The Namib Sand Sea digital database of aeolian dunes and key forcing variables

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ABSTRACT

A new digital atlas of the geomorphology of the Namib Sand Sea in southern Africa has been developed. This atlas incorporates a number of databases including a digital elevation model (ASTER and SRTM) and other remote sensing databases that cover climate (ERA-40) and vegetation (PAL and GIMMS). A map of dune types in the Namib Sand Sea has been derived from Landsat and CNES/SPOT imagery. The atlas also includes a collation of geochronometric dates, largely derived from luminescence techniques, and a bibliographic survey of the research literature on the geomorphology of the Namib dune system. Together these databases provide valuable information that can be used as a starting point for tackling important questions about the development of the Namib and other sand seas in the past, present and future.

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1. Introduction

1.1. The context for the project

Aeolian depositional landforms cover large areas of Earth ($\approx$5,000,000 km^2) and other planetary bodies including Mars ($\approx$800,000 km^2) and Titan (possibly >16 million km^2) and reflect the interaction between wind regime and sediment. Whilst single dunes can occur, most aeolian sand dunes are not isolated and occur as part of a dune field or sand sea ($\leqslant$30,000 and >30,000 km^2, respectively, although the terms are often used interchangeably and we will use the term 'sand sea' in this paper for all accumulations of dunes, whatever their extent). These groups of dunes can cover immense areas: for example the largest active sand sea on Earth is the Rub'al Khali, Saudi Arabia at 560,000 km^2.

Early studies of aeolian sand deposits date back to expeditions in the late 1800s and have continued since then, driven forward by social, economic, political, and technical developments (Stout et al., 2008). Although some early researchers offered insights at the dune-field scale, systematic studies of extensive areas of dunes have largely been facilitated by satellite remote sensing data. Following the launch of the Earth Resources Technology Satellite (ERTS-1) in 1972 – now known as Landsat 1 – a major study by the United States Geological Survey mapped the distribution of dune morphology and sand sheets in eight desert regions on earth (McKee, 1979). This demonstrated the variability of dune forms both within individual deserts and across different arid regions (Breed et al., 1979) and, by combining these maps with studies of meteorological data, relationships between wind regime and dune type were proposed (Fryberger, 1979). McKee's (1979) study has served the aeolian community very well for thirty years but, as demonstrated by Hayward et al. (2007) using the Mars Global Digital Dune Database, the potential for extracting detailed dune morphology and dune field extent from remote sensing data has expanded considerably. Since the 1970s new data have become available. These include higher resolution satellite imagery, digital elevation data with the potential to yield insights into topographic variation and dune geomorphology (Blumberg, 2006; Potts et al., 2008), global data sets focusing on factors affecting dune development such as wind data (e.g. ERA-40), rainfall (e.g. TRMM), temperature and vegetation (e.g. NDVI) as well as more site-specific field data, particularly concerning geochronology and sedimentology.

The authors of this paper are members of the British Society for Geomorphology Fixed Term Working Group on Sand Seas and

Dune Fields. One of the aims of the group is to explore and examine the potential value of multiple new data sources for improving our understanding of global sand seas and dune fields, as well as developing a method for integrating these with other published data. It is intended that the findings of the group and the protocols that are developed for data management can be applied to aeolian sand seas worldwide. However, as a first step the focus is on a single sand sea: the Namib Sand Sea. This has been chosen because: it is a manageable size for a pilot study; it has been well studied and there is considerable understanding of its dune geomorphology; there is consequently a mix of past and present data sources available; and it is widely used as a terrestrial analogue for studies of other planetary bodies (e.g. Radebaugh et al., 2008, 2009).

The aim of this paper is to outline the data sources identified as most relevant to understanding the past, present and future development of the sand sea and to describe the development of a database through which relationships among variables can be explored. It is hoped that the Namib database will establish a framework within which studies of other global sand seas can be situated and similar databases utilising the same protocols can be developed to facilitate global-scale studies. In addition, it is intended that the database described here could, in future, be linked to other projects such as the Sand Seas and Dune Fields of the World Digital Quaternary Atlas (Desert Research Institute, 2008) which focuses on sand sea geochronologies (Bullard, 2010). The paper will also discuss the potential and limitations of each of the data sets.

1.2. Controls on the geomorphology of sand seas and dune fields

At the regional scale, climate provides a primary control on sand sea development. This control is typically the balance between precipitation and potential evapotranspiration (P-PE) and is important because aridity limits vegetation cover making sediments more erodible. Once a sand sea has accumulated, variation in vegetation cover can have an influence on geomorphology by affecting the response of dunes to wind regime. For example, in regions where the climate allows a partial vegetation cover to be maintained, dunes may only respond to the highest velocity winds due to the impact of vegetation on surface roughness (e.g. Tsoar and Møller, 1986). Sand seas described as inactive, fixed or relict are often in regions where a change in climate has resulted in increased vegetation cover. In the past, it was difficult and resource-intensive directly to study vegetation at the sand sea scale. However, satellite data are now available that give a more precise indication of vegetation cover over large areas and are arguably better to use than the surrogate of P-PE.

Extensive aeolian sand deposits are located in a variety of situations worldwide. The larger sand sea accumulations tend to be associated with shield and platform deserts (such as the central Sahara, Kalahari and central Australia) while the smaller dune field accumulations are more commonly found in basin and range deserts (such as in central Asia and the Great Basin, USA). In addition to accumulation space, topography also has an influence on two of the most important requirements for the development of sand seas and dune fields: wind regime and sediment supply. Most sand seas are located in relatively low-lying parts of the landscape where sediment has accumulated under the influence of aeolian, fluvial, marine or lacustrine processes. Wilson (1973) and Fryberger and Ahlbrandt (1979) highlighted the impact of regional topography on wind regime through its effect on airflow acceleration, deceleration and directional variability. Regional topography also plays an important role in defining the boundaries of some sand seas: for example, many are flanked along one or more margins by escarpments or mountain ranges (Mainguet and Callot, 1978).

Any aeolian deposit builds up when the quantity of sand arriving at a site exceeds that being removed. At the scale of sand

seas this can happen relatively rapidly within a few hundreds or thousands of years (e.g. the Nebraska Sand Hills) or over considerably longer periods of time (e.g. the Namib Sand Sea). Studies of many sand seas have identified multiple sediment sources during periods in the past that have been activated as a result of sediment availability and changes in wind regime (e.g. Beveridge et al., 2006; Lancaster et al., 2002). The interplay between wind directional variability and sediment supply is generally agreed to be the main determinant of free dune type within sand seas (Wasson and Hyde, 1983; Livingstone and Warren, 1996). In addition to these, other variables such as vegetation and sedimentology assume considerable importance for some types of dunes. Sand sea development, particularly growth and migration, is dependent on bedform type.

Many of the dune types found in the sand seas are most easily differentiated by their planform shape, crestlines and the number of slipfaces present. These features are relatively straightforward to map using remotely-sensed data such as aerial photography and satellite imagery and measurements such as dune wavelength can be determined. It is therefore usually possible to map dune type independently of contemporary wind regime and sediment supply and discordant relationships among these variables are sometimes used to infer environmental change (e.g. Grove, 1969; Ewing et al., 2006). New data sources such as SRTM can also be used to quantify the morphometry of individual dunes or groups of dunes to determine their height and cross-sectional profiles which may enable the calculation of dune cross-sectional area and volume. This can provide information about variations in sediment volume within the sand sea which may also be related to sediment source and to dune chronology.

The main inter-relationships that are likely to provide insight into sand sea development are therefore between wind regime, vegetation, topography (regional and local), dune type and morphometry and it is data available at the regional scale, i.e. from remote sensing platforms, that are particularly of interest.

Although remote sensing data are particularly appropriate for sand sea studies, at-a-point data can also be very valuable. These include data from meteorological stations, which can be used to calibrate or 'ground-truth' modelled data, and data from field studies. The latter includes chronological data, such as luminescence or radiocarbon dates, and these 'point' data have effectively been used in global-scale studies of aeolian deposition, for example through the DIRTMAP database (e.g. Harrison et al., 2001; Kohfeld and Harrison, 2000; Mahowald et al., 1999). In some sand seas sediment characteristics such as size and sorting (as opposed to sediment volume) can play an important role, but until recently this variable has not been readily extractable from globally available data sets such as satellite data. In some locations, geochemical data can be mapped using visible-shortwave infrared (Blount et al., 1990; White et al., 2001) and thermal infrared (Ramsey et al., 1999; Scheidt et al., 2008) remote sensing data, and there can be close relationships between geochemistry and particle size (e.g. Rawlins et al., 2009) which it may be possible to exploit in the future. In addition, the advent of global hyperspectral data (from NASA's Hyperion mission) may enable more detailed mapping of sediment characteristics in the future. Sediment characteristics at specific sites are widely reported in the literature and can be used to obtain broad textural parameters (e.g. Ahlbrandt, 1979) but there are many challenges associated with comparing different studies that derive from different sampling strategies and methods of analysis (Livingstone and Warren, 1996). For this reason, we have not extracted data from published research but instead have compiled a bibliographic database alongside the environmental database. This bibliographic database makes it possible to determine where fieldwork has taken place, but users will need to read the primary source.

