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Dust storms and ephemeral lakes

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Abstract

In drylands, both dust storms and ephemeral salt lakes (playas) are common. Observations using remote sensing and ground studies have shown that these playas can be major sources of saline dust storms. Some basins have recently become desiccated as a result of water abstraction by humans, and these have become significant sources of dust. The timing and amounts of dust emissions depends on such factors as rainfall and drought events, the availability of sediment, and the nature of surface crust materials.

***Keywords*:** Dust; Salt; Playas; Sodium sulphate; Deflation

1. Introduction

Dust storms generated from drylands are important phenomena, with a wide range of impacts on the Earth System (Goudie and Middleton, 2006; Ravi *et al*., 2011) and on human health (Goudie, 2014). In recent years, climatological records and remote sensing techniques have been employed to establish the source areas for dust storms (Prospero *et al*., 2002; Washington *et al*., 2003; Washington *et al*., 2006; Ginoux *et al*., 2012). One result of such work is that it has become clear that dust storms can be associated with a role range of geomorphological environments, including river valleys and their terraces (von Holdt *et al*., 2017; Dansie *et al*., 2017), sand dunes (Sweeney *et al*., 2016), loessic soils (Crouvi *et al*., 2017) shale outcrops, and alluvial fans (Zhang *et al*., 2016). However, pre-eminence has been given to closed basins (playas, pans, salt lakes, etc.) (Engelstaedter *et al*., 2003; Mahowald *et al*., 2003), though Crouvi *et al*. (2012) have suggested that in parts on the Sahara this is not the case.

Prospero *et al*. (2002, p. 23) recognised that 'TOMS [the Total Ozone Mapping Spectrometer] shows a remarkably consistent association of dust sources with playas.' Likewise, researches in the Bodélé Depression have shown its primacy in world dust generation (Warren *et al*., 2011). Pans are also highly important in southern Africa, where Vickery *et al*., (2013) reported that more than half of all the dust plumes detected on satellite images originated from them. In the case of the Chihuahuan Desert, Baddock *et al*. (2011) found that despite a total area of only 4%, ephemeral lakes were the source of 48% of the observed dust plumes. In contrast, only 21% of the dust plumes mapped were associated with the high relief alluvial systems which cover over 43% of the area. In the Great Basin of Utah, Hahnenberger and Nicoll (2014) showed that the largest number of observed dust plumes (~60% of all plumes) originated from playas. In the Lake Eyre basin of Australia, Bullard *et al*. (2008), using MODIS data, found that for 2003–6, 37% of plumes originated in areas of aeolian deposits, 30% from alluvial deposits and floodplains and 29% from ephemeral lakes or playas. However in terms of number of dust sources per unit area, they found that ephemeral lakes dominated with 11 times as many dust plumes originating from this category when compared with aeolian deposits, and 6 times as many per unit area compared with alluvial deposits. After a global analysis, Ginoux *et al*.

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(2012) found that 30% of global dust emission originates from terrains associated with ephemeral water bodies. They remarked that 'in West Africa, they account for only 18% of regional emissions, while in all other regions they contribute over twice as much….It is notable that in Australia ephemeral water sources, natural and anthropogenic, make the largest contribution to total emissions, 71%.' Parajuli and Zender (2017) also undertook a global survey of dust activity in relation to landform types, and found that playas were particularly important.

That many basins are associated with wind erosion, deflation and dust emissions is revealed by various characteristics which they possess, including their orientation and alignment with respect to winds, the presence of lunettes on their lee sides, and the existence of yardangs on their floors (Goudie and Wells, 1995). Moreover, dust plumes coming from their floors have been witnessed in the field, and on many satellite images (Figures 1, 2 and 3).

Fig. 1. A dust plume blowing off Lake Siletiteniz, Kazakhstan (from AQUA, April 21st, 2012) (Courtesy of NASA)


Fig. 2. A dust plume blowing from the Mkgadikgadi Pan, Botswana, April 1992

Fig. 3. Dust blowing from the floor of the Death Valley playa, California, May 1979

As shown in Table 1, we now have empirical evidence that many ephemeral lake are associated with substantial dust storm generation and activity. However, what has also emerged is that such dust storms are highly variable in space and time, depending on a whole range of factors, including the nature of the basin surface materials, and the climatic conditions that exist (Figure 3). The purpose of this paper is to review what is known about the links between dust storms and closed basins.

