



**Michigan  
Technological  
University**

Michigan Technological University  
**Digital Commons @ Michigan Tech**

---

Department of Physics Publications

Department of Physics

---

8-6-2009

## Mineral content analysis of atmospheric dust using hyperspectral information from space

A. Chudnovsky  
*Weizmann Institute of Science*

E. Ben-Dor  
*Tel-Aviv University*

A. B. Kostinski  
*Michigan Technological University*

I. Koren  
*Weizmann Institute of Science*

Follow this and additional works at: <https://digitalcommons.mtu.edu/physics-fp>



Part of the [Physics Commons](#)

---

### Recommended Citation

Chudnovsky, A., Ben-Dor, E., Kostinski, A. B., & Koren, I. (2009). Mineral content analysis of atmospheric dust using hyperspectral information from space. *Geophysical Research Letters*, 36(15), 1-5.

<http://dx.doi.org/10.1029/2009GL037922>

Retrieved from: <https://digitalcommons.mtu.edu/physics-fp/209>

Follow this and additional works at: <https://digitalcommons.mtu.edu/physics-fp>



Part of the [Physics Commons](#)

## Mineral content analysis of atmospheric dust using hyperspectral information from space

A. Chudnovsky,<sup>1</sup> E. Ben-Dor,<sup>2</sup> A. B. Kostinski,<sup>3</sup> and I. Koren<sup>1</sup>

Received 28 February 2009; revised 28 May 2009; accepted 16 June 2009; published 6 August 2009.

[1] The Bodélé depression of northern Chad is considered one of the world's largest sources of atmospheric mineral dust. Mineral composition of such transported dust is essential to our understanding of climate forcing, mineralogy of dust sources, aerosol optical properties, and mineral deposition to Amazon forests. In this study we examine hyperspectral information acquired over the Bodélé by EO-1 Hyperion satellite during a dust storm event and during a calm clean day. We show that, for the suspended dust, the absorption signature can be decoupled from scattering, allowing detection of key minerals. Our results, based on the visible and shortwave infrared hyperspectral data, demonstrate that the Bodélé surface area is composed of iron-oxides, clays (kaolinite) and sulfate groups (gypsum). Atmospheric dust spectra downwind of Bodélé reveal striking differences in absorption signatures across shortwave infrared from those of the underlying surface. **Citation:** Chudnovsky, A., E. Ben-Dor, A. B. Kostinski, and I. Koren (2009), Mineral content analysis of atmospheric dust using hyperspectral information from space, *Geophys. Res. Lett.*, *36*, L15811, doi:10.1029/2009GL037922.

### 1. Introduction and Motivation

[2] Mineral dust suspended in the atmosphere interacts with the solar and earth's thermal radiation, thereby affecting the climate radiative budget [Miller and Tegen, 1998; Sokolik et al., 2001]. Dust may affect clouds properties in two ways: by serving as cloud condensation nuclei (CCN) changing the cloud microphysical and dynamical properties [Twomey et al., 1987; Rosenfeld et al., 2001; Kaufman et al., 2005], or by changing the local stability by absorbing and scattering the solar radiation [Hansen et al., 1997; Sokolik et al., 2001; Koren et al., 2008]. Such changes will affect the cloud lifetime, coverage and optical properties [Albrecht, 1989]. The last Intergovernmental Panel on Climate Change (IPCC) report [IPCC, 2007] acknowledged that the forcing due to atmospheric aerosol poses the largest uncertainties in our understanding of the climate system. The knowledge of mineral composition of transported dust is essential to understanding of climate forcing and its magnitude, mineralogy of dust sources, aerosol optical properties, and dust biogeochemical feedbacks. Dust min-

erological content may provide clues for understanding the mechanisms behind dust variability and continental provenance [Sokolik et al., 2001].