1.3. The Namib Sand Sea

The Namib Sand Sea covers an area of approximately 34,000 km^2 and includes a wide variety of dune types (Lancaster, 1989). It is located on the south west coast of Africa and is bordered to the west by the southern Atlantic Ocean and to the east by the Great Escarpment of southern Africa. The climate is arid to hyper-arid and, near the coast, much of the precipitation is associated with fog. Although the main direction of regional sand transport is from south to north, this becomes variable at the distal end of the sand sea. To the south of the sand sea are sand sheets and the Orange River – one of the sources of sediment to the dune field (Bluck et al., 2007) – while to the north the main sand sea terminates in the Kuiseb River, although some dunes extend northwards across the Kuiseb delta (Fig. 1).

2. Compiling data for the Namib digital atlas

The data layers chosen for inclusion in the digital atlas are shown in Table 1. These data were largely compiled using ArcGIS (ESRI, 2010). All shapefiles and image data were kept in geographic (lat/long) coordinates, using the latest revision of the World Geodetic System (WGS84) dating from 1984 and last revised in 2004, as the reference ellipsoid. This enables atlas data to be used in combination with other, widely available spatial environmental data, such as remote sensing data products. It should also simplify the incorporation of users' own field and model data. For all geographic data sets, ArcCatalog was used to generate associated XML metadata documents. These metadata conform to the Content Standard for Digital Geospatial Metadata (CSDGM, 1998; see http://www.fgdc.gov/metadata/csdgm/) and ISO/IEC 11179 Metadata Registry (MDR) standards. ArcCatalog metadata are linked to each dataset that they describe, and as a result certain inherent properties of the dataset (bounds, coordinate system, feature count, attribute names) were automatically populated and maintained in the metadata. Additional data (e.g. source and version codes) were added manually. For other layers within the database that were not initially processed using ArcGIS (e.g. wind data) metadata were generated manually using a standard form in MS-Excel using the most relevant components of the ArcCatalog XML files, and saved as *.xml files alongside the original data.

2.1. Remotely-sensed imagery

Remotely-sensed imagery, particularly satellite data, has been used to map the distribution of different dune types within sand seas worldwide (Al Dabi et al., 1997; Breed et al., 1979; Fitzsimmons, 2007; McFarlane and Eckardt, 2007) and sequences of images can be used to monitor dune migration (Necsoiu et al., 2009; Vermeesch and Drake, 2008). Data from a range of satellites are available over the Namib but Landsat Thematic Mapper data were chosen for the database.

Five Landsat Thematic Mapper (TM) scenes were required to cover the conterminous sand sea with no gaps and were downloaded from the Landsat archive held at the University of Maryland as part of the Global Land Cover Facility (Table 2). The six solar reflectance bands of the thematic mapper (bands 1–5 and band 7) were selected, providing visible-shortwave infrared image data at 30 m pixel resolution.

The scenes were selected to provide full coverage of the sand sea, while being close together in date of acquisition. This required using Landsat 5 Thematic Mapper images of the early part of the decade of 1990. More recent images from Landsat 7 enhanced Thematic Mapper (ETM+) were either too far apart in date of
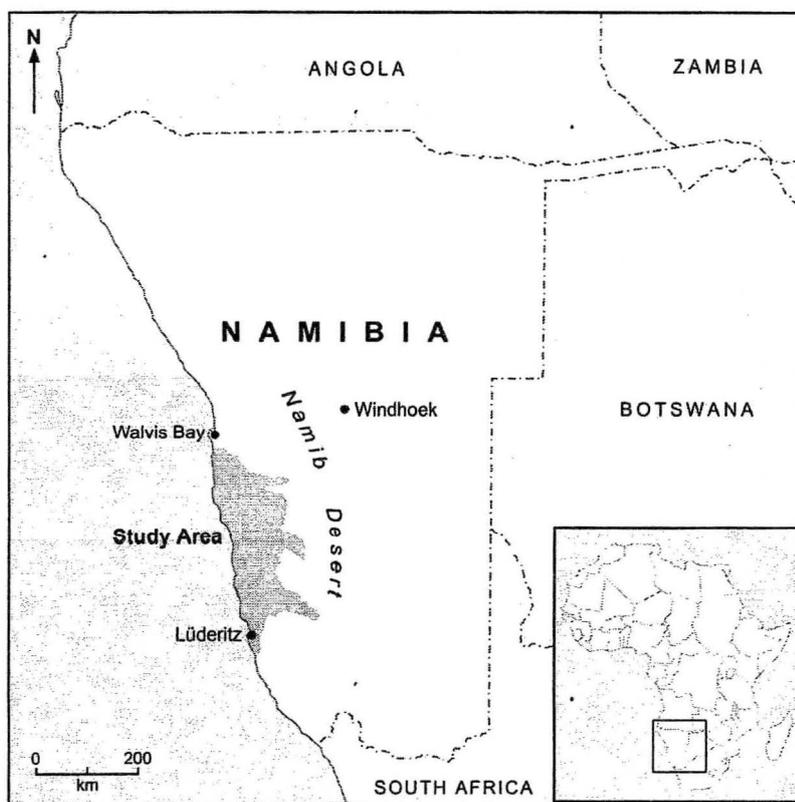

Fig. 1. Location of the Namib Sand Sea in southern Africa.

Table 1
Data layers used in the Namib digital dune atlas.

1. Digital elevation models
  1.1 SRTM DEM
  1.2 ASTER GDEM
  1.3 Individual ASTER DEM tiles
2. Remote sensing imagery
  2.1 Landsat 5 TM mosaic
  2.2 Individual ASTER image tiles
3. Vegetation index data
  3.1 PAL NDVI data
  3.2 GIMMS NDVI data
4. Quaternary dune age database
5. Map of dune types
6. Ancillary map data
  6.1 Administrative boundaries
  6.2 Drainage basin catchments
  6.3 Mean annual rainfall
  6.4 Potential annual average evaporation
  6.5 Average daily maximum temperature for the hottest month
  6.6 Average daily minimum temperature for the coldest month
  6.7 Annual average number of days with rain
  6.8 Rainfall for October–March as a percentage of the annual average
  6.9 Average deviation of rainfall as percentage of the annual average
7. Wind data
  7.1 ERA-40 data
8. Bibliographic database

Table 2
Landsat scenes used as the basis for the Namib digital database.

Landsat scene (worldwide reference system)		Acquisition date
Path 178 row 77	p178r77_5t910415	15th April 1991
Path 178 row 78	p178r78_5t910415	15th April 1991
Path 179 row 76	p179r76_5t920526	26th May 1992
Path 179 row 77	p179r77_5t910305	5th March 1991
Path 179 row 78	p179r78_5t911015	15th October 1991

acquisition, or were of lower image quality. The images were concatenated into a mosaic covering the conterminous sand sea.

Orthorectified visible/near-infrared images from the ASTER instrument were acquired at the same time as the associated DEM products. ASTER provides multispectral image data in three wavelength bands (visible blue, visible red and near infrared) at 15 m pixel resolution. These data are provided as part of the Namib dune atlas as individual scenes.

2.1.1. Map of dune types

A map of dune types was constructed based on visual interpretation of Landsat imagery supplemented with CNES/SPOT imagery via Google Earth (Fig. 2). Dune types were defined using the McKee (1979) system, dividing dunes into barchan, transverse, linear and star types based on their plan form (i.e. shape and number of slipfaces). These were further sub-divided into simple, compound and complex dunes. Simple dunes are those where only one type of dune is present with no secondary forms. Compound and complex dunes are those where smaller, secondary dunes are superimposed on a larger dune of the same type, or different type, respectively. As well as these, some hybrid dune types such as intersecting or network dunes were also recognised, as were sand sheets with no discernible dune forms. Although the boundary between different dune types can be very sharp and clearly identified, in some parts of the sand sea the boundary between dune types is less clear and there is a transition from one dune type to the next. Where transitions occur, the boundary between dune types is identified where one dune type becomes more dominant than the other in terms of spatial coverage. This is a similar method of mapping dune spatial distribution to that used by other researchers.

Previous maps of Namib dune types have been produced by Besler (1980), Breed et al. (1979) and Lancaster (1989) using various combinations of aerial photography and Landsat imagery. Not surprisingly the dune types recognised and the positioning of the boundaries between them do not vary significantly between these three maps and ours. The huge advantage that is gained by placing the classification of dune types into the database is that it enables us to investigate the coincidence of dune morphology with other variables such as climate or vegetation, and to compare our dune form classification with the available digital elevation models. Each dune type map is made available as part of the Namib dune atlas as separate polygon shapefiles. This enables other data layers to be subset for individual dune types.

2.2. Digital elevation models (DEMs)

The SRTM digital elevation model (DEM) was produced from data collected by a C-band interferometric synthetic aperture radar system, carried onboard Space Shuttle *Endeavour*, during a 10-day mission in February 2000. To acquire elevation data, the two radar antennas were deployed; one in the shuttle payload bay and the other on the end of a 60 m mast that extended from the payload bay. The resulting data can be resampled to different grid sizes, but the maximum resolution released for all the land surface between 60° latitude North and 54° latitude South (about 80% of the Earth's land surface area) was 3 arc seconds (approximately 90 m cell size over most of the coverage area). These data have been used for a wide variety of geomorphological studies in drylands (see e.g. Drake et al., 2008; White and Eckardt, 2006).

ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) DEM data are acquired using photogrammetric methods applied to nadir and backward looking near-infrared images produced by the ASTER instrument, carried on board the AQUA and TERRA missions. The data are generated to a 30 m grid (half the resolution of the 15 m image data). The use of ASTER DEM data for mapping and monitoring dune fields has been demonstrated by Vermeesch and Drake (2008). Thanks to an agreement with the NASA Land Processes Distributed Active Archive Center User Services, ASTER DEM data were acquired free of charge for use in this project. A total of 100 individual ASTER DEM scenes were downloaded for the project.

During the course of assembling the data layers for this project (June 2009) the Ministry of Economy, Trade, and Industry of Japan, along with NASA, jointly released the ASTER Global Digital Elevation Model (GDEM), covering the land surface between 83° North and South of the Equator. The ASTER GDEM is in GeoTIFF format with geographic coordinates sampled to a 1 arc-second (30 m) grid, referenced to the WGS84 geoid. Pre-production estimated accuracies for this global product were 20 m at 95% confidence for vertical data and 30 m at 95% confidence for horizontal data. It was decided to include these data as a DEM data layer in the Namib dune Atlas, along with the 100 individual scenes.

2.3. Wind data

The 10-m elevation surface wind data for speed and direction used here were derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-40 Reanalysis Project archived online at the British Atmospheric Data Centre (British Atmospheric Data Centre, 2006). A complete time series at 6-hourly intervals for the period 1980–2002 was extracted. The original Gaussian grid was interpolated to 1° resolution for the domain 26.5S–22.5S and 14E–15E (see Fig. 3). From the time-series, u (west to east vector) and v (north to south vector) components were extracted and reconciled to produce wind magnitude and direction.
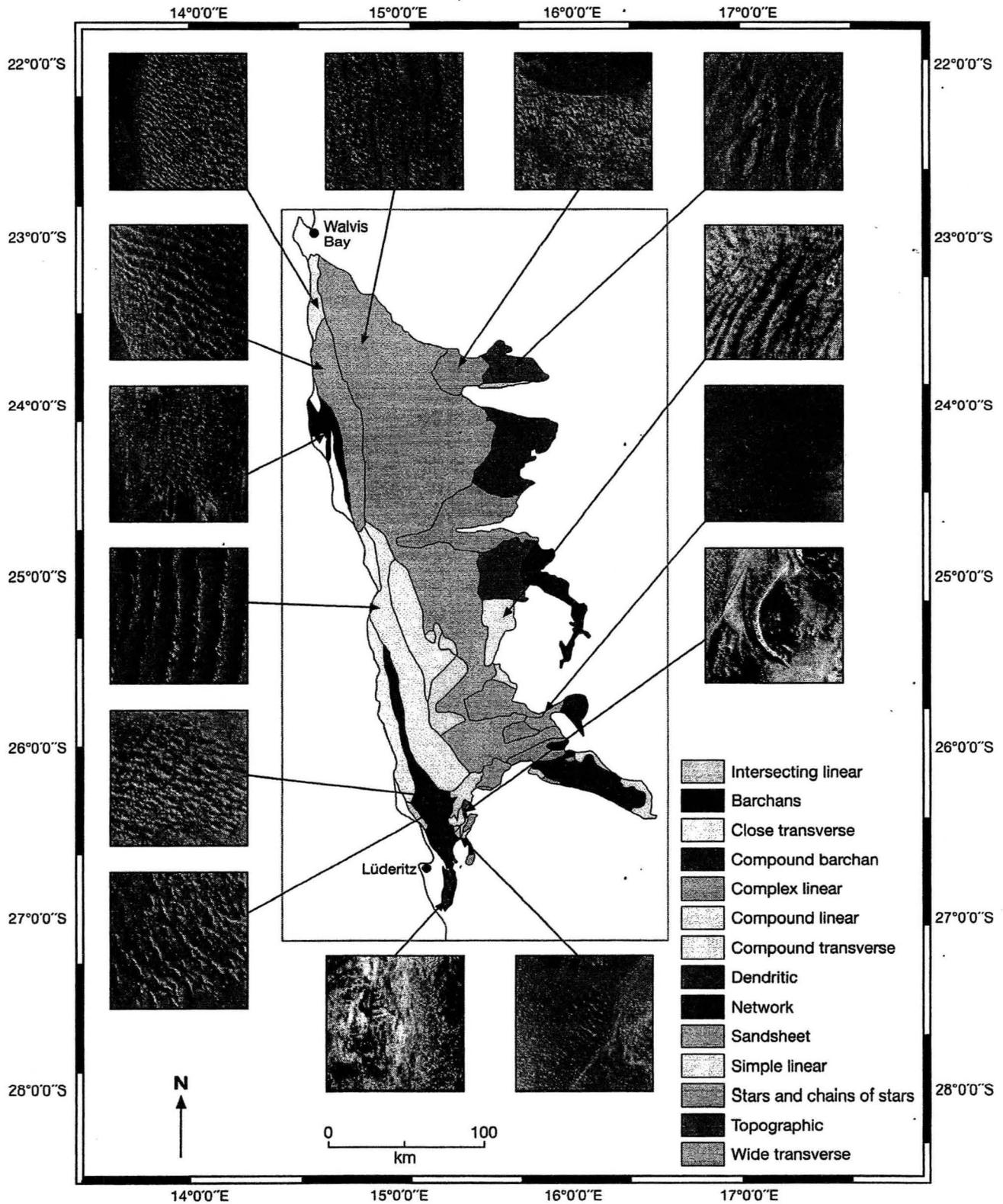
Fig. 2. Map of dune types in the Namib Sand Sea, with example Landsat ETM + images (15 km by 15 km squares).

There are a number of scaling and averaging issues associated with the use of reanalysis wind speed and direction data to infer conditions conducive to present or past sand transport at any one location (e.g. Sridhar et al., 2006; Bryant et al., 2007). Conse-quently, we have also extracted comparable and overlapping sur-face wind speed time series (1980–2001) from the Gobabeb meteorological station on the northern edge of the Namib Sand Sea (Latitude 23° 33.67′ S and Longitude 15° 02.47′ E, 461 m
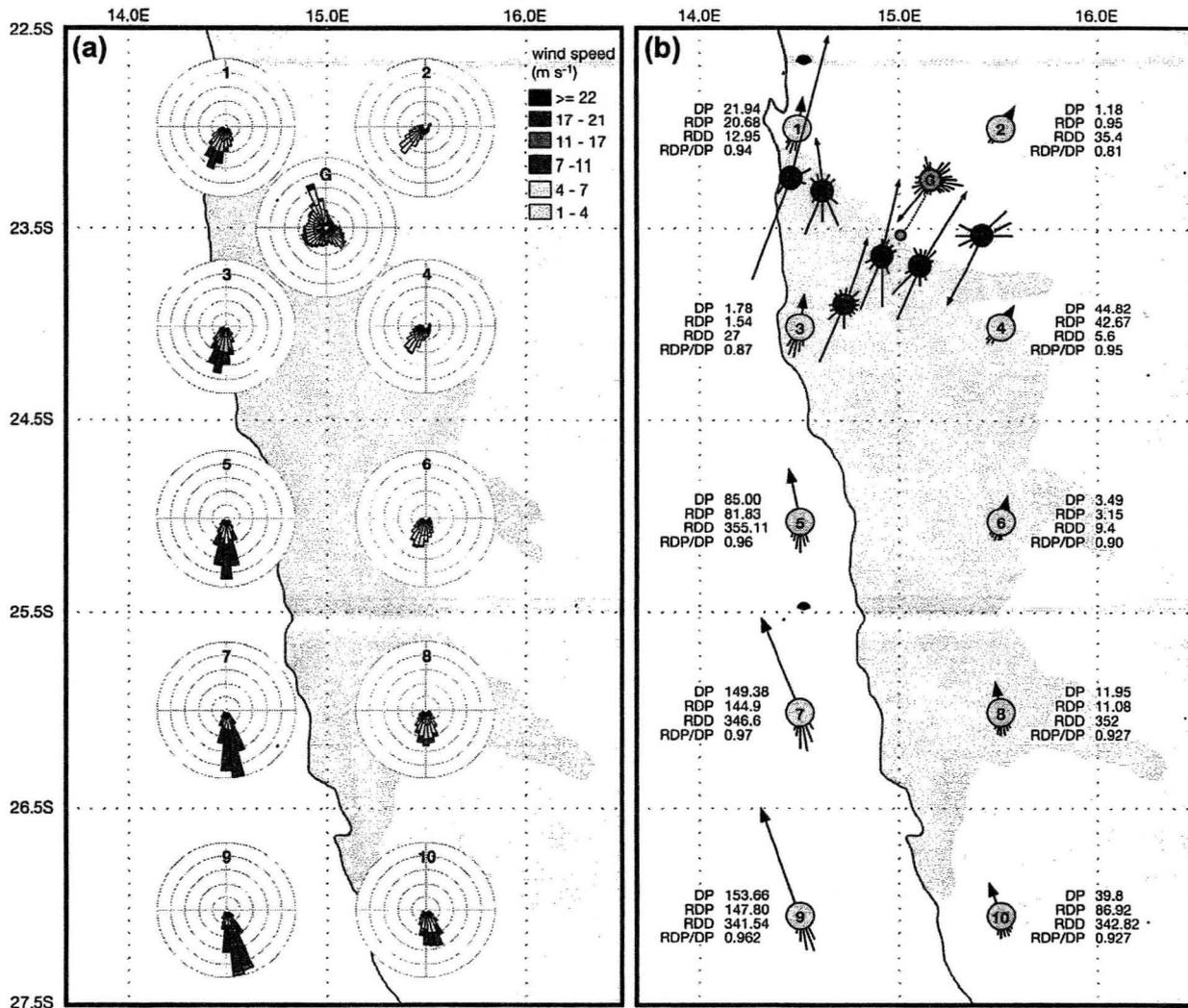
Fig. 3. Location diagram showing: (a) wind roses for the ERA-40 1° grid data used in this study for the period 1980–2002 (roses 1–10; 36 sectors, with frequency in ms⁻¹ as a percentage of total winds), and their relation to the Namib Sand Sea. Field data for Gobabeb (G) are also included. (b) ERA-40 data processed to generate wind roses displaying: Drift Potential (DP – feathers on wind rose); Resultant Drift Direction (RDD – large arrow); Resultant Drift Potential (RDP – length of large arrow); and the ratio of RDP/DP which gives a measure of wind directional variability. For comparison, similar wind rose sand transport data from Lancaster (1985) A–F, and Gobabeb (1993–2002) G are included.

