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Influence of the soil moisture effect on the thermal infrared emissivity

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Abstract

The influence of soil moisture in thermal infrared emissivity is a known fact, but poorly studied in the past. An experiment for quantifying the dependence of emissivity on soil moisture has been designed. Six samples of superficial horizons of different Mediterranean soil types have been selected. Their emissivity has been measured at different soil water contents, using the two-lid variant of the box method, whereas the gravimetric method has been selected for obtaining the soil moisture. As a result, the study shows that emissivity increases significantly when water content becomes higher, especially in sandy soils in the 8.2-9.2 μm range. A set of equations has been derived to obtain emissivity from soil moisture at different spectral bands for the analysed soil types.

1 Introduction

Ground temperature is an input parameter in meteorological and climatological studies as well as in hydrological and agricultural analysis. However, the emissivity of natural surfaces is a required magnitude for the determination of temperature from thermal infrared (TIR) radiance measurements. If the first one is not well determined, it can involve a significant error in obtaining the second one. An uncertainty in emissivity of 1% may lead to an error in temperature of approximately 0.5 K when the surface temperature is near 300 K and when the atmospheric effect is not considered (Sobrino and Caselles, 1989). For the mentioned reason, it is necessary to study the factors that influence emissivity, since it must be estimated with the highest accuracy as possible.

The soil type influence on emissivity is well-known from experimental studies (Salisbury and D'Aria, 1992). However, the analysis of the variation of TIR emissivity with soil moisture (SM) is one of the pending issues in thermal remote sensing. There are scarce studies concerning this topic, mainly in the experimental domain (Van Bavel and Hillel, 1976; Chen et al., 1989; Urai et al., 1997; Xiao et al., 2003; Ogawa et al., 2006).The SM dependence must be taken into account in emissivity retrievals from satellite data observations, since the SM increase causes a high systematic error in this parameter, e.g. about +0.1 for an increase from 0.04 to 0.10 g cm^{-3} in SM (Ogawa et al., 2006) for sandy soils.

Nevertheless, in the microwave region there are several theoretical (Galantowicz et al., 2000) and also experimental (Alex and Behari, 1998; Jackson et al., 1999; Burke and Simmonds, 2003) studies about the emissivity variation with SM. In this region, this variation is much more significant than in the thermal infrared. The microwave emissivity measurements by passive radiometry are, in fact, the basis of one of the synoptic measurement methods of soil moisture in remote sensing (Martín-Neira and Goutoule, 1997).

The main objective of our research is to improve the description of the soil TIR emissivity variation with SM. This will allow us to estimate more accurate emissivity values from space using the SM estimates, provided by future sensors such as the MIRAS instrument of the ESA's Soil Moisture and Ocean Salinity (SMOS) mission. In this paper, a set of equations are proposed to retrieve emissivity as a function of SM at different spectral bands for the analysed soil types.

Some details of the experiment setup both for emissivity measurement and for SM measurement, and the soils description are shown in Section 2. The results and discussion of this experiment are analysed in Section 3. Finally, conclusions are given in Section 4.

Table 1. Physical and chemical soil properties. EC: electric conductivity; OM: organic matter; CEC: cationic exchange capacity; V: base saturation.

