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Diurnal emissivity dynamics in bare *versus* biocrusted sand dunes

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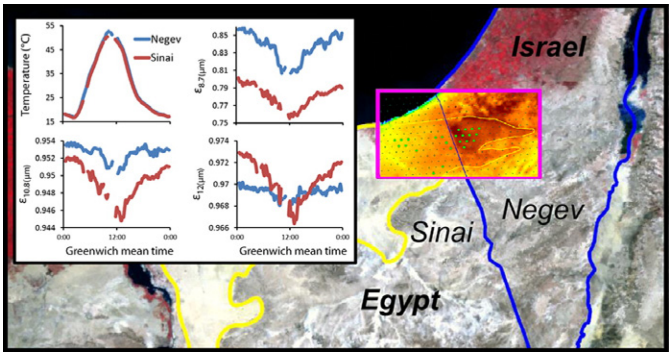
HIGHLIGHTS

- A geostationary space observation of land surface emissivity dynamics was conducted.
- Diurnal emissivity variations were greater in biocrusted than in bare sands.
- The emissivity variations were caused by water vapor adsorption and evaporation.

GRAPHICAL ABSTRACT



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ABSTRACT

Land surface emissivity (LSE) in the thermal infrared depends mainly on the ground cover and on changes in soil moisture. The LSE is a critical variable that affects the prediction accuracy of geophysical models requiring land surface temperature as an input, highlighting the need for an accurate derivation of LSE. The primary aim of this study was to test the hypothesis that diurnal changes in emissivity, as detected from space, are larger for areas mostly covered by biocrusts (composed mainly of cyanobacteria) than for bare sand areas. The LSE dynamics were monitored from geostationary orbit by the Spinning Enhanced Visible and Infrared Imager (SEVIRI) over a sand dune field in a coastal desert region extending across both sides of the Israel–Egypt political borderline. Different land-use practices by the two countries have resulted in exposed, active sand dunes on the Egyptian side (Sinai), and dunes stabilized by biocrusts on the Israeli side (Negev). Since biocrusts adsorb more moisture from the atmosphere than bare sand does, and LSE is affected by the soil moisture, diurnal fluctuations in LSE were larger for the crusted dunes in the 8.7 μm channel. This phenomenon is attributed to water vapor adsorption by the sand/biocrust particles. The results indicate that LSE is sensitive to minor changes in soil water content caused by water vapor adsorption and can, therefore, serve as a tool for quantifying this effect, which has a large spatial impact. As biocrusts cover vast regions in deserts worldwide, this discovery has repercussions for LSE estimations in deserts around the globe, and these LSE variations can potentially have considerable effects on geophysical models from local to regional scales.

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1. Introduction

Land surface emissivity (LSE) is the ratio between the radiance emitted by the land surface and the radiance emitted by a black body at the same temperature (Li et al., 2012, 2013a). The estimation of LSE by remote sensing in the long-wave infrared (LWIR) spectral region (8–13 μm) is mainly dependent on the surface cover (rock, soil, vegetation, *etc.*) and viewing angle (Hulley et al., 2010; Li et al., 2013a). However, LSE also nonlinearly varies according to changes in soil moisture caused by precipitation, condensation, and evaporation (Mira et al., 2007, 2010; Sanchez et al., 2011). In drylands, even small-scale changes in soil moisture that occur due to dew formation, as well as direct water vapor adsorption by the soil, can cause LSE variations (Li et al., 2012). Water vapor from the atmosphere may be directly absorbed by the soil matrix as a result of capillary condensation and/or physical adsorption. The former is the predominant mechanism when the relative humidity in the pores is high, while the latter predominates at low values of relative humidity (Philip and De Vries, 1957). Accurate LSE estimation is vital for the derivation of various surface and atmospheric variables. For instance, hydrological, climate, and weather models rely on LWIR LSE for determining the surface radiation budget (Immerzeel and Droogers, 2008; Zhou et al., 2003). In addition, retrieval of land surface temperature (LST) (Becker and Li, 1990; Li et al., 2013b; Rozenstein et al., 2014a; Wan and Dozier, 1996), monitoring land-use and land-cover change (French et al., 2008; Hulley et al., 2014), dust and aerosol properties (Li et al., 2007; Zhang et al., 2006), atmospheric water vapor content (Seemann et al., 2008), and trace gas content (Clerbaux et al., 2003) are all sensitive to the accuracy of LSE estimations.

In recent years, emphasis has been placed on the study of the temporal variations of LSE. The LSE derived from polar-orbiting satellites, having a revisit time of the same area of twice a day at best, can only reveal weather related LSE variations (Ogawa et al., 2008), while the diurnal dynamics are under-sampled (Li et al., 2012). Consequently, geostationary satellites with high-temporal resolutions are used to observe the diurnal dynamics of LSE. Previous studies analyzed images derived by the geostationary Spinning Enhanced Visible and InfraRed Imager (SEVIRI) and reported strong diurnal dynamics over deserts, especially for the 8.7 μm channel (Li et al., 2012; Masiello et al., 2013, 2014; Masiello and Serio, 2013), where emissivity in quartz reststrahlen bands is attenuated as soil moisture increases (Salisbury and D'Aria, 1992). These observations were explained by the diurnal soil moisture cycle resulting from direct water vapor adsorption by the soil throughout the late afternoon and night and the consequent evaporation over the following morning (Agam and Berliner, 2004).