Surface conditions

Moisture – rainfall, groundwater

Cohesiveness – clay content, salt cementation

Salt type (e.g. sodium sulphate)

Vegetation cover (dependant on salinity and moisture)

Saltation activity (to breakdown aggregates)

Sediment Inputs and availability (Past and Present)

Fluvial alluvium

Fans

Aeolian sand

Dust

Biological (e.g. diatoms)

Precipitates

In situ salt weathering

Anthropogenic activity

Desiccation (due to water withdrawal)

Surface disturbance (e.g. by mining, trampling of crust by domestic stock, vehicular activity)

Climatic conditions

Wind activity (including gustiness, topographic funnelling, etc.) leading to deflation and saltation

Rainfall events

Droughts

Temperature and humidity cycles (which effect salts)

Frost effects on aggregates

Fig. 4. Controls on dust emissions from playas

Table 1. Locations where links between dust emissions and playas have been established

Name of basin	Reference
Aiby Lake (China)	Mu, 2002
Alkali Lake (Nebraska)	Zlotnik *et al*., 2012
Aral (Kazakhstan, Uzbekistan)	Indoitu *et al*., 2015
Bodélé (Chad)	Washington *et al*., 2016
Chihuahuan lakes (Mexico)	Baddock *et al*., 2011
Chotts (Algeria)	Mahowald *et al*., 2003
Chotts (Tunisia)	Drake *et al*., 2004
Corop (Australia)	Greene *et al*., 2006
Death Valley (USA)	Goudie and Day, 1980
Eagle Valley Playa, Nevada (USA)	Blank *et al*., 1999
Ebinur Lake (China)	Abuduwaili *et al*., 2011; Ge *et al*., 2016; Liu *et al*., 2011
Etosha (Namibia)	Bryant, 2003
Eyre (Australia)	Bullard *et al*., 2008; McGowan and Clark, 2008
Franklin Lake (USA)	Reynolds *et al*., 2009
Garabogazköl (Turkmenistan)	Kharin, 1984
Great Salt Lake (USA)	Hahnenberger and Nicoll, 2014
Hakskeenpan (South Africa)	Vickery *et al*., 2013
Jaz Murian (Iran)	Rashki *et al*., 2017
Kavirs (Iran)	Gherboudj *et al*., 2017
Kazak Balqash (Ozero Balhas) (Russia)	Gulnura *et al*., 2014
Laguna Salada (Mexico)	Gill, 1996
Laramie Basin (USA)	Greene *et al*., 2006
Mar de Chiquita (Argentina)	Bucher and Stein, 2016
Mkagadikgadi (Botswana)	Bryant *et al*., 2007
Mojave lakes (USA)	Goldstein *et al*., 2017
Mono Lake (USA)	Ono *et al*., 2011
Mourdi depression (Chad)	Gherboudj *et al*., 2017
Namib playas (Namibia)	Eckardt *et al*., 2001
Old Wives Lake (Canada)	Gill, 1996
Owens Lake (USA)	Saint-Armand *et al*., 1986; Cahill *et al*., 1996
Palomas (Mexico)	Baddock *et al*., 2011
Pyramid Lake (USA)	Gill, 1996
Salar de Coipasa (Bolivia)	Bryant *et al*., 2004
Salinas Grandes (Argentina)	Gaiero *et al*., 2013
Salton Sea (USA)	Buck *et al*., 2011; King *et al*., 2011; Frie *et al.*, 2017
Sebkhet te-n-Dghâmcha (Mauretania)	Gherboudj *et al*., 2017
Seistan, (Iran, Afghanistan)	Hickey and Goudie, 2007; Rashki *et al*., 2013
Sevier Dry Lake (USA)	Hahnenberger and Perry, 2015
Siletiteniz (Kazakhstan)	Goudie *et al*., 2016
Taoudenni (Mali)	Goudie and Middleton, 2006
Tarim (China)	Washington *et al*., 2003
Tule Dry Lake (USA)	Hahnenberger and Nicoll, 2014
Tyrrell (Australia)	Greene *et al*., 2006
Umm as Samin, (Oman)	Goudie and Midleton, 2002; Goudie and Middleton, 2006
Urmia (Iran)	AghaKouchak *et al*., 2015
Uyuni (Bolivia)	Gaiero *et al*., 2013; Gholampour *et al*. 2015
Yellow Lake, Texas (USA)	Stout, 2003; Sweeney *et al*,, 2011