[3] The Bodélé depression, Chad in North Africa, is widely regarded as the world's largest source of mineral aerosols [Prospero et al., 2002; Washington et al., 2006]. A rare combination of global wind pattern, topography, mineralogical composition and surface soil properties could explain the intense dust production observed throughout the year in this area (Figures 1a and 1b). The following is known about the dust dynamics of Bodélé: (1) the existence of the Bodélé Low Level Jet (LLJ) winds playing a key role in the dust emission and initial transport out of the region leading to long-range transport in the large-scale Harmattan northeasterlies [Washington et al., 2006]; (2) the structure of the valley between the Tibesti (2600 m) and Ennedi (1000 m) massifs serves as a 'wind lens', guiding and focusing the surface winds to the Bodélé [Koren et al., 2006]; and (3), Bodélé mainly consisting of low density diatomite (remains of silicate algae) and eroded diatomite sand [Bristow et al., 2009], and free of vegetation;

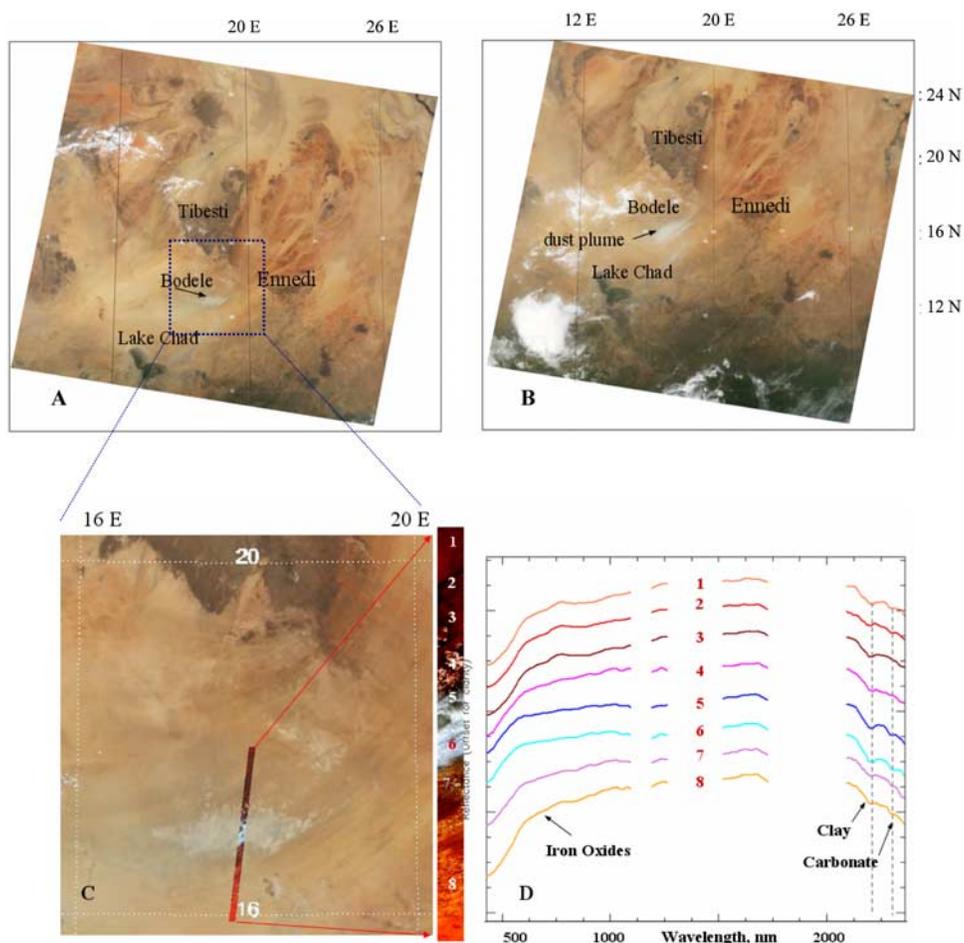
[4] Dust from the Bodélé extends for thousands of kilometers [Washington et al., 2006]. Koren et al. [2006] estimated that more than half of the dust that is deposited annually in the Amazon forest originates in the Bodélé depression, therefore providing the nutrient supply to the soil of the Amazon which is shallow, lacking of soluble minerals and due to heavy rains poor in nutrients. The corresponding plumes have been monitored by a variety of satellite-based instruments [Prospero et al., 2002; Meloni et al., 2004; Kaufman et al., 2005; Chappell et al., 2008]. Nevertheless, the conventional aerosol inversion of a few selected wavelengths (such as MODIS; see Figure 1a and 1b) was designed to retrieve the aerosol optical depth and some information on the spectral dependence (such as fine fraction or Angstrom exponent). Therefore, the spectral resolution does not suffice to determine the mineral composition of atmospheric dust.