a.m.s.l) to both report and investigate any disparities between the two data types (Fig. 4). Livingstone (2003) also analysed the time series from Gobabeb in some detail, and provided useful guidance on data reliability, identifying and accounting for gaps within data records for this location.

Both time series were analysed using the 'Fryberger method' (Fryberger, 1979). This widely-used approach (e.g. Bullard et al., 1996; Lancaster et al., 2002; Wang et al., 2002) employs standardised wind data to estimate regional aeolian sediment transport vectors, to aid the interpretation and classification of aeolian dune landscapes. The method essentially uses raw or generalised wind speed and direction data, measured at the World Meteorological Organisation (WMO) standard height of 10 m, to calculate the potential for sand drift in a region. In essence, this involves calculating the frequency of winds above a transport threshold over some fixed time period within pre-determined wind speed–direction categories. To minimise inherent frequency/magnitude bias in the way these data are incorporated within the Fryberger approach, the wind speeds for both data sets were rounded and grouped in 36, 10 - degree direction classes (e.g. Bullard, 1997;

Pearce and Walker, 2005). A wind transport threshold of 5.5 ms⁻¹ was assigned based on field evidence (Livingstone, 2003), and from these data drift potential (DP) was estimated for all possible wind speed–direction categories on a monthly, annual and complete time series basis, then summed for each direction sector, and totalled to yield a directionless, total DP value. Vector analysis was then used to determine a resultant drift direction (RDD) and resultant drift potential (RDP) vector that describes the net sand transport. With these data we were also able to use DP and the ratio of RDP/DP to characterise the directional variability of the wind regime. High RDP/DP values were assumed to reflect unimodal winds, while low values were taken to infer greater complexity in the wind regime (Pearce and Walker, 2005). Results were graphed as a drift rose showing potential sand drift from each of the direction classes scaled by its DP value and an RDP vector pointing in the direction of net transport, and the information summarised for each grid cell or location point for inclusion as either a linked table or an image within the database (Fig. 3). Seasonal and interannual time-series for comparative ground and reanalysis data were also processed to allow
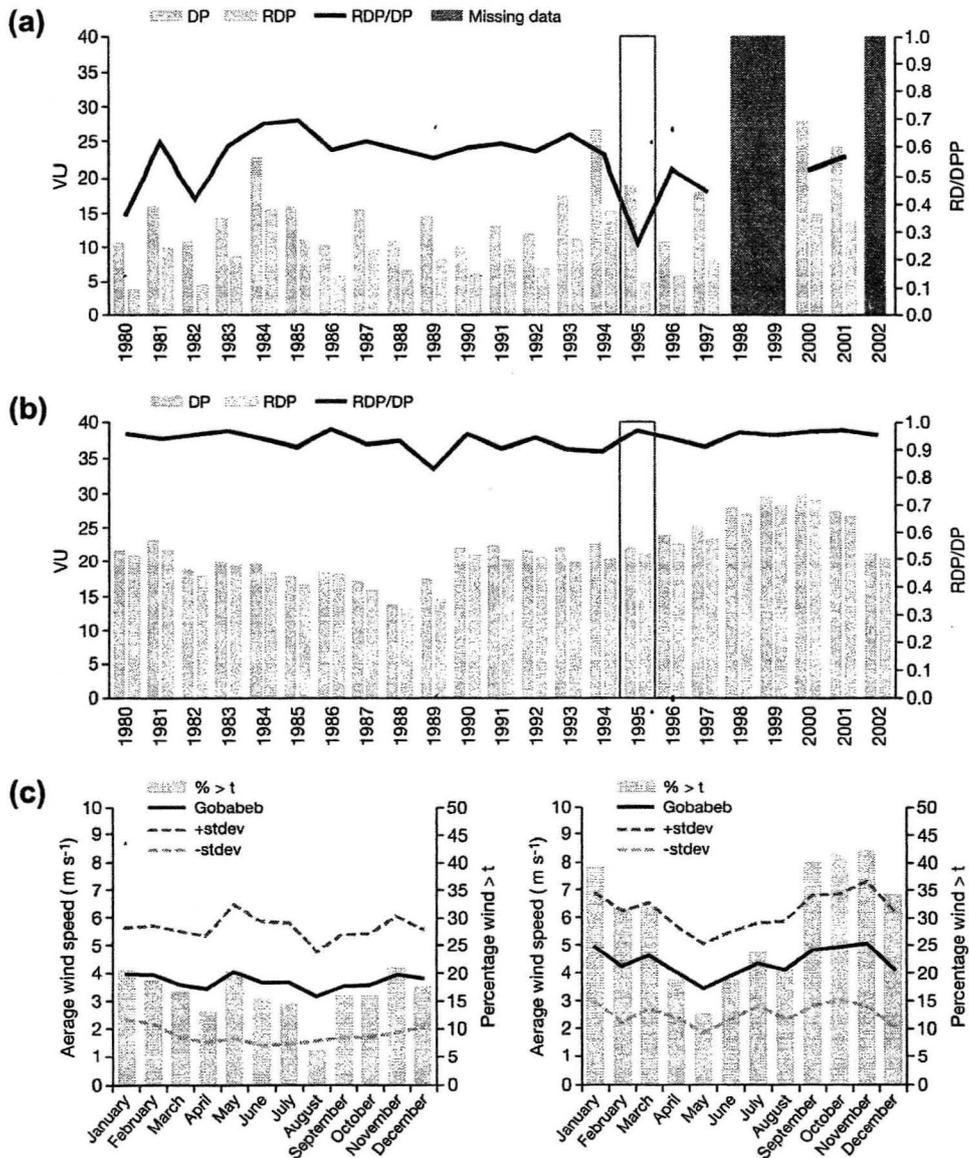
(a)

(b)

(c)

Fig. 4. Graphs of extracted regional and station wind speed data wind showing: (a) time series data for annual DP, RDP and RDP/DP for the Gobabeb ground station covering the period 1980–2002, indicating periods of missing data; (b) time series data for annual DP, RDP and RDP/DP for the ERA-40 reanalysis data for the grid square closest to Gobabeb, covering the period 1980–2002; and (c) graphs for both data in 1995 (boxed on a and b) sets showing seasonal variability in average wind speeds and the proportion of wind speeds for each month that were in excess of the sand transport threshold t where $t = 5.5$ ms^{-1}).

evaluation of long-term variability in sand transport potential (e.g. Fig. 4A and B), and to allow any discrepancies between seasonal wind speed variability between the two data sets to be determined (see Fig. 4C which takes data from 1995 as an example).