Anthropogenic influences

As Gill (1996) pointed out, there are many examples of dust storm generation being influenced by human activities, including vehicular disturbance, mining, trampling of crusts by domestic stock, and overgrazing of vegetation. Probably the most potent human action is to expose basin floors to wind attack as a result of causing lake desiccation by water removal. This has been established for a number of basins, including Owens Lake (Cahill *et al*., 1996), Salton Sea (Frie *et al*., 2017), and Mono Lake in the USA (Saint-Armand, *et al*., 1986; Ono *et al*., 2011), Old Wives Lake in Canada (Gill, 1996), Lake Urmia in Iran (AghaKouchak *et al*., 2015), the Aral Sea (Indoitu *et al*., 2015), and Lake Ebinur in China (Abuduwaili *et al*., 2011). In the case of Ebinur, there was a clear trend of increasing numbers of dust storms between 1960 and 1966. Lake Urmia's area has been reduced by 88% since the 1970s (AghaKouchak *et al*., 2015), while the Balkhash-Alakol depression in eastern Kazakhstan, which has been rapidly desiccating since 1970 after completion of a dam on the Ili River is a significant source of dust (Ginoux *et al*., 2012). Exposure of the lakebed at Mono Lake to wind erosion was primarily caused by the diversion of water from the Mono Basin by the City of Los Angeles from 1941 through 1989. This resulted in lowering the lake level and exposing over 24 km^2 of the lakebed to wind erosion (Ono *et al*., 2011). On the other hand, the flooding or irrigation of dry lake floors can suppress dust storm activity, as in Mexico City (Jáuregui, 1990).

2. Surface conditions

Basins have surface conditions that vary between playas and within playas and which have a marked influence on dust emissions. These include the presence of moisture depending on rainfall events and groundwater conditions, surface cohesiveness relating to clay content and salt cementation, the salt type (e.g. sodium sulphate) that makes up surface crusts, the nature of the vegetation cover (which is dependent on salinity and moisture), and the presence or absence of frost and saltation activity (to breakdown surface aggregates).

The types of salt found in arid basins is highly variable (Goudie and Cooke, 1984). Salt crusts composed of hydrous/anhydrous minerals (such as the two forms of sodium sulphate, mirabilite/thenardite), are more likely to dissolve and re-precipitate repeatedly (i.e., diurnally or seasonally), generating loose crusts, and at Mar Chiquita in Argentina salt emissions were greatest in the cold winter months, when mirabilite tended to dominate (Bucher and Stein, 2016). This confirmed the observation made at the Salton Sea by Buck *et al*., (2011). Their results also indicated 'that surfaces with the highest emissions, up to ∼1 mg m^{-2} s^{-1}, are composed of hydrous/anhydrous salt minerals and minerals with acicular or prismatic crystal habits. Hydrous/anhydrous minerals (mirabilite/thenardite, eugsterite/glauberite, gypsum/bassanite, and numerous Mg sulfates) are more unstable under changing environmental conditions, are likely to dissolve and reprecipitate repeatedly, form less cohesive tiny individual crystals or small aggregates, and are therefore more likely to result in highly emissive surfaces. Salt minerals with acicular or prismatic habits are more likely to be disruptive, enhance salt heave, lessen the degree of interlocking precipitates, and form loose, "puffy" crusts that are highly emissive'. At Sua Pan in Botswana, Nield *et al*. (2016) monitored crust behaviour, and again noted that crust dynamics were related to diurnal hydration and dehydration of key sulphate bearing evaporite phases. By contrast, as Bullard *et al*. (2011) and Goldstein *et al*., (2017) pointed out, sodium chloride-rich evaporites tend to form hard, cemented layers reducing sediment erodibility by wind. Wind tunnel experiments by Nield *et al*. (2016) showed that sodium sulphate rich crusts were more emissive than crusts formed from sodium chloride, while degraded versions of both crusts had a lower emission threshold than fresh, continuous crusts. They also found that dust emission from salt crusted surfaces can occur without saltation, although the vertical fluxes were orders of magnitude lower (∼10 μg/m/s) than for aeolian systems where entrainment is driven by particle impact.