[5] Here we argue that because of the complex nature of light scattering by aspherical, size-distributed atmospheric dust, its spectral scattering features are, likely, smooth – in contrast to the distinct spectral features (e.g., sharp peaks) characterizing mineral absorption. Thus, the two can be separated. This argument, along with the possibility of high spectral and spatial resolution, pointed us to hyperspectral technology from space. The Hyperion data onboard the Earth Observing 1 (EO-1) satellite is used in this study. The Hyperion is a hyperspectral sensor designed to simultaneously acquire data in 244 spectral bands across the 350–2500 nm region with 10-nm sampling interval (see Figures 1c–1d) and 30-m pixel size.

<sup>1</sup>Department of Environmental Sciences, Weizmann Institute of Science, Rehovot, Israel.

<sup>2</sup>Remote Sensing and GIS Laboratory, Department of Geography and Human Environment, Tel-Aviv University, Tel Aviv, Israel.

<sup>3</sup>Department of Physics, Michigan Technological University, Houghton, Michigan, USA.



**Figure 1.** MODIS Terra RGB image (a) for a clean day, June 21, 2003, at 0930 UTC and (b) for a dust storm day, June 7, 2003, at 0925 UTC. (c) Hyperion image collected during the clean day (June 21, 2003) centered above the Bodélé depression as seen from MODIS image. (d) Reflectance spectra of selected areas, denoted as 1–8. The intrinsic spectral features that appear in the form of bands and slopes in the VIS (400–700 nm) and NIR-SWIR (1300–2500 nm) bidirectional reflection spectra of minerals are caused by various electronic and vibrational modes, for example, the 2200 nm features caused by vibrational combination tones involving the AlOH fundamental-bending mode. Materials that exhibit these features can be distinguished from those based on the MgOH bending modes, such as amphibole and carbonates, because the latter produce bands near 2300 nm and 2335 nm [Hunt, 1977].

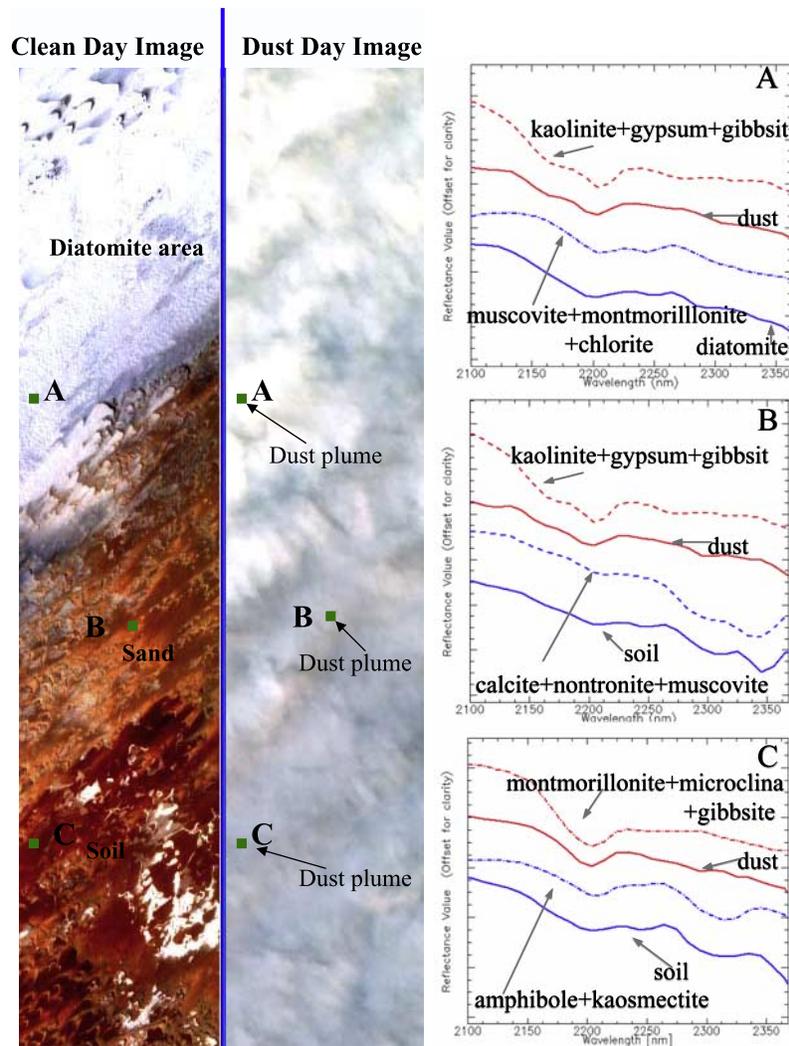
[6] While so far such hyperspectral technology has been used mostly for land and water applications, here we make the first attempt of using it to study atmospheric dust from a mineral perspective. In this study we confine ourselves to two questions: (1) Can we sense the atmospheric dust features in the short wave infrared spectral range (2100–2380 nm), despite the strong signal of the underlying surface? (2) If so, is it possible to extract atmospheric dust mineral composition? Below, we report that the answer is yes to both questions.

