Landsat identifies aeolian dust emission dynamics at the landform scale

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Abstract

The modelling of windblown mineral dust emissions remains a challenge. This is in part due to the coarse spatial and temporal resolution of the data on which these models are based, but also because the processes and mechanisms of aeolian dust emission are not well understood. Satellite imagery has been used extensively in the study of dust from the late 1990s with important contributions being made in terms of sources, transport pathways and deposition areas. Using MODIS imagery, the Namib Desert has been identified as one of the largest sources of dust in southern Africa. The recent

opening of the Landsat archive presents the opportunity to investigate these events at a higher spatial resolution (up to 15 X 15 m) than previously possible. Despite the low temporal resolution, we used Landsat imagery to identify 40 major dust episodes over the last 25 years that originated primarily from the ephemeral river valleys and pan complexes, providing new insight into the spatial and temporal evolution of the dust sources from the Namib Desert. Examination of the imagery enabled the identification of local-scale landform source points to direct ground based testing of the surfaces responsible for dust emission. Emissivity tests were undertaken using a PI-SWERL portable wind tunnel in three of the major dust producing river systems along the Namib coast, namely the Kuiseb, Omaruru and Huab Rivers. Preliminary observations suggest that human impact on the hydrological systems in two of the river basins, to cater for the increasing demand of water, have dramatically altered the emission of dust. The source areas of greatest dust emission are found to be located on recently deposited fluvial surfaces which are not active in the contemporary environment.

1 Introduction

Windblown dust has significant impacts on the earth's climate (IPCC 2013) and biogeochemistry, including the atmosphere, ocean and terrestrial systems (e.g. Knippertz & Stuut, 2014; Maher et al., 2010; McTainsh & Strong, 2007; Soderberg & Compton, 2007; Xuan & Sokolik, 2002). The aeolian dust cycle can be divided into three general stages, namely, the emission of dust from source areas, transport in the atmosphere and deposition of dust both on land and in the ocean (Mahowald et al., 2005). The influence of the emitted dust on other Earth systems depends largely on its physical characteristics including size, mineralogy and morphology of the particles (Formenti et al., 2011). These particle characteristics are in turn determined by the physical attributes of the emissive dust sources. Improving our understanding of the characteristics of dust sources will improve our understanding of how, when and where dust emission takes place. Remote sensing has been used extensively in identifying dust sources (Table 1), initially at a global scale and currently at landscape scale resolution.

The major global atmospheric dust sources were first identified with the use of the Total Ozone Mapping Spectrometer (TOMS) Aerosol Index (AI) (Herman et al., 1997; Prospero et al., 2002; Washington et al., 2003). This index is best suited to identifying large and consistent regional dust sources, such as the Bodélé Depression and Etosha Pan. This data set has certain spatial and temporal constraints when applied to atmospheric dust, with the result that it has been most useful in highlighting long range transport and dispersion, and inter-annual and seasonal variations of higher altitude dust loadings, with a clear bias towards the world's large inland basins. Some of these constraints include the inability to detect dust at low altitudes (<1-2 km) or non-UV absorbing aerosols, such as sea-salt particles and sulphates (Mahowald, 2004). Consequently, several areas known to emit dust, for example the Gobi Desert of Mongolia, Kuwait and the Namib Desert, are not represented in the TOMS AI (Washington et al., 2003) (Figure 1e). The importance of many of these dust sources have been highlighted with the advent of remote sensing data of higher spatial and temporal resolution and utilising different wavelengths. Two of the sensors that have been widely used include MODIS

62 **Table 1 Dust source scale and nomenclature from large scale regions to surface types and grain size analysis.**

Spatial classification (adapted from MacMillan et al. 2000 and Smith et al. 2011)	Map scale:	Dimension	Webb and Strong, 2011		DEM resolution (MacMillan et al. 2000)	Dust data (remote sensing, field observation and laboratory analysis)		Source areas	Global		Southern African	
		m	m			Spatial resolution	Temporal resolution					
Physiographic region	1 000 000	10 000	$>10^4$	Regional	9x9km, 1x1km	13x24km TOMS, 4x4km MSG, 1x1km Seawifs	Daily, 15 minutes, Daily	Large-inland draining basins, agricultural areas	Bodele Depression, Lake Eyre basin	Prospero et al., 2002; Washington et al., 2003	MAK (Botswana), Etosha (Namibia), Kuiseb River (Namibia), Free State (RSA)	Eckardt et al., 2005; Wiggs et al., 2011; Vickery et al., 2013
Physiographic system	100 000	1 000	10^3	Landscape	100x100m	250x250m MODIS	Twice daily	Lakes, alluvial systems, stony surfaces, aeolian systems (PDS as per Bullard et al. 2011)	Strzelecki dunefields (Australia), alluvial deposits and floodplains of the Channel Country (Australia)	Bullard et al, 2011; Lee et al., 2012	Kuiseb river delta (Namibia)	Vickery et al., 2013
Landform type	10 000	100	10^2	Plot	10x10m	15x15m Landsat (pan) 30x30m Landsat (MS)	16 days	Lake margins, active river channel, delta terraces			Current study	
Landform element	1 000	10	10^1		5x5m	Fieldwork		Landforms and surface characteristics	Playa salt crust, aeolian ripples, silt crust, biological crust, stone pavements	Bacon et al., 2011; King et al., 2011; Sweeney et al., 2016; Wang et al., 2012		
Surface type	100	<1	$<10^{-2}$	Grain		Fieldwork, Laboratory						

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(Moderate Resolution Imaging Spectroradiometer) and Meteosat Second Generation (MSG) Spinning Enhanced Visible and InfraRed Imager (SEVIRI).

MSG-SEVIRI data has a better spatial and temporal resolution than TOMS (Table 1) with the infrared wavelength channels being suited to detect dust as a result of the temperature difference between the dust and the land/ocean surface (Schepanski et al., 2012; Schepanski et al., 2007). Although the spatial resolution still limits the identification of dust sources at a regional scale, the 15-minute data acquisition is one of the main advantages of this sensor. This allows the dust plumes to be tracked from the source region and for each event to be linked to meteorological conditions as the dust event progresses. The MSG infra-red data performs better over land than over the ocean or adjacent to coastal regions due to the decreased temperature differential between the dust and water; and the large influence of columnar water vapour (Brindley et al., 2012).

