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Preferential dust sources: a geomorphological classification designed for use in global dust-cycle models.

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Abstract

We present a simple theoretical land-surface classification that can be used to determine the location and temporal behaviour of preferential sources of terrestrial dust emissions. The classification also provides information about the likely nature of the sediments, their erodibility and the likelihood that they will generate emissions under given conditions. The scheme is based on the dual notions of geomorphic type and connectivity between geomorphic units. We demonstrate that the scheme can be used to map potential modern-day dust sources in the Chihuahuan Desert, the Lake Eyre Basin and the Taklamakan. Through comparison with observed dust emissions, we show that the scheme provides a reasonable prediction of areas of emission in the Chihuahuan Desert and in the Lake Eyre Basin. The classification is also applied to point source data from the western Sahara to enable comparison of the relative importance of different land surfaces for dust emissions. We indicate how the scheme could be used to provide an improved characterization of preferential dust sources in global dust-cycle models.

1 Introduction

Mineral aerosol plays an important role in the land-atmosphere-ocean system. Wind erosion causes removal of fine particles (usually <100 μm in diameter) from the land surface, affecting soil moisture holding capacity and nutrient content [e.g. *McTainsh and Strong*, 2007; *Li et al.,* 2007]. Whilst suspended in the atmosphere, mineral aerosol has a range of direct and indirect effects on regional and global climate [*Forster et al.*, 2007], including changing radiative forcing [e.g. *Haywood and Boucher,* 2000; *Yoshioka et al.*, 2007], cloud properties [*Rosenfeld et al.*, 2001] and the chemistry of precipitation [*Dentener et al.*, 1996], suppressing tropical cyclone formation [*Sun et al.*, 2007] and possibly increasing hurricane intensity [*Foltz and McPhadden*, 2008]. Dust deposited over land can affect soil development, soil fertility and geomorphic processes [e.g. *McFadden et al.*, 1987; *Muhs et al.*, 2007]. Dust may regulate phytoplankton activity in the oceans [*de Baar et al.*, 2005; *Wolff et al.*, 2006] and has been (inconclusively) linked to disease and bleaching in corals [*Shinn et al.*, 2000]. Dust emissions even from small, localised sources can have an important impact on health [*Griffin and Kellogg*, 2004] and through creating hazardous conditions for traffic [*Ashley and Black*, 2008]. The impact of dust in the Earth's system depends partly on the location, magnitude, frequency and intensity of dust emissions and partly on the size, shape and mineralogy of the emitted dust particles [*Jickells et al.*, 2005; *Durant et al.*, 2009]. Although dust concentration and particle characteristics change during transport [*Desboeufs*, 2005; *Schütz et al.*, 1981], they are initially determined by the terrestrial sources from which the particles are entrained.

Models developed to investigate the impacts of climate changes on atmospheric dust loading explicitly simulate dust emission, atmospheric transport, and removal by wet and dry deposition. The largest difference between these models lies in the treatment of emissions: some models parameterize emissions solely as a function of wind speed and surface roughness [e.g. *Tegen and Fung*, 1994; *Ginoux et al.*, 2001], while other schemes explicitly include sandblasting as a mode of dislodging particles [e.g. *Shao et al.*, 1993; *Alfaro and Gomes*, 2001; *Zakey et al.*, 2006]. Many models now include the control of seasonally-varying vegetation cover on dust emission, either by prescribing vegetation cover [e.g. *Mahowald et al.*, 1999; *Zender et al.*, 2003; *Mahowald et al.*, 2006] or through explicitly simulating vegetation dynamics and phenology [e.g. *Werner et al.*, 2003].

Field and satellite observations have shown that dust sources are highly localized

spatially [*Middleton et al.*, 1986; *Ginoux et al.*, 2001; *Prospero et al.*, 2002; *Mahowald et al.*, 2003; *Washington et al.*, 2003]. Models of the dust cycle that define source-area erodibility, using observations of surface reflectance [*Grini et al.*, 2005] or surface roughness [*Koven and Fung*, 2008], implicitly include these preferential sources. Prescription of land-surface properties is of limited applicability, however, when the aim is to model emissions under radically different climate conditions such as those which pertained in the geologic past or which could arise with global warming in the future. An alternative modeling approach has been to define the spatial distribution of preferential dust sources such as topographic depressions [*Ginoux et al.*, 2001] and dry lake basins [*Tegen et al.*, 2002] explicitly. Soil properties or dust fluxes are then changed to ensure increased emissions from these areas. The inclusion of preferential sources produces a more realistic simulation of emissions, both under modern and past climate states, although model output is significantly affected by the way in which land-surface characteristics are incorporated [*Uno et al.*, 2006, *Yin et al.*, 2007]. However, current modeling approaches still do not capture the small-scale spatial and temporal variability in emissions apparent from observations. Furthermore, the identification of significant emissions from surfaces not previously considered important, such as alluvial fans in the Sahara [*Schepanski et al.*, 2007], suggests that current modeling approaches may neglect some preferential sources. A more comprehensive treatment of the geomorphic controls on emission is therefore required to improve the performance of dust-cycle models.

It would be possible to adopt a purely empirical approach to identifying potential sources and characterizing the spatial and temporal heterogeneity in emissions using remotely sensed data. Such an approach has been adopted in several papers [*Schepanski et al.*, 2007; *Bullard et al.*, 2008] but it has a number of limitations. Firstly, although the length of the record is increasing and the quality of data improving, remote-sensing products are only available for a limited number of years. Some dust sources are active very sporadically [e.g. *Bessagnet et al.*, 2008; *Sharma et al.*, 2009] and may not have been active during the period covered by the remote sensing record. Secondly, the relative importance of different sources as reconstructed from remotely-observed emissions is determined by prevailing meteorological conditions during the observation period – again, this may not represent the full range of environmental conditions experienced in any region. Thus, an empirical classification will not be a reliable guide to emissions under changed conditions such as those experienced in the geologic past or expected in the 21st

century. Thirdly, it is difficult to extend an empirical classification beyond the area for which it was developed, making it less suitable for incorporation in a global modeling framework and particularly a framework designed to be applied with climate-change scenarios. We have therefore chosen an alternative approach of developing a theoretical classification of different types of geomorphological surface with respect to their potential as dust sources, drawing on knowledge accumulated through extensive field mapping of land surface characteristics and information on how these surfaces react under different meteorological and environmental conditions gathered during many years of research.

Studies characterizing the geomorphology and surface properties of dryland regions, and relating these to the occurrence and frequency of dust emissions [e.g. *Reheis and Kihl*, 1995; *Bullard et al*., 2008; *Wang et al*., 2006; *Wang et al*., 2008b] have provided a reasonably good understanding of the geomorphic controls on dust sources and how these will affect both the spatial extent and the temporal behavior of sources. In this paper, we present a synthesis of current knowledge about the geomorphic controls on dust sources, and develop a conceptual model of how different geomorphic sources will affect the temporal variability in dust emissions. We demonstrate that the resulting classification scheme can be used to map potential modern-day dust sources in three regions: the Chihuahuan Desert, the Lake Eyre Basin and the Taklamakan. We test how well the conceptual model predicts emission sources in the Chihuahuan Desert and in the Lake Eyre Basin through comparison with observed dust emissions. We also present a preliminary assessment of its application to the western Sahara, by using point source data to enable comparison of the relative importance of different land surfaces for dust emissions. Finally, we suggest ways in which a classification scheme based on our conceptual model could be used to derive an improved characterization of preferential sources for dust-cycle modeling and conclude with suggestions about how this scheme could be implemented in a modeling framework. The focus of this paper is the relationship between surface geomorphology and sedimentology and dust emissions – we have explicitly not tried to link this to other variables controlling emissions, such as wind velocity, vegetation cover or human land use, because these variables are already treated in global dust models.

2. Conceptual Model of the Geomorphic Controls on Dust Sources

2.1. Geomorphic Characteristics and Dust Emissions

Although any terrestrial surface with a supply of suitable-sized sediment and appropriate wind regime can be a dust source, most dust emissions are from arid (<250 mm yr^{-1} rainfall) inland drainage basins [*Middleton et al*., 1986; *Prospero et al*., 2002; *Washington et al*., 2003]. Dryland inland basins are extensive and their surface characteristics and geomorphic dynamics encompass many different sedimentary environments including stone pavement (also known as gobi, reg or gibber), unconsolidated aeolian deposits, endorheic depressions, fluvial, alluvial and groundwater-dominated systems, and consolidated or sealed surfaces such as evaporite crusts, duricrusts or bedrock. With the probable exception of consolidated surfaces [*Gillette*, 1999; *Callot et al*., 2000], all of these units have the potential to emit dust. However, they vary both in their relative importance as emission sources, and in the spatial and temporal patterns of emissions because the geomorphological characteristics of the units affect the amount of sediment available for wind erosion.

Studies in different regions have shown that the relationship between geomorphology and dust sources is not simply a function of gross geomorphic type. *Wang et al*. [2006] showed that most dust storms in northern China originate in gobi (stony deserts), whilst *Sweeney et al*. [2006] found stone pavements in the Mojave Desert had the lowest dust emissions. Similarly, *Prospero et al*. [2002] found that dunefields were not major dust sources, but dust emissions have been reported following the reactivation of semi-stabilized dunes [*Sweeney et al*., 2006; *Bullard et al*., 2008; *McGowan and Clark*, 2008] and from dunefields where river systems inundate interdunal areas with fresh sediment that is subsequently desiccated and deflated [*Bullard et al.,* 2008; *Wang et al*., 2006]. Iron oxide and other fine weathering coatings on dune sands are also potential dust sources [e.g. *Bullard and White*, 2005; *Bullard et al*., 2007; *Crouvi et al*., 2008]. *Reheis and Kihl* [1995] found that in the Mojave Desert and southern Great Basin of the southwestern USA, playa and alluvial sources produce almost the same amount of dust per unit area, but the greater surface area of the latter means the total volume of dust emitted from alluvial deposits is much higher. *Reheis* [2006] also found that alluvial sources in this region are the primary dust sources during drought, whilst playas are the primary dust producers during wetter periods.

The vegetation-free expanse of flat, fine-sediment dominated ephemeral lakes can be an important source of dust in terms of both intensity (emissions per unit area) and magnitude [e.g. *Reheis*, 1997, 2006; *Mahowald et al*., 2003; *Prospero et al*., 2002; *Washington et al*., 2003; *Bullard et al*., 2008]. Several studies have demonstrated the importance of sand-sized sediment in releasing dust to the

atmosphere from consolidated or compacted clays or silts [*Cahill et al*., 1996; *Gillette and Chen*, 2001; *Shao et al*., 1993; *Grini and Zender*, 2004]. These coarse saltators can trigger the release of fine dust particles from the bed and, through the process of aeolian abrasion, generate additional fine particles [*Gomes et al*., 1990]. On ephemeral lake beds, coarse saltators may be provided by adjacent sand dunes [*Stout*, 2003], or deposition of fine sands following flooding [*McTainsh et al*., 1999]. This emphasizes the importance of understanding not only the sedimentary environment of a particular landform, but also the degree of connectivity with adjacent landforms. Connectivity also influences sediment supply and can result in differences in emissions from similar geomorphic features from different regions [*Bullard and McTainsh*, 2003].