## 2. Image Processing and Data Analysis

[7] We examine two images over the Bodélé depression (17°N, 18°E), Chad, acquired by Hyperion EO-1: (1) June 7, 2003 at 9:04 local time during a heavy dust storm event; (2) June 21, 2003, at 9:06 corresponding to a calm, clean day. The images were pre-processed and adjusted similarly as described in the Hyperion user guide, [Barry, 2001]. This enabled us to distinguish between high frequency (e.g.

absorbencies) and low frequency (e.g. scattering) features. Both images were then processed to remove molecular attenuation via the ACORN atmospheric correction code (AIG-LLC, Boulder, CO). Strong water vapor bands near 1400 and 1800 nm were removed because of the very weak spectral signals at these regions. Finally, the images were mutually georeferenced for subsequent spatial change detection analysis and spectral smoothing (averaging of several consecutive values around a nominal wavelength) was applied to every pixel in the image and matched to known mineralogical information [Duckworth, 2004]. Additional smoothing filter (segment size for averaging  $3 \times 3$ ) was applied to SWIR region in order to remove the remaining noises.

[8] Spectral reflectances from eight representative sites, spanning the Visible-Near Infrared- Short Wave Infrared spectral range (VIS-NIR-SWIR: 420–2380 nm), are given in Figure 1d. However, to compare clean day and “dusty” day pixels, we confine our spectral range to the SWIR region only (2100–2380 nm) because of atmospheric



**Figure 2.** (left) Hyperion RGB image for a clean day (21 June, 2003) and a dust storm event (7 June, 2003). (right) Comparison of reflectance spectra of Hyperion satellite (continuous lines) and synthetic mixtures of pure minerals (dashed lines) over same locations between the clean day (blue lines) and the dust day (red lines). Differences in absorption wavelengths between dust and clean curves are significant. Doublet absorption at 2163 nm combined with 2200 nm due to presence of kaolinite, are evident in the dust spectra, thus indicating its upstream airborne origin. This constitutes evidence for mineral-based tracking of atmospheric dust.

transparency, constant optical properties and inclusion of distinct absorption features of hydroxyl-bearing minerals, sulfates, and carbonates common to many geologic units and hydrothermal alteration assemblages.