MODIS is suitable for studying aeolian dust activity, either by using true colour imagery, taking advantage of the colour difference between the land/ocean surface and the dust (O'Loingsigh et al., 2015; Vickery et al., 2013) (Figure 1c), or using spectral techniques based on brightness temperature differences between different wavelength bands to enhance the dust signal (Baddock et al., 2009; Bullard et al., 2008; Miller, 2003). The higher spatial resolution of the VIS bands means that sources of individual events can be identified at a landscape scale and inventories of commonly emitting source areas can be determined. In addition, the twice daily overpass (Terra and Aqua) provides enough coverage to create a time series of dust events from specific landscapes, allowing comparisons of dust emission frequency to be made between different sources. However, this method of dust source detection also has limitations, particularly when using simple true colour composites. Lee et al. (2009) point to the fact that many dust sources are in fact small areas and not discrete points. Furthermore, a certain amount of subjectivity is involved in selecting these areas, especially when the plumes are faint or the images not clear. Despite the moderate spatial resolution of c. 250m, the effective resolution of plume detection is in the order of ≈ 10 km (Bullard et al., 2008). Another limitation is that the identification, or pinpointing, of an emitting part of the land surface, does not

90 provide any measure of the intensity of the emission at each eroding point. Lastly, O’Loingsigh et al.
91 (2015) in a study from Australia
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Figure 1 Dust emission from Namibia. (a) Dominant Namibian dust sources according to MODIS from 2005-2015 with dust days greater than 30 (b) MODIS Terra true colour composite

for 17 June 2010 (c) Wind speed versus wind direction. Dust events identified with MODIS are only associated with winds from the north-east quadrant. Grey dots are wind events from Era-Interim and black dots are MODIS events for corresponding time step (d) Time series for the dust events identified with MODIS and average seasonal easterly wind events $> 6 \text{ m s}^{-1}$ for the Kuiseb River (Era-interim data extracted for Kuiseb area as indicated with box) (e) TOMS identified Etosha and MAK as main sources, but not the Namib coast (figure from Washington et al., 2003) (f) Placement of larger study area within southern Africa. River catchment shapefile from Mendelsohn et al. (2002).

found that dust event frequency, according to true colour MODIS images, was significantly underestimated when compared to data from a near-surface integrating nephelometer, due to its temporal resolution and cloud cover.

Notwithstanding these limitations, several studies have attempted to link MODIS identified dust sources (as geographical coordinate points) with geomorphology and land use/cover for various regions (Baddock et al. 2011, Hahnenberger et al. 2014, Lee et al. 2012, Vickery et al. 2013). In these studies, the geomorphological classification and land use/cover categories used to determine the land surface that each emission point was associated with were identified with a combination of topographic, soil and geological maps, high resolution satellite imagery, aerial photography and field verification where possible. An example of such a classification is the preferential dust source (PDS) scheme (Baddock et al., 2016) developed by Bullard et al. (2011). Although an important step forward, the dust sources identified with the medium resolution satellite imagery of MODIS and the geomorphological units associated with them are still not at a high enough spatial resolution to identify the specific landforms responsible for emission.

Only a very few of the geomorphological units that have been identified as dust sources have been the subject of intensive field observation and measurement attempts to better understand and quantify the processes of dust emission (Bryant, 2013; Haustein et al., 2015). This is because the resolution of dust source mapping from remote sensing data to date, still only provides a landscape scale assessment (≈ 10 km) of where the dust producing surfaces are located. Using these data to guide the location of field observation and measurement involves a substantial jump in scale, as measuring equipment for data collection is often situated within or downwind of a particular landform element deemed to act as a dust source (considering scales from ~ 10 m to ~ 100 m). Selecting sites for field observation therefore involves interpreting the landscape on the basis of the available knowledge of the landforms present and making a judgement regarding their emission potential based on factors that affect dust production, such as sediment supply and availability; and the fluvial-aeolian interactions of these within a system (Field et al., 2009; Bullard & McTainsh, 2003).

The dust source regions and landscapes of southern Africa have been studied by Eckardt et al. (2001) by means of hand-held Space Shuttle photography, by Eckardt & Kuring, (2005) with the aid of SEAWiFS and by Vickery et al. (2013) using MODIS and MSG (Table 1). The TOMS Aerosol Index identified the dry lake beds of the Makgadikgadi pan complex and Etosha Pan as southern Africa's major sources (Prospero et al., 2002; Washington et al., 2003). The MODIS imagery used for the study by Vickery et al. (2013) consisted of true colour composites. These images were particularly useful in identifying the Namib Desert coast as an important regional dust source for the period from 2005 to 2008 due to the easily recognisable light dust over the dark ocean. The Namib Desert on the other hand was not identified as an important regional dust source using TOMS AI (Figure 1 e) or MSG. The failure of TOMS AI to detect the Namib Desert as a dust source region is potentially a result of the dust being at low altitude and the likely presence of non-UV absorbing aerosols. Using MODIS Vickery et al. (2013) concluded that 62% of all detectable plumes from southern Africa for the period from 2005-2008 originated from the Namib Desert coastal sources, with dust emission predominantly associated with the strong north-easterly Berg winds from April to August.

The Namib Desert embraces a variety of physiographic systems, including the ephemeral westward flowing river catchments, pan complexes, dune fields and low relief gravel plains. Similar systems have been identified as potential dust sources in many arid regions of the world (Table 1). Each of these systems encompasses several landforms, such as the floodplain terraces and active channels of rivers; basins and margins of playas and sabkhas; and stone pavements and wadis of the gravel plains. These landforms are also present in the Namib Desert and some have been shown to have an ample supply of appropriate sized sediments that can be entrained by the wind (von Holdt & Eckardt, in press, Dansie et al., 2017). However, the erodibility and actual contribution of these landforms to the dust load has not been determined.