2.2 Controls of Temporal Variation in Dust Sources

The importance of different geomorphic units as dust sources varies in space and time depending on soil moisture, vegetation cover, the presence of biological crusts, mechanical disturbance (e.g. by animals or human activities) and wind strength. With the exception of mechanical disturbance and crusts, these controls are already incorporated in global models and so are not explicitly considered in our dust source mapping scheme. However, there are additional controls of dust emission brought about through the interaction of climate and landscape on sediment availability. These interactions can be described in terms of the aeolian sediment-system response framework developed by *Kocurek* [1998; see also *Kocurek and Havholm*, 1993]. In this conceptual model, sediment production peaks during humid conditions when weathering, and fluvial transport and sorting, are enhanced but aeolian sediment availability and transport capacity are low due to the presence of vegetation. As conditions become more arid, sediment production declines and sediment availability to the wind plus transport capacity increase (Figure 1). Applying this conceptual framework to dust emissions, a system can be in one of three states: supply-limited, where emissions are limited by lack of suitable sediment; availability-limited, where there is sediment in the system but it is not readily entrainable either due to vegetation cover or soil moisture levels; or transport-capacity limited, where sediments are available but wind energy is too low to entrain particles. Some attempts have been made to classify regional dust sources using similar principles. *Zender and Kwon* [2005] identified relationships among precipitation, dust loading and vegetation cover for dust source areas that highlighted regions where dust

emissions were supply limited. *Mahowald et al*. [2007] also found regions where higher water availability was associated with higher dust emissions and suggested that this reflected increased sediment delivery to emission zones. The division between supply-limited, availability-limited and transport-capacity limited is not perfect because the states are not mutually exclusive (for example there is a strong relationship between vegetation cover and the threshold wind strength required to entrain particles), however it does provide a useful way to account for some aspects of temporal variability in dust emissions.

<Figure 1>

2.3 Sediment Texture

Attribution of appropriate sediment texture information is important for characterizing potential dust sources. In most dust-cycle models, the characteristics of the surface material are specified from global soils data sets such as the various versions of the FAO soil data set [*Zobler*, 1986; *IUSS Working Group WRB*, 2007] at the spatial scale of the model (generally 0.5°x 0.5° to 1°x 1°). The textural information used to classify soils does not fit particularly well with the particle sizes that are susceptible to wind erosion, or those capable of generating such particle sizes through sandblasting. Wind is highly size selective and tends to only carry particles <2000 μm diameter by saltation or suspension: this incorporates sediments that are described as sand (63-2000 μm, or 50-2000 μm), silt (4-63 μm, or 2-50 μm), and clay (<4 or <2 μm) in traditional grain-size classifications (size boundaries according to *Wentworth*, [1922] and *Urquhart*, [1959] respectively). Furthermore, the soil texture data refers to particle sizes determined using dispersed or disaggregated sediments which may not reflect particle sizes in the field [e.g. *Chatenet et al*., 1996]. Fine particles may be present, for example, as sand-sized aggregates that can be broken down into component dust-sized grains during transport or sandblasting, or as clay or metal oxide deposits on the surfaces of sand grains, which can be removed by abrasion to form dust. The importance of sandblasting for dust production is expressed in the observed relationship between vertical dust flux F, and horizontal mass flux (saltation), q [*Shao et al*., 1993; *Gillette et al*., 1997; *Okin*, 2005]. The effectiveness of abrasion in generating dust for a given surface is represented by the ratio of dust emission to horizontal sediment flux ($k = F/q$). The k factor varies between different

surfaces, being controlled by local sediment properties such as texture, crusting and moisture. Finally, although the sorting of material may be important in determining susceptibility to wind erosion, information on sorting is rarely given in soil datasets.

Grain size, the presence of aggregates, and sorting are highly variable, both within sedimentary environments and between different sedimentary environments. Nevertheless, there are some basic relationships between these properties and the more important geomorphic types in dust source regions. We have therefore developed a simple description of broadly defined sediment classes (Table 1) that can be directly related to specific geomorphic types in terms of their susceptibility to wind erosion and their potential for dust generation. In general, erodibility is reduced by the admixture of coarse gravel-sized particles but in some situations coarser (sand-sized) particles are required to promote deflation of cohesive fine-grained material.

<Table 1>

3. Development of a Global Scheme

3.1 Basic Criteria

There is no global database of land surface characteristics including soil type, texture, organic content, particle size and sorting, sediment budget, sedimentary environment and geomorphology. Reasonably high quality data on some or all of these variables are available for some regions. However, each regional study tends to use different methods of data collection and compilation, different classification schemes and different mapping resolutions. These differences can be further compounded if the area of interest extends across national boundaries [e.g. *Baddock et al.*, 2011]. This poses problems in reconciling the different datasets into a single, global dataset that would be suitable for dust-cycle modeling.

We initially considered the types of geomorphic features that are characteristic of arid and semi-arid regions, differentiating them in terms of mode of formation and likely sedimentological characteristics. This type of geomorphic classification and mapping has been conducted by others; early studies include those by *Raisz* [1952] and *Clements et al*. [1957], more recent work has been carried out by *Callot* [2000] and

Ballantine et al. [2005]. Our geomorphological types cover the same range of landscape features as these studies.

Our focus in developing a new scheme for dust source mapping has been to ensure that the data required to apply it are easily available, globally-consistent and verifiable. Thus, we sought to create a scheme using a limited number of easily recognizable geomorphological units, the location and extent of which could be defined using e.g. satellite remote sensing, aerial photography, topographic, soil and geological maps and field data. The use of remote-sensed data or field mapping means that the scheme is based on surface characteristics rather than the nature of the underlying sediments. In some situations, the underlying sediments could have been important for dust production in the past or provide a future source of dust, but including this stratigraphic information is beyond the scope of a globally-applicable scheme. Although the boundaries between the different geomorphologies are clearly delimited in some cases (e.g. perennial lakes) in other cases there is a gradual transition between different types (e.g. sandy aeolian deposits may grade into sand sheets or loess over distances ranging from a few to hundreds of kilometers: *Crouvi et al.,* [2008]). This introduces a certain amount of subjectivity into the mapping that is unavoidable. In developing the scheme, we have borne in mind that its primary purpose is to provide a basis for global mapping of dust source types which could then be used to prescribe dust source types in global dust-cycle models. This has led to a simplification of the micro-scale complexity which characterizes specific arid and semi-arid regions, but a more complex classification scheme would be difficult to operationalize either in a mapping or a modeling context.

3.2 Geomorphic Types

We identified seven geomorphic types that are commonly found in arid and semi-arid regions, which differ in terms of surface characteristics influencing their susceptibility to aeolian erosion, and which matched our criterion for being readily identifiable using remotely-sensed information. The seven basic types are lakes [1], high relief alluvial deposits [2], low relief alluvial deposits [3], stony surfaces [4], sand deposits [5], loess [6] and low emission surfaces [7]. These were further sub-divided (Table 2) to reflect perceived differences within each basic type in the spatial and/or temporal variability of emissions. The resultant classification relies primarily on our collective field experience, including explicit field studies of the relationships between geomorphic setting and dust emission, as well as our evaluation of the literature on dust

emissions from key regions. In the sections below, we examine each of the geomorphic types (and sub-types) in turn in order to explain the reasoning behind their differentiation in terms of their importance and behaviour as potential dust sources. Our subsequent analyses of the application of this classification in different regions (see Results) can be seen as a test of our initial, somewhat theoretically-based, classification.

<Table 2>

3.2.1 Lakes [1a-d]

Perennial (wet) lakes [1a] may contain sediments suitable for wind erosion but the presence of water means that the system is availability limited. Perennial lakes can be an efficient trap of fine sediments and hold a detailed record of past periods of dust activity [e.g. *Muhs et al*., 2003]; they are also potential future dust sources if fully or partially desiccated [*Gill*, 1996]. Delimitation of perennial lakes using remote sensing is usually reliable because water has significantly different spectral properties from vegetation or exposed lacustrine sediments [*Drake and Bryant*, 1994].

Ephemeral lakes [1b] are one of the most important dust sources globally [*Prospero et al*., 2002; *Washington et al*., 2003]. In general, these lakes have been perennial at some stage in the past, and thus contain considerable quantities of fine-grained material of fluvial, groundwater-derived and/or biogenic origin. Some of these materials are particularly productive: diatomites, for example, are very erodible as their silicate skeletons are readily abraded to dust size particles by sandblasting [*Warren et al*., 2007]. The diatomite deposits of the Bodélé Depression in Chad are the world's biggest dust source in terms of fluxes [*Washington et al*., 2006].

The importance of lakes without a plentiful store of fine-grained sediment as dust sources depends on the delivery of new sediment through ephemeral flooding or fluvial activity. Flow deceleration when rivers enter a lake causes rapid deposition of coarse sediment near the lake margin and concentrates fines increasing towards the centre of the basin. Coarser material settles out of the water column more rapidly than finer material depositing a fining upwards sequence. Following desiccation, these fine sediments will deflate and may expose coarser material that promotes sandblasting [*Cahill et al*., 1996]. Ultimately, deflation may strip away the fines and

lead to the development of a coarse lag deposit, causing the system to switch to being availability-limited.

When groundwater levels are close to the surface of the lake bed (or deflation lowers the surface of the lake bed to the groundwater table) increased cohesion may reduce sediment availability. Salts precipitated from near-surface groundwater have different effects on dust production depending on their chemistry: sulfate and carbonate evaporites can create 'soft puffy' surfaces or loose fine salt deposits that are prone to erosion [*Cahill et al.*, 1996; *Katra and Lancaster*, 2008; *Reynolds et al.*, 2007; *Rojo et al.*, 2008], while sodium chloride-rich evaporites tend to form hard, cemented layers reducing sediment erodibility [*Handford*, 2006].

Sediments exposed on permanently dry lake beds may be consolidated by salts cementing the particles together [1c] or unconsolidated [1d]. Assuming no change in other environmental factors (such as particle sorting, groundwater level or surface moisture availability), deflation of unconsolidated sediments of appropriate size (or aggregate size) is effectively limited only by transport capacity until all sediments are deflated and the system becomes supply-limited. Consolidated dry lake sediments are availability-limited.

3.2.2 High Relief Alluvial Deposits [2a-d]

Alluvial deposits are sub-divided according to relief, armouring and incision. Relief (or gradient) determines the energy available in the fluvial system; it also affects the sediment type such that high relief systems generally comprise coarser material than low relief systems. Although there is no universal threshold in terms of gradient dividing low and high relief systems, typically alluvial systems with a gradient of less then 2-3º are classified as low relief whereas those with steeper gradients are high relief. In practice these values are always used in conjunction with interpreting the geomorphic signature - alluvial plains are easily recognizable and are classified as low relief alluvial deposits while high relief surfaces such as fans, piedmont slopes and bajada also have a distinct geomorphologically-recognizable signature. Armouring of the surface of an alluvial deposit by coarse particles reduces potential dust emissions. Channel incision affects the floodplain extent and frequency of inundation, which is the main mechanism by which sediments are transferred from the fluvial to the aeolian system [*Bullard and McTainsh*, 2003]. The numerous ways

in which these three variables combine mean that alluvial deposits contain a wide range of sediment textures.

