A 45-year time series of dune mobility indicating constant windiness over the central Sahara

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Received 1 June 2012; accepted 8 June 2012; published 19 July 2012.

[1] Although evidence is mounting that links global warming to changes in atmospheric dynamics over the Atlantic realm, similar studies over the African continent are lacking. And even if such models would exist, it would be difficult to verify their validity due to the paucity of meteorological observations and anemometers in the central Sahara. A pragmatic way around this problem is to monitor barchan dune velocity as a proxy for the windiness of desert areas. Dune migration rates are a measure of the amount of work done by the wind which does not require field measurements but can be observed from space instead. This paper presents a novel application of the remote sensing tool COSI-Corr for the construction of time series of dune mobility from sequences of optical satellite imagery. The technique has been applied to the Bodélé Depression in northern Chad, to demonstrate that dune migration rates in the central Sahara have been remarkably constant for nearly half a century, leading us to conclude that wind velocities have not changed more than 0.2% per year over that period. It is therefore unlikely that the frequency and intensity of dust storms originating from this 'hot spot' has significantly changed over the past decades either. **Citation:** Vermeesch, P., and S. Leprince (2012), A 45-year time series of dune mobility indicating constant windiness over the central Sahara, *Geophys. Res. Lett.*, *39*, L14401, doi:10.1029/2012GL052592.

1. Introduction

[2] As the average global temperature rises due to the greenhouse effect, the polar regions heat up more rapidly than the low latitudes [*Gitelman et al.*, 1997; *Holland and Bitz*, 2003]. This decrease in thermal gradient affects the dynamics of the atmosphere, leading to an overall weakening of atmospheric circulation [*Held and Soden*, 2006] while paradoxically increasing the storminess over the Atlantic as well [*Emanuel*, 2005]. Much less is known about the presence or absence of large scale trends in the windiness over the African continent, despite the important implications that such trends might have on the global aeolian dust budget. To overcome the lack of long term meteorological records, we propose dune migration rates as a sensitive proxy for the 'effective windiness' of desert areas, i.e., the amount of work done by the wind on the land. The rationale is as follows. *Bagnold* [1941] showed that the velocity (v) of barchan dunes is inversely proportional to their height (h) and proportional to sand flux, which in turn is approximately proportional to the cube of wind (shear) velocity (u_*) so that:

$$v = Cu_*^3/h \tag{1}$$

where C is the constant of proportionality. By taking the partial derivative of v with respect to u_* and rearranging, it can be shown that:

$$\frac{\partial v}{v} = 3\frac{\partial u_*}{u_*} \tag{2}$$

In other words, any change in wind velocity is 'magnified' by a factor of three in the dune velocity, or slightly less if an alternative transport equation is used instead of equation (1) [e.g., *Ungar and Haff*, 1987]. Furthermore, the dust emission flux (f) generated by saltating sand grains is closely proportional to sand flux as well [*Shao et al.*, 1993]. Therefore, changes in aeolian dust production are also governed by wind velocity according to equation (2) (substituting 'v' with 'f'), and hence scale linearly with dune celerity. In other words, every 1% increase in wind velocity results in a ~3% change in dune celerity and a ~3% change of dust production as well.

2. Study Area

[3] The central Sahara contains a number of localized 'hot spots' of dust production, the single most important of which is the Bodélé Depression of northern Chad [*Goudie and Middleton*, 2001; *Koren et al.*, 2006]. This 24,000 km^2 area supplies an estimated 6.5 million tonnes of Fe and 0.12 million tonnes of P to the Atlantic Ocean and Amazon Basin each year [*Bristow et al.*, 2009, 2010], due to a unique coincidence of two factors. First, the Bodélé is located downwind from a narrow gap between the Tibesti and Ennedi Mountains on the border with Libya, which accelerates the northeasterly trade winds to a low level jet with the capacity to do a lot of work [*Washington et al.*, 2006]. Second, it once formed the deepest part of palaeolake Megachad which rivaled the Caspian Sea in size as recently as 8,000 years ago [*Drake and Bristow*, 2006]. Today, the lake has disappeared, but its sediments remain. In the Bodélé, these sediments form white crusts of diatomite, which is readily broken down and transported to form some of the world's largest and fastest barchan dunes (Figure 1).