[9] Next, we identify surface minerals lifted by the wind and staying aloft as dust. To that end, we analyze spectral reflectance from three different sites. Region of interest (ROI) is delineated on the dust image in a centre of a dust plume (Figure 2); the corresponding ROI in the clean day data (Figure 2) was delimited along the same image column ( $2 \times 2$  or  $2 \times 3$  pixels in average, covering an area of 80 to 120 m, respectively). The average spectra of all pixels within each ROI for clean and dust days data were examined and then compared (Figure 2, right). The clean image pixels were chosen so that they are similar in their mineralogical composition both, visually and spectrally, for each studied area. To deduce mineralogical composition of the selected ROIs, we show the weighted spectral synthetic

mixtures of pure minerals (dashed lines) that are closest to the spectra measured from Hyperion (continuous lines) on the clean and dust day. The synthetic spectra are obtained from using the Linear Spectral Unmixing techniques (LSU) [Adams *et al.*, 1986]. Briefly, LSU deconvolves spectrum into several pure minerals (end-members, EM), derived from a laboratory-based pure mineral spectral library. The spectral library used in this study was generated by selecting spectra from USGS Spectral Library for Minerals database according to the Chad formation mineralogy. The source of reference was based on geologic map [Cratchley *et al.*, 1984] and a literature search [Wright *et al.*, 1985; Claquin *et al.*, 1999; Mounkaila *et al.*, 2003; Moreno *et al.*, 2006]. The constructed library contained phyllosilicates, sulfates, iron oxides, and carbonates (20 minerals).

[10] In summary, because obtaining field data is still not a straightforward mission [see Mounkaila *et al.*, 2003], LSU is employed to estimate as accurate as possible the main

**Table 1.** Main Mineral Content of Several Representative Areas Highlighted in Figure 1d Based on Linear Unmixing Analyses of the VIS and SWIR Spectral Regions

Surface	VIS Region (400-700 nm)	SWIR (2080-2370 nm)
1	goethite	muscovite+montmorillonite+kaosmectite+gypsum
2	goethite	nontronite+montmorillonite+muscovite+chlorite
3	goethite	kaolinite+montmorillonite
4	absorption features absent	smectite+gypsum+montmorillonite+nontronite
5	absorption features absent	montmorillonite+muscovite+nontronite+chlorite
6	absorption features absent	gibbsit+muscovite+smectite+chlorite
7	goethite	smectite+bassanite+calcite+montmorillonite
8	goethite	kaosmectite+gypsum+montmorillonite+microcline

mineralogical components within an image [Adams *et al.*, 1986].

### 3. Results

[11] Figures 1c–1d and Table 1 summarize the spectra of selected surfaces at the Bodélé depression, as obtained from the Hyperion clean day (no suspended dust) data. At the top of the image, in the vicinity of Tibesti, soils across VIS region exhibit absorption due to the high iron content. These effects are slightly weaker at the southern part of the image, across sand dunes, and absent on the diatomite surface. Across the SWIR region all sediments are relatively homogeneous and rich with alumino-silicate and clay minerals. The clay mineral composition is dominated by kaolinite, kao-smectite, montmorillonite and muscovite. Absorption features related to amphibole, nontronite, dolomite, calcite, chlorite and gypsum are also observed. These results are at least partially supported by the field measurements conducted by Mounkaila *et al.* [2003], who collected 200 samples over the Bodélé and Lake Chad area. They found that clay mineral composition is dominated by smectite and kaolinite in the topsoils, with Fe-oxides/oxy-hydrates occurring regularly, with the exception of some limnic deposits, and that quartz and feldspars are the predominant minerals in the bulk samples.

[12] Similar spectral analyses were used on the dust image. A direct spectral analysis of the dust pixels is a tremendous challenge due to its size-distributed wavelength-dependent morphological and optical properties, chemical composition, nonsphericity, and its large spatial and temporal variability [e.g., Sokolik and Toon, 1999; Sokolik *et al.*, 2001; Dubovik *et al.*, 2002]. The question is whether the absorption spectral signatures of the atmospheric dust can be detected despite these difficulties? With the hyperspectral and high spatial resolution data, the answer is *Yes* as can be seen in Figure 2.

