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Satellite observations of the land surface emissivity in the 8–12 µm window: effect of soil moisture

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Abstract Monthly and 8-day composites of thermal infrared (TIR) surface emissivity data from the MODerate resolution Imaging Spectrometer (MODIS) sensor on NASA's Terra satellite were analysed for temporal variations over North Africa. It was found that the emissivity of the 8.55 µm band (MODIS band 29) increased by about 0.1 each July/August in the southwestern Sahara (19°N, 3°W). To understand this increase, the emissivity variation was compared with the normalized difference vegetation index (NDVI) also derived from MODIS, with soil moisture estimates from the Advanced Microwave Scanning Radiometer (AMSR-E) microwave sensor on NASA's Aqua satellite and with ground measures of soil moisture. No correspondence was found with NDVI in this area. However, the TIR emissivity increase was found to be qualitatively correlated with an increase in the AMSR derived soil moisture. This increase in TIR emissivity with soil moisture is in agreement with the laboratory measurements.

Key words AMSR; emissivity; Mali; MODIS; soil moisture; thermal infrared

INTRODUCTION

The land surface emissivity is often overlooked when considering surface properties that affect the energy balance. However, knowledge of the emissivity in the window region is important for determining the longwave radiation balance and it subsequent effect on surface temperature. The longwave radiation balance is strongly affected by the difference between the temperature of the emitting surface and the sky brightness temperature, this difference will be greatest in the window region. The emissivity variability is typically greatest in arid regions where the exposed soil and rock surfaces display the widest range of emissivity. For example, the dune regions of the Sahara have emissivities of 0.7 or less in the 8 to 9 µm wavelength region due to the quartz sands of the region. Sensitivity studies by Zhou *et al.* (2003) using the Community Land Model have shown that a 0.1 decrease in emissivity can cause about a 1°C increase in surface temperature. Emissivity decreases of this magnitude are observed over the arid regions of North Africa and the Arabian Peninsula.

The multispectral thermal infrared data obtained from MODerate resolution Imaging Spectrometer (MODIS) sensor on NASA's Terra satellite have been shown to be of good quality and provide a unique new tool for studying the emissivity of the land surface. Two years of monthly composites of thermal infrared (TIR) surface emissivity data from MODIS were analysed for temporal variations over a site in Mali, North Africa, 19°N, 3°W, (Fig. 1). It was found that the emissivity of the 8.55 μm band (MODIS band 29) increased by about 0.1 at this site each July/August. To understand this increase, the emissivity variation was compared with the normalized difference vegetation index (NDVI) also derived from MODIS and with soil moisture estimates from the Advanced Microwave Scanning Radiometer (AMSR-E) microwave sensor on NASA's Aqua satellite. As seen in Fig. 1, no correspondence was found with NDVI in this area. However the TIR emissivity increase was found to be qualitatively correlated with an increase in AMSR derived soil moisture at this location. This increase in TIR emissivity with soil moisture is in agreement with the lab measurements (Salisbury & d'Aria, 1992). As at visible wavelengths, they found that the reflectivity decreases (emissivity increases) as the soil gets wet.

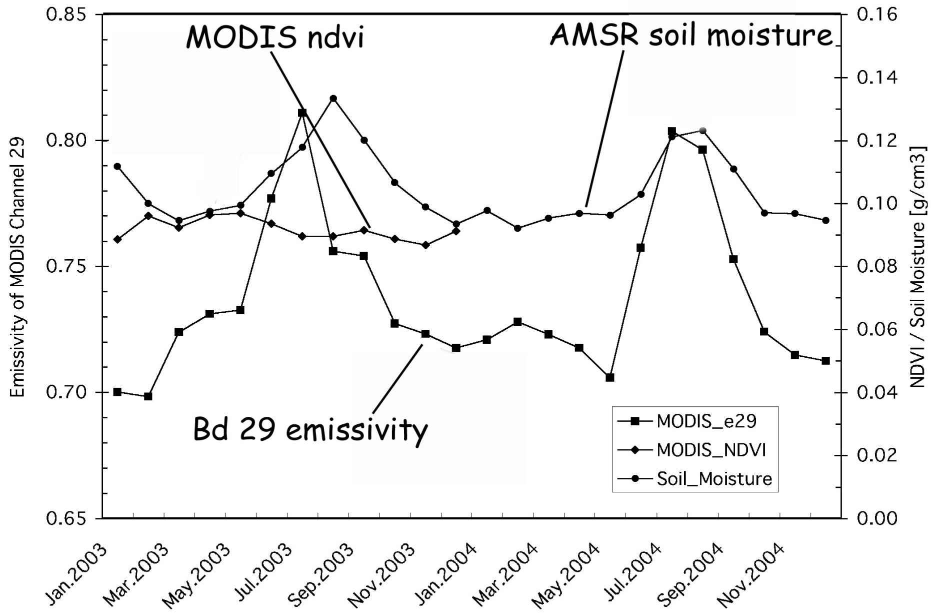

Fig. 1 Comparison of monthly composites of MODIS band 29 (8.55 μm) emissivity with soil moisture and NDVI for a 2 year period for a location in Mali at 19°N, 3°W.