Landsat, which offers a much higher spatial resolution, has been used to study dust to a lesser extent than other sensors primarily due to its poor temporal resolution (Kaufman et al., 2001; Chavez et al., 2002), such that no studies have systematically used Landsat to identify dust source areas. A dust event captured by Landsat, however, offers the opportunity to investigate the source points in greater

detail than has been done in the past. The archive of Landsat imagery made publicly available by the USGS provides an easily accessible platform to search and download these data. Although the temporal resolution is poor (one overpass every 16 days), the 30 x 30m resolution (15 x 15m with the panchromatic band for Landsat 8) offers a level of spatial detail not possible with other continually collected satellite data used to date. These images provide the ability to identify with greater accuracy and detail specific landform types and elements responsible for dust emission for wind erosion events captured by Landsat. The ability to identify these dust emitting small-scale source terrains and surfaces means they can be subjected to surface characterisation and dust emission tests using field experiments. One such instrument that has become widely used in dust research is the PI-SWERL portable mini wind tunnel to test the erodibility and emission potential of surfaces in dust source areas (Bacon et al., 2011; Etyemezian et al., 2007; King et al., 2011; Sweeney et al., 2011). The placement of dust measurement and sampling equipment, such as the PI-SWERL, can be optimised based on accurate local-scale dust source identification using Landsat.

The study presented here utilised the higher spatial resolution of Landsat to identify the small-scale geomorphology and landform types that act as dust sources in the Namib Desert. The study area was chosen based on the analysis of MODIS true colour images for an 11-year period (2005-2008 carried out by Vickery et al., 2013 and 2009-2015 carried out as part of the present study), which identified persistent dust sources from Namibia. Finally, field visits were undertaken to determine to the local-scale source points identified with the Landsat imagery and the aeolian dust emission potential of the sites was determined using a PI-SWERL portable wind tunnel.

2 Methods

2.1 Identifying dust source systems

MODIS true colour composites from the Terra and Aqua sensors were used to identify source areas of plumes from Namibia using the same method as Vickery et al., 2013 for the study period from 2005 to 2008. In addition, processed MODIS true colour images (bands 1,2,3) were obtained from the MODIS Rapidfire online facility for the period from January 2009 to May 2012, followed by NASA Worldview up to 2015. The images analysed as part of the study by Vickery et al. (2013) were reanalysed as part of this study to ensure consistency. The source points for visible dust on images were identified by placing a point where the plume origin was judged to be and attributing these points to a physiographic system, such as specific catchment areas or pan complexes. These source areas highlighted the most active dust source systems within the Namib Desert which then provided the focus areas for the higher spatial resolution Landsat analysis.

2.2 Identifying landform types responsible for aeolian dust emission

The available Landsat archive accessible with LandsatLook Viewer (<http://landsatlook.usgs.gov/>) was studied to identify images in which windblown dust was visible. Over 2,000 images were examined as part of this study available on the online archive, consisting of a subset of Landsat 1-8 images. Cloud cover was restricted to a maximum of 20 %. Full resolution Level-1 product individual band files were downloaded for images with visible dust and stacked using Erdas Imagine 2015-16 (Leica Geosystems, Atlanta, Georgia, USA). The same software was used for Landsat 7 ETM+ and 8 OLI images to merge the high-resolution panchromatic band with the medium-resolution multispectral data to improve the resolution of the multispectral images from 30 m to 15 m. Dust was detected on selected Landsat 7 images with SLC-off, but these were excluded from the analysis for areas where the imagery did not provide complete coverage. Various band combinations were tested for optimal identification of plume origin, of which two combinations were selected and used for all source point identification: the true colour (3,2,1 for Landsat 5 and 7 and 4,3,2 for Landsat 8) and false colour image comprising bands 7,4,2 for Landsat 5 and 7; and bands 7,5,3 for Landsat 8. In addition to

identifying dust plume origins, the false colour image was particularly useful in distinguishing different landforms within the landscape. Four of the Landsat 5 scenes used (listed in the supplementary section), lacked the geometric accuracy to be perfectly aligned and had to be geo-rectified. The maximum error encountered amounted to approximately 500 m. This problem occurs for some of the older scenes as a result of the use of predictive instead of definitive ephemeris data to record the position and velocity of the satellite at the time the data is collected (USGS EROS User Services, pers com, https://landsat.usgs.gov/what_is_definitive_ephemeris.php). This information is available in the scene metadata.

The Landsat images were interrogated using various local contrast enhancements by applying linear minimum and maximum histogram stretches with Erdas Imagine, both over land and over the ocean. Performing local area histogram stretches to specific areas and around specific features provided maximum clarity for plume source point identification. A min-max stretch over the ocean resulted in images which showed the full extent of the dust plumes. Source points were identified manually and classified according to two categories. Firstly, as “certain” for source points which could be clearly identified and for which the plume origin could be associated with a specific landform type or element. Secondly, as “uncertain” if a plume was visible, but the plume origin could only be linked to a physiographic system and not linked to specific landform types or elements.

A list of all the imagery used as part of this study is provided in the supplementary section.

2.3 Dust emission frequency: reanalysis wind data

ERA-Interim 10 metre wind speed data corresponding to the 11-year MODIS record was used to compare the frequency of MODIS dust events to the frequency of wind events with sufficient friction velocity to entrain dust for the Kuiseb River catchment (Dee et al., 2011). This reanalysis data set was chosen as it has a better correlation with MODIS deep blue aerosol optical depth (AOD) as a measure of dust loading in the atmosphere than NCEP/NCAR reanalysis 1 data (Kjeldsen et al., 2014). For the purposes of this comparison, the threshold friction velocity was taken as the minimum wind speed at 10 m for which dust was detected with MODIS (6 m s^{-1}). Six-hourly horizontal (u_{10}) and vertical (v_{10}) wind components were downloaded from the ECMWF Public Datasets web interface at 0.125°

resolution for the study site from 2005 to 2015. Data for specific areas were extracted and mean values across latitude and longitude computed for every 6-hour time interval (12am, 6am, 12pm and 6pm) using Climate Data Operators (CDO) software v1.7.2 (<http://www.mpimet.mpg.de/cdo>). Calculated u10 and v10 vector components were corrected with the relevant off-set and scaling factors, from which wind speed and wind direction were computed. This data set was also used to determine the wind speed on an event basis where indicated.