[13] Three different regions are selected in Figure 2 and in each case, dusty day and underlying (calm, clean day) surface pixels, are extracted as paired spectra for comparison. Combining the paired spectra with the LSU (synthetic spectral model) analyses, we can state with confidence that “dusty” mineral composition differs significantly from that of the clean day surface. The following can be gleaned from the reflectance information in Figure 2. In area A, the ground diatomite surface displays a relatively broad absorption at 2200 nm which we attribute to the clay component mixed with some alumino-silicate minerals. In contrast, particles of the dust source in area A contained a mixture of kaolinite with gypsum. Kaolinit characterized by doublet absorption at 2163 nm combined with 2200 nm. This

double absorption feature is absent at the equivalent surface pixels. In area B, sand surface denoted as B exhibits presence of calcite (CaCO<sub>3</sub>, absorption near 2340 nm) mixed with nontronite (absorption centered at 2300 nm). As for area A, dust pixels of area B exhibit a strong presence of kaolinite with sulfate group minerals. In area C, soil surface C is interpreted as a mixture of kaosmectite with amphibole. The dust spectra above exhibit the strong presence of montmorillonite mixed with microcline or muscovite: both, in turn, displaying similar V-structures at 2200 nm and absent at the surface.

[14] All three cases highlight differences in absorption wavelengths between the “dusty day” and “clean day” curves, indicating that the spectrum of airborne dust is distinct from that of the underlying surface. Therefore, atmospheric dust originates upwind of the studied area, from sources containing the suspended minerals. The characteristic spectral signature of the dust pixels from areas A and B, associated with kaolinite, is absent on the ground. Different absorption structure at dust source of area C fit the spectral composition of montmorillonite with muscovite or microcline, and is significantly different from the ground spectra. Moreover, the absorption features of the all underlined surfaces (A, B, and C) around 2300 nm are also absent on their corresponding dust spectra.

### 4. Discussion

[15] The unique (high frequency) spectral features observed within the SWIR region of the atmospheric dust spectra, and their exact wavelength position, are unlikely to be scattering artifacts. Indeed, it appears improbable that multiple scattering would conspire to mimic such distinct spectral features at the exact spectral values. Differences in absorption features of the three underlying surfaces (A, B and C) around 2300 nm are also evident. These findings practically rule out multiple scattering as a possible cause for the observed spectral differences, thereby constituting first evidence for mineral-based tracking of atmospheric dust.

[16] The minerals that appear only on the dusty day data (for the same geographic location) eroded, most likely, from upwind sources (relative to the sampling area) and are surely part of the suspended dust. It is the combination of the source and dust entrainment conditions that determine the mineral composition of the suspended dust as well as subsequent particle aggregation [Sokolik *et al.*, 2001]. Therefore, for the minerals that were detected in both the clean day and dusty day data, we can not rule out that the information came from the underlying background though it

is likely that these minerals compose the atmospheric dust as well.

[17] Despite the insight we gained into the mineral composition of the dust derived from hyperspectral Hyperion image, much work remains to be done. There is the problem of contrast, typical of much remote sensing: how can one analyze dust pixels when the contrast with the underlying surface is weak? This is often the case, particularly in the immediate vicinity of the dust source, and then it is difficult to separate contribution of the dust plume from that of the underlying surface. What minerals are lifted and what are settled in the vicinity and downwind of the dust source? Another interesting question relates to the relative abundance of various minerals in the dust mixture or precise quantitative determination of dust mineralogical composition.

[18] In this paper, we asked whether the hyperspectral technology can assist in exploration of atmospheric dust. The main idea was: does the hyperspectral technology allow one to compare key minerals contained in atmospheric dust, relative to the underlying surface seen on a clear day. To that end, we demonstrated that indeed the spectral information of some of the key minerals in the suspended dust is not obscured by the scattering process and absorption features are detectable across SWIR region of spectra. Our evidence shows characteristic spectral signatures of atmospheric dusts, unlikely to be scattering artifacts. The dust properties were derived from the spectral signature in the SWIR (2100–2380 nm) while those of the surface so from the VIS as well. Our approach of inferring mineralogical information of atmospheric dust aerosols from remote optical measurements suggests new possibilities in the general field of atmospheric remote sensing.