The availability of saltating grains of lacustrine sand and broken crust to abrade and disaggregate the playa surface into fine aerosols was noted as very important in the case of Owen's Lake and the resulting PM_{10} concentrations recorded during major dust storms were among the highest ever recorded in North America (Cahill *et al*., 1996). Measurements at Mono Lake by Ono *et al*. (2011) showed that high PM_{10} emissions correlated with times of high saltating sand flux. In Aiby Lake, China, Mu *et al*. (2002) found that dust was generated by the break up of clay-rich aggregates by freezing-and-thawing action during the winter season, and this also occurs on the Llano Estacado in Texas (Sweeney *et al*., 2016).

There are two main types of playa. In a 'dry' playa, groundwater depth is generally greater than 5 m and so groundwater does not interact with the surface. In a 'wet' playa the groundwater depth is less than 5 m, and so it is near the playa surface, though which water can be lost by evaporation or fluid outflow (as at springs) (Reynolds *et al*., 2007). These two types of groundwater condition are an important factor in dust emissions. As Elmore *et al*., 2008, p. 1758) wrote: 'Fluctuations in groundwater levels can influence dust mobilization through altering surface soil chemistry, forming soil crusts, varying soil moisture, and shifting vegetation community structure and individual plant morphology. The evaporation of soil water, which is replenished by rising groundwater tables, generates salt efflorescences and soil crusts. One surface feature that is found on wet playas is referred to as "puffy ground". The formation of puffy ground seems to be pronounced in systems experiencing seasonal fluctuations in groundwater levels. In these cases, groundwater transports salts to the playa surface via capillary action.' The significance of groundwater depth was also discussed by Pelletier (2006) who noted that playa surface moisture affects dust emissions in two primary ways: first, as a direct influence on threshold wind speed through its effects on soil cohesion, and second, as an indirect control through its effect on vegetation cover. Reynolds *et al*. (2007) drew a clear distinction between wet playas, fed by groundwater, and showed that the production of evaporite minerals during evaporative loss of near-surface ground water results in both the creation and maintenance of several centimeters or more of loose sediment on and near the surfaces of wet playas. Observations that characterize the texture, mineralogic composition and hardness of playa surfaces at Franklin Lake, Soda Lake and West Cronese Lake playas in the Mojave Desert (California), along with imaging of dust emission using automated digital photography, indicate that these kinds of surface sediment are highly susceptible to dust emission. By contrast they found that dry playas have hard surfaces that produce little or no dust if undisturbed except for transient silt and clay deposited on surfaces by wind and water.

Vegetation cover controls deflation. The nature of vegetation cover depends on moisture availability, but also on salinity, with saline areas having less vegetation. If, after a rainfall event, vegetation recolonization occurs rapidly, then dust emissions will be reduced (Zhao *et al*., 2011).

3. Sediment types and inputs

The outputs of dust from basin surfaces depends on a number of factors. In particular the basin surfaces need to provide sources of readily mobilised material, which either exists as a legacy of past conditions (e.g. sediment accumulation in former pluvial lakes) or results from present day inputs. Among these inputs are fluvial alluvium, alluvial fans, aeolian sand, dust, biological material (e.g. diatoms), precipitates of salts, and bedrock that has been broken down by salt attack.