2.4 Characterising dust potential of surfaces

Fieldwork was carried out in selected areas based on the MODIS and Landsat dust source point analysis. The Portable *In-Situ* Wind EROsion Lab (PI-SWERL) (Etyemezian et al., 2007; Sweeney et al., 2011, 2016) was used to test the dust emission potential of landform elements guided by the most certain Landsat source points. The PI-SWERL consists of a cylindrical chamber which is placed over the test surface with a shear stress applied to the surface by means of a rotating annular ring set at a fixed height of 0.07 m from the surface. Once the applied shear stress exceeds the entrainment threshold any emitted dust is monitored by a DustTrak monitor, mounted on top of the chamber, using a light scattering technique to measure the concentration of PM₁₀ (particles with optical diameter $\leq 10 \mu\text{m}$). The PM₁₀ size range has traditionally been regarded as the most important fraction due to its long-range suspension and transport potential and recognition of its influence on air quality and potential health impacts (Goudie, 2014; Prospero, 1999; US EPA, 1995). Estimates of dust flux from the PI-SWERL have been shown to correlate well with large field wind tunnels (Sweeney et al., 2008). The small size, portability and ease of use of the PI-SWERL enables the testing of many more surfaces than previously possible and in locations that are difficult to access.

Experiments with the PI-SWERL consisted of between 3 and 7 replicates with all runs conducted as a ramp test up to 3300 rpm, at a constant flow rate and a run time at maximum rpm of 180 seconds. A rotation speed of 3300 rpm provides a friction velocity, u^* of between 0.55 and 0.58 m s^{-1} for the majority of the surfaces tested as part of this study, where the effective friction velocity depends on the surface roughness of the test surface (Etyemezian et al., 2014; PI-SWERL manual v1.3, 2011). A constant rotation speed was chosen to compare emissions from all the surfaces at different sites tested.

This friction velocity is in agreement with previous studies that used the PI-SWERL (King et al., 2011; Sweeney et al., 2011) and exceeds the threshold at which saltation is initiated (Fryberger, 1979; Stout, 2007). Saltation in an aeolian context is the movement of sand sized particles by wind in short hops or leaps. This mechanism has been regarded as essential for dust emission as the saltating sand grains bombard the surface, and consequently results in the release of dust sized particles for suspension. Direct aerodynamic entrainment of small dust sized particles has thus far been regarded as insignificant in comparison due to the binding strength of interparticle cohesive forces (Shao et al., 1993).

PI-SWERL measurements were conducted at the end of the dry winter dust season in September 2015. Rainfall in the Namib Desert average less than 25 mm/year towards the coast and occur predominantly in conjunction with sporadic convective summer thunderstorms (Eckardt et al., 2013). Fog occurs more regularly than rain in the Namib Desert, but the quantity of fog-water precipitation on a daily basis is very low (Lancaster et al., 1984). The average annual precipitation (rain and fog) for 2015 at the Kuiseb delta was 12 mm (http://www.sasscalweathernet.org/weatherstat_infosheet_we.php?loggerid_crit=E7631). With the highest recorded in January (4.9 mm, 40 % of the annual precipitation) and September recording no precipitation events. Further north at the Omaruru River, the average annual precipitation for 2015 was even less at 9.1 mm, with September recording only 0.8 mm (http://www.sasscalweathernet.org/weatherstat_infosheet_we.php?loggerid_crit=31200).

Unfortunately, there are no monitoring stations close to the Huab River to obtain accurate amounts, but conditions will be similar to that reported for the Kuiseb and Omaruru regions. This is in stark contrast to the headwaters of these rivers situated on the escarpment, where rainfall increases to approximately 350 mm/year and flow in the rivers only occur when sufficient rain has fallen in the highlands predominantly in summer (Jacobson et al., 1995). The quantity and extent of the floods vary, but they rarely reach the Atlantic Ocean. The Kuiseb River has only reached the ocean 18 times in the last 180 years, with the last flood to reach that far occurring in 2011 (data from Gobabeb

285 Research Station, Morin et al., 2009). Testing was only conducted during the hottest part of the day
286 when all dew present from the previous night had dried out.

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3 Results

The extended 11-year record from 2005 to 2015 identified the Kuiseb, Omaruru and Huab River catchment as the three dustiest systems within the Namib Desert (Figure 1 a and b). The events identified with MODIS true colour images take place only in conjunction with high magnitude north-easterly winds (Figure 1 c), which occurred predominantly during winter (JJA) as noted by Vickery et al. (2013). Figure 1 d shows the number of dust events compared to the 10 m easterly winds according to Era-Interim greater than 6 m s^{-1} for the same period and highlights the seasonality associated with dust events identified with MODIS. Winds of this magnitude occurred for 16 % of the 11-year period, with 11.2 % from the south-west and 4.1 % from the north-east (Table 2).

The higher frequency of dust emission events from the Kuiseb, Omaruru and Huab catchments increased the likelihood of dust events being captured by Landsat's repeat coverage of every 16 days. Consequently, Landsat images used from the available archive focused on these areas and included images taken along three paths (179, 180 and 181) and five rows (73-77) from 1972 onwards (Figure 2 b). A total of 40 images with visible dust events were found, starting from 1989 up until 2016 and include images from Landsat 5, 7 and 8 (listed in the supplementary section). The image from 21 July 1989 (Figure 3) was excluded from this analysis as it was deemed to be an extreme event and the source points associated with this image were therefore regarded as potential anomalies.