Sample name	A	B	C	D	E	F
Colour dry	5YR4/6	10YR8/1	10YR4/2	10YR6/2	10YR5/6	10YR5/4
Colour wet	7.5YR3/4	10YR7/2	10YR2/2	2.5Y4/2	10YR3/3	10YR5/3
pH (H_2O) 1:2.5	7.50 ± 0.04	9.28 ± 0.06	7.50 ± 0.10	7.7 ± 0.4	5.180 ± 0.010	8.2 ± 0.2
pH (KCl) 1:2.5	6.9 ± 0.3	8.79 ± 0.04	6.70 ± 0.07	7.1 ± 0.4	4.460 ± 0.010	7.70 ± 0.10
EC 1:5 (dS/m)	0.40 ± 0.12	0.040 ± 0.009	0.48 ± 0.10	0.58 ± 0.09	0.150 ± 0.010	0.20 ± 0.03
OM (%)	2.1 ± 0.3	< 0.1	8.9 ± 0.5	4.5 ± 0.4	1.50 ± 0.10	3.5 ± 0.4
$CaCO_3$ (%)	1.70 ± 0.10	< 0.1	24 ± 3	44 ± 6	0	46 ± 8
CEC ($cmol_c\ kg^{-1}$)	21.3 ± 1.7	0	35 ± 4	24 ± 3	9.8 ± 1.9	14.7 ± 1.4
V (%)	100	0	100	100	59 ± 6	100
Sand (%)	41 ± 3	99 ± 6	20.0 ± 1.0	14 ± 6	67 ± 4	50 ± 3
Silt (%)	28.0 ± 1.0	1.0 ± 1.0	43 ± 2	50 ± 8	20.0 ± 1.0	30 ± 2
Clay (%)	31 ± 2	0 ± 0	37 ± 3	35 ± 4	13.0 ± 1.0	20.0 ± 1.0
Texture (USDA)	Clay Loam	Sand	Silty Clay Loam	Silty Clay Loam	Sandy Loam	Loam

2 Experiment setup

2.1 Soils description

A variety of samples of superficial horizons (0-15 cm) of different Mediterranean soil types has been selected for this experiment. The variation of TIR emissivity with SM has been studied according to different soil textures (i.e. particle size). Parameters such as texture, porosity, structure, among others, are responsible of this variation.

Firstly, each sample has been characterized by its physical and chemical soil properties (Table 1) related to soil texture, colour, organic matter content (OM), total carbonates, soil reaction (pH), electric conductivity (EC), cationic exchange capacity (CEC) and base saturation (V). The soil texture was fixed according to the standard ISO 11277:1998 (ISO, 2002), based on breaking and sedimentation mechanical techniques.

Secondly, the taxonomic class of the soils and its diagnostic horizons have been identified according to FAO-ISRIC-SICS (1999) and Soil Taxonomy (USDA, 1999) classifications (Table 2). All the samples belong to a Mediterranean climate, except sample E that belongs to an Atlantic climate.

Thirdly, the identification of clay minerals of all samples was determined by means of the X-ray diffraction (XRD) technique since it is always considered to be one of the fastest procedures. According to this semi quantitative analysis shown in Table 3, quartz is the predominant mineral on samples A, B and E, whereas calcite is the main mineral on samples C, D and F. The result is important since quartz contributes to increase the reflectance of the material between 7.7 and 9.7 μm as well as near 12.6 μm. This means an emissivity decrease in those spectral regions.

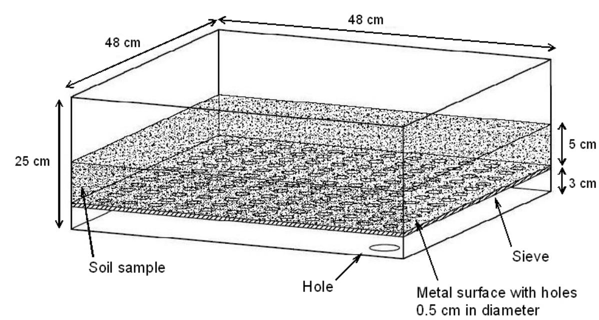

Figure 1. Glass container for keeping the samples and allowing an easy measurement of emissivities, as well as the water drainage.

2.2 Soil moisture measurement

The first step in the measurement strategy was to grind and blend each sample before allowing it to be air-dried, and to sieve it into 2 mm. Then, it was flooded allowing the water filtration through the recipient that contains the soil. Since that moment, it was freely dried.

