Remote Sensing of Environment 115 (2011) 1013–1024

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Hyperspectral spaceborne imaging of dust-laden flows: Anatomy of Saharan dust storm from the Bodélé Depression

A. Chudnovsky [a,*], A. Kostinski [b], L. Herrmann [c], I. Koren [a], G. Nutesku [d], E. Ben-Dor [d]

[a] Department of Environmental Sciences and Energy Research, Weizmann Institute of Science Rehovot, Israel
[b] Department of Physics, Michigan Technological University, USA
[c] Institute of Soil Science and Land Evaluation (310), University of Hohenheim, D-70593 Stuttgart, Germany
[d] Department of Geography and Human Environment, Tel-Aviv University, Remote Sensing and GIS Laboratory, Israel

ARTICLE INFO

Article history:
Received 2 March 2010
Received in revised form 12 November 2010
Accepted 4 December 2010
Available online 20 January 2011

Keywords:
Atmospheric dust
Mineral dust
Hyperspectral technology
Hyperion satellite
Bodélé Depression

ABSTRACT

We study hyperspectral images of the Bodélé Depression in Northern Chad, acquired by the Hyperion sensor onboard EO-1 spacecraft. Relative abundances of four major mineral components are obtained on a pixel-by-pixel basis and we report on the comparison of images of a dust storm with the same areas on a calm day. Minerals lifted and suspended particles downwind of a dust source are thus identified. Linear Spectral Unmixing (LSU) decomposition results for the calm condition match those of our field study. LSU calm vs. stormy comparison, based on absorbance features, highlight the spectral contrast. Despite low contrast above bright areas, morphological dissimilarity is evident via the wave and tongue-like features, aligned with the prevailing northeasterly winds. We analyze the longest part of shortwave infra-red (2080–2380 nm) wavelengths where the atmosphere is transparent, optical properties are stable, and absorption features of hydroxyl-bearing minerals, sulfates, and carbonates are pronounced. The results of our spectral analyses reveal that clay minerals may be used as tracers for atmospheric dust monitoring even above bright areas. Such clay minerals include kaolinite, illite-moscovite, and Fe-rich nontronite.

1. Introduction and background

The Bodélé Depression in Northern Chad (17° N, 18° E) is the largest source of atmospheric mineral aerosols on Earth (e.g. Prospero et al., 2002; Washington et al., 2003, 2009). The reasons for this include: the strength of the Bodélé Low Level Jet (Washington et al., 2005); the structure of the lowland between the Tibesti (2600 m) and Ennedi (1000 m) massifs, guiding and focusing the surface winds to the Bodélé (Koren et al., 2006); extreme surface gustiness (Goudie, 2009); availability of paleo-lake sediments, including diatomite, for large-scale wind erosion and deflation (Mounkaila, 2006; Schwanghart & Schütt, 2008; Warren et al., 2007; Washington et al., 2006).

Mineral dust particles are lifted into the atmosphere during frequent wind erosion events (Claquin et al., 1999; Tegen & Kohfeld, 2006). The dust particles lifted from a specified location are likely to have composition similar to finer particles (called potential dust fraction, Herrmann, 1996) found in nearby soils or sediments. Dust samples originating from the Bodélé Depression are generally dominated by quartz, with admixtures of clay minerals and Fe-oxyhydrates. The samples contain abundant freshwater Aulacoseira diatoms eroded from desiccated lake deposits (Moreno et al., 2006). Finer grain size fractions are more phyllosilicate-rich (illite, kaolinite, and montmorillonite) and contain higher concentrations of Al, Na, Mg, and Fe (Castillo et al., 2008; Herrmann et al., 2009; Moreno et al., 2006).

