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Sub-basin scale dust source geomorphology detected using MODIS

Joanna Bullard,¹ Matthew Baddock,¹ Grant McTainsh,² and John Leys³

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[1] The spatial and temporal variability of dust emissions from different surfaces in the Lake Eyre Basin, Australia is determined using MODIS data. For 2003–6 the sources of 529 dust plumes were classified: overall 37% of plumes originated in areas of aeolian deposits, 30% from alluvial deposits and floodplains and 29% from ephemeral lakes or playas. At this sub-basin scale, the relative importance of different dust source geomorphologies varied primarily in response to sediment supply and availability and was not related to aeolian transport capacity, suggesting the Lake Eyre Basin is a supply-limited system. **Citation:** Bullard, J., M. Baddock, G. McTainsh, and J. Leys (2008), Sub-basin scale dust source geomorphology detected using MODIS, *Geophys. Res. Lett.*, 35, L15404, doi:10.1029/2008GL033928.

1. Introduction

[2] Research at global and continental scales to determine spatial and temporal patterns of dust emission has identified inland basins as persistent dust sources [Prospero *et al.*, 2002; Washington *et al.*, 2003]. Importantly many such basins are extensive and their surface characteristics are heterogeneous. At the sub-basin scale different sedimentary environments can be identified including stone pavement (also known as gobi or gibber), aeolian deposits, endorheic depressions, fluvial systems and consolidated surfaces. All these environments have the potential to emit dust but their relative importance varies spatially and temporally. This is particularly so in supply-limited systems because factors such as whether landforms are dominated by sediment accumulation, throughput or erosion (whether fluvial, aeolian or colluvial), and the extent to which they are coupled to other landforms [Bullard and McTainsh, 2003] affect the amount of material available for deflation. If supply is not maintained, for example following inputs from sediment-laden floods, or new sediment does not become available for transport, for example due to devegetation, the magnitude and frequency of dust events diminishes.

[3] Studies focusing on the relationship between geomorphology and dust sources draw different conclusions. According to Wang *et al.* [2006] most dust storms in northern China originate in gobi, whilst Sweeney *et al.* [2006] found stone pavements had the lowest dust emissions in the Mojave, USA. Prospero *et al.* [2002] suggested

dunes were not major dust sources due to the absence of a suitable fine fraction, however emissions from semi-stabilized dunes can be high following reactivation [Sweeney *et al.*, 2006]. In southern Nevada and California, playa and alluvial sources produce almost equivalent amounts of dust per unit area, but alluvial deposits emit a higher total volume of dust due to their greater surface area [Reheis and Kihl, 1995]. Vegetation-free, fine-sediment dominated ephemeral lakes are often dust sources but the controls on these dust emissions are poorly understood [Mahowald *et al.*, 2003; Bryant *et al.*, 2007]. On ephemeral lake beds coarse saltating sediments, provided by adjacent sand dunes or flood deposits, may eject dust into the atmosphere or self-abrade.

[4] One of the gaps in current understanding of dust emissions is at the sub-basin scale. Whilst some global aerosol models parameterise geomorphology, vegetation cover and hydrology [e.g., Zender *et al.*, 2003], improving dust models requires better data concerning the physical characteristics and dynamics of source areas. This paper determines, and explores preliminary explanations for, the spatial and temporal variability of sub-basin scale dust sources using Moderate Imaging Spectroradiometer (MODIS) data.