[4] We have tracked the movement of these dunes by remote sensing, using a technique called COSI-Corr, which stands for '*Co-registration of Optically Sensed Images and Correlation*' [*Leprince et al.*, 2007]. COSI-Corr quantifies

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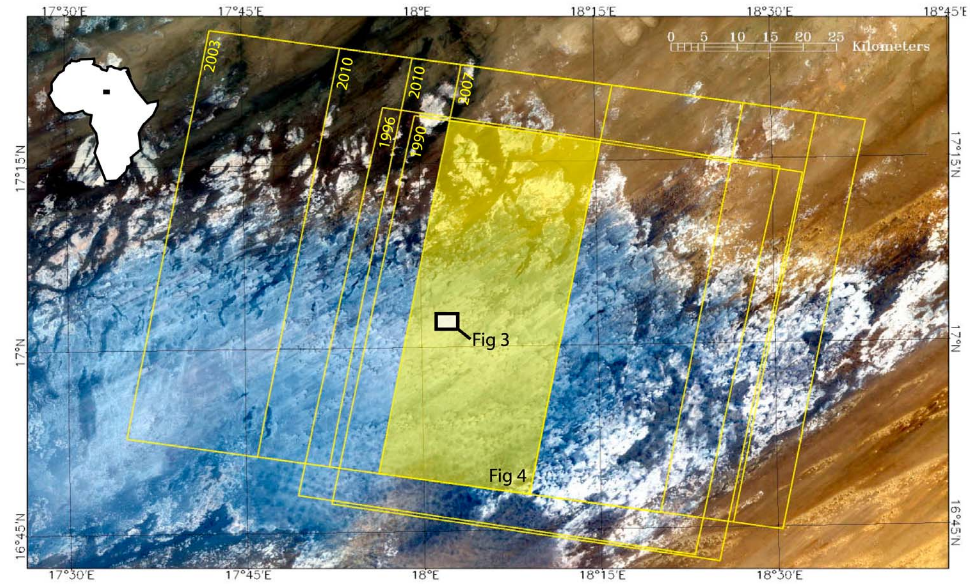

Figure 1. Landsat-4 image (from 1984) of the eastern Bodélé Depression with indication of the footprints (yellow rectangles) of the other imagery used in the automated time series analysis. Yellow shaded areas indicate areas of overlap between the seven images.

Earth surface displacements from sub-pixel correlations of pairs of remotely sensed optical imagery. Although the technique was originally developed for the detection of co-seismic displacements [*Avouac et al.*, 2006], it has since found applications in the study of glaciers, landslides, and sand dunes [*Leprince et al.*, 2008; *Vermeesch and Drake*, 2008; *Necsoiu et al.*, 2009]. COSI-Corr has been used to show that the barchan dunes of the Bodélé Depression, which are made of diatomite flakes, are some of the fastest on the planet, with sand flux at the dune crest in excess of 200 m^2 yr^{-1} [*Vermeesch and Drake*, 2008]. A 20 m high barchan will therefore migrate approximately 10 m per year which is comparable to the resolution of commercial satellite imagery available since the mid-1980s. This enables the creation of time series of dune mobility with a temporal resolution of just a few years, allowing the detection of temporal trends in the dune mobility, and therefore windiness, of the Bodélé Depression.

3. Method

[5] To create such a time series, seven Landsat-4 (1984), SPOT-3 (1990 and 1996), and ASTER (2000, 2003, 2007, and 2010) scenes were acquired from the central Bodélé Depression (Figure 1). The images were resampled to a common resolution of 15 m, georeferenced by selecting tie points on a Landsat-7 image (band 8) from 1999, and orthorectified using an SRTM digital elevation model. Animations of the imagery used in the time series analysis can be viewed at http://www.ucl.ac.uk/~ucfbpve/bodele. Thanks to the exceptionally high sand flux in the Bodélé Depression, aeolian processes are accelerated so that subtle trends and rare events are magnified and multiplied. For example, detailed observations of this image sequence has revealed several examples of shape preserving binary dune collisions (http://www.ucl.ac.uk/~ucfbpve/solitons) [*Vermeesch*, 2011].