The Landsat source points identified from 39 event days for the most prolific systems are depicted in Figure 2 (a). At this regional scale, the dust source map does not appear very different from the MODIS source map (Figure 1 b). Using the superior spatial resolution of Landsat and zooming into the local-scale is where the advantage of using this sensor becomes apparent. Figure 2 insets 1 – 6 shows Landsat images for selected events, with the clearly visible individual dust plumes and the source points that were identified for that specific event. Drawing conclusions regarding the frequency of emission from various landform types and elements between various systems using

Table 2 Wind events according to Era-interim capable of producing dust for all directions. Note that dust events recorded by MODIS were only detected with the north-east wind. Wind events exceeding 6 m s^{-1} occurred for 16 % of the time in the 11-year period. Era-interim data can be used to determine potential dust days, which can then be linked to any satellite sensor's record by the corresponding overpass for a specific area.

Wind speed (m s^{-1})	Number of wind events				NE only		
	NW	SW	SE	NE	Wind events at night $> 6 \text{ m s}^{-1}$	Number of MODIS dust events	Wind events for which dust detected (%)
All	1555	8059	2894	3560			
6-8	50	1765	17	457	108	74	16 %
8-10	2	40	1	184	58	91	49 %
+10	0	0	0	14	3	11	79 %
Total > 6	52	1805	18	655	169	176	27 %
					26 %		
Total % > 6 of total	0.3 %	11.2 %	0.1 %	4.1 %

Figure 2 Dust emission sources identified using Landsat from 1990 to 2016. Insets 1-6 are examples of false colour dust images (bands 742 and 753) and source points identified, with corresponding Era-interim maximum wind speed on the day of the event. White dots are “certain” source points and black dots “uncertain”. All source points are provided in the supplementary section.

Figure 3 An extreme dust event captured by Landsat 5 on 21 July 1989. This event is known as the Superstorm of 1989 and Era-interim wind data for this day shows 10 metre wind speeds of up to 40 m s^{-1} , compared to a maximum of 12 m s^{-1} from 2005 to 2015.

the Landsat source point classification should be done with caution due to the poor temporal resolution of this data. Notwithstanding, the Kuiseb, Omaruru and Huab Rivers provided the largest number dust events identifiable in Landsat and, more importantly, consistently emitted dust from the same landforms. These data are in agreement with MODIS due to the closeness of the Landsat and MODIS Terra overpass (equatorial crossing time of 10:00 AM for Landsat and 10:30 AM for Terra).

The following sections identify the dust sources within each river valley. However, it should be noted that although this study uses the river catchments as the basis for classifying the dust source points, the specific emission surfaces are not exclusively of fluvial nature. Some of the identified points of emission do not strictly fall within the hydrological catchment of the rivers, but they do receive significant local aeolian input from the fluvially deposited sediments of the rivers and for the sake of this analysis are classified as falling within the specific river's sphere of influence.

Kuiseb river dust sources

The Kuiseb River is the most active catchment with the highest percentage of the MODIS dust images for Namibia showing dust originating from this area (on 58 % of all images showing dust). Figure 4 shows a shift of dust source points, with most of the Landsat points originating from a northern arm of the delta, whereas the MODIS source points from the period of 2005-2008 (Vickery et al., 2013) were all placed in the southern arm. The gravel plain further inland produced 20 % of the dust source points identified with Landsat for the Kuiseb landscape, compared to 67 % of the dust source points from the Kuiseb delta northern arm. Only 3 % of the plumes could be placed in the river channel, whereas the precise landform origin of 10 % of the plumes could not be determined and were therefore classified as "uncertain". The gravel plain consists of both stone pavements and ephemeral dry washes or wadis intersected by playas. The northern arm of the delta has remained a consistent source of dust with dust plumes visible from 1989 to the present. Another persistent landform identified within this region is the Tumas River terraces (Figure 4) situated just east of the dune corridor between Walvis Bay and Swakopmund.

The PI-SWERL analysis conducted at a selection of source points identified with Landsat not only provides confirmation of these landforms as significant dust sources, but also the potential mechanism of dust emission from these surfaces. The depositional silt crusts of the terraces both in the Kuiseb and the Tumas are the predominant sources of fluvially deposited fine material that are eroded and suspended during high magnitude wind events. The highest emissions recorded by the PI-SWERL were from between the silt terraces in the Kuiseb northern arm (Figure 5 line a). The consolidated silt crusts of the terraces are also able to emit significant quantities of dust, but primarily with the presence of sand for sandblasting. Figure 5 lines (b) and (c) show the PM_{10} concentrations respectively from the Kuiseb and Tumas terraces with abundant quantities of sand present, compared to reduced

Figure 4 Dust emission sources identified using Landsat imagery in the Kuiseb River delta. The emission points are situated predominantly in the abandoned northern arm of the delta,

367 **whereas the MODIS source points from 2005 – 2008 (Vickery et al., 2013) were placed in the**
368 **fluvially active southern arm. The northern arm was blocked off in 1961 to prevent flooding in**
369 **Walvis Bay and resulted in an extensive area of abandoned terraces with an available supply of**
370 **depositional sediments. The Pi-SWERL sites from field observations conducted in September**
371 **2015 are indicated with triangles a, b, c and d correspond with PI-SWERL results and inset**
372 **photo presented in Figure 5.**

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375 **Figure 5 Dust emission potential of the Kuiseb River. The PI-SWERL results show the most**
 376 **emissive surfaces are the unconsolidated material between silt terraces (a), followed by the silt**
 377 **crusts when there is an abundant supply of sand present (b: Kuiseb northern arm and c:**
 378 **Tumas). In contrast, significantly reduced emissions are produced from silt crusts with**
 379 **negligible sand present (d). Photo insets show the surfaces from the Kuiseb before a PI-SWERL**
 380 **run. Panorama shows the silts and sands of the Kuiseb northern arm terraces. Photo of the**
 381 **Tumas terraces corresponding to (c) is included in Figure 4. TRPM denotes the targeted RPM**
 382 **produced by the PI-SWERL.**

emissions with negligible amounts of sand present (line d). The gravel plain stone pavements provided some of the lowest emissions tested during this study (an average of 5 mg/m³) when armoured with a dense gravel cover (> 30 %), but had much higher emission with low density gravel covers (< 30 %) (an average of 28 mg/m³). Disturbed stone pavements were shown to potentially emit substantial quantities of dust (75 mg/m³). The dust emission potential of the stone pavements of the gravel plain will be discussed as part of a separate study.

