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Dust emission and environmental changes in the dried bottom of the Aral Sea

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ABSTRACT

In the 1990s, the western world became aware of the ecological disaster of what was once the fourth largest lake in the world – the Aral Sea. The drastic desiccation of the Aral Sea led to the intensive development of desertification processes in the region and the formation of a new desert, the Aralkum. In the last few decades, the Aralkum has become the new "hot spot" of dust and salt storms in the region. Dust storms and their source areas have been determined and analyzed by the NOAA AVHRR, TOMS and OMI data. An analysis of the land-cover changes in the dried bottom of the Aral Sea revealed that the north-eastern part of the Aralkum Desert is one of the most active dust sources in the region, responsible for high aerosol concentrations in the atmosphere. Dust plumes that sweep up from the dried bottom of the Aral Sea have become larger, and dust storms have become more powerful, since the bottom exposure. The main change that occurred in the land cover was the considerable reduction of vegetation and small water bodies, while the areas of solonchaks (salty pans) and sandy massifs increased significantly.

1. Introduction

In the 1990s, the western world became aware of the ecological disaster occurring at the fourth largest lake in the world – the Aral Sea. The demise of the Aral Sea has been called one of the 20th century's worst environmental catastrophes and has been referred to as a "quiet Chernobyl" (Glantz and Figueroa, 1997). The drastic desiccation of the Aral Sea led to the intensification of desertification processes in the region and the development of a new desert, the Aralkum, on the dried sea bottom. In the last few decades, the exposed bottom has become the new "hot spot" of dust and salt storms in the region.

The drylands of Southern Kazakhstan, Uzbekistan and Turkmenistan have always been affected by hazardous dust storms. In the last thirty years of the 20th century, however, the dust storm activities showed a significant downward trend over the entire region (Indoitu et al., 2012). In contrast, the Aral Sea region has shown a major increasing trend in dust storms' strength and frequency (Spivak et al., 2012). In the absence of the conventional system of dust storm monitoring – there are no meteorological stations established on the dried bottom of the Aral Sea, *and the meteorological station on Vozrojdenie Island was closed in 1992* – the only source of information is remote sensing.

Remotely sensed data from satellite-based platforms such as the Advanced Very High Resolution Radiometer on-board the NOAA Polar Orbiting Environmental Satellite (NOAA AVHRR), the Total Ozone Mapping Spectrometer (TOMS) on the Nimbus and Earth Probe platforms, METEOSAT, the Geostationary Operational Environmental Satellites (GOES) series, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS), and the Earth Observing System's MODerate resolution Imaging Spectroradiometer (MODIS) monitor and collect data regarding dust emission sites and trajectories of dust aerosol movement (Chavez et al., 2002; Fan Yi-da et al., 2001; Prospero et al., 2002). The above listed high temporal resolution data as well as moderate spatial resolution data such as Landsat and SPOT are widely used for dust storms studies.

In most cases, the satellite images capture clouds near the dust plumes, which consequently, create difficulties in differentiating the two. Many researchers have shown that to be able to distinguish between clouds and dust aerosol, it is necessary to display the images in VIS- and IR-band combinations and to pay close

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attention to the specific dust plume structures. False color images with an RGB combination of the 1, 2, and 4 bands show the dust plumes in a light yellow–brownish color, and clouds in a bright yellow color (Rivera et al., 2006). Janugani et al. (2009) showed that a band combination of 1, 4, and 5 for the colors red, green, and blue of the 5-band NOAA-AVHRR imagery was probably the best one with which to locate the dust sources during visual interpretation. Miller (2003) proposed using the combination of MODIS bands 1, 3, 4 and 26 in the visible spectrum and infrared bands 31–32 to discriminate dust loads from clouds and the desert background.

Several techniques have been developed to detect dust storms based on visible and thermal infrared satellite data: band math analysis, differencing of radiation temperature or the infrared split-window technique (BTD), single band thresholding and multi-band combinations (Ackerman, 1989, 1997; Janugani et al., 2009). Recent studies have demonstrated the efficiency of using thermal bands for monitoring dust aerosol outbreaks (Hu et al., 2008). An effective method for detecting and differentiating dust from clouds using satellite remote sensing has been the brightness temperature difference (BTD) of NOAA/AVHRR channel 4 and channel 5 (Chavez et al., 2002; Janugani et al., 2009; Tsolmon et al., 2008; Prospero, 1999). The BTD of the two bands can distinguish not only a dust storm but also the density of dust and sand in the moving mass (Tsolmon et al., 2008).

Dust particles produce specific emissivity characteristics in the VIS (8.6 μm)–NIR (11 μm) and NIR (11 μm)–TIR (12 μm) bands. In the first spectral range the dust particles create brightness temperature differences similar to those of thin cirrus clouds (Roskovensky and Liouand, 2005), whereas in the second spectral range the BTD is negative because dust has a higher emissivity at 12 μm than at 11 μm (Huang et al., 2007). At the same time, the thermal infrared spectrum of minerals strongly depend on the particle size and there is a temperature difference between the surface and the dust aerosols in the air (Hu et al., 2008). A negative BTD is mainly caused by the silicate absorption of the shorter wavelengths, while the ice and water particles absorb longer wavelengths (Li et al., 2010).