2. Study Area

[5] This research focuses on the 1.17 million km² Lake Eyre Basin (LEB), Australia (Figure 1) - an important southern hemisphere dust source [Washington *et al.*, 2003]. The basin features five basic sedimentary environments which were subdivided to reflect geomorphological connectivity as discussed above (Table 1): (1) ephemeral lakes, playas and claypans (2.26% basin area) - subdivided into central lake beds, lake margins and pans (≤ 5 km maximum dimension); (2) alluvial channels and deposits (11.55%) - subdivided into low floodplains between multiple anastomosing channels, floodplains/inundation areas without channels and single channels; (3) gibber (14.83%) - stone-covered plains; (4) aeolian sand deposits (32.63%) - including sand sheets and dunes; divided into sand dunes with sandy interdunes (continuous sand cover), sand dunes with interdune pans (which do not disrupt dune wavelengths) and sand dunes where the interdunes are susceptible to flooding; and (5) plains and low hills (38.73%) - including bedrock and duricrusts.

3. Data and Methods

[6] Dust events in the LEB occur in the austral spring and summer and to reflect this meteorological data were analysed using dust storm years (DSY) starting in July and ending in June. Focusing on high intensity dust storms, we define a dust storm day (DSD) as any day when

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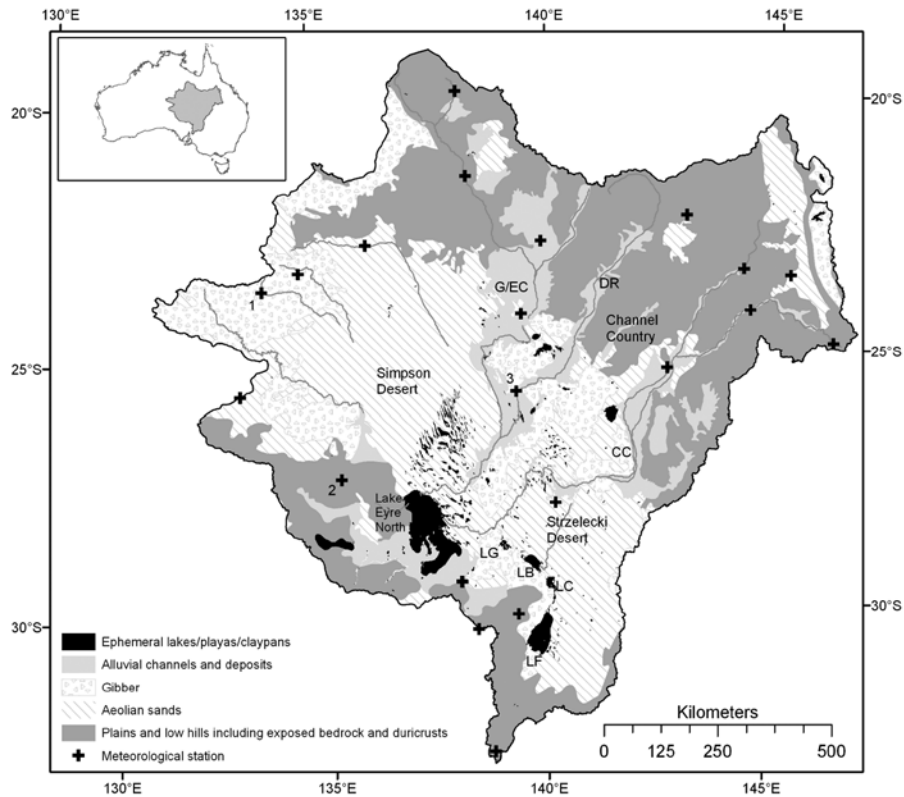


Figure 1. The Lake Eyre Basin showing distribution of dominant surface geomorphology (Geoscience Australia), locations of meteorological stations (1. Alice Springs, 2. Oodnadatta, 3. Birdsville) within the catchment and key locations named in the text: LG – Lake Gregory; LB – Lake Blanche; LC – Lake Callabonna; LF – Lake Frome; G/EC – Georgina River/Eyre Creek; DR – Diamantina River; CC – Cooper Creek.