2.4. Vegetation index data

Two sets of vegetation index data (Pathfinder AVHRR Land (PAL) and Global Inventory Modelling and Mapping Studies (GIMMS)) are provided for the Namib Sand Sea. These data enable models of sand flux and dune mobility to incorporate vegetation as a dynamic parameter. In order to achieve a high temporal sampling rate (a minimum of two vegetation estimates per month), spatial resolution must be sacrificed, so both sets of vegetation index data included have coarse spatial resolution (approximately 8 km pix-

els). However, this resolution still permits the significant variations in vegetation cover across the Namib Sand Sea to be captured. Both of these data sets provide global Normalised Difference Vegetation Index (NDVI) values derived from Advanced Very High Resolution Radiometer (AVHRR) Global Area Coverage (GAC) radiances (James and Kalluri, 1994); the main difference is that the PAL data are subject to a partial atmospheric correction, whereas GIMMS NDVI data are corrected for instrument effects and artefacts only. GAC data are produced on a daily basis for the whole globe from the Local Area Coverage (LAC) 1.1 km pixels, using a rather idiosyncratic sampling and averaging technique. For a given scan line, the first four pixels are averaged, then one pixel is ignored, the next four pixels are averaged, the following pixel is ignored, and so on. Once completed for a scan line, the next two scan lines are completely ignored and then the next line is sampled in the same way as the
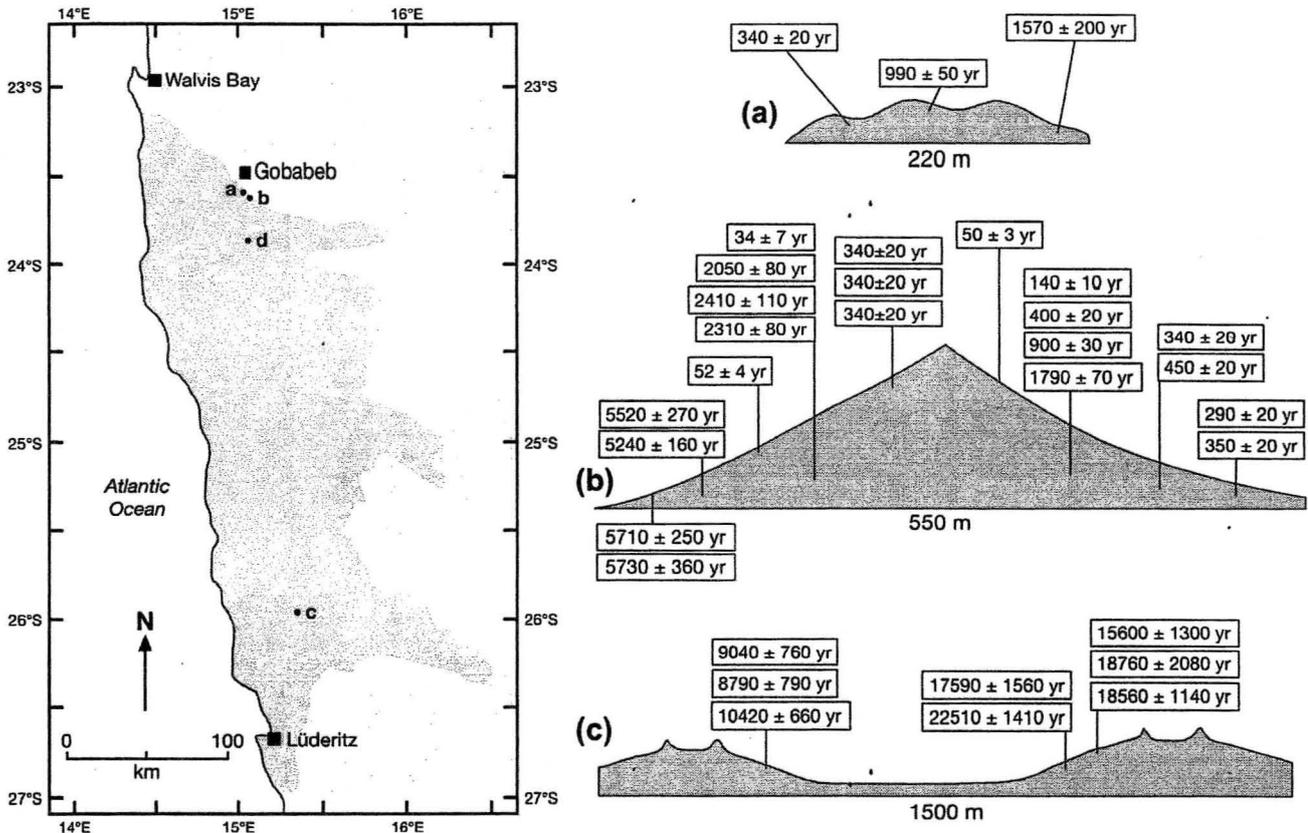
Fig. 5. Location map for OSL sample sites and schematic cross-sections of dated dunes (not to scale): section (a) from Bristow et al. (2005); (b) from Bristow et al. (2007); (c) from Bubenzer et al. (2007); data for (d) from Stone et al. (2010).

Table 3
Frequency of occurrence of assigned keywords.

Keyword	Frequency of occurrence			Total
	Keyword 1	Keyword 2	Keyword 3	
Sedimentology	19	8	2	29
Aeolian processes	16	7	3	26
Dune morphology	7	10	4	21
Climate	2	2	2	6
Remote sensing	5	1	0	6
Dating (e.g. OSL)	2	3	0	5
Hydrology	0	3	0	3
Soil	2	0	0	2
Geology	1	0	0	1
Ecology	1	0	0	1
Human impact	0	0	0	0

first. So each GAC pixel represents a 5 × 3 LAC pixel area (Townshend and Justice, 1986). The radiances in AVHRR channels 1 and 2 are then used to calculate NDVI. Following that the data are resampled to a grid size of 7.638 km by selecting the maximum value of NDVI from blocks of four 4 km GAC pixels over a 10-day (dekad) period, in order to minimize the influence of clouds, sun angle, water vapour, aerosols and directional surface reflectance (Holben, 1986).

As mentioned above, GIMMS NDVI data are derived from top-of-atmosphere reflectance estimates, without compensation for atmospheric scattering effect (although a stratospheric aerosol correction is performed to account for the volcanic eruptions of El Chichon (1982–1984) and Pinatubo (1991–1994)). The dataset begins in July 1981 and still continues. GIMMS data provide global NDVI

estimates at 8 km pixel spacing every 16 days. PAL NDVI is derived from surface reflectance estimates (with a correction being made for O_3 and Rayleigh scattering). The dataset only runs from July 1981 to September 2001, but global data are available at 7.638 km pixel spacing every 10 days.

2.5. Quaternary dune age database

The chronology layer of the database essentially highlights the paucity of good chronological control on Namibian dune movement during the Late Quaternary. Data included on this layer have been limited only to include direct age determinations on aeolian sediments to avoid inferences necessary in relating dates from associated deposits (e.g. desert loess or fluvial silts) to dunes (e.g. Srivastava et al., 2006; Eitel et al., 2006; Brunotte et al., 2009). We have not included dates from interdune deposits or sediments from around the margins of the sand sea that are not aeolian in origin even though some of these deposits will have interacted with dunes, for example where the Tsondab and Tsauchab rivers enter the dune field from the east (e.g. Brook et al., 2006). Reviews by Lancaster (2002) and Brook et al. (2006) provide interpretations of the interdune chronology.

In the absence of reliable preserved organic material within the sand sea, luminescence dating – particularly optically-stimulated luminescence (OSL) – has been the most widely applied chronometric technique to the dunes of the Namib Sand Sea. This technique utilises the ubiqitous quartz of the Namibian dunes and provides ages of when the dune sand was last exposed to sunlight during mobilisation. In the case of the deposition of sand on the dunes essentially this is a burial age. What few luminescence

ages have been reported for the Namib Sand Sea are distributed very unevenly: there is a cluster of ages reported from the northern end of the sand sea and a small group of ages from the south with none in the middle (Fig. 5). This uneven distribution is partially constrained by access and the problems associated with sample collection in large sand dunes. Due to the large size of the dunes near-surface samples from hand-dug trenches are not necessarily able to access the deeper and older parts of the dune stratigraphy. All of the published studies have collected samples from boreholes drilled into the dunes or shallow test pits. Three different drill rigs have been used: percussion drilling (Bristow et al., 2005); a combination of percussion drilling and motorised sand auger (Bristow et al., 2007); and a hand auger (Bubenzer et al., 2007). Transporting mechanical augers into the dune field and up the flanks of the dunes can present considerable logistical problems and this has no doubt contributed to the limited number and distribution of samples. The data are made available as part of the Namib dune atlas in the form of a point shapefile, with associated information in a data table.

The total number of published OSL ages is 43: of these, 21 are from one study of a single linear dune (Bristow et al., 2007), with three more dates from a study of dune migration (Bristow et al., 2005), and eight are in Bubenzer et al. (2007). Finally there are 11 quartz single aliquot regenerative (SAR) OSL ages from three sites with aeolian sediments rather than dunes (Stone et al., 2010). Bristow et al. (2005, 2007) showed the quartz SAR OSL age determinations from two sites in the northern Namib had maximal ages of 5 ka and significant dune over-turning and/or movement during the last 2.5 ka. Recently Stone et al. (2010) reported aeolian sedimentation adjacent to Tsondab Flats and Hartmut Pan in the periods 10.5–13.3 ka and 16.1–16.9 ka. Bubenzer et al. (2007) sampled large compound linear dunes at the southern end of the Namib Sand Sea and were able to show that some dune accumulation had occurred as far back as the last glacial maximum (18–22.5 ka) and early holocene (8.5–10 ka). However, with so few studied sites and such a limited dataset, the temporal variability of the evolution of the Namib Sand Sea remains unclear. Of what has been achieved older dune ages are almost certainly underrepresented, partly because of the problems associated with drilling deep boreholes through the dunes and sampling older sand that is buried by younger dune deposits, as well as the limited spatial distribution of samples. As such further studies are needed to address this important aspect of understanding how the Namib Sand Sea has changed through time.