Data from different sensors show a good consistency both in the long and the short term. A comparison of TOMS data with other sources of information (METEOSAT/VIS) demonstrates that in spite of certain limitations of the former, such as a low spatial resolution of 50 × 50 km and probable cloud contamination at the sub-pixel level, both datasets are consistent and allow for the analysis of dust loads at regional and global scales (Chiapello and Moulin, 2002; Chiapello et al., 2005). Evan et al. (2006) compared data from the Aerosol Robotic Network (AERONET), METEOSAT and TOMS over the North Atlantic to test the algorithm for dust detection over water and found that long-term AVHRR imagery plays an important role in the study of airborne dust. Narrowband satellite sensors (e.g. AVHRR, HIRS, MODIS, GOES) allow dust load detection, while higher spectral resolution imagery is necessary to quantify dust characteristics (Sokolik, 2002). Tsolmon et al. (2008) analyzed the potential of MODIS and AVHRR data for monitoring and mapping dust storms in Mongolia and northern China, and found the synergy between these two sources of information. Data from OMI coincident with events detected by other sensors have been widely used for tracking the dust trajectories. Jafari and Malekian (2015), who compared five different dust detection algorithms using MODIS data and collated them with OMI AI maps, revealed a high correlation between both products over water and desert surfaces.

Previous studies confirmed that the aerosol index (AI) values of NASA TOMS can be used to map the spatial and temporal distributions of atmospheric aerosols, and correspondingly, the dust storm sources (Engelstaedter et al., 2006; Prospero et al., 2002; Washington et al., 2003). According to the AI values determined by TOMS, the most active dust-producing areas are connected to large dried lake basins: the Tarim Basin in China, the Lake Eyre Basin in Australia, the Salar de Uyuni in Atacama, Chile, and the Great Salt Lake Desert in the USA (Washington et al., 2003). The key dust source in the world is the Bodélé Depression, in northern Chad, which is a shallow basin of exposed diatomite sediment, much of which was deposited under the paleolake Megachad some 7000 years ago when it was the biggest lake on the planet (Washington et al., 2003, 2009).

The drylands of Central Asia experience dust storms with frequencies that are among the highest in the world (Orlovsky et al., 2005). The appearance of additional vast area prone to wind erosion namely anthropogenically created Aralkum Desert had inevitably led to the activization of dust emission processes.

Prior to the modern recession, the Aral Sea experienced a number of water level declines and subsequent recoveries over the last 10 thousand years (Micklin, 2010; Singh et al., 2012). Recessions and advances of the sea waters resulted from major changes in the river discharge into it, caused by significant climatic changes, and during the past 3000 years, also by human activities (Micklin, 1988).

In modern times, the Aral Sea's ecological disaster was the result of the USSR government's decision, in the 1960s, to undertake an agricultural project for increasing cotton production in Soviet Central Asia. The expansion of irrigated fields resulted in a drastic reduction of the water volume discharged into the lake. In 1960, the water flow from the Amudarya and Syrdarya Rivers, which represented the major input for the Aral Sea, varied from $56 \times 10^9\ m^3$/year to $60 \times 10^9\ m^3$/year (Orlovsky and Orlovsky, 2001); by the mid-1980s, the water flow had almost ceased, and the water volume discharged was $3.5 \times 10^9\ m^3$/year (Saiko and Zonn, 2000). By 2007 the water inflow to the Aral Sea was about $5 \times 10^9\ m^3$/year $-10 \times 10^9\ m^3$/year (Dukhovny and Stulina, 2011). The lake has progressively shrunk due to a lack of recharge by the rivers and high evaporation during summer time. By 1999, the lake level had dropped by 18 m, down to the mark of 33.8.m MSL (Orlovsky and Orlovsky, 2001). Following the division of the Aral Sea in 2005, the salinity level in the Large Aral increased by as much as 90 g/l (western part, depth 21 m) and 160 g/l (eastern part, depth 28.3 m), while in the Small Aral, it decreased and reached 17 g/l (Aladin et al., 2009). By 2009, the Aral Sea was divided into three separate water bodies: the Small Aral, which has been restored after the construction of a dam in 2005; the western part of the Large Aral adjacent to the Ustyurt Plateau; and a little pond that appears during rainy seasons in the eastern part of the former Large Aral.

The glaciers from the surrounding mountain chains are the main providers of the water flow for the two major Central Asian rivers: the Syrdarya and the Amudarya. Rising (due to climate change) temperatures have been melting Central Asia's glaciers. The Pamir-Alai glaciers lost 19% of their mass during the second half of the 20th century (Perelet, 2008). The glaciers in the Tien Shan Mountains cover a surface of over 15,000 km^2, which in recent decades, have been losing between 0.1% and 0.8% of their surface per year (Sorg et al., 2012). The intensive melting of the glaciers in the last fifty years has reduced the water flow into the Amudarya and Syrdarya Rivers, contributing, as well, to the desiccation process of the Aral Sea.

These multiple changes have had an enormous environmental impact. The territory was proclaimed an "ecological disaster zone" (Saiko and Zonn, 2000). The critical transformations in the hydrometeorological regime of the Aral Sea has led to soil degradation and the desertification of immense areas (Orlovsky et al., 2004).

Studies of natural ecosystems executed during the 1960s-1990s showed that the desiccation of the sea affected micro- and