[6] The time series extraction algorithm comprised the following seven steps. First, dune displacements were measured for each time step using COSI-Corr's frequential correlator, using a 64 × 64 pixel correlation window [*Leprince et al.*, 2007]. Second, the raw correlation results were destriped to remove uncorrected attitude effects. Third, the destriped displacement fields were 'warped' back in time to a common reference, namely the first image in the sequence (Figure 2). Fourth, the correlation results were 'cleaned' with a combination of two filters, requiring the displacements to (a) have a high signal-to-noise ratio and (b) move in a consistent direction with time. Fifth, the 'surviving' pixels

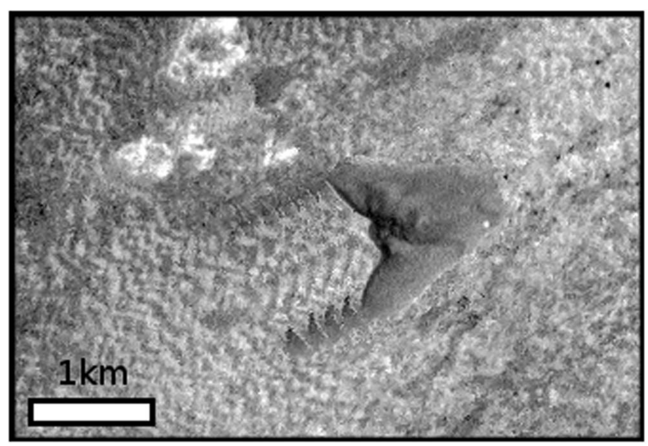

Figure 2. Semi-synthetic satellite image warped back in time using the displacement fields calculated by COSI-Corr. The 'tails' attached to the dune horns are caused by the so-called 'fattening effect', which affects features that are smaller in size than the (64 × 64 pixel) correlation window used for the COSI-Corr analysis. This fattening effect is partly responsible for the scatter observed in the resulting time series.