Many desert surfaces worldwide are covered by biocrusts, composed of microphytes and soil granules that play a prominent role in hydrological cycles (Belnap, 2006). Biocrusts formation is a successional process, generally beginning with the primary colonization of the surface by filamentous cyanobacteria (Rozenstein et al., 2014b), followed by more photoautotrophic organisms. Thus, as biocrusts develop, the make-up of these microphytic communities evolves into diverse compositions of cyanobacteria, lichens, mosses, green algae, microfungi, and bacteria (Belnap and Lange, 2001; Karnieli et al., 1996). Biocrusts change the topsoil texture significantly by incorporating fine soil particles found *in-situ* and captured from dust into their structure (Danin and Ganor, 1991; Ram and Aaron, 2007; Zaady and Offer, 2010). The amount of water adsorbed by the soil increases with the clay content, since clay particles have a larger surface area, *i.e.*, more adsorption sites, per a given soil volume (Agam and Berliner, 2006). Thus, the incorporation of clay particles by biocrusts increases their ability to both absorb dew and adsorb water vapor from the atmosphere, compared with bare sand. In addition to this, biocrusts contain pores, which effectively increase their surface area and, thus, increase their adsorption abilities (Felde et al., 2014). It has been found that dew plays a major role in biocrust development (Rao et al., 2009; Veste et al., 2001) and also that biocrust absorbs more dew than sand (Liu et al., 2006; Pan et al., 2010; Zhang et al., 2009).

The primary aim of this study was to quantify the diurnal variations in LSE, as detected from space, over bare *vs.* biocrusted sands and to explore the different dynamics between these two ecosystems.

2. Material and methods

2.1. Study area

The northeastern Sinai region is characterized by linear sand dunes advancing from west to east, split by the Israel–Egypt political border (Fig. 1) (Roskin et al., 2012). Both the pedology and the climate are identical between the dunes in the Negev Desert on the Israeli side of the border, and the dunes in Sinai, Egypt. However, the Sinai and Negev dune fields differ in the land-use policy implemented by the two countries. Following the Israel–Egypt peace agreements in 1982, the borderline was redrawn in its current location, preventing nomadic Bedouin tribes from passing through. Traditional pastoralist activities in the Negev Desert have, therefore, ceased, while in Sinai, grazing and wood gathering activities have continued (Karnieli and Tsoar, 1995; Tsoar et al., 2008). Biocrusts are very sensitive to disturbance by human activities, but this degradation is reversible, and once anthropogenic pressure ceases the biocrusts may recover (Belnap, 1990; Kuske et al., 2012). As a result of reduced pressure, the dunes in the Negev have been covered by biocrusts and, consequently, have stabilized (except for a small active portion on the dune crest). In contrast, the trampling of the sand surface by the nomadic herds in Sinai has prevented biocrust establishment, leaving the sands exposed and the dunes active and mobile.

The differences in land-use and, thus, land-cover on both sides of the border result in a brightness contrast observed in reflective remote sensing images (Tsoar and Karnieli, 1996). This phenomenon, which can be seen from the air and from space, is caused by the higher albedo of the bright bare sand dunes in Sinai relative to the dark encrusted dunes of the Negev. Respectively, the darker surface of the Negev absorbs more sun irradiance during the day than the bright surface of Sinai resulting with the encrusted sands being warmer than the bare sands by up to 4 °C during the dry summer (Karnieli and Dall'Olmo, 2003; Qin et al., 2002a). This LST contrast between the two sides of the border is apparent in spaceborne images (Karnieli and Dall'Olmo, 2003; Qin et al., 2002a). At night, this temperature contrast subsides (Qin et al., 2002a); however, the LSE contrast across the border is evident during both daytime and nighttime (Rozenstein and Karnieli, 2015).

2.2. Climatological and meteorological conditions

The climate in the study area is characterized by an average air temperature ranging from 9 °C in January to 27 °C in August. A sharp north–south rainfall gradient stretches along a 30 km length where the border intersects the dune field. Typically, the southern area (away from the Mediterranean Sea) receives less than 100 mm of precipitation, whereas more than 140 mm may fall in the northern region (close to the shoreline) (Siegal et al., 2013). Meteorological conditions were monitored using a standard meteorological station located at the crest of a dune on the Israeli side of the border within the study area. Air temperature and relative humidity during the summer months, measured with a model HMP50 sensor (Campbell Scientific, Logan, Utah, USA), were characterized by high fluctuations between day and night (Fig. 2A). Wind speed and direction were measured with a model 03002 R.M. Young Wind Sentry sensor (Campbell Scientific, Logan, Utah, USA). The prevailing wind direction was primarily northwestern, and to a lesser extent, northern (Fig. 2B). Note that Fig. 2 presents a mean day created by averaging the variables over June and July 2013. The stronger afternoon wind, due to the sea breeze phenomenon, carrying moisture from the Mediterranean Sea inland, was the main source of moisture uptake by the soil during the dry