For this purpose, a glass container (Figure 1) with dimensions 48 x 48 x 25 cm^3 was designed for allowing the water drainage and its later die-cast. The sample was kept over a metal drilling surface which was elevated some centimetres upon the receptacle base. Moreover, a sheet sieve was put on the metal surface to avoid the loss of the finest particles.

The gravimetric method was chosen for measuring the SM since this is the most accurate technique. It is based on the direct determination of the soil water content (Day, 1965). The main limitation is that it is a laborious and destructive method since small amounts of soil are removed from the total sample when SM measurements are done. This fact has prevented to take measurements very frequently. Furthermore, the feasibility of the measurements

Table 2. Taxonomic class of the soils and its diagnostic horizons.

Sample name	FAO-ISRIC-SICS (1999)	Soil Taxonomy (USDA, 1999)	Diagnostic horizons
A	luvic Calcisol	Rhodoxeralf	Irragric
B	albic Arenosol	Xeropsamment	Antropic
C	calcic Kastanozem	Calcixeroll	Mollic
D	gleyic-calcaric Fluvisol	Fluvaquent	Antraquic
E	dystric Cambisol	Dystrudept	Cambic
F	petric Calcisol	Petrocalcid	Ocric

Table 3. Semi quantitative analysis of the minerals identified by XRD technique.

Mineral	Quantity (%)					
Quartz	82	96	29	19	74	20
Feldspar	5	4	6	4	22	4
Filosilicate	5	-	9	6	4	4
Calcite	3	-	56	62	-	63
Hematite	5	-	-	9	-	9
Sample name	A	B	C	D	E	F

depends on the spatial variability of the soil moisture since not the whole sample becomes dry at the same time. That is the reason why an adequate sampling has been done for each water content measurement. Three soil samples for the analysis of water content were taken during each series of emissivity measurement in order to minimize the error of SM value.

The SM content is expressed by weight (wt) as the ratio of the mass of water present to the dry weight of the soil sample, or by volume as ratio of volume of water to the total volume of the soil sample. Following the gravimetric method, to determine any of these ratios for a particular soil sample, the water mass must be determined by drying the soil to constant weight and measuring the soil sample mass after and before drying. The water mass (or weight) is the difference between the weights of the wet and dry samples. The criterion for a dry soil sample is the soil sample that has been dried to constant weight in oven at temperature between 100-110°C (105°C is typical). Finally, the moisture content is calculated using the equation:

$$\Theta_d = \frac{wt_w - wt_d}{wt_d} \tag{1}$$

where:

- wt_w: wt of wet soil.
- wt_d: wt of dry soil.

Different techniques have been used to assure the homogeneity of the samples in terms of composition, texture and moisture, such as mixing the sample content or grinding up the soil. Furthermore, the soil cracks appeared in the drying process have been eliminated when necessary. Moreover, the sequence of soil saturation and drying were repeated at least twice in order to ensure the validity and reproducibility of emissivity measurements.

2.3 Emissivity measurement

The emissivities were determined through the two-lid variant of the box method (Rubio et al., 1997) and using a CIMEL CE 312 thermal infrared radiometer (Legrand et al., 2000). It has four spectral channels: one broad, 8-14 μm (channel 1), and three narrow channels, 8.2-9.2, 10.5-11.5, 11.5-12.5 μm (channels 4, 3, and 2 respectively). The radiometer has a field of view of 10°, a response time of 1 s, and accuracies of ±0.10 K for each channel.

The box that has been used is a bottomless box, with a base of 30 x 30 cm^2 and a height of 80 cm. The side walls are specular reflective surfaces of polished aluminium with an emissivity of ε_c = 0.03. Two interchangeable lids with different spectral responses, each having a small central hole through which the radiometric measurements are taken, are used as a top. The *hot lid* is a cover of rough anodized aluminium painted in Parson's black with an emissivity value of ε_h = 0.98 maintained at a temperature 15-20°C above sample's temperature by means of an electric heating system. The *cold lid* is a specular reflective cover of polished aluminium, with an emissivity value of ε_c = 0.03.