Omaruru River dust sources

84% of the identified emission points in the Omaruru River catchment were located within the floodplain channel in the downstream section of the river (Figure 6). The position of the source points remains within the river channel, initially originating from the most downstream position in the river where it is still aligned with the direction of the predominant high magnitude north-east winds. However, the source points undergo a shift, first moving upstream and gradually downstream to its present position over a period of 20 years. This change of source areas through time is shown in Figure 6. The field visit to the present Omaruru Landsat source points in the river channel revealed that the river channel and floodplain consists almost entirely of two surfaces, namely nebkhas and gravel covered, degraded silt crusts. The PM₁₀ concentrations emitted in the PI-SWERL tests from the gravel covered silt crusts proved to be negligible (Figure 7 line b), compared to significant emissions from the nebkha fields (line a). Many of the nebkhas had sparse and dying vegetation cover, providing very little protection from the wind. In certain areas, what appeared to once be nebkhas only show the remnants of dead vegetation, including large trees (Figure 6, photo inset).

Figure 6 Dust emission sources identified using Landsat imagery for the Omaruru River. This shows a longitudinal evolution of emission sites with time, consequent upon building of the Omdel dam in 1995. The surfaces responsible for dust have moved from downstream before the modification, to upstream afterwards and then appear to be gradually moving downstream as the sediment supply is depleted. Photos show the dead vegetation after being starved of water and sediments, and the settled silt collected at the dam wall. The Pi-SWERL sites a and b correspond with PI-SWERL results and inset photo (for a) in Figure 7.

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414 **Figure 7 Dust emission potential of the Omaruru River. Graph and inset (a) shows PM_{10}**
 415 **concentrations from the nebkha fields in the present source area compared to that from the**
 416 **surrounding gravel covered silt crusts (b). The nebkhas have vegetation that ranges from dead**
 417 **to fairly intact. The surfaces of river channel further upstream consist of the remnants of**
 418 **nebkhas with dead trees, surrounded by gravel lag deposits as shown in photo inset (b). Photo**
 419 **insets of surfaces before PI-SWERL run.**

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423 **Figure 8 Dust emission sources identified using Landsat imagery in the Huab River. The source**
 424 **points are distributed over a greater area, with the upstream section (a, b and d), delta (c) and**
 425 **playas (pan) proving to be consistent sources of dust. The delta terraces that are most emissive**
 426 **are devoid of vegetation. The incised channel's alignment with the high magnitude north-**
 427 **easterly wind potentially plays a role in the emissivity of the terraces in the upstream section of**
 428 **river acting as a consistent source of dust. The Pi-SWERL sites a, b, c and d correspond with**
 429 **PI-SWERL results and inset photo (for a, b and d) in Figure 9.**

Huab River dust sources

The Huab River persistent source points are more widely spread than the previous two river systems and are mainly concentrated around the Huab playa situated to the north of the river (34 %), the delta (16 %), an upstream river channel site (21 %) and the gravel plain within this landscape (29 %). Most of the gravel plain sources are situated just north of the delta and surrounding the playas (Figure 8). The PI-SWERL tests from this landscape reveal that the nebkhas and silt crust terraces (with sand present) are the most emissive surfaces in the area (Figure 9). The upstream site (at a,b and d) consists of silt crusts on the river terraces that become significant sources of dust in the presence of saltating sand. In addition, the river terraces are covered to a great degree by nebkhas varying in vegetation condition from healthy to completely dead. Much less dust is produced from the active channel, with significantly less dust coming from the occasional and sporadic silt deposits found within the active channel (an average of 29 mg/m³) and virtually no dust coming from the active channel sands (an average < 1 mg/m³). The terraces in the delta identified as a persistent dust source area consisted of large areas with no vegetation cover. PI-SWERL tests confirm the possibility of significant emissions from this landform (Figure 9 c). Testing done on the Huab playa proved difficult due to the persistent foggy conditions on the coast. Moisture is a significant control on dust emission (Gillies, 2013) and the presence of hygroscopic salts on the pan surface attracts moisture from the atmosphere with high humidity conditions. The diurnal cycle of condensation wetting and drying and fog precipitation along the coast could have a significant influence on dust production from the playas and sabkhas (Reynolds et al., 2007). Further research is needed to investigate the role of fog conditions on dust emission processes.

Figure 9 Dust emission potential of the Huab River. The graph shows the PM₁₀ concentrations from the nebkhas in upstream section of river (a), which cover the river silt crusts of the terraces. These silt crusts are significant sources of dust in the presence of sand (b), compared to much reduced emission potential where negligible sand available for saltation (d). The nebkhas in the delta (c) were also highly emissive. Photo insets taken before Pi-SWERL testing. Panorama shows silt terraces identified as predominant dust source in the upstream section of river (facing upstream).

4 Discussion

Landsat imagery has enabled us to identify the landform elements that act as source points for aeolian dust emission in three ephemeral river catchments at a local spatial scale. In the Kuiseb and Omaruru Rivers the source points for dust emission appear to centre around sites of significant direct anthropogenic modification, whereas the Huab River has not undergone the same degree of modification. All 12 major ephemeral rivers (Figure 1) flowing through the Namib Desert originate in the wetter highlands and drain westward towards the Atlantic Ocean. These rivers rarely reach the sea and aeolian transport is often the only way the fluvially deposited sediments reach the ocean (Dansie et al., in press). Groundwater within the alluvial deposits of the river systems is the major source of water for this region. The Kuiseb and Omaruru Rivers produce significant volumes of water for the mining industry and urban use from their aquifers.

