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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 opening of the Landsat archive presents the opportunity to investigate these events at a higher spatial resolution (up to 15 × 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 dryland surfaces. 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 patterns 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 and Stuut, 2014; Maher et al., 2010; McTainsh and Strong, 2007; Shao et al., 2011; Soderberg and Compton, 2007; Xuan and 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) (Fig. 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 the Moderate Resolution Imaging Spectroradiometer (MODIS) and Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI).

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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; 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	9 × 9 km, 1 × 1 km	13 × 24 km TOMS, 4 × 4 km MSG, 1 × 1 km SEAWiFS	Daily, 15 min, 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 and Kuring, 2005; Wiggs and Holmes, 2011; Vickery et al., 2013
Physiographic system	100,000	1000	10^3	Landscape	100 × 100 m	250 × 250 m 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	10 × 10 m	15 × 15 m Landsat (pan) 30 × 30 m Landsat (MS)	16 days	Lake margins, active river channel, delta terraces			Current study	
Landform element	1000	10	10^1		5 × 5 m	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						

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) (Fig. 1b), 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. 250 m, 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 provide any measure of the intensity of the emission at each eroding point. Lastly, O'Loingsigh et al. (2015) in a study from Australia 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 and Nicoll, 2014; Lee et al., 2012; Vickery and Eckardt, 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