In the two-lid method, three measurements of radiance are performed with three different configurations of the box-sample system, which are shown in Figure 2. Moreover, a fourth measurement (L^4) has been carried out in order to quantify the effect of a non-ideal box. In this way, the method gives the emissivity value of a ground sample by the expression (Rubio et al., 1997):

$$\varepsilon = 1 - \frac{(L^1 - L^2)(1 - \varepsilon_c)}{(L^3 - L^2) - (L^3 - L^1)P + (L^2 - L^4)Q} \tag{2}$$

where:

- ε_c = 0.03
- ε_h = 0.98
- $P = F^2(1\text{-}\varepsilon_c)(1\text{-}\varepsilon_h)$
- $Q = 1\text{-}F^2(1\text{-}\varepsilon_c)^2$
- F = 0.8674

Table 4. Maximum emissivity variation within the whole soil moisture range ($\Delta\varepsilon_i \pm \delta\Delta\varepsilon_i$), and average emissivity measurement errors ($\overline{\delta\varepsilon_i}$), for each sample at the different CE$\tilde{3}$12 channels.

Sample	$\Delta\varepsilon_1 \pm \delta(\Delta\varepsilon_1)$	$\Delta\varepsilon_2 \pm \delta(\Delta\varepsilon_2)$	$\Delta\varepsilon_3 \pm \delta(\Delta\varepsilon_3)$	$\Delta\varepsilon_4 \pm \delta(\Delta\varepsilon_4)$	$\overline{\delta\varepsilon_1}$	$\overline{\delta\varepsilon_2}$	$\overline{\delta\varepsilon_3}$	$\overline{\delta\varepsilon_4}$
A	0.029±0.008	0.024±0.007	0.017±0.009	0.036±0.009	0.003	0.005	0.004	0.004
B	0.074±0.018	0.046±0.007	0.036±0.007	0.16±0.02	0.006	0.004	0.004	0.009
C	0.060±0.007	0.050±0.009	0.058±0.006	0.055±0.010	0.004	0.005	0.006	0.006
D	0.031±0.006	0.031±0.009	0.029±0.010	0.041±0.011	0.004	0.004	0.004	0.005
E	0.034±0.004	0.027±0.006	0.032±0.006	0.046±0.010	0.003	0.004	0.004	0.005
F	0.023±0.005	0.030±0.008	0.028±0.008	0.037±0.007	0.003	0.005	0.004	0.005

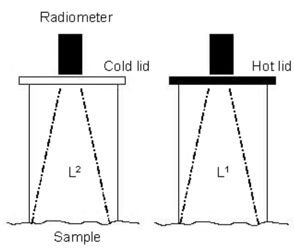

Figure 2. Procedure followed for the emissivity measurement with the two-lid variant of the box method. L^4 belongs to an additional measurement when the box is not considered ideal. The sequence of field measurements is from left to right (i.e., L^2, L^1, L^3 and L^4).

Following Rubio et al. (1997), F is an energy transference factor that depends on the geometry of the box and on ε_c, and represents the proportion of energy from the base (top) that reaches the top (base). Meanwhile, P and Q are constant values dependent of F, and L^i (with i = 1, 2, 3, 4) are the values of the effective radiance (mW cm^{-2} sr^{-1} cm)measured with the radiometer through the small opening.

According to this method above-mentioned, a set of 30 emissivity measurements per channel and sample was carried out with the purpose of obtaining a good statistic and reducing the error. Note that if you consider that each emissivity measurement is obtained from four radiance measurements (L^i; i = 1, 2, 3, 4), a total of 120 individual measurements are required for inferring a unique emissivity value for each channel and each sample.