Table 1. Frequency (%) of Dust Plume Origination by Dust Source for Dust Storm Years (DSY) 2003/4 to 2005/6^a

Dust Source		DSY 2003/04				DSY 2004/05				DSY 2005/06				All Years Total (%)
Sedimentary Environment	Geomorphology	P	Z	B	Total	P	Z	B	Total	P	Z	B	Total	
Ephemeral lakes/claypans/playas (2.26%)	Lake beds	8	2	2	12 (7.4)	21	3	7	31 (11.1)	1	0	0	1 (1.1)	44 (8.3)
	Lake margins	10	3	1	14 (8.6)	41	6	9	56 (20.1)	4	0	0	4 (4.6)	74 (14.0)
	Pans	6	3	0	9 (5.5)	14	3	0	17 (6.1)	5	5	2	12 (13.8)	38 (7.2)
Alluvial deposits and floodplains (11.55%)	Floodplain between multiple channels	13	3	0	16 (9.8)	10	9	0	19 (6.8)	3	6	1	10 (11.5)	45 (8.5)
	Floodplain/inundation area – no defined channels	13	1	0	14 (8.6)	22	23	6	51 (18.3)	9	4	4	17 (19.5)	82 (15.5)
	Alluvial channels	2	0	0	2 (1.2)	3	3	0	6 (2.2)	2	0	0	2 (2.3)	10 (1.9)
Gibber (14.84%)	Gibber	3	1	0	4 (2.5)	1	2	1	4 (1.4)	1	1	0	2 (2.3)	10 (1.9)
Aeolian sands (32.63%)	Dunes with interdune pans	13	5	0	18 (11.0)	13	8	3	24 (8.6)	2	3	3	8 (9.2)	50 (9.5)
	Dunes with sandy interdunes	32	23	5	60 (36.8)	5	28	7	40 (14.3)	8	8	1	17 (19.5)	117 (22.1)
	Dunes with interdune inundation	4	2	0	6 (3.7)	11	8	3	22 (7.9)	5	1	0	6 (6.9)	34 (6.4)
Undulating plains, hills, duricrusts (38.73%)	Plains, hills, bedrock	6	1	1	8 (4.9)	2	6	1	9 (3.2)	3	5	0	8 (9.2)	25 (4.7)

^a'P' = point source, 'B' = broad source, 'Z' = zonal source; see text for explanation.

≥ 1 meteorological station within the LEB or within 250 km of the catchment boundary recorded a dust-induced visibility reduction to ≤ 1 km (WMO SYNOP WW 09). For DSY 2003–4, 2004–5 and 2005–6 the number of DSDs was 17, 19 and 7 respectively. While robust, this method underestimates dust storm frequency due to the low density of meteorological stations in the centre of the basin (Figure 1) but will detect intense sub-basin scale events.

[7] For each DSD, dust plumes were identified using MODIS data from the Terra (morning) and Aqua (afternoon) satellites, passing over the equator at local time $\approx 10:30$ and $\approx 13:30$. MODIS provides good spatial resolution data with a number of useful spectral band widths and is widely used in dust studies. As suspended dust is spectrally-similar to desert surfaces and is difficult to differentiate from some cloud types several techniques to enhance the dust signal have been proposed and have been demonstrated to be effective in this region [McGowan and Clark, 2008]. These techniques are compared in detail elsewhere (M. C. Baddock et al., Dust source identification using MODIS, submitted to *Remote Sensing of Environment*, 2008) and here we use a bispectral split window technique, calculating the brightness temperature difference (BTD) between the $11\mu\text{m}$ and $12\mu\text{m}$ infra-red channels, to enhance the dust signal [e.g., Ackerman, 1997]. On 26% of DSDs it was not possible to identify any active dust sources due to the timing of satellite passes (14%) or cloud cover (12%).