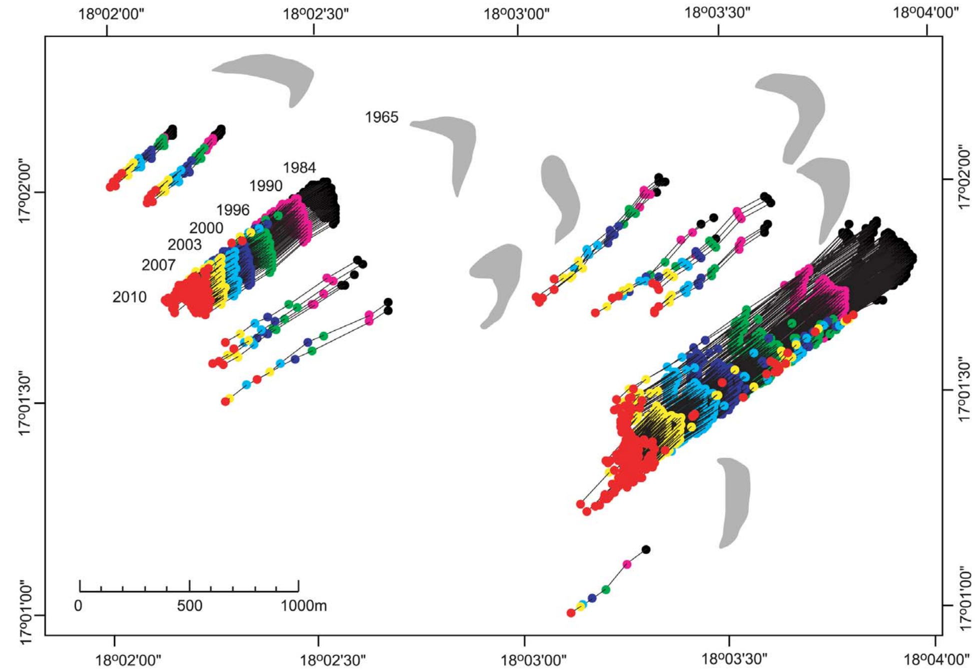

Figure 3. Map-view of individually tracked image pixels of sand dunes in the central Bodélé Depression. Black lines and coloured dots were produced by the automated COSI-Corr algorithm. Grey crescents mark the footprints of the corresponding barchan dunes in an analog Corona (KH-4) declassified American spy satellite image.

of the displacement map were connected and tracked across the image with time, yielding a map-view of dune migration paths (Figure 3). Sixth, the stepwise displacements of each dune track were projected on the resultant migration direction [*Necsoiu et al.*, 2009], yielding a broad distribution of cumulative dune displacements. Seventh, a celerity time series was created by selecting those pixels with a total displacement near the mode of this distribution, and dividing their stepwise displacements by the time elapsed between the satellite exposures (Figure 4).

[7] The accuracy of this algorithm was demonstrated on a semi-synthetic data set generated in the following manner. Five repeat exposures of a large interdune area were extracted from 15 m-resolution Landsat-7 images from the central Bodélé Depression (N 16°50′, E 17° 50′). Then, a barchan dune was 'extracted' from elsewhere in one of the images (N 16°56′, E 17° 05′) using a graphics editor, and superimposed on the first interdune image. Thus, the first image in the time sequence was obtained. The second image in the synthetic time series was generated by superimposing the same barchan dune 'clipping' on the next interdune

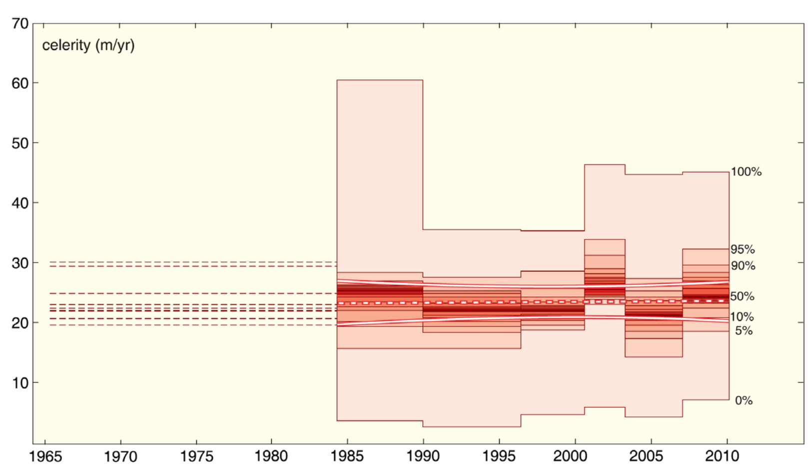

Figure 4. Normalised time series of dune mobility for the Bodélé data set, based on 2583 dune displacements with a total displacement of 600 ± 100 m. The red contours mark the percentiles of the observed distribution, with the darkest shade of red corresponding to the median. The dashed lines show the migration rates of ten dunes tracked by hand between a 1967 Corona spy satellite image and a Landsat image from 1984. White lines mark a linear least squares regression of the mean celerities and its 95% confidence envelope. The lack of any trend in the time series indicates that the 'effective storminess' of the Sahara has remained constant over the past 45 years.

image, with an offset of 10 pixels (150 m) to the east, and 5 pixels to the south (75 m). This process was repeated for the remaining three interdune images. The five synthetic images were subjected to the same analytical procedure as described in the previous paragraph. Figure 2 shows the last image mapped back to the time of the first image, using the displacement fields calculated by COSI-Corr. This demonstrates the effectiveness of the method used to warp the displacement fields. Sending the raw displacements between the four time steps of the synthetic dataset through the signal-to-noise and directional filters yields a histogram with total displacements of 669 $\pm$ 23 m (2σ), which is in good agreement with the known displacement of 668 m (=$4 \times \sqrt{150^2 + 75^2}$).