3 Results and discussion

In relation to the SM, an exceptional value of the highest SM value is obtained for calcic Kastanozem (sample C). Probably the main cause of this high value is the wealth of organic matter (OM) content of this soil. Table 1 shows that OM content of sample C is fourfold the average OM content of the other samples. Although OM is generally a minor component of soils, it is the principal storage of plant available water due to the high percentage of water-stable

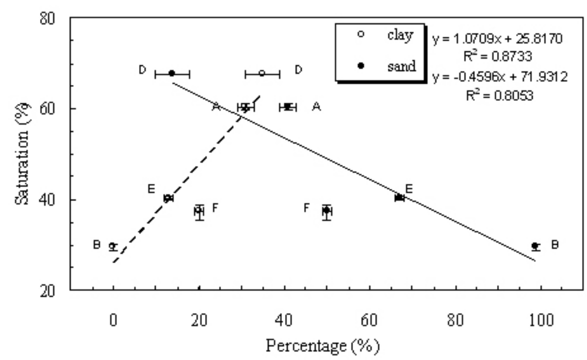

Figure 3. Relationship between sand content and saturation point of each soil sampled, except for sample C taken into account its particular behaviour due to its high OM content.

aggregates. For this reason, soils with a high OM content have a different behaviour than the others regarding the retained water. The rest of samples show an accused trend to decrease their saturation point value with increasing sand content, as can be seen in Figure 3. Saturation point values were obtained in the laboratory (Porta, 1986) following the gravimetric method, with the purpose of checking this relationship. This is a consistent result since the soil matrix retains water by two mechanisms: first, water can be absorbed on particle surfaces (especially clay particles due to their reactive large surface area); and second, water can be held in soil pores by capillarity. Water is held more tightly in smaller than in larger pores. Therefore, clay soils retain more water and for longer time than sandy soils.

Experimental results of the dependence of the TIR emissivity on SM for each spectral channel of CE$\tilde{3}$12 are shown in Figure 4. In all cases an increase of emissivity with SM is observed. Table 4 compares the emissivity increase to the measurement errors, resulting that the increase is clearly larger than the experimental uncertainty. According to values of Table 4, the mean error of emissivity is about ±0.5%. Note that the emissivity error is derived as the standard deviation of the set of 30 emissivity measurements taken each time.

The highest variation of emissivity with soil moisture is observed in the 8.2-9.2 μm on channel 4, followed by