Many basins and their adjoining mountains are the result of tectonic activity, and alluvial fans often form the link between the two systems. Thus, for example, in western China and the Basin and Range Province of the USA, fans deliver sediments into lake basins. The fine component of these fan sediments can be evacuated by wind, and they can also have their size reduced by salt weathering on the playa margin, as was shown in the case of Death Valley in California (Goudie and Day, 1980) (Figure 5).

Fig. 5. A major alluvial fan entering the Death Valley playa at Badwater in 2011, and showing exceptional salt weathering of fan boulders

That salt weathering occurs on playa margins causes and causes rock breakdown to occur, was shown empirically by rock block emplacements undertaken in Tunisia by Goudie and Watson (1984). The process has also been implicated in the formation of the Qattara Depression in Egypt (Aref *et al*., 2002), and has been noted around the saline lakes of the Ethiopian rift (Goudie and Cooke, 1984). The rock flour thus created is susceptible to wind evacuation. One of the most aggressive salt types is sodium sulphate (Goudie, 1977), and this is present in many playas from which dust storms are generated.

One exceptional source of erodible sediment is the material that accumulated in lake basins during past pluvials. This material may be fine-grained material composed of silt and fine sand, or, as in the case of the Bodélé depression in the central Sahara may consist of friable, non-dense diatoms, that are eroded into yardangs (Figure 6) and emitted in dust storms. More generally, lacustrine silts have sometimes been eroded by wind at rapid rates, as indicated by the presence of deep yardangs in early Holocene pluvial sediments. Yardangs formed in dried playa lake sediments are widespread in the Dakhla and Farafra depressions in the Libyan Desert of Egypt. Some of the yardangs are up to 11 m high and given that these yardangs developed in Holocene lacustrine and swamp deposits that were accumulating until about 4000 years ago, this implies late Holocene deflation rates of in excess of 200 cm per 1000 years (Goudie, 2007) (Figure 7). As Prospero *et al*. (2002, p. 23) remarked, 'The playa is the ultimate receptacle of almost all the fine-grained sediments eroded within a basin over a geological time period; thus they are storehouses of fine, dry, unconsolidated (and thus wind-erodible) sediments often in amounts far in excess of production rates in the present climate.'