4. Results

[8] Applying the time series extraction algorithm to our sequence of seven coregistered images from the Bodélé Depression yielded 2853 individually tracked pixels with raw dune celerities between 0 and 50 m yr^{-1} and a broad distribution of total displacements with a mode at $\sim$600 m. The automated analysis was extended further back into the past by comparison of the 1984 image with declassified American spy satellite (Corona) images from 1965 and 1970. Due to the presence of specks of dust as well as image distortions caused by shrinking of the photographic film, it was not possible to automatically measure the dune displacements of these scenes with COSI-Corr. Instead, the image was georeferenced and coregistered to the 1984 Landsat imagery by third order polynomial fits to 531 tie points, and the displacements of ten large barchan dunes were measured by hand. Thanks to the 19-year time lapse between the two images used for these 'analog' measurements, their precision is better than 5%, which is comparable with that of the automated COSI-Corr analysis. The resulting dune celerities are identical to the automated measurements, which themselves show less than 10% temporal variability over the subsequent 26 years (Figure 4). The lack of any trend in the time series of dune celerity paints a picture of remarkably stable dune mobility over the past 45 years.

5. Discussion

[9] Previous studies [*Prospero and Lamb*, 2003; *Mukhopadhyay and Kreycik*, 2008] have indicated that the dust output of the Sahara has undergone significant variations over the course of the past few decades, with relatively low dust levels during the 1960s, high dust production during the 1970s and 1980s, and a gradual decrease after that. These changes can be explained either by (a) changes in precipitation and vegetation cover [*Middleton*, 1985; *Schlesinger et al.*, 1990; *Nicholson et al.*, 1998], or (b) changes in the wind regime and storminess of the desert [*Ruddiman*, 1997; *Gillette*, 1999; *Goudie and Middleton*, 2001; *Bozzano et al.*, 2002; *Prospero and Lamb*, 2003]. Whereas the first model has been validated by remote sensing [*Tucker et al.*, 1991; *Nicholson et al.*, 1998], the second model is much harder to test. In a recent study, *Young et al.* [2011] used a 23-year record of GEOSAT altimeter data to reconstruct trends in wind speed over the oceanic realm. For the north Atlantic, they found an increasing trend of 0–1% per year. As discussed before, no such data are available over the African continent, and herein lies the value of our dune celerity time series. A 95% confidence envelope for a linear least squares regression of our data set indicates that dune velocities have changed less than 10% over the 26 year duration of the automated analysis, corresponding to an annual change of less than 0.4% per year. Using equation (2), this translates into an annual change of the windiness of probably less than 0.13% and (accounting for different transport equations) certainly less than 0.2%.

[10] As briefly mentioned in section 1, wind tunnel experiments have shown that the emission flux of aeolian dust is proportional to the saltation flux of aeolian sand [*Shao et al.*, 1993; *Shao*, 2009], which in turn is proportional to dune velocity. There should therefore exist a correlation between dust production and dune mobility in the area. The constance of dune mobility in the 45-year time series of the Bodélé dunes indicates that the 'effective windiness' of the so-called 'Bodélé Low Level Jet' [*Washington et al.*, 2006; *Warren et al.*, 2007] has not significantly changed over the past half century, and it is therefore unlikely that the frequency and intensity of aeolian dust storms originating from this important area has significantly changed over that time period either. In conclusion, we have found no evidence that (anthropogenic) climate change has significantly affected atmospheric circulation over the central Sahara.

[11] **Acknowledgments.** Part of this research was done during an academic visit of P.V. to Caltech, sponsored by a grant from the Keck Institute for Space Studies (KISS) awarded to S.L. We would like to thank the help of two anonymous reviewers, one of whom suggested equation (2) to us.

[12] The Editor thanks the anonymous reviewer.

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