heavy metal concentrations.

The stations in Khorezm are grouped closer to each other and thus the variation in the heavy metal concentration is far less variable between these stations. The overall average concentrations ranged between 198 ppb (Urgench) and 216 ppb (Yangibazar; 206 ppb in Beruniy) and none of the stations showed a significant increase of the heavy metal concentration near the soil surface (in Urgench) the concentration at the surface even dropped by 88 ppb. This is remarkable, especially as the dust samples collected in 21 meteorological stations across the Aral Sea basin during the CALTER project between 2006 and 2009 (Groll et al., 2013) were characterized by heavy metal concentrations that were 42% higher than the concentrations found in the soil samples (300 ppm in the dust samples from Khorezm, Fig. 12). Dust samples from Kazakhstan and Turkmenistan, for which the Kyzyl Kum and the Kara Kum are more important as a source of dust than the Aral Kum were characterized by lower heavy metal concentrations, but as Khorezm is not only located relatively near the Aral Kum but also densely populated and supplied by the Amu Darya with its own heavy metal load (Kulmatov and Hojamberdiev, 2010b) it is, based on the available data, impossible to assess the influence the Aral Kum dust has on the influx of heavy metals in the southern Aral Sea region.

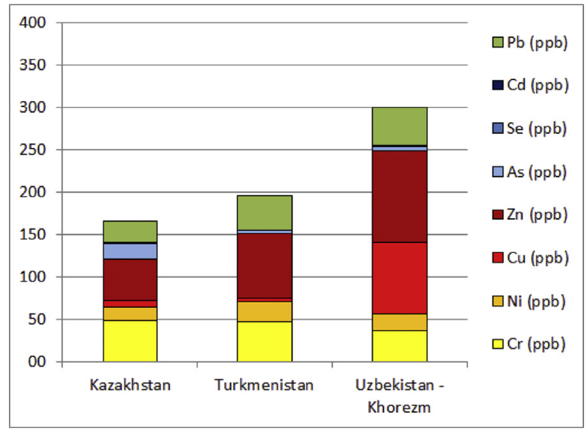

Fig. 12. Heavy metal concentration in dust samples from Central Asia.

5. Conclusions

As the Aral Sea shrinks and is replaced by the newly formed salty desert known as the Aral Kum the potential for the mobilization of salts and heavy metals raises considerable concerns for the southern Aral Sea region, which is mainly affected by dust from the Aral Kum. This study has analyzed the spatial and temporal variability of the dust deposition in this region and shown that both the dust deposition intensity and the health related deposition threshold excess have increased during the last ten years. However, the dust deposition also follows seasonal patterns with the summer and autumn months being especially prone to high intensity dust deposition events (dust storms) while the overall average deposition intensity causes stronger health concerns during the spring and early summer month. The variability is even greater at the level of individual stations and local factors can play an important role for the dust deposition. Buzubay was characterized by the highest dust deposition intensity, caused by the proximity to the Kyzyl Kum, while in Takhiatash the dust deposition was much smaller, but due to anthropogenic impairments the heavy metal concentrations were much higher there. Muynak, located directly on the southern shore of the former Aral Sea, showed very small heavy metal concentrations, indicating that the Aral Kum might not be the major source of these pollutants, but that local geological and anthropogenic factors are prevalent. The high variability of the temporal and spatial dust deposition intensity, the grain size composition and of the chemical composition of the dust lead to the conclusion that a continuous on-site monitoring is needed for a better understanding of the dust translocation processes in the densely populated areas of the southern Aral Sea region and their impact on the human health and the intensely used land. The research setup presented here is very cost effective and easy to maintain so that a continuation of this long-term ecological monitoring is feasible, even during times of monetary restrictions.

Acknowledgements

Funding for this study had been provided by the 6th research framework of the European Union and the Volkswagen Foundation.

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