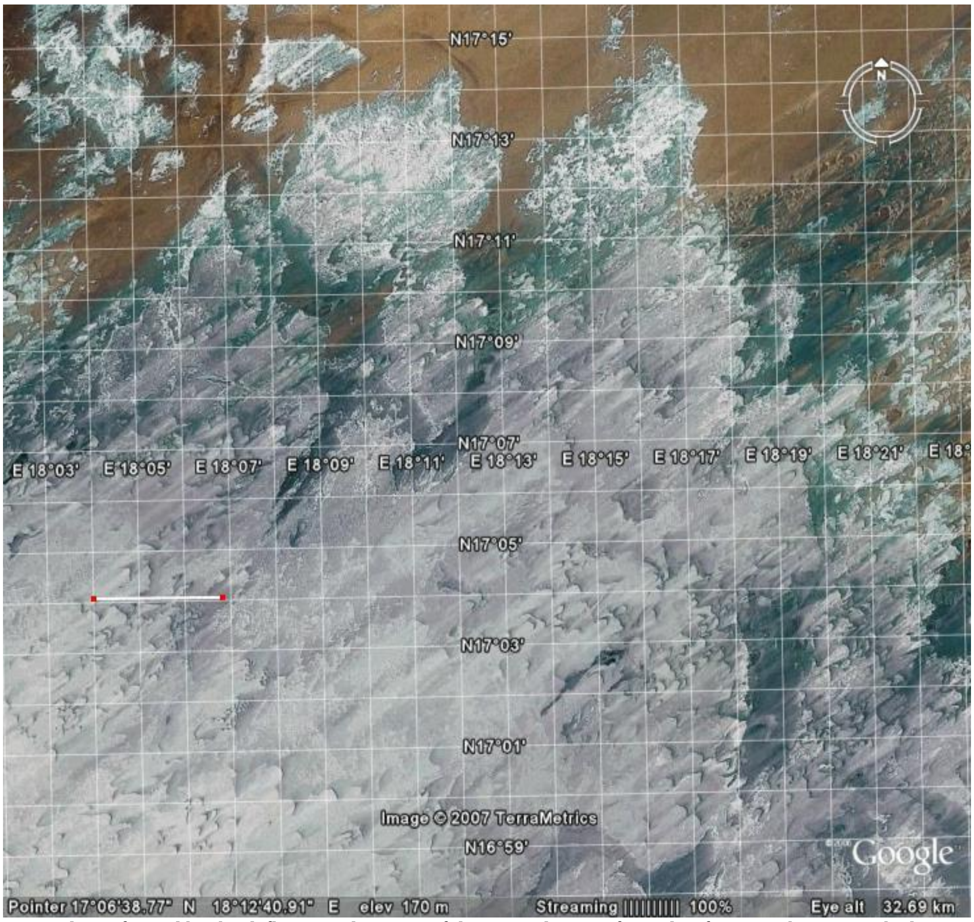

Fig. 6. Yardangs formed by the deflation and erosion of diatomite deposits formed in former Lake Mega-Chad. Courtesy ©2007TerraMetrics and Google Earth

4. Climatic conditions

The climatic conditions that exist in a basin's catchment are another important control of emissions of dust. Among these are wind activity (including gustiness, topographic funnelling, etc.) leading to deflation, rainfall events (leading to sediment inputs, changes in vegetation cover, and changes in surface cohesion), droughts (which cause basin desiccation, reduce fluvial sediment inputs and lead to vegetation die-back), and temperature and humidity cycles (which impact upon salts).

Fig. 7. Tall yardangs formed by wind erosion in early Holocene lake deposits in the Dakhla Oasis, Egypt

Lakes in dryland basins may be subject to frequent changes in extent in response to rainfall events. This has, for example, been shown in the context of the Seistan Basin (Rashki *et al*., 2013) where dust outputs from the Hamoun Lakes have responded to wetting and drying cycles caused by water inputs from the Helmand River (Rashki *et al*., 2031) (Figure 8). After the 1999 drought, the Hamoun lakes complex was absolutely dry and the soil moisture and vegetation cover were significantly reduced, leaving deflatable soil material easily uplifted by intense local winds. As a direct consequence, dust-storm activity increased in both frequency and severity. The same is true with regard to Etosha pan, where inundation events initially cause a reduction in dust emissions (Bryant, 2003). Bryant *et al* (2007) related these inundation events to El Niño-Southern Oscillation (ENSO) and Indian Ocean sea surface temperature anomalies. Lake activity and dust events have also been related to ENSO in Nevada (Reheis, 2006). In Argentina, as a result of rainfall decline the Mar Chiquita shrunk from a maximum area of 7319 km^2 in 2003 to 2448 km^2 in 2014, leaving about 4871 km^2 of exposed dry bottom mudflats. The number of serious dust events remained below five until 2008, and then increased markedly, peaking in 2010 with 36 events. From 2011 to 2013, annual salty dust storms events ranged between 25 and 28 (Bucher and Stein, 2016).

Although wet seasons are intuitively seen as being likely to lead to suppression of dust activity in comparison with drought phases (Mahowald *et al*., 2003), this is not inevitably true (Sweeney *et al*., 2016). There are two effects of precipitation: one that reduces dust and a second that provides new erodible material to surfaces prone to dust generation (such as alluvial and lacustrine sediments) (Reheis, 2006; Elmore *et al*., 2008). Reynolds *et al*. (2009), working at Franklin Lake Playa in the Mojave Desert also noted an association between wet events and dust emissions: ‘High frequency of dust generation appears to be associated with relatively wet periods, identified as either heavy precipitation events or sustained regional precipitation over a few months. Several factors may act separately or in combination to account for this relation. Dust emission may respond rapidly to heavy precipitation when the dissolution of hard, wind-resistant evaporate mineral crusts is followed by the development of soft surfaces with thin, newly formed crusts that are vulnerable to wind erosion and (or) the production of loose aggregates of evaporite minerals that are quickly removed by even moderate winds. Dust loading may also increase when relatively high regional precipitation leads to decreasing depth to the water table, thereby increasing rates of vapor discharge, development of evaporite minerals, and temporary softening of playa surfaces.’