[8] MODIS data for each DSD were cross-referenced with meteorological data to identify the direction of dust transport and the upwind boundary of dust plumes. Dust can occur as a single coherent plume or multiple dispersed plumes, consequently for a single DSD more than one dust source may be identified. For each plume its size, coherence and density was estimated by classifying it as a point source (narrow, discrete plume with a ‘sharp’ upwind edge ≤ 10 km across), a broad source (sharp upwind edge > 10 km across) or a zonal source (> 10 km across with a ‘soft’ upwind margin). The latter may describe a large, source area or the coalescence of > 1 point source. The latitude-longitude co-ordinates of the upwind edge of each plume were recorded as the dust source and, with some caveats, this is considered the best source identification method at this scale [Lee et al., 2008]. These co-ordinates were cross-referenced against topographic, land systems, soil and geology maps and Landsat imagery, and ground-truthed where necessary to allocate each source to one of the 11 categories in Table 1.

[9] The magnitude and frequency of dust emissions depends on aeolian transport capacity, sediment supply and sediment availability. The relationship amongst these variables is modified directly and indirectly by numerous factors including climate, through wind speed, temperature and precipitation. The latter two variables are key determinants of vegetation cover which reduces wind erosion and sediment availability. Any evaluation of the significance of geomorphology must therefore consider the climate-driven likelihood of wind erosion occurring. Calculation of wind erosion potential is used to determine areas or times when aeolian deflation is more or less likely. Here, the dimensionless E_w climatic index of potential wind erosion [McTainsh et al., 1990] was calculated for each DSY using

$$E_w = W(P - E)^{-2}$$

where W is the annual mean wind run (km) calculated using the daily wind speed record and $(P - E)$ is the annual Precipitation-Evaporation Index. Evaporation data are not available for all stations so $(P - E)$ is estimated using

$$(P - E) \sum_{i=1-12} \left[1.644(R/T + 12.2)^{\frac{10}{9}} \right]$$

where i = one of 12 months of the year, R = mean rainfall in month i , T = mean temperature in month i .

4. Results

[10] Table 1 summarises the geomorphologies with which dust sources were associated in each DSY. Of the 529 dust plumes examined, 55.9% were point sources (≤ 10 km across), 33.3% zonal sources (> 10 km) and the remainder broad sources. From 2003–6, 37% of plumes originated in areas of aeolian deposits, 30% from alluvial deposits/floodplains and 29% from ephemeral lakes. Gibber and plains areas together account for $< 6\%$ of dust plumes. Although point, zone and broad plumes come from all geomorphologies, aeolian and alluvial deposits are more likely to produce plumes > 10 km across than ephemeral lakes and playas where nearly 70% of dust plumes are point sources. Within the geomorphological subdivisions, lake margins are consistently more common sources of dust than central lake beds or pans, floodplains (with or without defined channels) dominate over alluvial channels and dunes with sandy interdunes are 2–4 times more likely to be dust sources than dunes with interdune pans or interdunes subject to inundation. These summary values mask considerable inter-annual spatial and temporal variation, discussed below.

[11] In 2003/4 aeolian deposits were the most common dust source in terms of frequency of emissions, accounting for 84 out of 163 plumes examined (51.5%). Of these, most originated from dunes with sandy interdunes and were located in the Simpson or eastern Strzelecki dunefields (Figure 2a). Alluvial deposits, primarily in the west of the catchment, accounted for 19.6% of plumes and ephemeral lakes accounted for 21.5%. Values of E_w , the lowest of the three DSYs examined, peak at 18.61 in the southeast of the basin. The mean (range) values of E_w associated with dust sources from different geomorphologies are 4.52 (0.41–14.1), 4.29 (0.3–11.30) and 6.69 (0.47–10.10) for aeolian deposits, alluvial deposits and ephemeral lakes respectively.

[12] The 2004/5 data indicate 37.3% of dust plumes originated from ephemeral lakes, 27.3% from alluvial deposits and 30.8% from aeolian deposits. Clusters of dust sources can be identified along the margins of the larger dry lakes in South Australia (Figures 1 and 2b). This DSY included the highest wind erosion potentials with E_w reaching 94 in the southwest of the basin, although the majority of dust sources are towards the centre and southeast. The mean (range) values of E_w associated with dust sources are 28 (1.81–67.17), 20.06 (1.03–62.26) and 29.14 (2.46–62.98) for aeolian deposits, alluvial deposits and ephemeral lakes respectively.