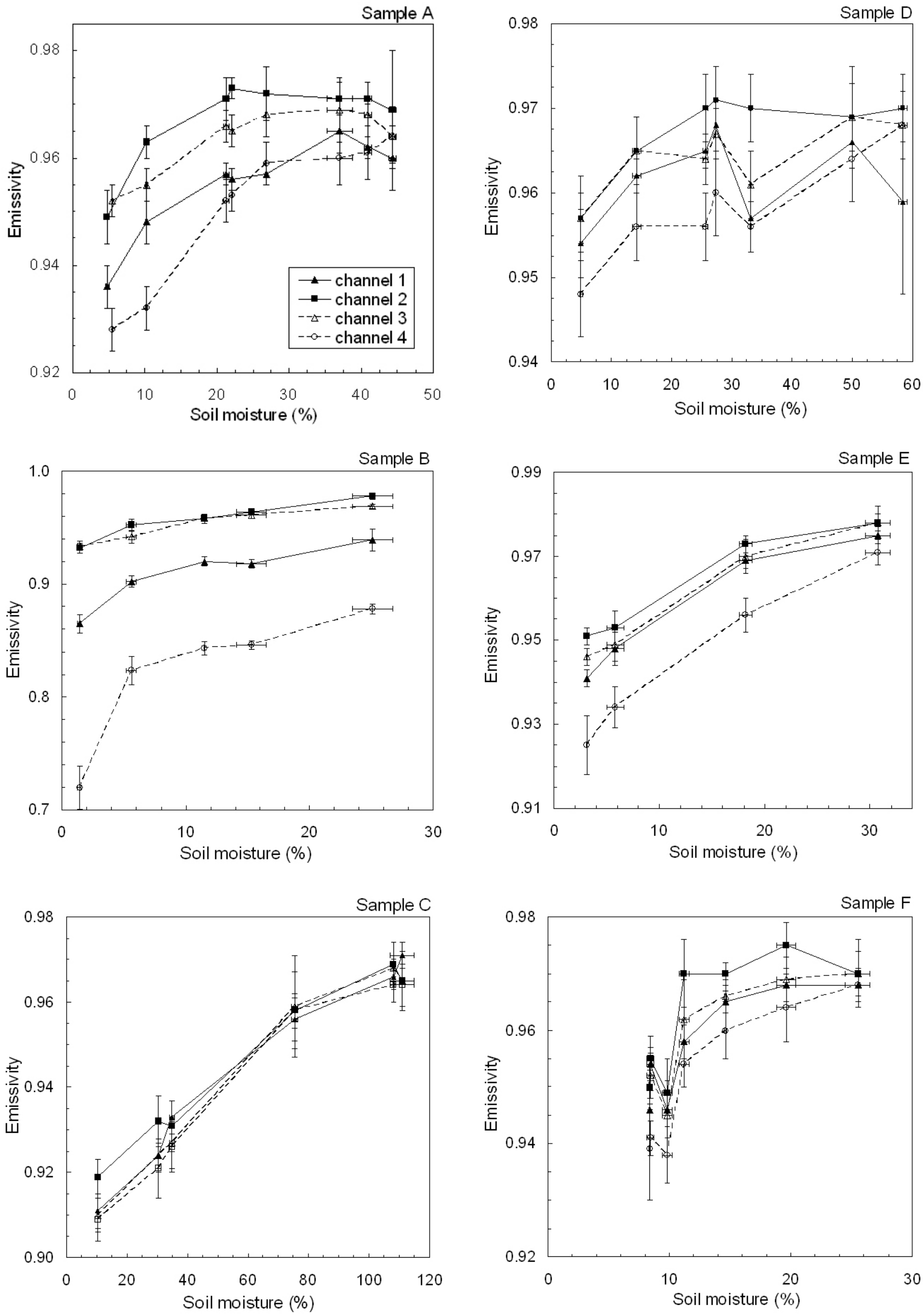

Figure 4. Measured emissivity of soils sampled in the spectral channels of thermal infrared radiometer CE 312 for various moisture contents.

Table 5. Fitting regression of emissivity against soil water content for each channel and sample. ε: emissivity; Θ_d: soil water content; R^2: determination coefficient; σ_f: fit standard error.

		$\varepsilon_i = a \cdot \Theta_d^2 + b \cdot \Theta_d + c$				
Sample name	**Channel**	a x 10^{-3}	b x 10^{-2}	c	R^2	σ_f
A	1	-0.024	0.18	0.930	0.953	0.002
	2	-0.034	0.21	0.942	0.946	0.002
	3	-0.024	0.16	0.943	0.971	0.0013
	4	-0.029	0.24	0.914	0.978	0.002
B	1	-0.13	0.6	0.862	0.931	0.010
	2	-0.05	0.3	0.931	0.954	0.005
	3	-0.059	0.31	0.928	0.990	0.002
	4	-0.4	1.5	0.72	0.878	0.03
C	1	-0.0031	0.10	0.901	0.991	0.003
	2	-0.0025	0.08	0.910	0.986	0.003
	3	-0.004	0.11	0.897	0.988	0.003
	4	-0.004	0.11	0.895	0.985	0.004
D	1	-0.010	0.08	0.951	0.396	0.006
	2	-0.011	0.088	0.954	0.928	0.0016
	3	-0.003	0.03	0.957	0.586	0.003
	4	0.000	0.03	0.948	0.874	0.003
E	1	-0.05	0.291	0.9326	0.999	0.0003
	2	-0.038	0.23	0.943	0.989	0.002
	3	-0.034	0.23	0.938	0.995	0.0019
	4	-0.031	0.27	0.918	0.997	0.0019
F	1	-0.12	0.5	0.914	0.844	0.005
	2	-0.19	0.8	0.902	0.798	0.006
	3	-0.12	0.5	0.914	0.824	0.005
	4	-0.13	0.6	0.897	0.919	0.004