2.6. Ancillary map data

A variety of other types of data are made available as part of the Namib dune atlas. Line shapefiles of the administrative boundaries of Namibia were provided by the Famine Early Warning Systems Network (FEWS NET) Africa Data Dissemination Service (FEWS NET, 2010).

Polygon files of the ephemeral drainage basin catchments impinging on the Namib Sand Sea were digitised from maps in Jacobson et al. (1995). A variety of spatial climate data were derived from the Namib Atlas. These comprise mean annual rainfall, potential annual average evaporation, average daily maximum temperature for the hottest month, average daily minimum temperature for the coldest month, annual average number of days with rain, rainfall for October–March as a percentage of the annual average, and average deviation of rainfall as percentage of the annual average. The data were presented as contour maps in Van der Merwe (1983), based on climate data obtained from the Weather Bureau, Windhoek, with additional data from Barnard (1964). The contours were digitised and used to create a triangular irregular network (TIN). From the TIN, a gridded dataset was produced; pixel spacing

varies between 5 and 8 km. Significant caveats must be attached to these climate data, as the period of observation upon which these maps were derived, and the accuracy and density of the observations, are unknown. However, they are provided as an example of published climate data for the Namib, as an alternative to model data such as the ECMWF ERA-40 data.

2.7. Bibliographic database

The bibliographic database was compiled from extensive searches of online records, university archives, the authors' personal collections and other personal documents. A series of broad searches were initially conducted to locate all published records relating to the physical environment of the Namib Sand Sea. This search produced a total of 175 references of possible interest that included literature focussed on such topics as climate, geology and ecology as well as aeolian processes and sand dune dynamics.

With the aim of producing a searchable and accessible bibliographic database referenced to locations of individual sites and samples each source was reviewed and categorised using a standard convention. This convention was constructed so that references which were not easily accessible to an international readership were excluded from the final database. Further, as our aim was not to provide a comprehensive listing of Namib dune references, but rather a user-accessible and searchable database of site-specific literature, those references that generally dealt with the sand sea as a whole were also excluded. This resulted in 81 references remaining, each of which were reviewed and catalogued using a series of keywords in descending order of importance with regard to the focus of the bulk of the manuscript. These keywords were chosen to represent the most likely search selections of users interested in the science of sand seas and dune fields (see Table 3). Not every reference was assigned three separate keywords as some references could be adequately summarised with the use of one or two. Further, data on particle size were seldom found to be the focus within individual references and so a keyword for 'particle size' was not included in the cataloguing procedure. However, given that database users would likely wish to easily search for references that included particle size data, references including such data were highlighted separately.

For each reference the locations of individual sampling sites referred to in the text were recorded so that they could be represented visually in the atlas. Where given, these locations were directly recorded in the database as latitude/longitude (decimal or angular) or as UTM co-ordinates (Fig. 6). Where the locations of sites were described by authors rather than directly measured (e.g. "5 miles SW of Gobabeb") the approximate co-ordinates were determined using Google Earth and recorded in the database. In some instances it was only possible to determine more general site locations (e.g. "along the Kuiseb River") and these were described in text in the database so that the general region of interest within the sand sea could be later recorded in the database.

The dates of publication of the final 81 references ranged from 1926 to 2008 although only 3 references were published prior to 1966 with the majority post-1970. With reference to these latter sources it is clear that the 1980s were a period of particular interest in the physical environment of the Namib Sand Sea with over 30 site-specific publications (Table 4). Since the 1980s there has been a fairly consistent publication rate or 16–17 per decade and over the 1970–2008 period the publication rate averages at about 2.5 per year. With regard to the subject matter of the database references it is clear that topics concerning sedimentology, aeolian processes and dune morphology dominate the group (Table 3). This is unsurprising given the physical environment under examination but the lack of references concerning dating of sediment (5) or remote sensing (6) suggests there is particular scope for
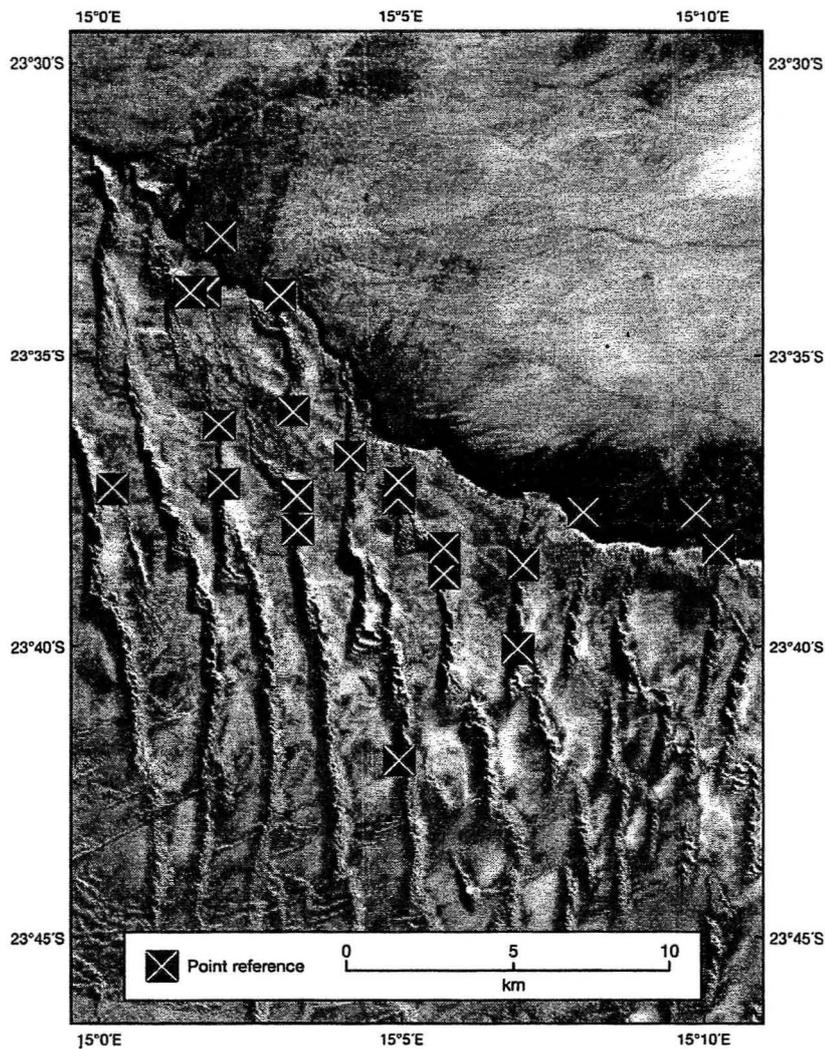
Fig. 6. Locations of point-data from the bibliographic database overlaid on an image extract for the northern margin of the Namib Sand Sea. Some of the bibliographic entries are also stored as areal shape-data, and are not represented here.

Table 4
Publication dates of bibliographic database references.

Publication decade	Number
1970s	13
1980s	31
1990s	17
2000s	16

investigation in these topics. Of the 81 references a total of 27 were found to include some data on particle size.

3. Discussion: what are the applications of a digital database?

While the data contained in the atlas are interesting enough, it is our intention that producing the digital atlas should be the starting point for future work both by this group and, we hope, by others. There is increased awareness of landform development through popular resources such as Google Earth and NASA World Wind and this atlas brings together additional resources to support this interest. Much more than that, however, there are a number of important research issues associated with the world's sand seas, many of which reflect global concerns about environmental change. This atlas, and others that could be produced using the protocols outlined here, will provide valuable data for tackling some of these research questions.

For the dune geomorphologist new data sources enable us to re-visit widely-accepted ideas that may need re-examining. For example, Tchakarian (2005, p. 3) suggested that McKee's (1979) widely-used dune classification system "warrants a substantial revision" in the light of new developments in aeolian geomorphology but this has not yet taken place. A further application of the work on terrestrial sand seas arises from the discovery of extensive sand seas on Mars and Titan and from recent improvements in the range and quality of the data being produced from these planetary bodies (e.g. Hayward et al., 2007). If these technological improvements are to be matched by enhanced interpretation of data, we require good quality explanations of the terrestrial analogues. A new audit of global sand seas using protocols similar to those we have devised for the Namib Sand Sea could help us to develop a re-vised dune classification.

Global modelling scenarios suggest that sand seas will respond rapidly to future environmental change (Thomas et al., 2005; Wang et al., 2009). If we are to make good predictions about those responses, there is a need to understand the relationship between individual dunes (and the patterns which they create collectively) and wind regime under contemporary conditions. Beyond that, because dunes do not respond only to wind regime, we need to examine their relationship to other climatic variables. The work presented in this paper demonstrates that there is now a range of datasets to help us to characterise the climates of sand seas. Re-examination of sand seas and dune fields using these higher quality (and globally available) data should improve our understanding of the relationships between dunes and contemporary climates.