Zlotnik *et al*. (2011, p. 8), working on a salty playa in the Nebraska Sandhills, found that there was a climatically-determined seasonal pattern of dust activity: (1) a winter and early spring phase where precipitated minerals and dehydrated salts cover beaches with snow-like crust and dust; (2) a rainy spring-summer phase where uniform and cohesive crusts are created; and (3) a late summer-fall phase, where receding lakeshores exhibit desiccated salt crust and are deflated through abrasion by saltating dune sand.

5. The nature of sediment outputs

Dust being blown off ephemeral lake basins is often highly saline. Abuduwalli *et al* (2008), working on Ebinur Lake, found that the salinity of dust was high: soluble salts composed 10–25% of the total mass of the collected dust material. Salts were predominantly represented by sodium and calcium chlorides and sulfates. Dust deposition in g/m^2/yr was 68-590, of which salt deposition was from 14-77. Dust emanating from Eagle Valley Playa in Nevada was also very rich in water-soluble salts (Blank *et al*., 1999), while that coming from Mar Chiquita is rich in sodium sulphate (Bucher and Stein, 2016). In the case of Urmia Lake in Iran, the work of Gholampour *et al*. (2015) showed that water soluble salts composed 3–20% of the total mass of TSP and PM_{10}. Gypsum may also be removed from playas. In the case of the Tunisian Chotts (Watson, 1985; Drake 1997) and the Namib Plains playas (Eckardt *et al*., 2001), the emission of gypsum (calcium sulphate) plays a role in gypcrete formation downwind (Drake *et al*., 2004). Some of these materials may be transported over large distances from source. McGowan and Clark (2008) showed that air parcels containing dust originating from Lake Eyre can affect regions many thousands of kilometers from the Australian continent in a relatively short period of time.

Fig. 8. Moderate Resolution Imaging Spectroradiometer (MODIS) image from September 23, 2003 of the Seistan Basin in Iran and Afghanistan. This shows dust plumes coming off the dried up Hamoun Lakes. The Seistan Basin is one of the largest closed basins on Earth and is also subject to high intensity winds (Hickey and Goudie, 2007)

6. Conclusions

Dust storms generated from drylands are important phenomena, with a wide range of impacts on the Earth System and on human health. In recent years, climatological records and remote sensing techniques have been employed to establish the source areas for dust storms. We now have empirical evidence that many ephemeral lake basins are associated with substantial dust storm generation and activity. However, dust storms are highly variable in space and time, depending on a whole range of factors, including the nature of the basin surface materials, and the climatic conditions that exist. Moreover, human actions expose basin floors to wind attack as a result of causing lake desiccation by water removal. Basins have surface conditions that vary between playas and within playas and which have a marked influence on dust emissions. These include the presence of moisture depending on rainfall events and groundwater conditions, surface cohesiveness relating to clay content and salt cementation, the salt type (e.g. sodium sulphate) that makes up surface crusts, the nature of the vegetation cover (which is dependent on salinity and moisture), and the presence or absence of saltation activity (to breakdown surface aggregates). Basin surfaces need to provide sources of readily mobilised material, which either exists as a legacy of past conditions (e.g. sediment accumulation in former pluvial lakes) or results from present day inputs. Among these inputs are fluvial alluvium, alluvial fans, aeolian sand, dust, biological material (e.g. diatoms), precipitates of salts, and bedrock that has been broken down by salt attack. The climatic conditions that exist in a basin's catchment are an important control of emissions of dust. Among these are wind activity (including gustiness, topographic funnelling, etc.) leading to deflation, rainfall events (leading to sediment inputs, changes in vegetation cover, and changes in surface cohesion), droughts (which cause basin desiccation, reduce fluvial sediment inputs and lead to vegetation die-back), and temperature and humidity cycles (which effect salts). The dust emitted from playas can be highly saline and can be transported over large distances.

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