Armoured alluvial deposits associated with high relief [2a and 2b] are typically availability-limited due to poor sorting, a relatively low silt content and the presence of armoured surfaces which increases surface roughness and lowers wind erosion potential. In contrast, unarmoured, high relief, alluvial deposits [2c and 2d] are more likely to be dust sources but may be supply-limited. In this case, significant dust emissions only occur after periodic rains bring fresh sediment into the system (although over long periods weathering may also supply some fine sediments; *Viles and Goudie*, [2007]). When sediment textures are very mixed, alluvial fans can be dust sources if there is active reworking to maintain a supply of fine material at the surface or to prevent the surface from becoming armoured [*Derbyshire et al.*, 1998, *Wang et al.*, 2006, 2008b, *Reheis*, 2006]. Topographic enhancement of winds can also play an important role in dust entrainment, as in the foothills of the Aïr Mountains in the Sahara [*Karam et al.*, 2009; *Schepanski et al.*, 2007].

3.2.3 Low Relief Alluvial Deposits [3a-d]

Alluvial deposits associated with low relief may still contain gravels that can cause armouring. Armoured surfaces are present on palaeodeltas associated with the Jilantai dry lake, for example [*Yang et al.*, 2008]. Low relief alluvial deposits may also be incised, limiting any replenishment of fines by floodwaters [3a and 3b]. The low relief category also includes braided fluvial systems and outwash plains in paraglacial and periglacial landscapes. These regions can be significant dust sources [*McKenna Neuman and Gilbert*, 1986; *Muhs et al.*, 2003; *Nickling*, 1978] with the timing of dust emissions linked to meltwater flooding and seasonal or local availability of suspended sediment [Bullard and Austin, 2011] or, over longer time periods, to the formation or drainage of proglacial lakes [*Sugden et al.*, 2009].

Unarmoured, low gradient alluvial surfaces [3d] are either transport-capacity limited or, if they are vegetated, availability-limited. In the Okavango Delta, for example, peak periods of dust deflation occur during drought years when vegetation cover is reduced [*Krah et al.*, 2004]. Similarly, in the extensive unarmoured floodplains in Australia's Channel Country fine sediment supply is related to occasional high

magnitude flood events; dust emissions here are strongly controlled by both sediment supply and availability through vegetation [*McTainsh and Strong*, 2007].

3.2.4 Stony Surfaces [4]

Although colluvial deposits [7] and alluvial deposits [2, 3] may have stony surfaces, stony surfaces *sensu stricto* are low angle, stone-mantled surfaces formed by a range of different processes [*McFadden et al*., 1987; *Adelsberger and Smith*, 2009]. They are a store of relatively fine sediment overlain by a thin surface mantle of gravels (>2000 μm diameter) [*Springer*, 1958; *Cooke*, 1970; *Peterson*, 1980]. The underlying material is typically dominated by silt but sand-sized material does occur in some locations [e.g. *Marticorena et al*., 1997; *Pelletier et al*., 2007]. The coarse surface layer limits aeolian erosion of the underlying finer fraction such that these are availability-limited sedimentary environments. These units can emit dust, however, if the surface is significantly disturbed or under strong winds [e.g. *Belnap and Warren*, 2002].

3.2.5 Sand Deposits [5a-b]

Sand deposits are sub-divided into sand sheets and aeolian sand dunes. Sand sheets [5a] are areas of low relief sandy deposits. The size and sorting of the sediments makes them susceptible to wind erosion but, in many cases, aeolian entrainment is limited by vegetation, coarse sands or the level of the water table.

In contrast to sand sheets, aeolian sand dunes [5b] are a wind-worked deposit with distinct relief. The contribution of sand dunes to dust emissions depends on type, activity level, and palaeoenvironmental history. Active, young or small sand dunes with a relatively rapid turnover of sand are unlikely to be major or persistent dust source because they contain little fine material. Large, more stable or older dunes may accumulate fines within the dune structure due to weathering or, in semi-arid regions, through in-wash of finer particles by precipitation. Dunes in hyper-arid regions are less likely to contain fine material than those in semi-arid and temperate zones; large areas of the latter have partial vegetation cover which, although it will trap fine wind-blown sediments, also reduces sediment availability unless it is disturbed. Dune activity and palaeohistory are not easy to detect from remote sensing, consequently here all dunes are classified in a single category [5b].

3.2.6 Loess [6]

Loess is a depositional landform of silt and clay-sized dust particles. There is often a marked gradient in sediment size with coarser sediments near the dust source and finer sediments further away, and there may be a wide transitional zone from sand to silt and clay-sized material. Loess can become a significant dust source during periods of reduced vegetation or disturbance.

3.2.7 Low Emission Surfaces [7]

Bedrock, steep rocky slopes, duricrusts, and permanent snow and ice cover in cold deserts, are surfaces where sediment supply and/or sediment availability are typically low to zero and thus emissions are low.

4 Application of Geomorphic Classification to Major Dust Source Regions

The applicability of the geomorphic classification scheme was first tested in two regions (the Chihuahuan Desert and Lake Eyre Basin); we performed more limited tests in a further two regions (the Sahara west of 17°E and Taklamakan Deserts) to demonstrate the scheme's global potential. All four regions have previously been examined in terms of the relationship between dust sources and surface geomorphology [*Wang et al*., 2006; *Drake et al*., 2008; *Bullard et al*., 2008; *Lee, et al*., 2009] – though using very different classification approaches -- and differ in terms of the relative importance of different geomorphological types and the temporal variability of the dust sources (Table 3). Attempting to apply the geomorphic classification scheme outlined in this paper in all four regions is a first step towards establishing the feasibility of a common mapping protocol.

The Chihuahuan Desert (CD), North America and Lake Eyre Basin (LEB), Australia were mapped in detail. The mapping scheme was then evaluated by using dust point source data for the CD and LEB and overlying this on the geomorphic maps to determine whether or not the actual distribution of dust sources coincided with theoretically predicted areas of high or medium emissions. The Taklamakan (TAK), China was mapped using the mapping scheme but, as no point source data were available from the region, the map was then evaluated using existing literature. The western Sahara (SAH), North Africa was not mapped in detail because of its large size and resource constraints, but the mapping scheme was applied to an existing data set of dust point source data.

4.1 Geomorphic Mapping

The spatial extent and the distribution of the seven geomorphic classes (and their sub-classes) were mapped across the CD, the LEB and the TAK by applying the scheme to an existing digital base map of polygons which had been established for each region. Each polygon was then attributed to a geomorphic class from Table 2. The allocation was based on interpretation of remote sensing imagery. This allocation was cross-checked against secondary sources, including regional maps and literature. This kind of mapping is a standard practice in geomorphology and the results are generally robust between operators; cross-checking against secondary sources provides a further check on this robustness. This procedure resulted in a vector polygon map for each region, suitable for analysis in a geographical information system.

The Chihuahuan Desert covers 322,450 km^2 of southwestern North America in Mexico and the USA as delineated climatically by *Schmidt* [1979]. There are no detailed land unit maps that continue across the international border so a base map was compiled using 1:1,000,000 landform/landscape unit maps obtained from the Mexican Sistema de Topoformas dataset [*INEGI*, 2001] and 1:250,000 soils maps produced by the US Department of Agriculture's Natural Resource Conservation Service [*USDA-NRCS*, 2006]. A base map covering the entire Chihuahuan Desert was created by merging the USA and Mexican primary source maps and adjoining common polygons were unified across the international border. The positional accuracy of the polygon boundaries is ≈250 m for the Mexican data and varies from 250 m to 1 km for the USA data [*USDA-NRCS*, 2011]. The smallest polygon on the base map has an area of 1 km^2. Each polygon in the base map was then assigned to one of the 17 different geomorphic sub-classes described in Table 2 and adjacent polygons with the same geomorphic characteristics were merged with the result that the smallest polygon increased in size to 2 km^2. Where available and appropriate, metadata provided with the base maps were used to assist with classification of land surfaces (for example wet lakes [1a]) but assignment of geomorphic characteristics was primarily achieved using the NASA Geocover mosaic created from Landsat ETM+ (at 14.5 m spatial resolution; *Tucker et al.*, 2004), the authors' field knowledge, dedicated ground-truthing sorties and published literature [*Baddock et al.*, 2011]. The boundaries of the geomorphic classes were fine-tuned using these data sources

which helped to improve the positional accuracy; this was especially important in areas of complicated geomorphology and where sub-types within the scheme (e.g. lake sub-types) were in close proximity to one another.

The base map of polygons used for the classification of the 1.14 million km^2 Lake Eyre Basin, defined by the watershed boundary, was the 1:1,000,000 Surface Geology of Australia base map. This dataset is compiled from a number of different sources and the polygon boundaries have a positional accuracy ranging from 200 m to 1 km depending on the quality and date of the original input data [*Raymond and Retter*, 2010]. The smallest polygon in the base map has an area of 0.25 km^2. Each polygon in the LEB map was then assigned to one of the 17 different geomorphic sub-classes and adjacent commonly-classified polygons were merged. Although most of the geomorphologically-assigned polygons increased in size, geomorphology is spatially very variable in some areas of the watershed and the smallest polygon still had an area of 0.25 km^2. Where available and appropriate, metadata provided with the base maps were used to assist with classification of land surfaces (for example aeolian sand dunes [5b]), however assignment of geomorphic characteristics was primarily achieved using the global NASA Geocover mosaic [*Tucker et al.*, 2004], the 1:250,000 digital topographic map series of Australia (positional accuracy ±120 m; Geosciences Australia, 2008), SPOT (Satellite Pour l'Observation de la Terre) data (spatial resolution ≤10 m), the authors' field knowledge and dedicated ground-truthing sorties. The boundaries of the geomorphological type polygons were adjusted where necessary using these higher resolution data sources.

A 523,545 km^2 area of the Tarim Basin, encompassing the Taklamakan Desert was mapped using a base map digitised from the geomorphic map by *Tungsheng et al.* [1996]; this was georectified and then the polygon boundaries were checked and, where necessary, modified to include additional detail using other published data [e.g. *Wang et al.,* 2008a,b] and SPOT imagery. The positional accuracy of the polygon boundary is estimated to range from 1 km to 20 km, decreasing towards the margins of the mapped area. The geomorphology was mapped at a lower resolution than the other regions, with the smallest polygon being 675 km^2. Although the original

basemap for the Taklamakan was digitised from an existing, and quite detailed, geomorphic map, the allocation of polygons to our scheme was done independently.

The three maps were produced using ArcGIS (ESRI) and the area of each geomorphic type was calculated. For all maps, where transitions between geomorphic types were identified, the boundary was placed where the dominant type changed. We estimate that the overall error in determining the geomorphic boundaries for CD and LEB is no greater than 1 km.

4.2 Dust Source Data

Dust point source data was obtained for the CD, the LEB and SAH (Table 4). Meteorological records from El Paso International Airport, from 1st January 2001 to 31st December 2009, were used to identify days in which visibility in the CD was reduced by dust/haze/sand or other aeolian phenomena (excluding smoke, and anthropogenic pollutants). For the LEB all days during the period July 2003 to June 2006 were identified when at least one meteorological station within the LEB or within 250 km of the watershed recorded a dust-induced visibility reduction to ≤1 km [*Bullard et al.*, 2008]. For both regions, we analysed MODIS (Moderate Resolution Imaging Spectroradiometer) images (Terra and/or Aqua) for each different meteorologically-defined dust day and for days where plumes were evident, the upwind source position of the dust plumes was identified through cross-referencing with meteorological data to identify the direction of dust transport. MODIS data has been widely and successfully used to identify dust sources and track dust storms in desert regions [e.g. *Gassó and Stein*, 2007; *McGowan and Clark*, 2008; *Walker et al.*, 2009].