[13] There were fewer DSDs in 2005/6 and alluvial deposits accounted for 33.3%, aeolian deposits 35.6% and ephemeral lakes 19.5% of the sources. Some of these

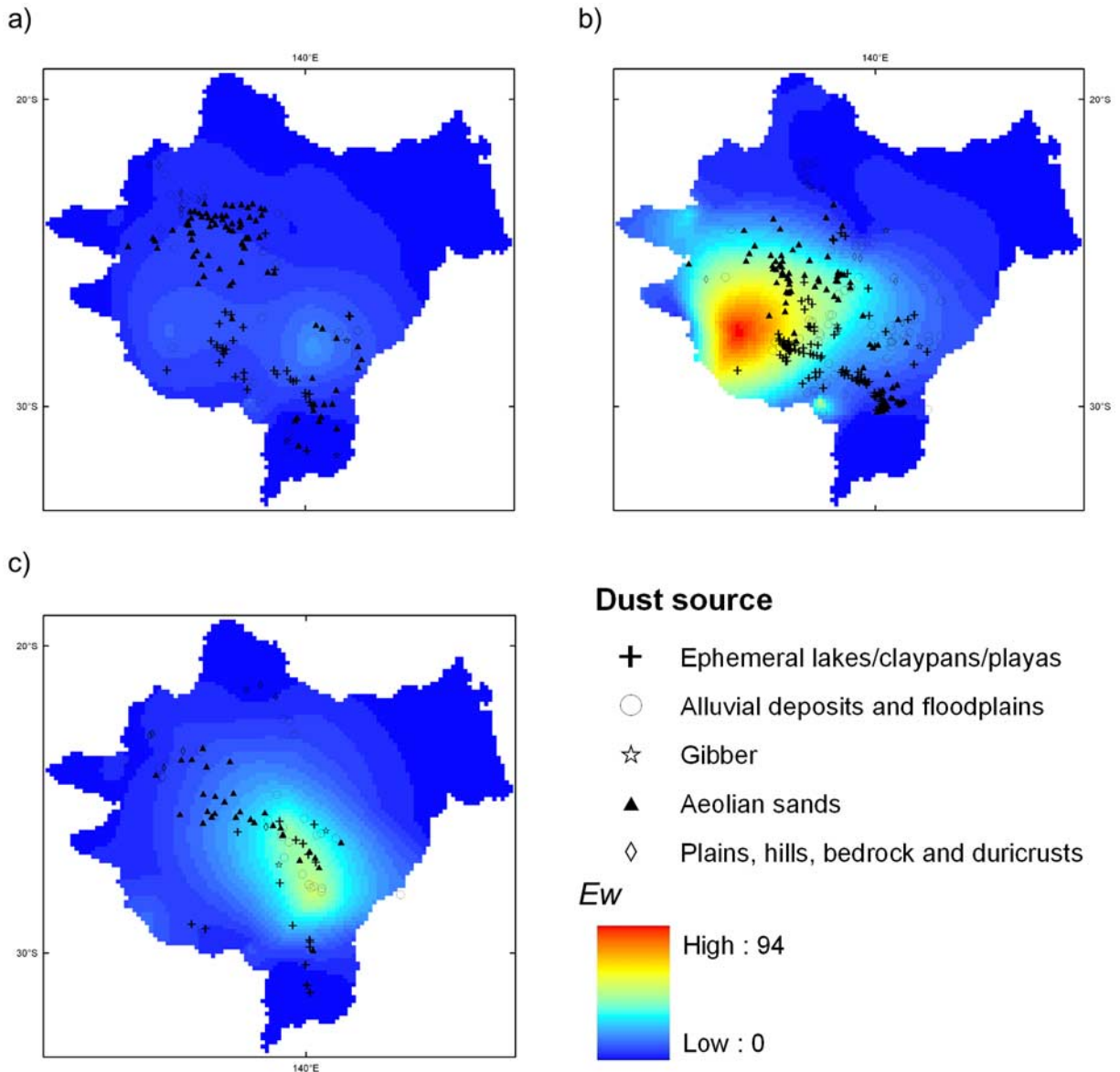


Figure 2. Values of E_w and spatial distribution of dust sources for (a) DSY 2003/4, (b) DSY 2004/5, and (c) DSY 2005/6. For explanation see text.

sources are the South Australian dry lakes but none are from Lake Eyre itself and the majority of dust sources in 2005/6 were from the floodplains of the Channel Country and the Simpson dunefield (Figure 2c). Maximum values of E_w (48.91) in the central part of the basin coincide with a concentration of dust sources. The mean (range) values of E_w associated with dust sources are 20.42 (3.16–41.09), 24.22 (2.02–47.34) and 20.20 (0.54–40.43) for aeolian deposits, alluvial deposits and ephemeral lakes respectively.

5. Discussion

[14] *Washington et al.*'s [2003] study of global dust emissions (1979–1993) suggested the current bed of Lake Eyre was the dominant dust source within the LEB. In this study from 2003–6 only 4% of identified dust sources came from the actual bed of Lake Eyre. However in terms of number of dust sources per unit area, ephemeral lakes

dominate 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. The results demonstrate that dust sources are associated with a range of geomorphologies, however there is no clear relationship between wind erosion potential (E_w) and dust emissions. This may be because different environments respond in varying ways to precipitation or drought according to the balance between sediment supply (through flooding) and sediment availability (affected by desiccation rates and vegetation cover). Studies of dust emissions from dune, claypan and interfluvial surfaces in the LEB by *McTainsh et al.* [1999] showed that in a low rainfall year (1994) dunes had the highest dust flux but when rainfall increased (1995–1997) dust flux on the dunes and the interfluvial decreased as vegetation cover increased and restricted wind erosion. The claypan response to rainfall was complex, initially decreasing with increasing rainfall