The identification of the dust emission source points using MODIS in the southern arm of the Kuiseb delta is subjective given the effective resolution of MODIS as suggested by Lee et al. (2009) and is dependent on the information about the area available when performing the classification. It is intuitive to place the source points in the southern arm based on the fact that the river has only flowed in the southern arm since 1961 and the existence of an abandoned northern arm is not widely known. Given the fluvial-aeolian interaction that occurs in many ephemeral river systems in drylands, it would be reasonable to assume that the sediments deposited after the floodwater dissipates (Jacobson et al., 2000) would act as a supply source for dust emission (Bullard & Livingstone, 2002). Historical records state that the northern arm used to be the main flood channel and the river, when in flood, would flow directly through Walvis Bay towards the sea (DWAF, 1991; Huntley, 1985). This channel was abandoned when a flood wall was built in 1961 to direct the water into the southern arm to prevent any further flooding of Walvis Bay. This desiccated northern arm of the delta has been a consistent source of dust for the duration of the Landsat record, with this hydrological modification taking place long before the Landsat program started in 1972. As the floodwall predates the start of the Landsat record, it is unclear what the dust emission pattern was apparent prior to the blocking off of the northern arm. The silt terraces, situated at the terminal stages of the Tumas River, have been cut

off by a railway line and road and our data show that they have acted as consistent dust emission sources. Water flow and sediment recharge are severely restricted to the silt terraces due to the funnelling effect caused by the limited number of culverts underneath the built structures.

The abandoned section of the Kuiseb River delta consists of extensive, exposed depositional silt sediments surrounded by sand supplied from the Namib Sand Sea to the south where the sand crosses the river (Figure 4). Both the silt sediments and sand are important components of the dust emission process involved at this site. Tests conducted with the PI-SWERL confirm the dust emission potential from these surfaces of the northern arm of the Kuiseb delta (Figure 5). The emission potential of the silt terraces in the Tumas River (Figure 4 c) is very similar to those found in the Kuiseb River delta when sand is present. The mechanism of entrainment in this system is dominated by saltation as the silt crusts are sandblasted during wind events of sufficient magnitude. The resulting unconsolidated sediment is easily entrained and potentially builds up as the terraces erode due to the repeated bombardment by sand and other loose erodible material (LEM) from a variety of wind directions, predominantly the lower magnitude, higher frequency south-west winds (Table 2). The conditions determining the availability of these unconsolidated sediments for entrainment remains uncertain and could be dependent on the direction of the wind and protection afforded by silt crusts acting as roughness elements whilst they are still intact.

The modification to the Omaruru River hydrological system is more recent, but more severe than in the Kuiseb River. The Omdel dam (Figure 6) was completed in 1995 approximately 38 km upstream from the coast with the aim of increasing the infiltration of water to the aquifer by removing suspended silts and clays from the flood water (DWA, 1995; WBG, 2013). This is achieved by collecting all the water flowing down the river in the dam during the rainy season (Oct-Feb), after which the suspended sediments are allowed to settle out and collect at the bottom for 6-8 weeks. Once the sediments have settled out, the clear water is released from the top by a pump tower into settling areas where it infiltrates the aquifer. There is no water recharge downstream of the settling areas situated at approximately 27 and 32 km from the coast (Figure 6 site 1 and 2) and the dam therefore

starves the downstream river of sediment. Our data show that this modification has changed the dust emission pattern of the Omaruru River significantly.

The imagery available prior to construction of the dam wall, show the dust originating from the lower sections of the river channel aligned with the high-magnitude north-easterly winds (Figure 6). This is similar to what is found for river systems elsewhere in the world, where dust originates from the low-slope, low-fluvial energy terminal stages of a river (Koven & Fung, 2008). The sources of dust emission appear to initially move upstream after dam construction (1997-2002) and then gradually migrate downstream towards the latter part of the study period (2004-2013). At the start of the Landsat record, prior to dam construction, dust emission from this river appears to be much reduced compared to plumes identified later in the time series. Here the Landsat time-series provides a good low resolution temporal record of the evolution of the dust emission source points following the change in river hydrology.

The absence of downstream water flow and sediment recharge following the construction of the dam wall resulted in the dust emission source points shifting 8 km upstream to nebkha fields surrounded by fluvially deposited river silts, now starved of surface moisture. The lack of water and flood sediments has had severe consequences for the vegetation in the river, especially in the nebkha fields found along the entire river section downstream of the dam wall. Since the hydrological modification the sediments were increasingly exposed due to the die-back of the vegetative roughness, resulting in erosion by the wind and eventually depletion of entrainable sediments. This has resulted in the dust emission source points gradually moving downstream to where they are situated at present. The lack of fluvial recharge and constant deflation has turned the silt crusts into lag deposits. In addition, the river silt crusts under the gravel has become increasingly hardened and degraded without the replenishment and reorganisation of physical crusts that the surface water flow provides. The settling silt accumulating at the dam wall has not been shown to produce dust, most likely because of its position within the protective incised canyon and the absence of sand to sandblast the deposits of silt crusts. The wind streaks emanating from the vicinity of the infiltration sites are composed of light coloured sands in nebkha fields, which originate from the active channel in the river (Figure 6). The

alignment of the river with the north-east wind is potentially significant for exit points of sand for the wind streaks.

From the field investigation and PI-SWERL testing it appears that the present source area is made up mainly of small degraded nebkhas (Figure 7 photo) surrounded by gravel covered river silt crusts. The PI-SWERL results show that the most likely source of dust is the sparsely vegetated nebkha fields (Figure 7 a), being significantly more emissive than the silt crusts (Figure 7 b). These gravel covered river silt crusts can be considered as a human induced gravel plain following the alteration of the river hydrology. The question remains to what extent the modification of the river has potentially changed the dust emission from this system. From the Landsat imagery, it would seem that the quantity of dust emitted has increased substantially as none of the images prior to the construction of the dam wall shows the dramatic plumes witnessed post-construction (Figure 2 photo 3). In addition, the post-construction longitudinal progression of the source points downstream and the completely degraded nebkhas would appear to suggest that this river system will have a finite lifespan as a dust source. Once the nebkha vegetation are all dead and the sediments depleted, all that will remain is a hardened river silt crust covered with gravel with very little emission potential.