Several techniques have been developed to enhance the dust signal over desert surfaces. A comparison of four of these techniques, and two aerosol products (MODIS Deep Blue and OMI AI; Ozone Monitoring Instrument Absorbing Aerosol Index) concluded that approaches using brightness temperature difference (the difference between the 11 and 12 μm bands; *Ackerman*, [1997]) were the most consistently reliable for accurate source identification [*Baddock et al.*, 2009]. Although this approach makes it easier to identify the sources of dust plumes, it involves a loss of precision because the highest spatial resolution MODIS data to

which it can be applied is 1 x 1 km. This loss of precision is not important for the present purpose, and thus we used the brightness temperature difference to enhance the dust signal for the LEB. No dust enhancement algorithm was applied to the satellite data for the CD, which meant that the highest spatial resolution MODIS data (0.25 x 0.25 km) could be used.

For the SAH, dust events during the four months April-July 2003 (which are typically the months of greatest dust emission: *Goudie and Middleton*, [2001]) were identified using MODIS (Terra) in the western half of the Sahara (west of 17°E). The satellite data were enhanced using *Miller's* [2003] technique for dust enhancement (Table 4) and all visible plumes were traced to identify the upwind source positions. Landsat TM imagery, other satellite data and secondary sources were then used to classify the land surface at the dust source to one of the geomorphic types in our scheme. Some of the western Saharan dust plumes were traced to areas of complex geomorphology where it was difficult to identify the dominant surface type or to areas associated with human activity. However, these sources accounted for <5% of the observed plumes.

<Table 4>

The use of satellite data to identify dust plumes and meteorological data to trace the plume to its origin is relatively standard, but has some limitations (see e.g. discussions by *Bullard et al*., [2008]; *Lee et al*., [2009]; *Baddock et al*. [2009]). First, since many dust sources are not true 'points' but cover small areas, the allocation to a single upwind point source is somewhat subjective. Dust can occur as a single coherent plume or multiple dispersed plumes which means that even for a single plume more than one dust source may be identified (Table 4; *Walker et al*. [2009]). Additionally, the source points of some plumes may actually have been located a short distance upwind of the point at which they become visible from MODIS (depending on the relative timing of the dust emissions and the satellite overpass, and surface wind speed). Second, this method does not consider the size or concentration of the dust plume and the relative intensity (magnitude) of erosion at each point is unknown. Thus, the data can only be used to evaluate

presence/absence of dust emission from specific geomorphic types. Third, visibility measurements at meteorological stations tend to underestimate dust-event frequency due to the low density of stations in most arid regions but MODIS may also fail to capture dust events e.g. due to cloud cover or because of the relative timing of dust events and MODIS data capture times (e.g. events occurring at night or between satellite passes). Large and dense dust events, themselves, also tend to obscure the identification of additional active dust sources on MODIS images which produces a bias in favor of consistently upwind sources. Finally, over bright desert surfaces some upwind plume edges can be hard to detect using MODIS, but use of Level 1 band data from this sensor has been demonstrated more effective than MODIS products (Level 2) such as Deep Blue for highest resolution of source pin-pointing [*Baddock et al*., 2009]. Despite these issues, the approach yields sufficiently good results to allow testing of the proposed scheme.

5. Evaluation of the Dust Source Scheme

The aim of this project is to develop a theoretical classification of different types of geomorphological surface with respect to their potential as dust sources. The intention is that the classification can be applied globally and consequently can be used to inform the surface characteristic parameters of global dust models used for understanding dust emissions in the past, present and future. The maps and dust point source data described above were therefore used to evaluate how workable the proposed geomorphic scheme is in four different locations.

5.1 Spatial Patterns

It was possible to identify all seven basic geomorphic types across the CD, LEB and the TAK (Figure 2). Some sub-types are not represented in particular regions, for example there are no examples of loess in the CD. However, there were no surface types that could not be classified used the proposed scheme i.e. all geomorphic types present in these three regions are included within our theoretically-based classification.

The use of a common scheme across the three regions makes it possible to compare the relative spatial importance of each geomorphic type: this revealed considerable differences among the regions. For example, aeolian sand deposits are more

extensive in the TAK (ca. 55% of total area) and LEB (ca. 39%) than in the CD (ca. 5%), while high relief alluvial systems are more important in the CD (ca. 43%) than in the LEB (3%). Ephemeral lakes cover 4% of the CD and LEB and 7% of the TAK (Table 5). Specific geomorphology can also vary within classes: the alluvial low relief areas in CD are chiefly floodplains and deltas, for example, whereas in the LEB this category encompasses anastomosing rivers with very wide floodplains.

<Figure 2>

Studies in different regions have shown that areas of common superficial geomorphology do not necessarily behave in the same way (see section 2.1), and accordingly, the number of dust plumes associated with each geomorphic class was found to vary among the regions. Ephemeral and dry lakes (1b + 1d) account for a large number of dust plumes – 66% in the SAH, 48% in the CD, 11% in the LEB (Figure 3, Table 5). Sand sheets [5a] account for nearly 2%, 6% and 2% of dust plumes in CD, LEB and SAH respectively. Sand dunes [5b] are relatively unimportant in the CD (14%) and SAH (2%) compared with the LEB where they account for around 60% of dust plumes. In the CD, 21% of dust plumes are from high relief, unarmoured, unincised alluvial systems (2d). Across the CD, LEB and SAH, the most significant alluvial surface for dust emissions was low relief, unarmoured and unincised (3d): accounting for 12%, 16.5% and 25% of dust plumes respectively. Less than 1% of alluvial dust sources in the LEB are armoured and unincised. Stony surfaces [4] had low emissions in all three regions and there are no dust emissions from perennial lakes [1a]. Although we have no comparable point source data for the TAK, meterological stations within and downwind (southwest) of the dunefield record more dust events, particularly sand-dust storms than those to the north and east [*Ma et al.*, 2006] and are typically associated with unarmoured alluvial deposits (3d). Differences in emission from different geomorphic types may, of course, reflect variability associated with different wind regimes in each region. Nevertheless, these first-order comparisons show that emissions from many geomorphic types are negligible (e.g. perennial lakes, stony surfaces, armoured alluvial systems, sand sheets), and confirm the role of ephemeral lakes, unconsolidated and unarmoured surfaces, and unincised surfaces as major contributors to regional dust fluxes.

<Table 5>

<Figure 3>

The use of percentage frequency of emissions as a tool for evaluating the applicability of our geomorphic scheme to determine contribution to regional dust emissions is complicated by differences in the area covered by different geomorphic types in each region. To permit a more robust evaluation, we have calculated the number of plumes per km^2 from each geomorphic type in the CD and LEB (Table 5). In the CD, the most extensive geomorphic class is high relief alluvial, unarmoured and unincised (nearly 43% of the area) but the number of plumes per km^2 on this surface is 0.0003. There are over 20 times more dust plumes per km^2 from ephemeral lakes (0.0072) which cover only 3% of the region. Although the number of dust plumes per km^2 in the CD is similar for both ephemeral lakes (0.0072) and stony surfaces (0.0071) this comparison is somewhat misleading; only one dust plume was observed coming from a stony surface in the CD and a very small area of the desert is characterized by this surface type (141 km^2, or <0.0005% total area). Although sand dunes account for over 57% of dust plumes in the LEB, the number of plumes per km^2 is only 0.001. The number of plumes per km^2 is slightly higher for ephemeral lakes (0.0013) which cover less than 4% of the area and account for 11% of the dust plumes. Unarmoured, unincised low relief systems [3d] produce similar numbers of plumes per km^2 in the two regions, as do low-emission surfaces (Table 5). The most pronounced differences, in terms of plumes per km^2, between the CD and LEB is for sand dunes and ephemeral lakes. There are twice as many dust plumes from sand dunes in the LEB as in the CD, presumably reflecting the differences in the history and activity status of the dunes. There are about three times as many plumes from ephemeral lakes in the CD as in the LEB, again presumably reflecting differences in the hydrology, chemistry and/or sedimentology of these lakes. Nevertheless, the general pattern of relative importance of geomorphic types as dust sources is consistent with our conceptual scheme as is the variability within any geomorphic type.

Antecedent history and local factors clearly influence the amount of dust deflated from specific geomorphic types, such that quantitative comparisons in terms of plumes per km^2 tend to emphasize the differences between different regions. In order to assess the usefulness of the proposed geomorphological classification of potential sources at a more globally-applicable scale, we have therefore grouped the different

geomorphic types which, on theoretical grounds, are high, medium and low emitters (column 5, Table 2) and then compared the regional emissions from these three groups. In the CD, 48% of dust point sources are located in geomorphic types that are predicted to have high emissions, 48% in areas of medium emissions and 4% in areas of predicted low emissions. For the LEB, 11% of dust point sources are from areas of high emissions, 80% of emissions are from areas of medium emissions, and 9% from areas predicted to have low emissions. The major source of uncertainty here is the classification of sand dunes, which may either be low emitters (when they are young and/or active) or high emitters (when they are old and/or stabilised and have undergone recent disturbance).

5.2 Temporal Variability

We have not attempted to evaluate how well our scheme predicts temporal variability in emissions because the available dust plume records from each region cover such short periods of time (from 4 months to ten years). However, the data from the CD and LEB do show considerable inter-annual variability in emissions from some geomorphic types (Figure 4). Furthermore, variability in the activity of source surface may largely be driven by interannual variability in wind regime.

Severe drought between 2001-2004 reduced vegetation cover in the CD, and as a result, availability-limited alluvial surfaces were important emitters during this interval, and particularly in 2001 [*Rivera Rivera et al.*, 2009]. The strong summer monsoon in 2006 caused the filling of many ephemeral lakes and re-vegetation of lake margins and other surfaces, converting many areas from supply-limited to availability-limited systems, and increasing the transport capacity required to entrain dust. As a result, there was a significant decrease in the number of dust events in CD in 2006 and no dust plumes were observed in 2007.

The high emissions from aeolian deposits in 2003 in the LEB are attributed to the destablising effect of fires on vegetation cover in the Simpson Desert in the previous year [*Bullard, et al.*, 2008]. Different geomorphic types within the LEB are known to respond in different ways to precipitation or drought [*McTainsh et al.*, 1999]. The increase in emissions from supply-limited alluvial sources in 2005/6 is attributed to flood events that occurred within the basin in January-March 2004, transporting new sediment supplies to the lower basin [*Bullard et al.*, 2008].