variations in channel 1 (8-13 μm), channel 2 (11.5-12.5 μm) and finally channel 3 (10.5-11.5 μm). This variability is more apparent in albic Arenosol, sample B ($\Delta\varepsilon_4 \sim 16\%$), and less marked in luvic Calcisol, sample A ($\Delta\varepsilon_3 \sim 1.7\%$).

An accused growth of emissivity for small water content is generally observed in Figure 4, and almost no changes are observed from a certain SM value on. According to experimental data extracted from Israelsen and Hansen (1962), this certain SM value could coincide with field capacity (FC) point whose value depends on the soil type. A soil is at FC when, after saturation, all water has been drained from macropores by gravity. Then, micropores are able to hold water against the force of gravity due to capillary forces. This argument allows understanding the behaviour of TIR emissivity in relation to soil moisture since when soil is saturated, or even with a SM higher than its FC point, its thermal emissivity value is not only nearly constant but also almost equal to one which is the emissivity of water. However, below FC point, water is retained in micropores allowing lower emissivity values as well as emissivity variation with SM content.

A quadratic fitting regression of emissivity against soil water content for each channel of CE 312 and sample has been derived for implementing them in future atmospheric and emissivity algorithms. In Table 5 the set of coefficients as well as the determination coefficient (R^2) and the fit standard error (σ_f) are shown for every case. These fitting curves are acceptable since their average determination coefficient is around 0.90 and the fit standard error gets a value around $\pm$ 0.5%. It is important to emphasize that sample D is the one which presents the worst adjustment as its low determination coefficients show. We think that this is due to the compacted texture that it got through the experiment and the subsequent roughness reached. Meanwhile, sample E shows the best adjustment since its mean value of R^2 is the highest and its mean σ_f value is the lowest.

4 Conclusions

This paper stresses the importance of an accurate determination of emissivity variation with soil water content to permit suitable retrievals of temperature, mainly for sandy soils.

Firstly, a set of six mineral soils has been used as a basis for studying the dependence of the TIR emissivity on SM from laboratory measurements. Each soil has a different soil texture and therefore different emissivity behaviours have been observed. However, a general trend to increase the emissivity with soil water content is common for every soil studied. The results show that emissivity variation is larger mainly in 8.2-9.2 μm range and lower in 10.3-11.3 μm range, following the sequence $\Delta\varepsilon_4$(8.2-9.2 μm) > $\Delta\varepsilon_1$(8-13 μm) > $\Delta\varepsilon_1$(11.5-12.5 μm)$\sim\Delta\varepsilon_3$(10.5-11.5 μm). Additionally, the spectral contrast decreases with increasing SM. Meanwhile, in the case of the classical split-window channels, this contrast is almost constant. The variation of emissivity is more obvious for albic Arenosol (sample B) with an increase by about 16% (which causes a systematic error of 8°C in temperature) because it is the soil with a higher sand content. The above-mentioned variation is significant since it is clearly larger than the experimental uncertainty ($\delta\varepsilon \sim \pm 0.5\%$), fact that can involve an important impact in the current methods of temperature estimation from radiometric data.

Secondly, a quadratic fitting regression of emissivity against soil water content for each channel and sample has been derived for implementing them in future atmospheric and emissivity correction algorithms. To sum up, this study proves that the emissivity variation with SM should be considered in atmospheric and emissivity correction algorithms to avoid significant land surface temperature systematic errors.

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