The Huab River in comparison has undergone much less direct hydrological modification compared to the previous two river systems, with the coastal road running through the delta the only barrier to flow in the downstream dusty sections of the river. The identified dust emission source points in the Huab River are shown to be consistently located in three distinct areas. These are an upstream section of the river valley itself, and around both a delta and a playa situated north of the river (Figure 8). The emission sites located in the the upstream river valley are within the floodplain and consist of extensive silt crust terraces covered to a large degree with nebkhas. Testing with the PI-SWERL has shown these nebkhas to be the most emissive features within this system (Figure 9 a). As was the case for the Kuiseb River, the silt crust terraces only emit dust in the presence of sand or other loose erodible material (LEM), such as broken pieces of crust, to initiate saltation (Figure 9 line b). In contrast, crusts without sand or other LEM for saltation emit very little dust (Figure 9 line d).

The degraded nebkhas of the Huab delta also emitted significant amounts of dust when tested with the PI-SWERL (Figure 9 c). Large areas of the delta appear to consist of degraded nebkhas with very little to no vegetative cover remaining, the area downstream (west of the coastal road) being completely bare (Figure 8). These areas are a source of sediment for entrainment not only by the high magnitude wind events from the north-east, but also during the predominant southerly winds. This can be seen on the Landsat image in Figure 8 as “fingers” of deposited dust extending to the north of the delta onto the gravel plain. The sediment deposited on this low-density gravel plain area to the north become available for entrainment when the north-east Berg wind blows as is evident from the Landsat imagery (Figure 2 photo 2). PI-SWERL testing of this gravel plain yielded very little dust flux possibly due to high atmospheric humidity on the day of testing.

The ERA-Interim 10 m wind data for the Kuiseb River suggests that winds with the potential to emit dust from all directions occur only 16% of the time. As the MODIS and Landsat dust events identified in this study were only associated with winds from the north-east, the question remains as to what the dust potential of the predominant south-west winds is. MODIS and Landsat true colour images are not ideal for detecting dust emitted by the south-west wind, due to the lack of colour contrast between the transported dust and the surface. In addition, there are north-east winds of sufficient magnitude to emit dust for which none is detected with MODIS (Table 2). It is evident that friction velocity alone does not determine emission potential: only 27 % of the potential dust producing north-east winds was captured by MODIS as emitting dust, with this percentage increasing as the wind strength increased. Table 2 shows a breakdown of the ERA-Interim wind events from the north-east capable of producing dust, compared to the dust events captured by MODIS. The three wind events exceeding 10 m s^{-1} for which no dust was detected by the MODIS true colour composites occurred during the night.

The significance of the dust associated with the high magnitude wind events needs further investigation, both in terms of the quantity of dust and the impact of this dust. Field observation and measurement is vital to determine the dust signature and footprint across all seasons, wind directions and speeds. Furthermore, ground based techniques to account for dust emission and transport is also important to determine what the factors are that control dust emission, both in terms of environmental

conditions and surface characteristics. To guide fieldwork and determine the optimal location of measurement and testing equipment requires improved knowledge at higher spatial resolutions regarding dust emission processes and sources. The spatial resolution of Landsat imagery provides the opportunity to investigate dust emission at a local, landform scale. A more detailed analysis of the surfaces and landforms that produce dust will be considered in a separate paper to follow. This will include a more in depth look at surface characterisation, location of landforms within the landscape and erodibility controls and will provide the basis for integrating this research into schemes like the PDS proposed by Bullard et al., 2011)

5 Conclusion

This study analysed a dataset covering a period of 27 years from 1989 to 2016. Unlike any other sensor, Landsat constitutes the longest continuous record with over 40 years of available imagery. Given its high spatial resolution it is not surprising that Landsat offers one of the most detailed examinations of dust emission sources, especially when compared to TOMS, MSG and MODIS. We have demonstrated that the limited temporal resolution of the data is compensated for to a good degree by the length of the archive, which can yield sufficient dust events to advance our understanding of dust emitting landforms and their temporal dynamics including river catchments, coastal sabkhas and inland playas. This study also hints upon the dust emission potential of the vast Namib gravel plain, which has been overlooked as a potential dust source to date.

The attribution of source points for aeolian dust emissions achieved with Landsat can guide field observations. Our observations for Namibia's three dustiest west coast catchments stresses the regional importance of elevated, fluvial, paleo silts and terraces as significant sources of dust, which is accentuated by the decay of nebkha fields in response to recent and ongoing hydrological changes. Landforms that were not identified as emitters of detectable dust plumes in Landsat imagery were the sandy ephemeral river channels as well as sand dunes and sand seas. Although the sand seas themselves appear not to be significant dust sources, the presence of sand for saltation is vital for dust production from soft silty surfaces. According to various image records, coastal pans are known to be

significant dust sources, but prevailing foggy and moist conditions during the study period prevented meaningful PI-SWRL measurements. Results of this nature may provide a comparison of erodibility between different landforms and the different physiographic systems. Such results can make an important contribution to the development of preferential dust schemes (PDS) such as those developed by Bullard et al. (2011). Given the importance of anthropogenic modification to dust production from the Namib river catchments, we suggest that a category for modified and disturbed landscapes would be a suitable addition to such schemes.

The Landsat record for the Central Namib provides some evidence for dust emission changes in response to water management strategies especially for the Kuiseb and Omaruru River which are home to a series of extraction and diversion schemes. However, distinguishing natural from anthropogenically emitted dust remains difficult. A fluvial-aeolian connection for dust production has been highlighted by others, including Koven & Fung (2008) who suggests that dust emission is potentially greatest in systems where there has been a disruption in normal fluvial processes. It would appear that this may apply to our observations here.

This study has demonstrated that the global, long-term Landsat record can identify temporal and spatial dust emission patterns at a landform scale. Automatic screening, dust detection and flagging of the entire Landsat archive could potentially further global dust source research by identifying the most emissive landforms and increased emission potential associated with anthropogenic modification.

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