The soil moisture dependence was studied further with ground data from the African Monsoon Multidisciplinary Analysis (AMMA) site in Mali (15–18°N and 1–2°W) (Fig. 2). This site will be ground validation site for the Soil Moisture and Ocean Salinity (SMOS) satellite to be launched in 2008.

MODIS EMISSIVITIES

The MODIS sensor is a cross track scanner (±55°) that collects radiance measurements in 36 bands designed for land applications. The nadir spatial resolution ranges from 250 m for 2 bands in the visible to a 1 km for the TIR bands. The swath is 2330 km. As a consequence of this wide swath capability, the sensor provides almost global coverage twice a day (ascending and descending orbits), thus enabling the use of day/night pairs of observations to extract the emissivity. MODIS is on NASA's Terra spacecraft which was launched in December 1999 and has a nominal 10:30 AM equator crossing time. It is also on the Aqua spacecraft with an early afternoon crossing time. We will use only the data from the Terra instrument.

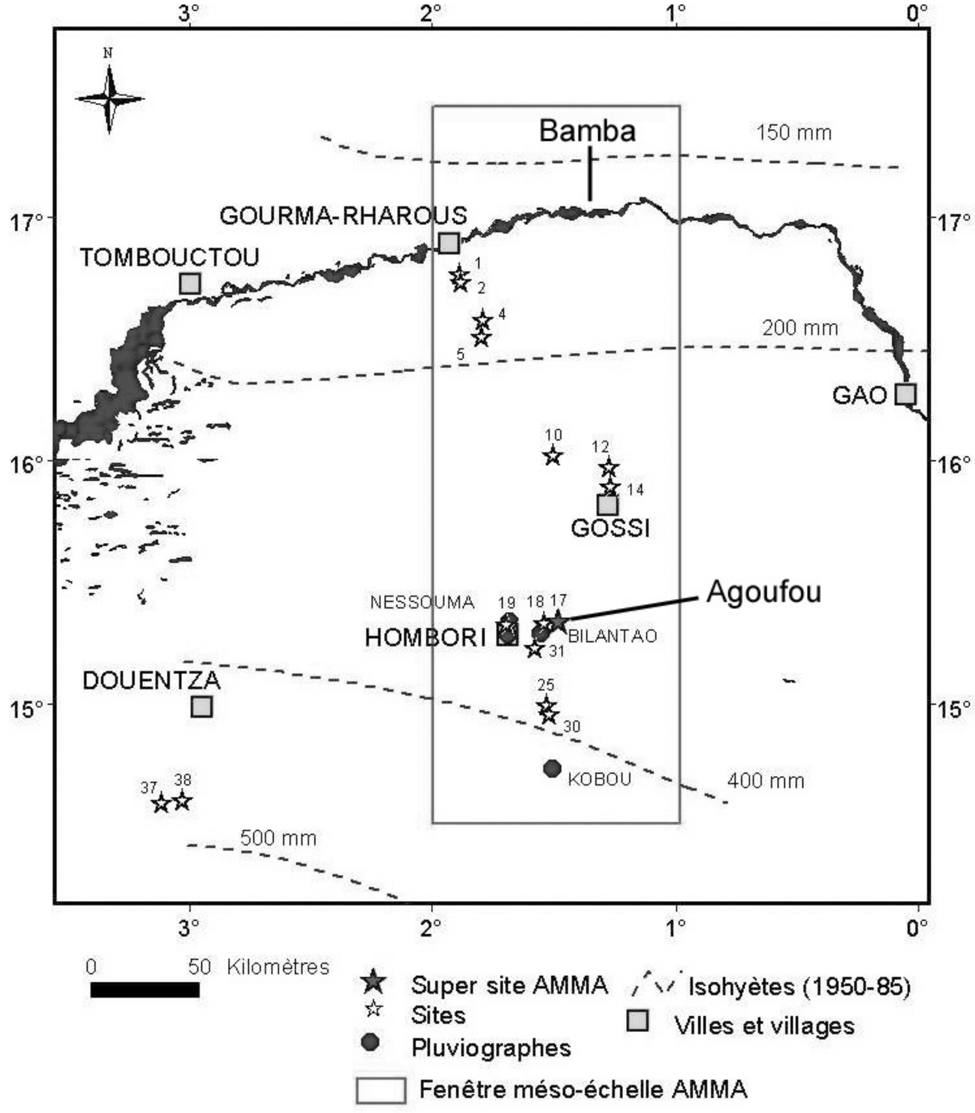

Fig. 2 The AMMA site in Mali showing the locations of the Agoufou and Bamba soil moisture sites.