[19] **Acknowledgments.** This research was partly funded by the Weizmann–Argentina Cooperation program and the Minerva Foundation. IK is incumbent of the Benjamin H Swig and Jack D. Weiler career development chair. ABK's work was supported by the NSF grant ATM05-5467 and by the Varron visiting professorship at the Weizmann Institute of Science, Israel. ABK is grateful to the Department of Environmental Sciences of the Weizmann Institute for their hospitality and support. The authors are very grateful to Chris Kratt from University of Nevada for providing the spectra of diatomite deposits collected at Brady-Desert Peak, Nevada, USA. The authors also wish to thank the anonymous reviewers for their constructive comments.

## References

Adams, J. B., M. O. Smith, and P. E. Johnson (1986), Spectral mixture modeling: A new analysis of rock and soil types at the Viking Lander 1 site, *J. Geophys. Res.*, *91*, 8098–8112, doi:10.1029/JB091iB08p08098.

Albrecht, B. A. (1989), Aerosols, cloud microphysics, and fractional cloudiness, *Science*, *245*, 1227–1230, doi:10.1126/science.245.4923.1227.

Barry, P. (2001), *EO-1/Hyperion Science Data User's Guide*, TRW Space, Def. and Inf. Syst., Redondo Beach, Calif.

Bristow, C. S., N. Drake, and S. Armitage (2009), Deflation in the dustiest place on Earth: The Bodélé depression, Chad, *Geomorphology*, *105*, 50–58, doi:10.1016/j.geomorph.2007.12.014.

Chappell, A., A. Warren, A. O'Donoghue, A. Robinson, A. Thomas, and C. Bristow (2008), The implications for dust emission modeling of spatial and vertical variations in horizontal dust flux and particle size in the Bodélé depression, northern Chad, *J. Geophys. Res.*, *113*, D04214, doi:10.1029/2007JD009032.

Claquin, T., M. Schulz, and Y. Balkanski (1999), Modeling the mineralogy of atmospheric dust sources, *J. Geophys. Res.*, *104*, 22,243–22,256, doi:10.1029/1999JD900416.

Cratchley, C., P. Louis, and D. Ajakaiye (1984), Geophysical and geological evidence for the Benue-Chad Basin Cretaceous rift valley system and its tectonic implications, *J. Afr. Earth Sci.*, *2*, 141–150.

Dubovik, O., B. Holben, T. Eck, A. Smirnov, Y. Kaufman, M. King, D. Tarré, and I. Slutsker (2002), Variability of absorption and optical properties of key aerosol types observed in worldwide locations, *J. Atmos. Sci.*, *59*, 590–608, doi:10.1175/1520-0469(2002)059<0590:VOAOP>2.0.CO;2.

Duckworth, J. (2004), Mathematical data processing, in *Near-Infrared Reflectance Spectroscopy, Agron. Monogr.*, vol. 44, edited by C. A. Roberts, J. Workman, and J. B. Reeves III, pp. 115–132, Am. Soc. of Agron., Madison, Wis.

Hansen, J., M. Sato, and R. Ruedy (1997), Radiative forcing and climate response, *J. Geophys. Res.*, *102*, 6831–6864, doi:10.1029/96JD03436.

Hunt, G. R. (1977), Spectral signatures of particulate minerals, in the visible and near-infrared, *Geophysics*, *42*, 501–513, doi:10.1190/1.1440721.

Intergovernmental Panel on Climate Change (IPCC) (2007), *Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the IPCC*, edited by S. Solomon et al., Cambridge, Univ. Press, New York. (<http://www.ipcc.ch/>)

Kaufman, Y. J., I. Koren, L. Remer, D. Rosenfeld, and Y. Rudich (2005), The effect of smoke, dust and pollution aerosol on shallow cloud development over the Atlantic Ocean, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 11,207–11,212, doi:10.1073/pnas.0505191102.