Hyperspectral images contain high resolution spectral curve for each of the image pixels. This adds to conventional tools of surface mapping the absorption bands, characteristic of mineral species (Goetz, 2009). Imaging spectrometry (IS) is typically used in surface mineral mapping where ground validation is possible. Such validation is not possible for dust storms because of their transient nature and poor access. Moreover, there is a problem of contrast, particularly in the immediate vicinity of the dust source above bright areas, where it is difficult to separate contribution of the dust plume from that of the underlying surface. Even if there are spectral differences between the suspended dust and the underlying surface, one has to separate effects due to composition from effects that are due to size distribution differences. Yet, tracking entrainment and deposition of dust in a low topographic area associated with strong winds and high sediment supply could be an exciting application of IS. Is it feasible?

To that end, Chudnovsky et al., 2009, used the Hyperion sensor onboard EO-1 spacecraft to study three representative surface areas (covering 60 × 120 m) over Bodélé Depression, Chad, during calm weather conditions and during a stormy day. Atmospheric dust spectra downwind of Bodélé revealed striking differences in absorption signatures across the longest wavelengths range of shortwave

* Corresponding author. Current address: Harvard School of Public Health, Boston, USA. Tel.: +1 617 3848846.
E-mail address: achudnov@hsph.harvard.edu (A. Chudnovsky).

0034-4257/$ – see front matter © 2010 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2010.12.006

infra red (2080–2380 nm) from those of underlying surface, thus providing evidence for mineral-based tracking of atmospheric dust. The atmospheric gas content is almost transparent at this range and distinct absorption features of hydroxyl-bearing minerals, sulfates, and carbonates are presented (common to many petrographic units of the study area).

Here, we substantially extend the analysis by applying pixel-by-pixel comparison of calm vs. stormy conditions. We ask: What are the differences in mineralogical composition of calm and stormy conditions, as indicated by spectral (IS) signature? Is it possible to monitor atmospheric dust over the source area, despite relatively low spectral contrast?

2. Study area

We compare two images of the same area, collected during calm and dust storm conditions. The area of comparison is highlighted in Fig. 1 by dashed red lines at the center of the original Hyperion image (acquired on June 21, 2003 on a calm day), overlaying on a mosaic of two LANDSAT images (acquired on June 2001 and August 2000) over the Bodélé Depression.

The Bodélé Depression in Northern Chad was once part of the largest lake in Africa (Drake & Bristow, 2006). The lake bed is now dry with the exception of Lake Chad in the southern basin. Topography in and around the Bodélé area is varied: flat in the east, rugged in the north-east, cuesta shaped in the north and frequent yardang and dispersed (barchan) dune fields within. Petrography is dominated by eolian sands, lacustrine sediments (including diatomite) and (coarse) sandstones. The former is of Holocene and the latter of tertiary age (Herrmann et al., 2009). Diatomites occur as large surfaces within the Bodélé and as dispersed outcrops in its surroundings, reaching a few meters in thickness (Chappell et al., 2008; Drake & Bristow, 2006; Herrmann et al., 2009; Warren et al., 2007; Wright, 1985). With respect to surfaces, three major types can be distinguished: moving sands (as sheets or dunes), lacustrine sediments (including diatomites) in erosion and desert pavement/serir (Herrmann et al., 2009). Serir surfaces prevail around the Bodélé, lacustrine sediments within, and sands are ubiquitous throughout. Between approximately 15 and 16°N, extended spots of whitish lacustrine sediments occur also eastward of the central basin. Further north (16–17°N) dunes of barchans types, sand sheets, as well as diatomites and swamp ores occur. Surfaces of serir type at eastern fringes of the depression have a dark red, dark brown or even black appearance, which was assumed by Herrmann et al. (2009) to be related to potentially Fe-rich sandstone outcrops. Approximately at 18°N–18°E, variable sediments occur: dunes, lacustrine sediments, and lacustrine sediments overlaying orange-brown dune sands and thin white carbonate crusts embedded in weakly consolidated siltstone. The Bodélé Depression itself is dominated by vast occurrences of lacustrine sediments. Yardang fields, with single yardangs up to 2 m high, mark the ongoing deflation. Northwards of the Depression the surface area is characterized by silty sediments and Fe-sandstones indicating strong Fe-translocation in the paleoenvironment (Herrmann et al., 2009).