Emissivity values are extracted from the MODIS TIR data using day/night pairs of images for the following 7 bands: 20 (3.660–3.840 µm), 22 (3.929–3.989 µm), 23 (4.020–4.080 µm), 29 (8.400–8.700 µm), 31 (10.780–11.280 µm), 32 (11.770–12.270 µm), and 33 (13.185–13.485 µm). From these 14 pieces of data the following parameters are extracted: 7 emissivities, 2 surface temperatures, 2 air temperature values, 2 water vapour values and a shortwave reflectance parameter; see Wan & Li (1997) or Wan *et al.* (2002) for details on the algorithm. The results are available as

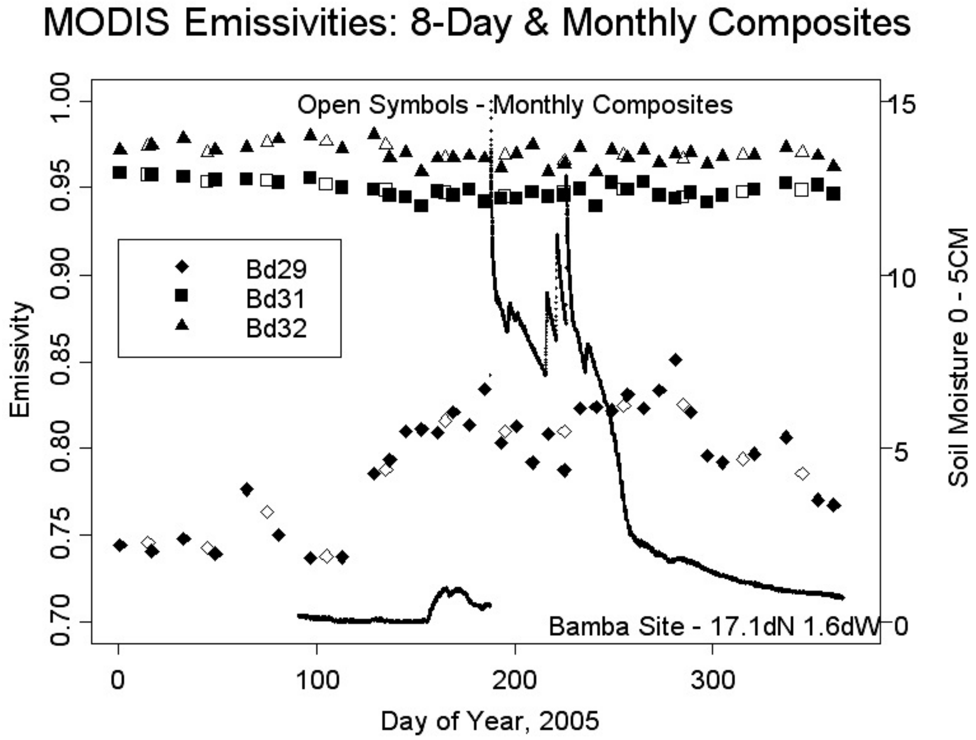

Fig. 3 Emissivity and soil moisture results for the Bamba, Mali site. The results are for bands 29, 31 and 32 of MODIS whose central wavelengths are 8.55, 11.03 and 12.02 µm. The soil moisture values are for the 0–5 cm soil layer. Note the longitude given in the figure is wrong, it should be 1.3 W.

8-day and monthly composites globally at 5 km resolution. In this analysis we have used the results from bands 29, 31 and 32 only. The results from 2005 for two sites in Mali are presented in Figs 3 and 4.

SOIL MOISTURE MEASUREMENTS

Unfortunately ground measurements of soil moisture are not available for the location presented in Fig. 1. However multi-scale soil moisture measurements were made nearby, at the Gourma meso scale site (Fig. 2) as part of the Enhanced Observing period of AMMA (de Rosnay *et al.*, 2006; Baup *et al.*, 2007). They are part of a complete land surface processes observing and modelling strategy which includes vegetation and meteorological field measurements as well as soil moisture remote sensing. The site is shown in Fig. 2. Data from the Agoufou and Bamba sites will be used in this analysis. The soil moisture measurements were made with the Campbell CS616 Theta probes. The probes were at several depths ranging from 5 cm to more than 2 m. The generic calibration relations given by Campbell are adjusted by local gravimetric measurements to compensate for soil differences. We will only use the data from the surface-5 cm probe for comparison with the TIR emissivity. The results for the 0–5 cm layer are also presented in Figs 3 and 4.