In addition to the direct links between climate and dune development, it is increasingly recognised that sand sea and dune field development is not only linked to periods of aridity but also to sediment supply and availability. Indeed, in some instances sediment availability may be the primary control on dune activity (e.g. Kocurek and Lancaster, 1999). There is therefore a clear need to understand the relationship between the aeolian system and the sediment sources and transport pathways that are providing the material for dune building. This will link sand seas and dune fields to other geomorphic processes, often associated with the presence of water such as coasts, rivers and lakes (Bullard and Livingstone, 2002).

Improvements in geochronological techniques, particularly the rise of luminescence dating, which is especially useful for dating periods of dune accumulation in arid environments where organic material is largely absent, mean that more information is now available about the long-term development of sand seas. However, it is essential to have a good understanding of the overall development of the sand sea – in particular the location of the sampling site, the type of dune and the dune's behaviour – to be able to interpret chronological data correctly (e.g. Munyikwa, 2005). The assembly of chronological data for global sand seas is the remit of the INQUA-funded project to produce a digital Quaternary atlas (Desert Research Institute, 2008). As noted in Section 2.5, the Namib Sand Sea currently has a rather striking dearth of chronological data.

To facilitate increased research on the applications outlined in this section, all the data listed in Section 2 are available for download via the internet from a dedicated website http://www.shef.ac.uk/sandsea/index.html in two principal formats: (a) standard geographical data formats (described below) which are appropriate for use in a range of research applications, or (b) *.kml files for general use and visualisation within Google Earth. In terms of standard geographical formats, raster image data (e.g. remote sensing imagery and DEM products) are provided as uncompressed ERDAS IMAGINE files, with each file having an associated pyramid (.rrd) file. Vector data are provided in ArcGIS shapefile format. All data are registered to the WGS84 datum and Geographic (latitude/longitude coordinate system). Metadata are provided for all data layers via associated *.xml files, as detailed in Section 2. A total of 2.5 Gbytes of data are available, split into thematic layers and zipped to facilitate easy download across the internet. All data can be analysed using ArcGIS software (see http://www.esri.com/software/arcgis/index.html) and a free viewer can be downloaded from http://www.esri.com/software/arcgis/arcreader/index.html. ArcReader can run in a number of configurations and across a range of computing platforms for Solaris, Linux, and Windows. Full details of system requirements are available at http://wikis.esri.com/wiki/display/ag93bsr/ArcReader. In addition, *.kml files can be easily imported into a freely distributed version of Google Earth (http://earth.google.co.uk/) for rapid display and visualisation on multiple platforms.

4. Conclusion

The establishment of a digital atlas for the Namib Sand Sea has enabled us to recognise and integrate data sources that will help us further to investigate the past, present and future development of the sand sea and to describe the ways in which the database can be used to examine relationships between key forcing variables. It is important to be cautious: some preliminary analysis to compare remote sensing data with data derived on the ground suggests that considerable discrepancies occur. None the less the atlas potentially provides the basis for important future work. The outcomes can be grouped into two categories. First, the Namib database provides a template that can be used to co-ordinate and collate information in other studies of other sand seas. Second, it is our intention to utilise the information collated in the database to investigate some of the issues raised in this paper. With the range of information provided in the database, much derived from remote sensing with some important input from ground surveys, it should be possible to move on to undertake important investigations which help us better to understand the development of our global sand seas.

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References

Ahlbrandt, T.S., 1979. Textural parameters of eolian deposits. United States Geological Survey Professional Paper 1052, 21–51.

Al Dabi, H., Koch, M., Al Sarawi, M., El-Baz, F., 1997. Evolution of sand dune patterns in space and time in north-western Kuwait using Landsat images. Journal of Arid Environments 36, 15–24.

Barnard, W.S., 1964. Die Streekspatrone van Suidwes-Afrika. Unpublished D.Phil Dissertation, University of Stellenbosch.

Besler, H., 1980. Die Dünen-Namib: Entstehung und Dynamik eines Ergs. Stuttgarter Geographische Studien 96, 208.

Beveridge, C., Kocurek, G., Ewing, R., Lancaster, N., Morthekai, P., Singhvi, A., Mahan, S., 2006. Development of spatially diverse and complex dunefield patterns: gran Desiert Dune Field, Sonora, Mexico. Sedimentology 53, 1391–1409.

Blount, G., Smith, M.O., Adams, J.B., Greeley, R., Christensen, P.R., 1990. Regional aeolian dynamics and sand mixing in the Gran Desierto: evidence from Landsat Thematic Mapper images. Journal of Geophysical Research 95, 15463–15482.

Bluck, B.J., Ward, J.D., Cartwright, J., Swart, R., 2007. The Orange River, southern Africa: an extreme example of a wave-dominated sediment dispersal system in the South Atlantic Ocean. Journal of the Geological Society 164, 341–351.

Blumberg, D.G., 2006. Analysis of large aeolian (wind-blown) bedforms using the Shuttle Radar Topography Mission (SRTM) digital elevation data. Remote Sensing of Environment 100, 179–189.

Breed, C.S., Fryberger, S.C., Andrews, S., McCauley, C., Lennartz, F., Gebel, D., Horstmann, K., 1979. Regional studies of sand seas using Landsat (ERTS) imagery. United States Geological Survey Professional Paper 1052, 305–397.

Bristow, C.S., Duller, G.A.T., Lancaster, N., 2007. Age and dynamics of linear dunes in the Namib desert. Geology 35, 555–558.

Bristow, C.S., Lancaster, N., Duller, G.A.T., 2005. Combining ground penetrating radar surveys and optical dating to determine dune migration in Namibia. Journal of the Geological Society, London 162, 315–321.

British Atmospheric Data Centre, 2006. European Centre for Medium-Range Weather Foreasts. ECMWF ERA-40 Re-Analysis data. Available from: <http://badc.nerc.ac.uk/data/ecmwf-e40/> (accessed 02.03.2010).

Brook, G.A., Srivastava, P., Marais, E., 2006. Characteristics and OSL minimum ages of relict fluvial deposits near Sossus Vlei, Tsauchab River, Namibia, and a regional climate record for the last 30 ka. Journal of Quaternary Science 21, 347–362.

Brunotte, E., Maurer, B., Fischer, P., Lomax, J., Sander, H., 2009. A sequence of fluvial and aeolian deposits (desert loess) and palaeosoils covering the last 60 ka in the Opuwo basin (Kaokoland/Kunene Region, Namibia) based on luminescence dating. Quaternary International 196, 71–85.

Bryant, R.G., Bigg, G.R., Mahowald, N.M., Eckardt, F.D., Ross, S.G., 2007. Dust emission response to climate in southern Africa. Journal of Geophysical Research – Atmospheres 112, D09207, doi: 10.1029/2005JD007025.

Bubenzer, O., Bödeker, O., Besler, H., 2007. A transcontinental comparison between the southern Namib Erg (Namibia) and the southern Great Sand Sea (Egypt). Zentralblatt für Geologie und Paläontologie Teil 1, 7–23.

Bullard, J.E., 1997. A note on the use of the "Fryberger method" for evaluating potential sand transport by wind. Journal of Sedimentary Research 67, 499–501. doi:10.1306/D42685A9-2B26-11D7-8648000102C1865D.

Bullard, J.E., 2010. Bridging the gap between field data and global models: current strategies in aeolian research. Earth Surface Processes and Landforms. doi:10.1002/esp.1958.

Bullard, J.E., Livingstone, I., 2002. Interactions between aeolian and fluvial systems in dryland environments. Area 34, 8–16.

Bullard, J.E., Thomas, D.S.G., Livingstone, I., Wiggs, G.F.S., 1996. Wind energy variations in the southwestern Kalahari Desert and implications for linear dunefield activity. Earth Surface Processes and Landforms 21, 263–278.

Desert Research Institute, 2008. Available from: <http://oldsite.dri.edu/deesprojects/Dune_Atlas/> (accessed 02.03.2010).

Drake, N.A., El-Hawat, A.S., Turner, P., Armitage, S.J., Salem, M.J., White, K., McLaren, S., 2008. Palaeohydrology of the Fazzan Basin and surrounding regions: the last 7 million years. Palaeogeography Palaeoclimatology Palaeoecology 263, 131–145. doi:10.1016/j.palaeo.2008.02.005.

Eitel, B., Kadereit, A., Blumel, W.D., Huser, K., Lomax, J., Hilgers, A., 2006. Environmental changes at the eastern Namib Desert margin before and after the Last Glacial Maximum: new evidence from fluvial deposits in the upper Hoanib River catchment, northwestern Namibia. Palaeogeography Palaeoclimatology Palaeoecology 234, 201–222.

ESRI, 2010. ArcMap [GIS software] Version 9.3. Environmental Systems Research Institute, Redlands, CA, 31, 1992–2010.

Ewing, R.C., Kocurek, G., Lake, R.W., 2006. Pattern analysis of dune-field parameters. Earth Surface Processes and Landforms 31, 1176–1191.

FEWS NET, 2010. Africa Data Dissemination Service. Available from: <http://igskmncnwb015.cr.usgs.gov/adds/geolist.php> (accessed 02.03.2010).

Fitzsimmons, K.E., 2007. Morphological variability in the linear dunefields of the Strzelecki and Tirari Deserts. Geomorphology 91, 146–160.

Fryberger, S.G., 1979. Dune forms and wind regime. United States Geological Survey Professional Paper 1052, 137–169.