but then, following major flooding in 1997 which deposited sediment across the area, dust fluxes increased.

[15] Several flood events occurred in the main river systems of the LEB from 2001–2006. In December–January 2001/2 there was minor flooding in Cooper Creek, the Diamantina River and the Georgina River/Eyre Creek system but the waters did not reach Lake Eyre. Major floods occurred in all three systems in January–March 2004 with waters reaching Lake Eyre. Moderate flooding occurred in the Georgina River/Eyre Creek system in January 2005 and a major flood occurred in the central reaches of Cooper Creek in April 2006. In DSY 2003/4 most dust sources from alluvial deposits were in the west of the catchment not on the floodplains of the Channel Country however in DSY 2004/5 and 2005/6 many dust sources are associated with Channel Country alluvial deposits. This may reflect the availability of sediment supplied by floodwaters in early 2004. Interestingly, for DSY 2003/4 and 2005/6 the mean E_w associated with each geomorphology is similar, but for DSY 2004/5 mean E_w is lower for alluvial deposits than the aeolian or ephemeral lake units. Low values of E_w indicate less climate-driven wind erosion, suggesting the high proportion of dust sources in the Channel Country in DSY 2004/5 was due to the influx of sediment rather than climatic conditions. Dust sources associated with the bed of Lake Eyre are most numerous during DSY 2004/5 and are clustered around the north and northeast margins of Lake Eyre North which is where floodwaters from the Channel Country rivers enter the lake forming sediment-rich deltas. Defining a more precise relationship between flood events and dust emissions would need to consider possible lags between sediment delivery and deflation and variations in the fluvial sediment budget.