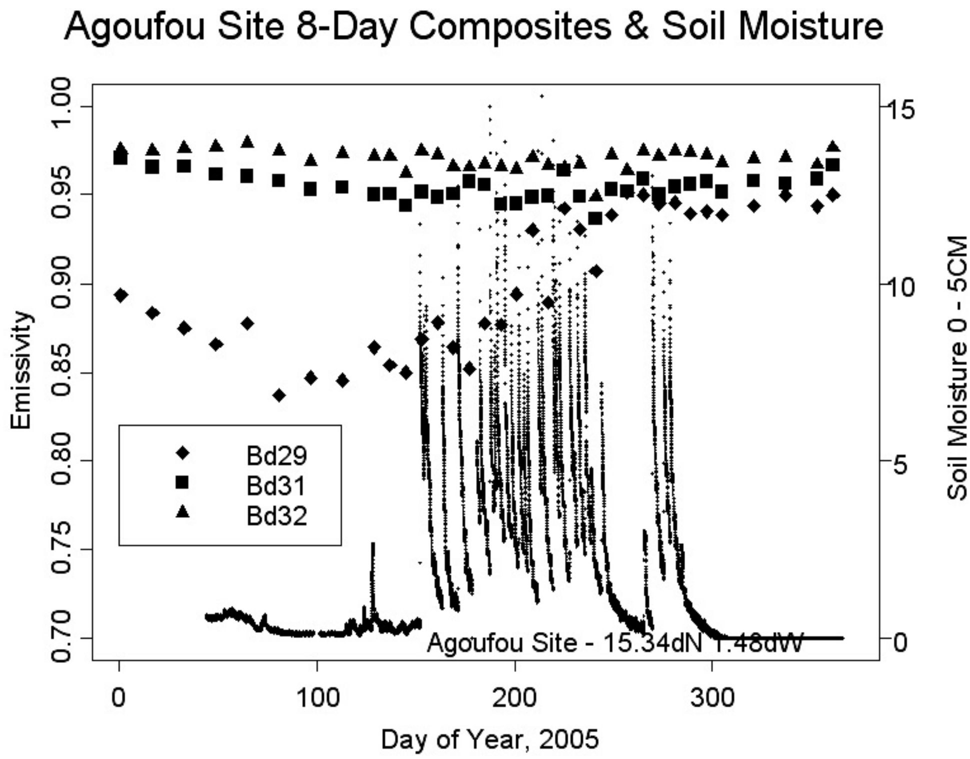

Fig. 4 Emissivity and soil moisture results for the Agoufou, Mali site.

RESULTS AND DISCUSSION

Figure 3 presents the results for the Bamba site which is the more arid of the two sites and has much less vegetation cover. The emissivity values are 8-day composites for the entire year 2005. The monthly composite values are also presented for comparison and are seen to agree very well. The 8-day composites were used in the hope of observing the short-term variations. The lowest values of the band 29 emissivity, 0.75, are about what is expected for a bare sand landscape. The band 29 emissivity does increase with increased soil moisture. However the rise in emissivity occurs before the increase in 0–5 cm soil moisture. It may be due to light rains which only wet the surface and do not increase the observed soil moisture. The emissivity of the two longer wavelength bands are also about what is expected for sand with the longer of the two, band 32, having a slightly higher emissivity. Also this emissivity difference does not go to zero as would be expected if there were significant vegetation cover.

The results for the more vegetated site, Agoufou, are presented in Fig. 4. In this case it is clear that there is an increase in the band 29 emissivity after the rains begin on about day 170. This increase is probably due to the combination of increased soil moisture and vegetation cover. By about day 300, after the rains had ceased, the emissivity of band 29 had increased to the level of that for bands 31 and 32. Also the difference between the emissivity of the two longer wavelength bands has decreased. This is consistent with what would be expected for a vegetated surface. The next step in our analysis will be to compare the emissivity variations with vegetation indices derived from MODIS data for these two sites.

The results shown in Figs 3 and 4 do not clearly demonstrate the soil moisture effect on the TIR emissivity. However, they do indicate that whatever the direct cause of the emissivity increase is, it is related to moisture changes. The TIR emissivity will be affected by the moisture in the surface layer of the soil, which stays wet for only a brief period following a rain event. Therefore it is somewhat surprising to us that we are able to observe any moisture effect on emissivity. For the MODIS sensor to observe the surface we would need clear sky conditions, in which case the moisture in the surface layer would rapidly evaporate under these arid conditions. So this paper is more of a status report on a problem being studied rather than a conclusive answer.

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