GeoInformation in Europe, M.A. Gomarsca (ed.)
 ISBN 9789059660618

Effects of the satellite spatial resolution on the surface energy fluxes retrieval. Application to the Basilicata region in Italy

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Keywords: spatial resolution, disaggregation, Landsat, MODIS

ABSTRACT: Remote sensing estimates of the surface energy balance, and daily evapotranspiration (LE_d) in particular, have become essential in recent studies on climatology, meteorology and hydrology. High spatial resolution satellites such as Landsat or ASTER provide surface information at pixel resolutions on the order or below 100 m, but the low frequency of repeated coverage limits the utility of these sensors in the routine monitoring of LE_d. Daily coverage is provided by regional to global sensors such as MODIS (1000 m) or METEOSAT (5000 m). However, most of the surface variability is lost at these coarse spatial resolutions. Recent studies have explored the possibility to estimate subpixel energy fluxes, at the spatial resolution of the sensor visible bands, to recover the mentioned surface variability. In this work, it has been firstly evaluated the loss of information in surface temperature variability with the degradation of the spatial resolution of a satellite image. Secondly, a disaggregation procedure to estimate subpixel surface temperatures has been applied at different spatial resolutions. Finally, a Simplified Two-Source Energy Balance (STSEB) model has been used to evaluate the effect of the disaggregation technique on the surface fluxes retrieval. Three satellite images of the Basilicata southern Italian region, Landsat7-ETM+, Landsat5-TM and MODIS Terra have been used. Three different targets were selected within each image in order to analyze the effect of the field size on the obtained results.

1 INTRODUCTION

Remote sensing estimates of the surface energy balance have become essential to determine the interaction between soil, vegetation and the atmosphere, not only for hydrological studies, but also for climatologic, meteorological and agronomical purposes. Besides, the provided information is very useful to agronomists to evaluate the effects of crop genotype and management practices to produce such a yield.

The remotely sensed surface temperature is the key input in most energy balance models. Therefore, the spatial resolution of the used sensor must be higher than the pattern size of the fields in order to avoid uncertainties in surface fluxes, associated with heterogeneous pixels.

Several works have used high spatial resolution data from Landsat or ASTER to retrieve surface fluxes at field scale (French *et al.* 2005). However, due to the long repeat cycle of these satellites (16 days) they are not appropriated for routine LE_d estimation. Others such as AVHRR, MODIS or METEOSAT, have a higher temporal resolution but a spatial resolution of 1 to 5 km, too coarse to discern individual fields.

Recent works have dealt with the effects of subpixel heterogeneity on the fluxes estimation. Using model simulations, Kustas & Norman (2000) showed unacceptable errors in two-source model predictions when there is a significant discontinuity in surface conditions. Kustas *et al.* (2004) studied the effect of sensor resolution on model output for an agricultural region in central Iowa using Landsat data. Results indicated that variation in fluxes between different crops is not feasible with an input resolution on the order of 1000 m. Taking advantage of the relationship between vegetation indices and radiometric surface temperature, Kustas *et al.* (2003) applied a disaggregation procedure to estimate subpixel variation in this temperature. Comparisons with actual observation showed the utility of this technique for estimating subpixel fluxes at resolutions corresponding to length scales defining agricultural field boundaries.

In this work will be explored the effect of the spatial resolution of the remotely sensed surface temperature and the aggregation techniques on the fluxes estimation using a Simplified Two-Sources Energy Balance (STSEB) model. For that, three satellite images with different thermal spatial resolutions, Landsat 5-TM (120 m), Landsat 7-ETM+ (60 m) and MODIS Terra (1000 m), corresponding to the Basilicata region (Southern Italy) will be used. The different landscapes will be characterized from the CORINE Land Cover land use maps and the required meteorological variables will be obtained by interpolating the data of forty meteorological stations distributed within the region.