<Figure 4>

6. Implementation of Geomorphologically-controlled Sources in a Modeling Context

The desire to prescribe “preferential” dust-emission sources, rather than using empirical information such as surface reflectance or surface roughness to capture the spatial variability in emissions, arises from the need to predict (or retrodict) the impacts of climate change on the dust cycle and the inadequacies of current global data sets of soil and land-surface properties. Modeling schemes which specify “preferential” dust-emission sources, such as topographic depressions or dry lake beds, generally use this information to modify the textural properties of the soil in a given source area to ensure it is highly susceptible to wind erosion, either explicitly by increasing the amount of silt-sized material present or implicitly by increasing the simulated emissions by some arbitrary factor (see e.g. *Tegen et al*. [2002]). Current approaches have been limited both in terms of the number of types of “preferential” sources they recognise, and because these sources have been mapped and applied at the spatial scale of the model (e.g. over a whole e.g. 0.5 x 0.5° grid cell). Our scheme characterizes the land-surface into a set of geomorphic types with different emission potentials (from non-emitters, through low emitters to high emitters) and recognises that, even under ideal meteorological conditions for dust deflation, each type can have a different temporal behaviour (from continuous emitters to sporadic emitters) depending on the degree to which they are sediment-limited. The scheme could be applied at a range of spatial scales: in the examples used here as test regions, we have mapped the different geomorphic types at 1 km resolution, sufficient to be able to calculate the varying proportions of each type with a 0.5 x 0.5° grid cell typical of the resolution of many dust-cycle models. There is a considerable amount of work to be done to provide a global map of geomorphic types using the current scheme. Nevertheless, such a map in combination with existing global soils data would be an invaluable tool to improve the modeling both of the spatial and temporal variability of emissions

Our scheme provides a way of distinguishing emitting and basically non-emitting surfaces within potential dust source areas. The scheme could therefore be used to

derive an estimation of the percentage of each of geomorphic subtype within a model grid-cell (see e.g. Figure 5a, b). At its simplest, the scheme provides a means to reduce emissions from individual model grid-cells by reducing simulated dust flux according to how much of a grid-cell is non-emitting, or only likely to emit intermittently. Furthermore, we have shown that the scheme can be used to sub-divide geomorphic types in a qualitative sense into low, medium and high emitters (Figure 5c, d, e), thus allowing simulated emissions to be tuned accordingly. Although the influence of antecedent conditions and local geomorphic factors makes the division into low, medium and high emitters more prone to error (unless guided by local information), this division would allow further tuning of model emissions and can be applied at a range of scales (Figure 6).

<Figure 5>

<Figure 6>

The scheme also provides information on the presence and relative importance of geomorphic types that are sediment supply-limited and the nature of the pre-conditioning that transforms these areas from non-emitters to emitters. Our data from the western Sahara (April-July 2003) do not include any dust emissions associated with high relief alluvial systems such as alluvial fans, however *Schepanski et al*. [2007] did identify alluvial fans as a potential Saharan dust source during June-August 2006. Although neither data set is long enough to test this conclusively, this is likely to be an example of the temporary transformation of a non-emitting surface to an emitting surface, and we have demonstrated similar behavior in longer records from the CD and LEB (Section 5.2). In a modeling context, it would be inappropriate to consider sediment-supply limited geomorphic types (such as alluvial fans) as major emitters because they do not emit on a regular basis but only for short and/or infrequent intervals as a result of specific pre-conditioning which provides readily erodible material. In regions where sediment supply to such geomorphic types is increased through sporadic flooding or through fluvial erosion, it should be possible to use information about recent and contemporary climate conditions to determine when these sources are likely to become dust sources. For example, an extremely wet season/year could be identified as a trigger for emissions in the subsequent season/year in sediment-supply limited geomorphic types [*McTainsh et al*., 1999;

Reheis and Kihl, 1995]. Incorporating such “transformations” in dust-cycle models could go some way to improving the simulation of inter-annual variability of dust emission, one of the most complex aspects of source behaviour.

The presence of a sand source (i.e. a source of coarse saltators) is the primary determinant of whether predominantly fine-grained materials (e.g. lake deposits) are an emission source or not. Surface mapping provides pertinent information on geomorphic adjacency, and thus can be used to determine sand availability upwind of an area of fine-grained material. Given that sandblasting is explicitly incorporated in many models, this information can be used as a switch: where sand is available upwind, areas of predominantly fine-grained material (e.g. lake beds) could be considered dust sources; where sand is not available upwind, they might not. Implementing this within a modeling framework requires two factors to be determined. The first is the distance threshold for adjacency. A sand source adjacent to a lake bed may act as a source of coarse saltators and lead to emissions but, if the lake deposits cover a considerable area, these emissions will be confined to the part of the lake closest to the sand source [*Cahill et al.*, 1996; *Bullard et al.*, 2008]. There will be no emissions in more distant parts of the lake bed. The distance threshold for adjacency is clearly dependent on wind speed and sand size, and thus would need to be calculated interactively by the model. The second factor that needs to be taken into account is the impact of changes in wind direction, since sand sources may be highly localised. Given the relatively coarse resolution of most dust-cycle models, changes in wind direction are unlikely to be sufficiently large under modern conditions to have an impact on sand-source adjacency but this is a factor that would need to be considered in running simulations under radically different climate forcings e.g. the last glacial maximum.

7. Discussion and Future Perspectives

We have developed a simple classification of geomorphic types related to their behaviour as dust sources, based on current understanding of the geomorphological controls on dust emissions. We have demonstrated that the scheme can be applied to four major dust source regions, primarily using remote-sensing imagery to classify surfaces, and thus is suitable for global application. We have shown that the scheme is useful in predicting areas of high or low emission, and that it also provides a

framework for understanding the temporal behaviour of intermittent emitters. Finally, we have indicated ways in which elements of this scheme could be incorporated into dust-cycle models in order to improve the simulations of preferential sources and the interannual variability of emissions. Although much of the detailed geomorphological information available in regional maps is lost, this simplified scheme incorporates far more complexity than is typically present in global dust models and effectively represents the geomorphic reality (albeit qualitatively) of dust emission processes and controlling factors.

We have demonstrated that our geomorphic scheme can be applied in four different locations. Although for the most part this was achieved using satellite data and secondary sources, field experience was particularly helpful in determining, for example, the difference between armoured and unarmoured surfaces. Mapping of landforms from aerial photographs or remotely sensed images has a long history and, when combined with field knowledge of a region, can provide detailed information (as shown here) that could not be generated using an automated pattern-recognition algorithm. The mapping scheme now needs to be tested in other regions, and particularly in regions where geomorphic surface sub-types that are not present in our test regions occur (see Table 2). It may be necessary to expand the classification in order to apply it globally. For example, the scheme does not currently include anthropogenically-modified surfaces, such as agricultural or urban areas, all of which have been identified as dust sources in the Sahara-Sahel [*Ginoux et al.*, 2010; *Ladji et al.*, 2010], southwestern North America [*Lee et al.*, 2009] and parts of China [*Wang et al.*, 2006]. Nevertheless, we believe the framework presented here provides a good basis for the development of a global map of dust sources and could be applied with only minor modification in other areas.

We have shown that some surface geomorphologies (e.g. ephemeral lakes and alluvial sources) are highly variable with respect to emission potential. In global terms, dunefields are not a significant source of dust: in the western Sahara <2% of dust plumes originate from dunefields and only 8% of plumes in the CD originate from dunes. However, in the LEB 60% of the observed plumes originated from dunefields. These differences probably reflect differences in dune type (i.e. migrating versus stable dunes), age (young versus old), sedimentology and climate (i.e. hyper-arid versus semi-arid). The contrast between dunefield emissions in the SAH and LEB, for example, appears to reflect the palaeoenvironmental history of the regions; the Saharan dunes have been reworked following successive glacial cycles whereas the dunes in the LEB have been stable for a longer period and hence accumulated

more fine material [*Lancaster et al*., 2002; *Muhs*, 2004; *Hesse*, 2010; *Strong et al*., 2010]. Subdividing the aeolian dune class [5b] according to dune type, activity and palaeo-history could certainly improve the current classification scheme but would be a significant task involving more extensive use of field studies.

There is also considerable variability in emissions from exposed lake beds. To some extent, this may reflect the availability of coarse saltators and hence the degree of connectivity between this geomorphic type and types that are sources of sand-sized material. The current scheme provides a mechanism for taking adjacency of different geomorphic types into account in the prediction of emissions. However, the variability in emissions from exposed lake beds also reflects the interplay between surface properties and palaeoenvironmental history, in particular as it determines lake hydrogeochemistry and hence the precipitation of different types of salts as well as crust strengths [*Reynolds et al*., 2007]. This can vary even within a single playa [e.g. *Gillette et al*., 2001] or throughout a source region as a whole. For example, in the LEB, Lake Eyre North is a major dust source while Lake Frome is not, because of the presence of surface salts on the latter. Remote sensing has been used to discriminate different types of salt deposits [e.g. *Crowley and Hook*, 1996; *Drake* 1995; *Drake et al*., 1994; *Katra and Lancaster*, 1998] and thus it should be possible to extend the current classification to take this factor into account in mapping ephemeral lake types. We would strongly argue for the need to test such a sub-division of ephemeral lakes against dust plume data in order to facilitate an extension of the current scheme.

Reliance on remote-sensing observations is necessary if the current scheme is to be applied globally. However, scale is a major issue in mapping the occurrence of specific geomorphic types and also affects our ability to test the relationship between these geomorphic types and dust emissions. Many potential dust sources (e.g. interdunal depressions) are small, and the existence of fine-scale mosaics of different geomorphic types may make the differentiation of dust sources difficult. Scale issues may have introduced considerable noise into our assessment of the relationships between geomorphic types and dust emissions. In the CD dataset, for example, 30 dust plumes were identified as originating from sand dunes in the area around White Sands and Palaeolake Palomas. Of these 11 were located within 2 km of a dry lake, a further 11 were located 2-5 km from a dry lake and 8 were located more than 5 km away. Given the resolution of the mapping and satellite data used (≤1 km) it is highly likely that some of the emission that we have attributed to dune sources closest to the lake may in fact have been from the lake surface or a direct result of interaction

between the dunes and the lake sediments [*Cahill et al.*, 1996; *Lee et al.*, 2009; *Baddock et al.*, 2011].

Despite these various caveats, the scheme proposed here provides a way of improving the current prescription of preferential sources in dust-cycle models. It allows improved delineation of emitting and non-emitting surfaces, provides a guide to surface texture of these features that could be used to modify standard soils input data sets, and indicates how the temporal behavior of potential sources can be considered in terms of climatic thresholds. We believe that implementing this kind of process-informed scheme within a global-modeling framework will considerably improve our ability to simulate dust emissions in response to climate change. However, there are a number of steps required before it is feasible to implement the proposed scheme globally. These are:

1) to expand the evaluation of the current scheme within the four major source regions examined here. In part, this requires additional work to make it possible to apply the same evaluation approach for all regions, by e.g. extending the mapping of the SAH and developing a dust point source data set for the TAK. However, additional tests of the scheme could be possible, for example by (a) extending the period for which point data is available for the LEB and SAH to cover the most recent years, (b) exploring the use of soils data (both local and global data sets) to improve the mapping of surface characteristics, and (c) utilizing (or in some cases implementing) ground-based measurements of dust emission from different dust source types;

2) to test the applicability of the current scheme in other dust source regions. Key questions here include (a) whether it is necessary to expand the scheme to include e.g. anthropogenically-modified surfaces; (b) whether it is feasible to use remote-sensing products to differentiate different types of salt crusts which influence erodibility of dry lakes; and (c) whether it is feasible to use field studies of geomorphic history to differentiate between dune types of different ages. Determining whether these modifications are necessary and helpful will in large part be determined by whether the modification is likely to affect a large area in global terms and whether the new categories can be mapped consistently from region to region;

3) to implement the scheme globally to provide a single gridded map of dust source characteristics as an input field for modeling. One possible way forward here is to use existing base maps (e.g. *Hesse*, 2010) or ongoing mapping projects (e.g. Sand Seas and Dune Fields of the World:

http://inquadunesatlas.dri.edu/background.htm) as an initial basis for mapping dust source areas;

4) to develop quantified relationships from well-studied regions between land surface types and dust fluxes, focusing specifically on active area, seasonal timing, and interannual variability.