2.1. Field samples

Eight reference samples were collected from the area (Fig. 1, Tables 1 and 2) during an expedition in 1997 as a part of the German Climate Research Program (DEKLIM). Stratified samples were collected on-site. After reconstruction of the surface features in the laboratory spectral reflectances in the range 320–2500 nm were measured in the BGR laboratory Hannover with an IRIS (Infra-Red Intelligent Spectroradiometer) radiometer, (Mounkaila, 2006) against a white baryta paper as reference material. Afterwards the fine earth fraction (<2 mm) was analyzed for bulk mineral composition using X-ray diffraction (Siemens D500, Cu Kalpha radiation, powder mounds) and Rietveld software. Geo-chemical composition was determined with a Siemens SRS 200 X-ray fluorescence apparatus (Cr radiation). Free iron was measured by an adapted DCB extraction (12 h, room temperature). Finally, granulometry was assessed using a combined

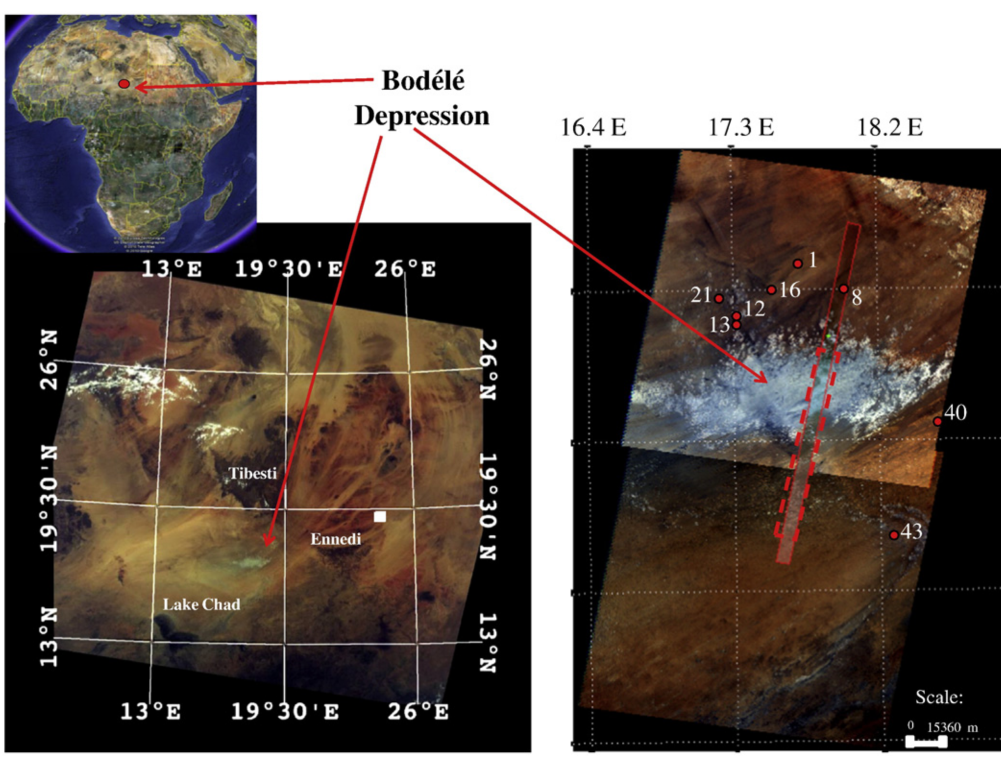

Fig. 1. Geographic setting: Hyperion satellite path pasted over the mosaic of two Landsat images. Also shown is the location of our reference field samples (Tables 1 and 2). Area demarcated by dashed lines is selected for the comparison between calm and stormy states. This figure shows the location of the calm image relatively to the upwind sources (relative to the sampling area).