Fryberger, S.G., Ahlbrandt, T.S., 1979. Mechanisms for the formation of eolian sand seas. Zeitschrift für Geomorphologie 23, 440–460.

Grove, A.T., 1969. Landforms and climatic change in the Kalahari and Ngamiland. Geographical Journal 135, 191–212.

Harrison, S.P., Kohfeld, K.E., Roelandt, C., Claquin, T., 2001. The role of dust in climate changes today, at the last glacial maximum and in the future. Earth Science Reviews 54, 43–80.

Hayward, R.K., Mullins, K.F., Fenton, L.K., Hare, T.M., Titus, T.N., Bourke, M.C., Colaprete, A., Christensen, P.R., 2007. Mars global digital dune database and initial science results. Journal of Geophysical Research 112, E11007. doi:10.1029/2007JE002943.

Holben, B.N., 1986. Characteristics of maximum-value composite images from temporal AVHRR data. International Journal of Remote Sensing 7, 1417–1434.

Jacobson, P.J., Jacobson, K.M., Seely, M.K., 1995. Ephemeral Rivers and Their Catchments: Sustaining People and Development in Western Namibia. Desert Research Foundation of Namibia, Windhoek.

James, M.E., Kalluri, S.N.V., 1994. The Pathfinder AVHRR land data set; an improved coarse resolution data set for terrestrial monitoring. International Journal of Remote Sensing 15, 3347–3363.

Kocurek, G., Lancaster, N., 1999. Aeolian system sediment state: theory and Mojave Desert Kelso dune field example. Sedimentology 46, 505–515.

Kohfeld, K.E., Harrison, S.P., 2000. How well can we simulate past climates? Evalauting the models using global palaeoenvironmental datasets. Quaternary Science Reviews 19, 321–346.

Lancaster, N., 1989. The Namib Sand Sea: Dune Forms, Processes and Sediments. Balkema, Rotterdam. 200.

Lancaster, N., 2002. How dry was dry? – Late Pleistocene palaeoclimates in the Namib Desert. Quaternary Science Reviews 21, 769–782.

Lancaster, N., Kocurek, G., Singhvi, A., Pandey, V., Deynoux, M., Ghienne, J.-F., Lo, K., 2002. Late Pleistocene and Holocene dune activity and wind regimes in the Western Sahara desert of Mauritania. Geology 30, 991–994.

Livingstone, I., 2003. A twenty-one-year record of surface change on a Namib linear dune. Earth Surface Processes and Landforms 28, 1025–1031. doi:10.1002/esp.1000.

Livingstone, I., Warren, A., 1996. Aeolian Geomorphology. Longman, London.

McFarlane, M.J., Eckardt, F.D., 2007. Palaeodune morphology associated with the Gumare fault of the Okovango graben in the Botswana/Nambia borderland: a new model of tectonic influence. South African Journal of Geology 110, 535–542.

McKee, E.D. (Ed.), 1979. A study of global sand seas. United States Geological Survey Professional Paper 1052, 429.

Mahowald, N., Kohfeld, K.E., Hansson, M., Balkanski, Y., Harrison, S.P., Prentice, I.C., Schulz, M., Rodhe, H., 1999. Dust sources and deposition in the last glacial maximum and current climate: a comparison of model results with paleodata from ice cores and marine sediments. Journal of Geophysical Research – Atmospheres 104 (D13), 15895–15916.

Mainguet, M., Callot, Y., 1978. L'erg de Fachi-Bilma (Tchad-Niger). Memories et Documents CNRS 18, 178.

Munyikwa, K., 2005. The role of dune morphogenetic history in the interpretation of linear dune luminescence chronologies: a review of linear dune dynamics. Progress in Physical Geography 29, 317–336.

Necsoiu, M., Leprince, S., Hooper, D.M., Dinwiddle, C.L., Mcginnis, R.N., Walter, G.R., 2009. Monitoring migration rates of an active subarctic dune field using optical imagery. Remote Sensing of Environment 113, 2441–2447.

Pearce, K.I., Walker, I.J., 2005. Frequency and magnitude biases in the 'Fryberger' model, with implications for characterizing geomorphically effective winds. Geomorphology 68, 39–55. doi:10.1016/j.geomorph.2004.09.030.

Potts, L.V., Akyilmaz, O., Braun, A., Shum, C.K., 2008. Multi-resolution dune morphology using Shuttle Radar Topography Mission (SRTM) and dune mobility from fuzzy interference systems using SRTM and altimetric data. International Journal of Remote Sensing 29, 2879–2901.

Radebaugh, J., Lorenz, R.D., Lunine, J.I., Wall, S.D., Boubin, G., Refet, E., Kirk, R.L., Lopes, R.M., Stofan, E.R., Soderblom, L., Allison, M., Janssen, M., Paillou, P.L., Callahan, P., Spencer, C.the Cassini Radar Team, 2008. Dunes on Titan observed by Cassini Radar. Icarus 194, 690–703.

Radebaugh, J., Lorenz, R., Farr, T., Paillou, P., Savage, C., Spencer, C., 2009. Linear dunes on Titan and earth: initial remote sensing comparisons. Geomorphology, doi:10.1016/j.geomorph.2009.02.022.

Ramsey, M.S., Christensen, P.R., Lancaster, N., Howard, D.A., 1999. Identification of sand sources and transport pathways at the Kelso Dunes, California using thermal infrared remote sensing. Geological Society of America Bulletin 111, 646–662.

Rawlins, B.G., Webster, R., Tye, A.M., Lawley, R., O'Hara, S.L., 2009. Estimating particle-size fractions of soil dominated silicate minerals from geochemistry. European Journal of Soil Science 60, 116–126.

Scheidt, S., Ramsey, M., Lancaster, N., 2008. Radiometric normalization and image mosaic generation of ASTER thermal infrared data: an application to extensive sand sheets and dune fields. Remote Sensing of Environment 112, 920–933.

Sridhar, V., Loope, D.B., Swinehart, J.B., Mason, J.A., Oglesby, R.J., Rowe, C.M., 2006. Large wind shift on the Great Plains during the medieval warm period. Science 313, 345–347. doi:10.1126/science.11,28,941.

Srivastava, P., Brook, G.A., Marais, E., Morthekai, P., Singhvi, A.K., 2006. Depositional environment and OSL chronology of the Homeb silt deposits, Kuiseb River, Namibia. Quaternary Research 65, 478–491.

Stone, A.E.C., Thomas, D.S.G., Viles, H.A., 2010. Late Quaternary palaeohydrological chnages in the northern Namib Sand Sea: new chronologies using OSL dating of interdigitated aeolian and water-lain interdune deposits. Palaeogeography, Palaeoclimatology, Palaeoecology 288, 35–53.

Stout, J.E., Warren, A., Gill, T.E., 2008. Publication trends in aeolian research: an analysis of the Bibliography of Aeolian Research. Geomorphology 105, 6–17. doi:10.1016/j.geomorph.2008.02.015.

Tchakarian, V.P., 2005. The resurgence of aeolian geomorphology. In: Tchakarian, V.P. (Ed.), Desert Aeolian Processes. Chapman and Hall, London, pp. 1–10.

Thomas, D.S.G., Knight, M., Wiggs, G.F.S., 2005. Remobilization of southern African desert dune systems by twenty-first century global warming. Nature 435, 1218–1221.

Townshend, J.R.G., Justice, C.O., 1986. Analysis of the dynamics of African vegetation using the normalised difference vegetation index. International Journal of Remote Sensing 7, 1435–1445.

Tsoar, H., Møller, J.-T., 1986. The role of vegetation in the formation of linear sand dunes. In: Nickling, W.G. (Ed.), Aeolian Geomorphology. George Allen and Unwin, Boston, pp. 75–95.

Van der Merwe, J.H., 1983. National Atlas of South West Africa (Namibia). Institute for Cartographic Analysis, University of Stellenbosch. National Book Printers, Goodwood, Cape.

Vermeesch, P., Drake, N., 2008. Remotely sensed dune celerity and sand flux measurements of the world's fastest barchans (Bodélé, Chad). Geophysical Research Letters 35, L24404. doi:10.1029/2008GL035921.

Wang, X., Dong, Z., Zhang, J., Chen, G., 2002. Geomorphology of sand dunes in the Northeast Taklimakan Desert. Geomorphology 42, 183–195.

Wang, X.M., Yang, Y., Dong, Z.B., Zhang, C.X., 2009. Responses of dune activity and desertification in China to global warming in the twenty-first century. Global and Planetary Change 67, 167–185.

Wasson, R.J., Hyde, R., 1983. Factors determining desert dune type. Nature 304, 337–339.

White, K., Eckardt, F., 2006. Geochemical mapping of carbonate sediments in the Makgadikgadi basin, Botswana, using moderate resolution remote sensing data. Earth Surface Processes and Landforms 31, 665–681.

White, K., Goudie, A., Parker, A., Al-Farraj, S., 2001. Mapping the geochemistry of the northern Rub' Al Khali using multispectral remote sensing techniques. Earth Surface Processes and Landforms 26, 735–748.

Wilson, I.G., 1973. Ergs. Sedimentary Geology 10, 77–106.