While there is still work to do to refine and test the proposed scheme, the real test of the usefulness of this classification will only come when it is implemented within a dust-cycle model. Initially, this can only be done for the three regions we have already mapped. However, these regions represent significant dust sources under current conditions and encompass a sufficient range of surface types and temporal behaviors to make a model-based evaluation worthwhile.

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Figures

Figure 1: Model of the impact of humid-arid phases on fine sediment (dust) production/availability and transport and the response of the aeolian system (simplified and adapted from *Kocurek*, [1998]).

Figure 2: Distribution of surface geomorphologies (left hand panel) and their relative importance for dust emissions (right hand panel) as detailed in Table 5 for A: the Chihuahuan Desert (modified from *Baddock et al.*, [2011], B: the Lake Eyre Basin and C: the Taklamakan desert. Right hand panels for the Chihuahuan Desert and Lake Eyre Basin also indicate the location of dust plume sources (see text and table 4).

Figure 3: The percentage frequency of dust emissions from the different main surface geomorphologies for the Chihuahuan Desert, the Lake Eyre Basin and the western Sahara for time periods given in table 4.

Figure 4: Annual variability of the frequency (%) of dust emissions from different surface geomorphologies for A: the Chihuahuan Desert 2001-2009, and B: the Lake Eyre Basin 2003-2006.

Figure 5: Maps of the Chihuahuan Desert (left hand panels) and Lake Eyre Basin (right hand panels) showing the percentage of each 0.5 x 0.5° grid cell containing A: ephemeral and dry lakes [1b-d], B: low relief, unarmoured, unincised alluvial deposits [3d], and C, D, E: surface geomorphologies with low, medium and high potential emissions respectively (where aeolian sand dunes [5b] are classed as medium; see text).

Figure 6: The distribution of aeolian sand dunes [5b] in the Lake Eyre Basin shown as a percentage of different-sized grid cells. A: 0.25 x 0.25°, B: 0.5 x 0.5°, C: 1 x 1°, D: 2 x 2°.

Tables

Table 1: Qualitative indicators of sediment texture and associated erodibility and dust generation potential.

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Table 4: Summary of dust point source data for three regions.

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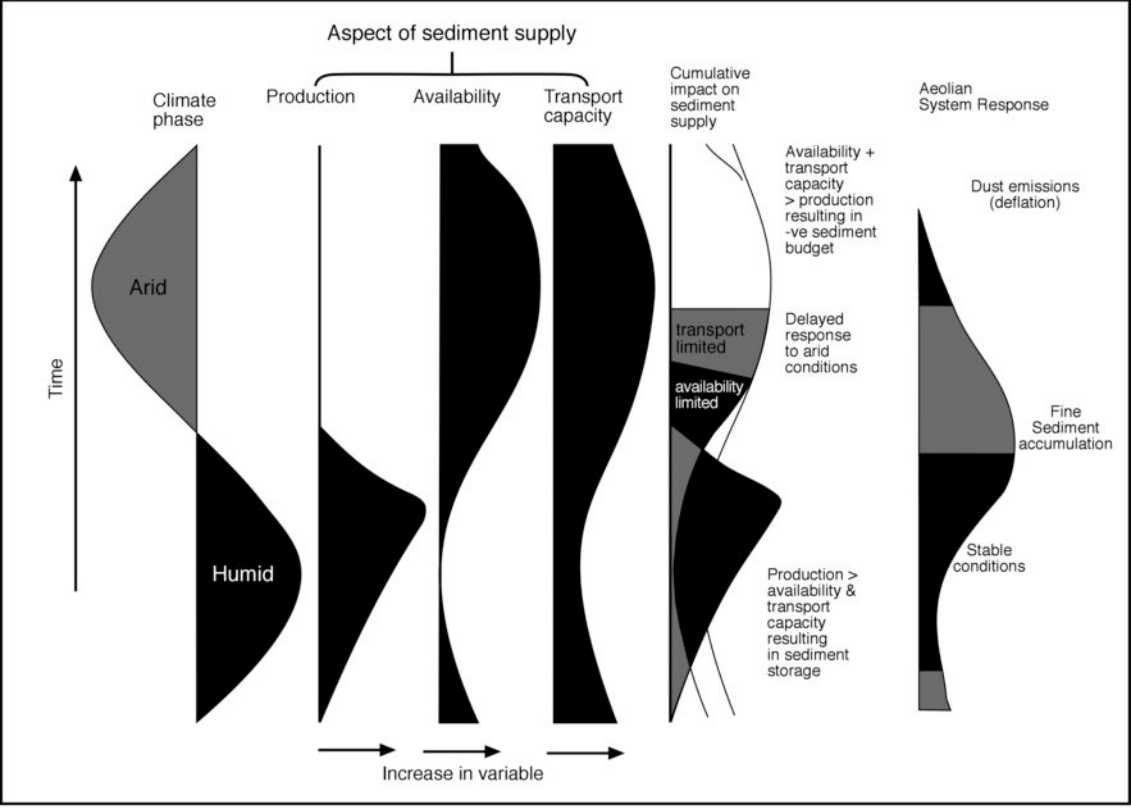


Figure 1: Model of the impact of humid-arid phases on fine sediment (dust) production/availability and transport and the response of the aeolian system (simplified and adapted from Kocurek, [1998]).

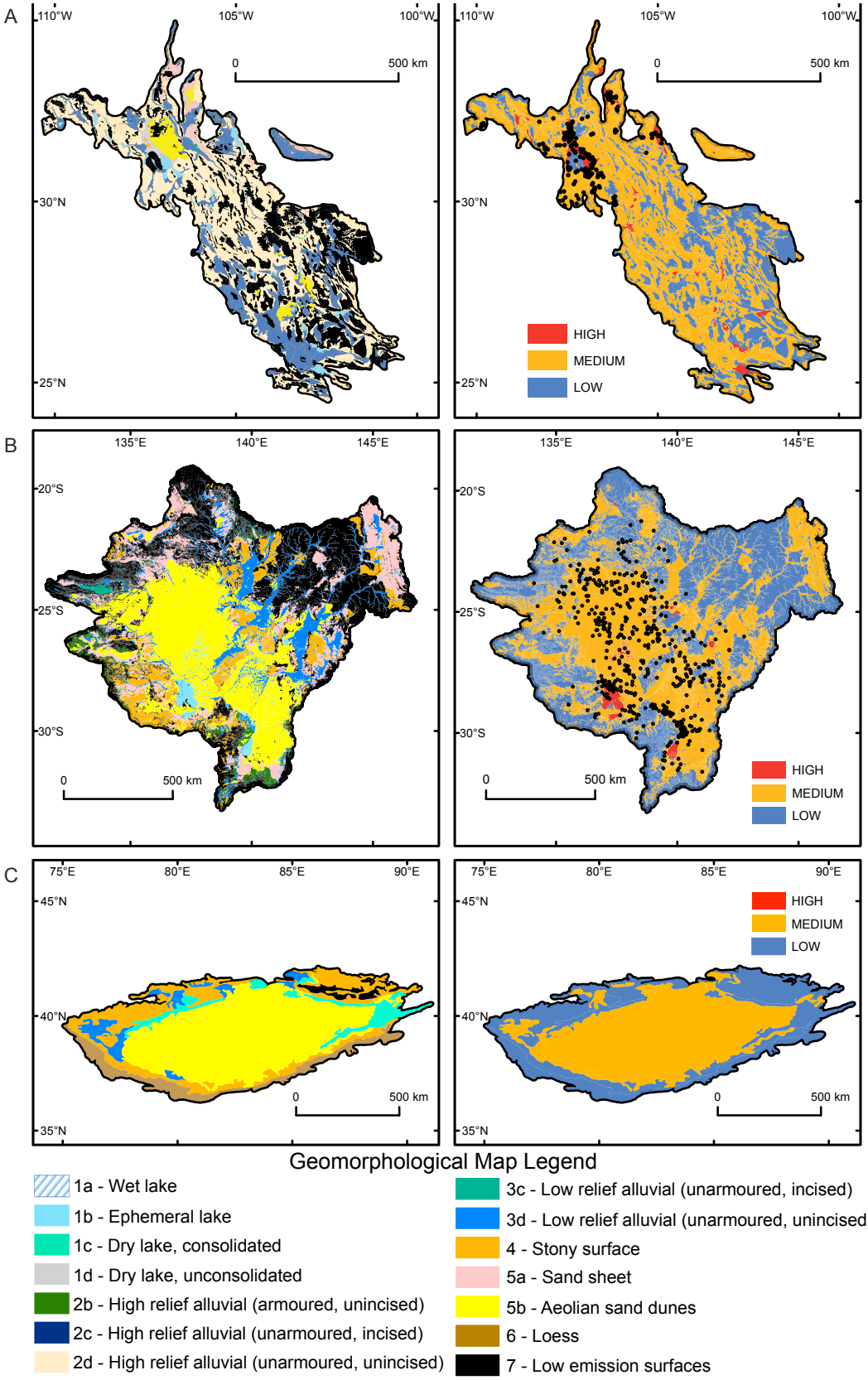
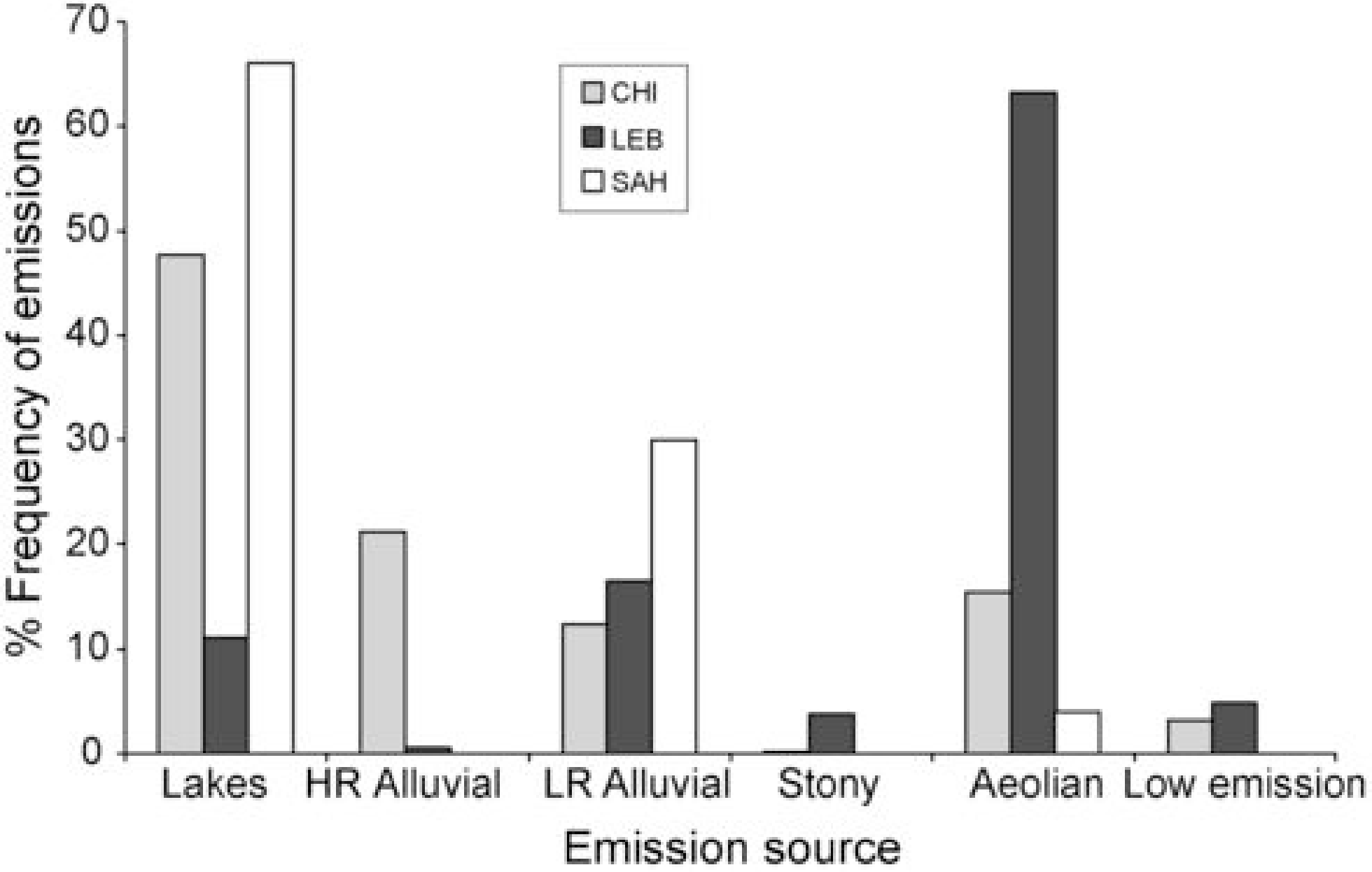