[16] The association of dust sources with aeolian deposits is notable and higher than expected. Not only do aeolian deposits account for 37% of all dust sources but they also produce large plumes. The Simpson-Strzelecki dunefield is dominated by partially-vegetated dunes. These include ‘red’ (iron-oxide rich) dunes, the crest sediments of which commonly contain <2% material <63 μ m in diameter [Bullard *et al.*, 2007] and ‘white’, clay-rich dunes which occur adjacent to some floodplains. Although the white dunes are clay-rich, the finer material (including clay, silt and very fine sand) aggregates into sand-sized pellets (5–12% of crest samples [Wasson, 1983]). Cross-referencing Wasson’s [1983] map of dune colour with the locations of dust sources from aeolian deposits indicates 84% of these sources coincide with red dunes and all of these are in the Simpson dunefield. In addition to dune sedimentology, the presence of vegetation (and crusts) dramatically reduces aeolian activity [Hesse and Simpson, 2006] preventing both the release of fines and the production of new material by abrasion.

[17] Although dunes are unlikely dust sources their erodibility can be heightened. First, drought and anthropogenic activities can reduce vegetation cover leading to activation of dunes [Hesse and Simpson, 2006], e.g. most of the east Strzelecki dust sources are associated with localised grazing. Second, fires are common in vegetated dunefields, can destroy perennial and ephemeral vegetation as well as biogenic crusts and firescars have been associated

with dust sources in the Simpson dunefield [McGowan and Clark, 2008]. Widespread fires occurred in the Simpson dunefield during October–November 2001 and very low precipitation in 2001/2 probably delayed the re-establishment of vegetation [Whicker *et al.*, 2006]. In DSY 2003/4, of the 84 dust sources identified in areas of aeolian deposits, 60% were located within an area that had burnt in 2001. In DSY 2004/5, only 8% of dunefield sources were associated with the 2001 firescars and in DSY 2005/6 the proportion was 19%. This suggests that aeolian deposits were the dominant source of dust in 2003/4 due to extensive earlier burning, but that by 2004/5 vegetation had recovered sufficiently to reduce wind erosion to some extent. It is notable that whilst many ephemeral lakes are persistent dust sources most source locations within aeolian deposits are unique; i.e. once the area has been a dust source, within the three year period, it is not recorded as a source again. For sources associated with firescars this may be due to the differential removal of sediment fractions, for example Rostagno [2007] recorded rapid removal of 90% of the clay and silt fractions during dust storms originating from rangelands following fire. After vegetation removal, dune surface activity will increase and whilst this activity may generate new dust-sized material [Bullard *et al.*, 2007], significant replenishment and retention of the <63 μ m fraction is only likely to take place once a vegetation cover has been re-established.

6. Concluding Remarks

[18] Although previous studies suggest the bed of Lake Eyre is the main source of dust emissions in Australia, during 2003–6 only 4% of dust plumes examined came from this location. The relative importance of different dust source geomorphologies varied primarily in response to sediment supply and availability, not aeolian transport capacity. Dry lake beds in the region have high dust emissions per unit area but because they cover only a small percentage of the drainage basin and generate small dust plumes they are not considered the dominant dust source. Our results suggest the LEB is a supply-limited system - emissions from lake beds and floodplains are closely linked to sediment supply from flood events; sand dunes in the region are significant dust sources where vegetation has been removed, enhancing erodibility and release of sediments.

[19] This study indicates that geomorphology at the sub-basin scale plays an important role in dust emissions. Local characteristics such as dune state (active or vegetated), or type of fluvial system are important. The method used here has the potential to bridge the gap between global modeling approaches and field studies. The discovery that ‘red’ (iron-oxide rich) sand dunes are common sources of dust emissions has potential implications for mapping contributions to the global iron-cycle. The results have significance for estimating and modeling dust emissions depending on the activity, dominance and interconnectedness of different geomorphological units for present-day environmental conditions and for palaeo-dust studies and the prediction of future dust emissions.

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