Koren, I., Y. Kaufman, R. Washington, M. Todd, Y. Rudich, V. Martins, and D. Rosenfeld (2006), The Bodélé depression: A single spot in the Sahara that provides most of the mineral dust to the Amazon forest, *Environ. Res. Lett.*, *1*, 014005, doi:10.1088/1748-9326/1/1/014005.

Koren, I., J. Vanderlei Martins, L. A. Remer, and H. Afargan (2008), Smoke invigoration versus inhibition of clouds over the Amazon, *Science*, *321*, 946–949, doi:10.1126/science.1159185.

Meloni, D., A. di Sarra, T. Di Iorio, and G. Fiocco (2004), Direct radiative forcing of Saharan dust in the Mediterranean from measurements at Lampedusa Island and MISR space-borne observations, *J. Geophys. Res.*, *109*, D08206, doi:10.1029/2003JD003960.

Miller, R. L., and I. Tegen (1998), Climate response to soil dust aerosols, *J. Clim.*, *11*, 3247–3267, doi:10.1175/1520-0442(1998)011<3247:CRSDA>2.0.CO;2.

Moreno, T., X. Querol, S. Castillo, A. Alastuey, E. Cuevas, L. Herrmann, M. Mounkaila, J. Elvira, and W. Gibbons (2006), Geochemical variations in aeolian mineral particles from the Sahara-Sahel dust corridor, *Chemosphere*, *65*, 261–270, doi:10.1016/j.chemosphere.2006.02.052.

Mounkaila, M., et al. (2003), Spectral and mineralogical properties of potential dust sources on a transect from Sahara to the Sahel in Chad, paper presented at 2nd International Workshop on Mineral Dust, Cent. Natl. Rech. Sci., Paris.

Prospero, J. M., P. Ginoux, O. Torres, S. E. Nicholson, and T. E. Gill (2002), Environmental characterization of global sources of atmospheric soil dust identified with the NIMBUS 7 Total Ozone Mapping Spectrometer (TOMS) absorbing aerosol product, *Rev. Geophys.*, *40*(1), 1002, doi:10.1029/2000RG000095.

Rosenfeld, D., Y. Rudich, and R. Lahav (2001), Desert dust suppressing precipitation: A possible desertification feedback loop, *Proc. Natl. Acad. Sci. U. S. A.*, *98*, 5975–5980, doi:10.1073/pnas.101122798.

Sokolik, I. N., and O. B. Toon (1999), Incorporation of mineralogical composition into models of the radiative properties of mineral aerosol from UV to IR wavelengths, *J. Geophys. Res.*, *104*, 9423–9444, doi:10.1029/1998JD200048.

Sokolik, I. N., D. M. Winker, G. Bergametti, D. A. Gillette, G. Carmichael, Y. J. Kaufman, L. Gomes, L. Schuetz, and J. E. Penner (2001), Introduction to special section: Outstanding problems in quantifying the radiative impacts of mineral dust, *J. Geophys. Res.*, *106*(D16), 18,015–18,027, doi:10.1029/2000JD900498.

Twomey, S., R. Gall, and M. Leuthold (1987), Pollution and cloud reflectance, *Boundary Layer Meteorol.*, *41*, 335–348, doi:10.1007/BF00120449.

Washington, R., M. C. Todd, S. Engelstaedter, S. Mbainayel, and F. Mitchell (2006), Dust and the low-level circulation over the Bodélé depression, Chad: Observations from BoDEx 2005, *J. Geophys. Res.*, *111*, D03201, doi:10.1029/2005JD006502.

Wright, J. B., D. A. Hastings, W. B. Jones, and H. R. Williams (1985), *Geology and Mineral Resources of West Africa*, Allen and Unwin, London.

E. Ben-Dor, Remote Sensing and GIS Laboratory Department of Geography and Human Environment, Tel-Aviv University, Tel Aviv 69978, Israel.

A. Chudnovsky and I. Koren, Department of Environmental Sciences, Weizmann Institute, Rehovot 76100, Israel. (alexandra.chudnovsky@weizmann.ac.il)

A. B. Kostinski, Department of Physics, Michigan Technological University, Houghton, MI 49931-1295, USA.