Figure 2: Distribution of surface geomorphologies (left hand panel) and their relative importance for dust emissions (right hand panel) as detailed in Table 5 for A: the Chihuahuan Desert (modified from *Baddock et al.*, [2011], B: the Lake Eyre Basin and C: the Taklamakan Desert. Right hand panels for the Chihuahuan Desert and Lake Eyre Basin also indicate the location of dust plume sources (see text and Table 4).



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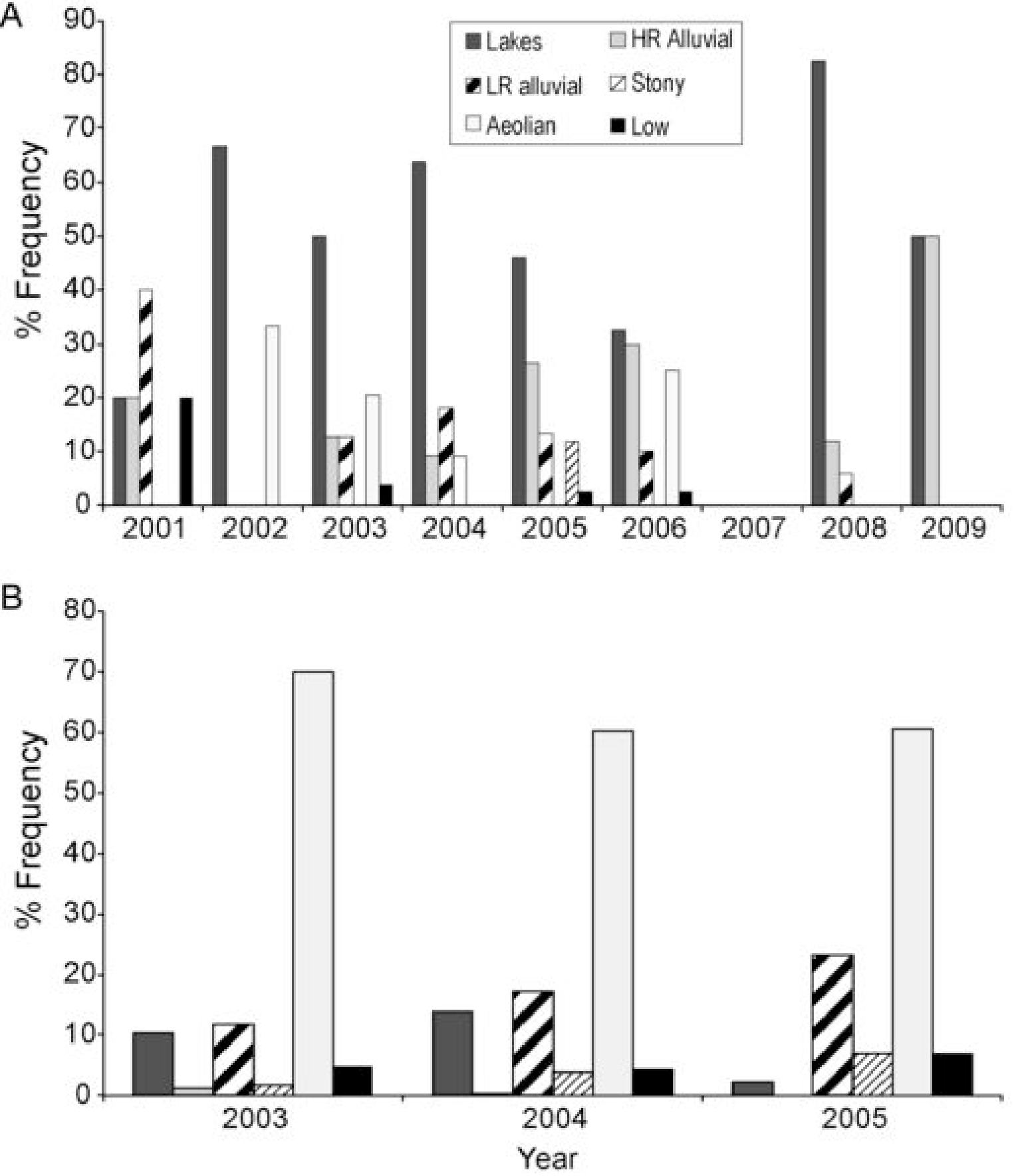

Figure 4: Annual variability of the frequency (%) of dust emissions from different surface geomorphologies for A: the Chihuahuan Desert 2001-2009, and B: the Lake Eyre Basin 2003-2006

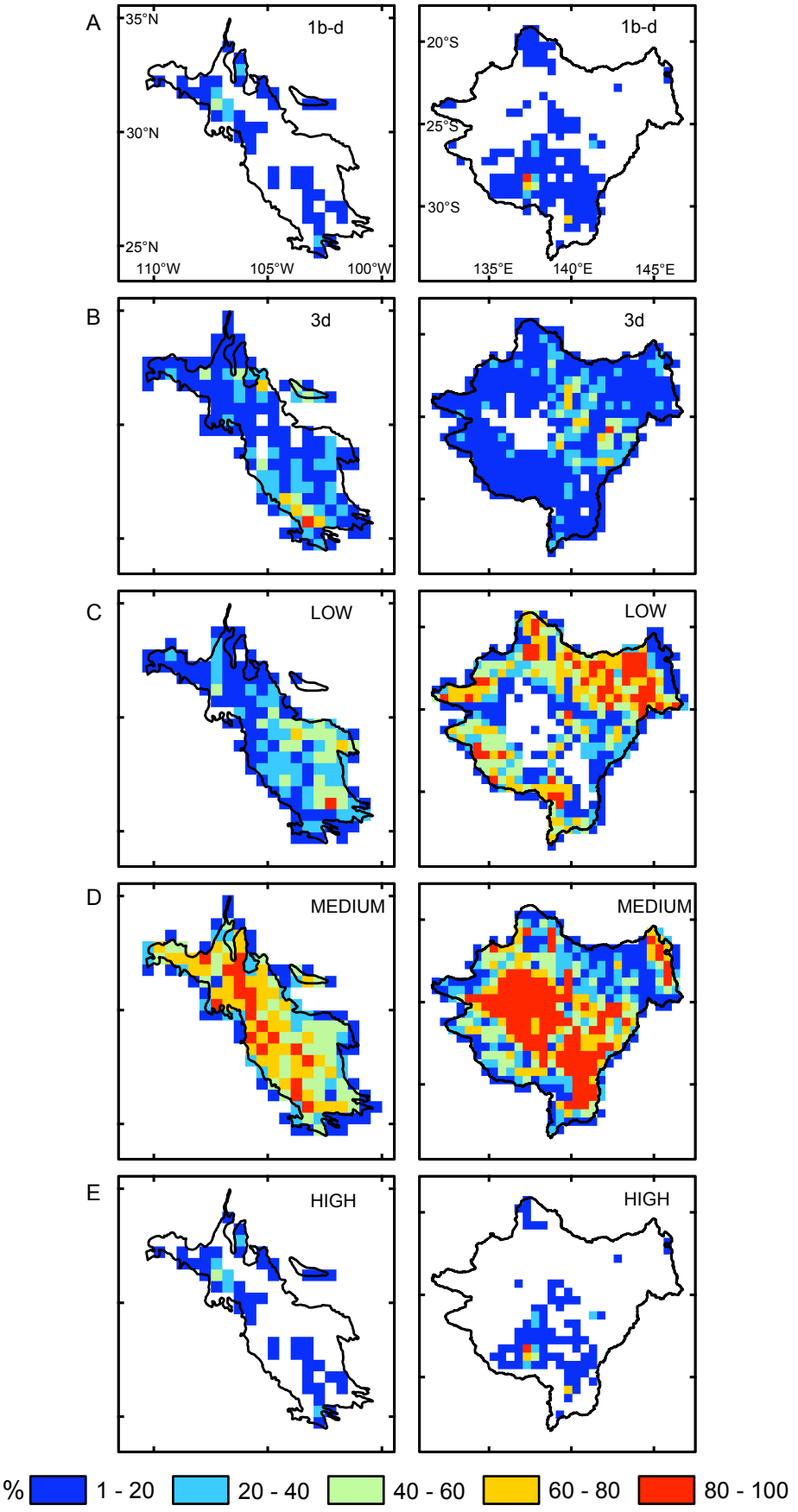

Figure 5: Maps of the Chihuahuan Desert (left hand panels) and Lake Eyre Basin (right hand panels) showing the percentage of each 0.5 x 0.5° grid cell containing A: ephemeral and dry lakes [1b-d], B: low relief, unarmoured, unincised alluvial deposits [3d], and C, D, E: surface geomorphologies with low, medium and high potential emissions respectively (where aeolian sand dunes [5b] are classed as medium; see text).

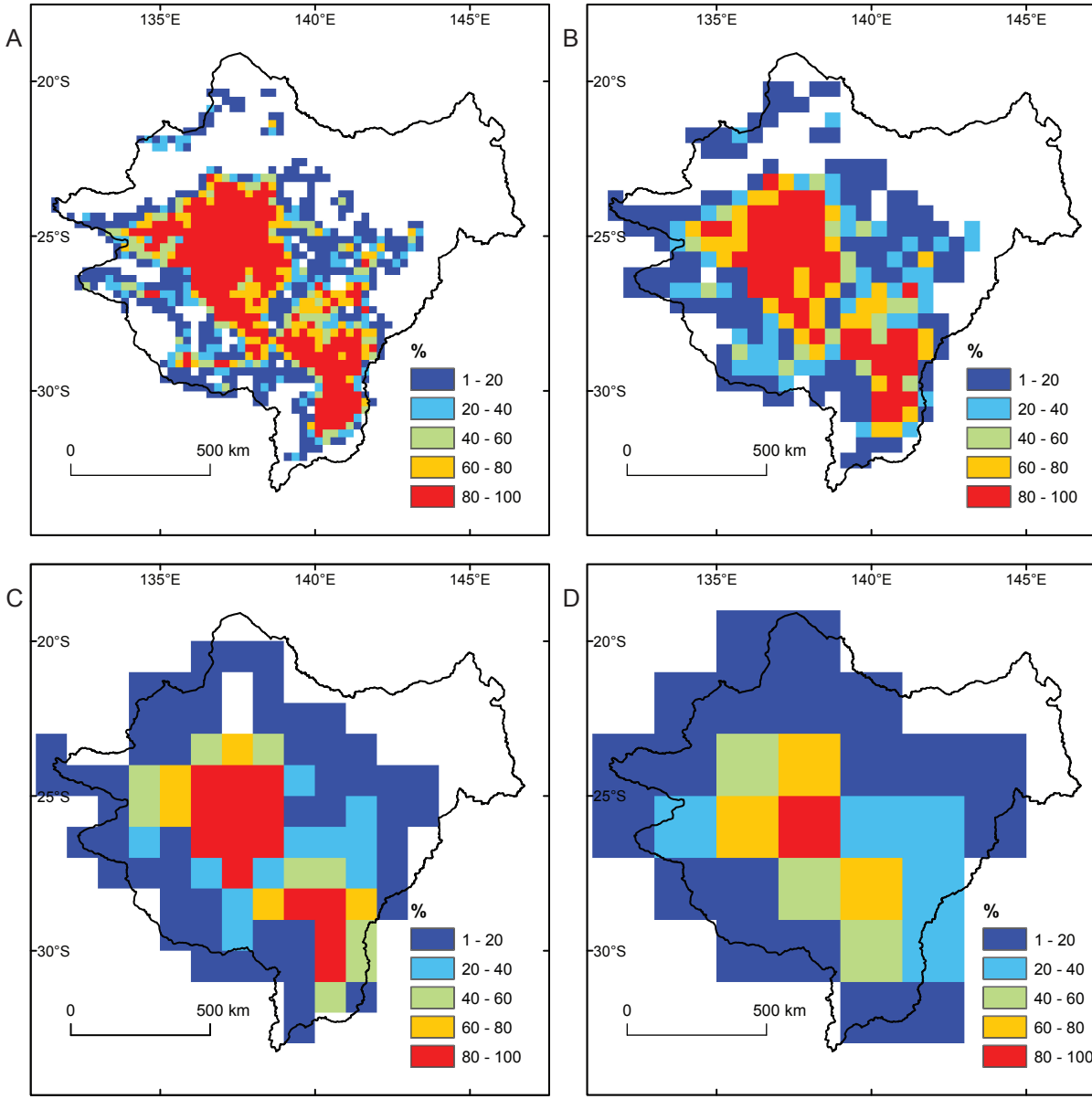

Figure 6: The distribution of aeolian sand dunes [5b] in the Lake Eyre Basin shown as a percentage of different sized grid cells. A: 0.25 x 0.25° B: 0.5 x 0.5° C: 1 x 1° D: 2 x 2°.

Table 1: Qualitative indicators of sediment texture and associated erodibility and dust generation potential.

Sediment texture	Wind Erodibility	Dust generation potential	Example sedimentary environments
Mixed sand/gravel	Low	Low	Proximal alluvial fans; non-emitting surfaces
Mixed clay/silt + gravel	Low	Moderate	Stony surfaces, distal alluvial fans
Sand	High	Moderate-variable	Sandy aeolian deposits, sand sheets, sand dunes
Mixed sand/silt	High	High	Source-proximal loess, fluvially-coupled ephemeral lakes
Silt/clay	High	Low	Ephemeral + dry unconsolidated lakes, source-distal loess
Sand/clay	High	High	Fluvially-coupled ephemeral lakes, margins of ephemeral and dry lakes, some dry or ephemeral lake/playa surfaces

Table 2: Identification of surface geomorphologies and their contribution to dust emissions in space and time.

	Emission sources	**Typical soil textures**	**Limitation on emissions**	**Dominant temporal pattern**	**Importance for dust emissions** [*value used for Figs 2 and 6 where a range is indicated*]
Lakes	1a Wet	Sand, Silt, Clay	Availability-limited	No variability	Low
	1b Ephemeral	Silt, Clay	Supply-limited	Periodic emissions triggered sediment supply and reworking following high rainfall	High (if sandblasting) – Medium [*high*]
	1c Dry – consolidated	Silt, Clay	Availability-limited	No systematic variability	Low
	1d Dry – non consolidated	Silt, Clay	Transport capacity limited	Emission when wind velocity > entrainment threshold	High (if sandblasting) – medium [*high*]
High Relief Alluvial Systems	2a Armoured, incised	Mega-gravel, Gravel, Sand	Availability-limited	No systematic variability	Low
	2b Armoured, unincised	Mega-gravel, Gravel, Sand	Availability-limited	No systematic variability	Low
	2c Unarmoured, incised	Gravel, Sand, Silt, Clay	Supply-limited	Periodic emissions triggered by sediment supply and reworking following high rainfall	Medium
	2d Unarmoured, unincised	Sand, silt, clay	Supply-limited	Periodic emissions triggered by sediment supply and reworking following high rainfall	Medium-High [*medium*]

Table 2 (continued)

Low Relief Alluvial Systems	3a Armoured – incised	Gravel, Sand,	Availability-limited	No systematic variability	Low
	3b Armoured - unincised	Gravel, Sand, Silt, Clay	Supply-limited	Periodic emissions triggered by sediment supply and reworking following high rainfall	Medium
	3c Unarmoured – incised	Sand, Silt, Clay	Transport capacity limited	Emission when wind velocity > entrainment threshold	Low
	3d Unarmoured– unincised	Sand, Silt, Clay	Supply-limited	Periodic emissions triggered by sediment supply and reworking following high rainfall	Medium
	4 Stony surfaces: low angle surfaces; not connected to fluvial source of fines	Gravel, Sand, Silt, Clay	Availability limited	No systematic variability	Low
Aeolian Systems	5a Sand Sheet	Sand	Supply- and/or availability-limited	Variability dependent on vegetation cover, water table etc.	Low to medium [*medium*]
	5b Aeolian sand dunes	Sand	Supply- and/or availability-limited	Variability dependent on dune type, dynamics, sedimentology and palaeohistory	Low to high [*medium*]
	6 Loess	Silt, Clay	Availability-limited	Variability dependent on vegetation cover	Low to medium [*low*]

7 Low emission surfaces - bedrock, rocky slopes, duricrust (snow/ice permanent cover)	Mega-gravel, Gravel, Sand, Silt, Clay	Supply-limited	No systematic variability	Low

Table 3: Comparison of geomorphic classifications used for attributing dust emissions. % DPF = % dust plume frequency, Mean DSF = mean number of dust storms days per year. *local name.

SW North America *Lee et al.*, [2009]		**Lake Eyre Basin** *Bullard et al.*, [2008]		**Western Sahara** *Drake et al.*, [2008]		**Northern China** *Wang et al.*, [2006]	
Surface	% DPF	Surface	% DPF	Surface	% DPF	Surface	Mean DSF
Playa	21	Dry lakes	29	Palaeolakes	54		
				Palaeorivers	17		
		Rivers & floodplains	26	Floodplains & inland deltas	2		
		Stony desert (gibber*)	2	Stony desert (hamada*)	1	Stony desert (gobi*)	9
		Sand dunes	39	Sand dunes	1	Sand dunes (mobile)	6
						Sand dunes (semi-mobile)	14
Agricultural lands	40			Agricultural lands	5	Agricultural lands	3
Rangelands	34					Grasslands	4
Other	5	Other	5	Other	1	Oasis	11

Table 4: Summary of dust point source data for three regions.

	Chihuahuan Desert	Lake Eyre Basin	Western Sahara Desert
Data type	MODIS Terra or Aqua	MODIS Terra or Aqua	MODIS Terra
Spatial resolution used (km)	0.25 x 0.25	1 x 1	1 x 1
Additional processing	None	Bispectral split window analysis (Ackerman, 1997)	Miller (2003) Dust Index
Dust event selection criteria	Reduction in visibility at meteorological station (combined with low humidity and high wind)	Visibility $\leq$ 1 km at meteorological station	Dust storm visible in MODIS colour composite.
Period examined	January 2001-December 2009	July 2003-June 2006	April-July 2003
Number dust event days	26	27	11
Number traceable individual dust plumes	217	529	98

Table 5: Surface area covered by different geomorphologically-defined emission sources and the frequency (%) with which dust plumes are observed from those surfaces. Dust plume data for time periods given in Table 4. Not all data are available for each region, see text for details. Limits to area of Chihuahuan Desert from *Schmidt* [1979], Lake Eyre Basin watershed determined using GeoScience Australia catchment boundary, Taklamakan Desert defined as land <1400 m altitude within the Tarim Basin.

			Chihuahuan Desert				Lake Eyre Basin				Sahara		Taklamakan
			Area	Dust plumes			Area	Dust plumes			Dust plumes		Area
		Emission sources	km^2	Freq	%	Plumes per $1km^{-2}$	km^2	Freq	%	Plumes per $1km^{-2}$	Freq	%	km^2
Lakes	1a	Wet	243	0	0	0							
	1b	Ephemeral	8905	64	29.5	0.0072	43818	58	11	0.0013	3	3	
	1c	Dry – consolidated											7.1
	1d	Dry – non consolidated	3564	40	18.4	0.0112					62	63	
High relief alluvial systems	2a	Armoured, incised											
	2b	Armoured, unincised					35251	3	0.6	0.0001			
	2c	Unarmoured, incised	32	0	0	0							
	2d	Unarmoured, unincised	138728	45	20.7	0.0003							
Low relief alluvial systems	3a	Armoured – incised											
	3b	Armoured - unincised											
	3c	Unarmoured – incised	436	0	0	0	7571	-	-	-	5	5	
	3d	Unarmoured–unincised	64683	26	12.0	0.0004	172401	87	16.5	0.0005	24	25	5.5

Table 5 (continued)

	4	Stony surfaces	141	1	0.5	0.0071	132531	20	3.8	0.0002			22.2
Aeolian systems	5a	Sand Sheet	7178	4	1.8	0.0006	161747	30	5.7	0.0002	2	2	
	5b	Aeolian sand dunes	9450	30	13.8	0.0032	305888	304	57.6	0.0010	2	2	54.5
	6	Loess											8.8
	7	Low emission surfaces	89090	7	3.2	0.0001	330404	26	4.9	0.0001			1.9