This work is organized as follows. Section 2 shows an overview of the STSEB model used to retrieve the surface fluxes, as well as a summary of the disaggregation procedure to estimate subpixel surface temperatures. The experimental site and measurements are described in Section 3. Results and discussion are shown in Section 4. Finally, the conclusions are given in Section 5.

2 METHODOLOGY

2.1 *The STSEB model*

Sánchez *et al.* (2007) proposed a Simplified version of the Two-Source Energy Balance (STSEB) model to estimate surface fluxes over sparse canopies. The advantage of the STSEB is that it does not require any in situ calibration of an excess resistance formulation or any a priori assumption of canopy transpiration.

The net energy balance of soil-canopy-atmosphere system is given by:

$$R_n = H + LE + G \tag{1}$$

where R_n is the net radiation flux (W m^{-2}), H is the sensible heat flux (W m^{-2}) and G is the soil heat flux (W m^{-2}). The effective radiometric surface temperature in the same system, T_R (K), is the result of the composition of the soil temperature, T_s (K), and the canopy temperature, T_c (K):

$$T_R = [P_v T_c^4 + (1-P_v) T_s^4]^{1/4} \tag{2}$$

where P_v is the fractional vegetation cover. Eq. (2) will be used to estimate temperature components.

The sensible heat flux is given by the equation:

$$H = P_v H_c + (1-P_v) H_s \tag{3}$$

where H_c and H_s are the canopy and soil contributions, respectively, to H. They are expressed as:

$$H_c = \rho C_p \frac{T_c - T_a}{r_a^h} \tag{4a}$$

$$H_s = \rho C_p \frac{T_s - T_a}{r_a^a + r_a^s} \tag{4b}$$

where ρC_p is the volumetric heat capacity of air (J K^{-1}m^{-3}), T_a is the air temperature at a reference height (K), and r_a^h, r_a^a and r_a^s are the aerodynamic resistances to heat transfer between different levels (m s^{-1}). Details about how to estimate these resistances can be seen in Sánchez *et al.* (2007).

Net radiation is estimated trough the equation:

$$R_n = (1-\alpha)S + \varepsilon L_{sky} - \varepsilon \sigma T_R^4 \tag{5}$$

where S is the solar global radiation (W m^{-2}), α is the albedo, ε is the surface emissivity and σ is the Stefan-Boltzmann constant. L_{sky} is the incident long-wave radiation (W m^{-2}).

At a daily scale G can be neglected and, taking into account the relation between instantaneous ("i") and daily ("d") values of H and R_n (Itier and Riou 1982), LE_d can be obtained by the expression:

$$LE_d = \frac{R_{nd}}{R_{ni}} (R_{ni} - H_i) \tag{6}$$

where the rate R_{nd}/R_{ni} shows the relative net radiation contribution, at the considered time, when global radiative exchange is integrated.

2.2 *Disaggregation procedure for radiometric surface temperature (DisT$_R$)*

The relationship between vegetation indices and radiometric surface temperature has been commonly used by remote sensing-based energy balance schemes. In particular, Kustas *et al.* (2003) designed the following procedure to derive T_R at the NDVI pixel resolution. For a better understanding, the procedure scheme is presented applied to the Landsat5-TM particular case (NDVI with 30 m pixel resolution and T_R with 120 m pixel resolution).

Firstly, the original NDVI image at 30 m resolution ($NDVI_{30m}$) is aggregated to the spatial resolution of T_R to obtain a new NDVI image at 120 m resolution ($NDVI_{120m}$), for the considered case. These 120 m pixels are divided into three groups according to the NDVI value, namely, $0 < NDVI_{120m} < 0.2$, $0.2 < NDVI_{120m} < 0.5$, $NDVI_{120m} > 0.5$ and a subset of the most uniform pixels (lowest deviation computed among the 4×4 pixels that make up each $NDVI_{120m}$ pixel) is selected from each class. Then a fitting between these T_{R120m} and $NDVI_{120m}$ is performed trough the second order expression:

$$T'_{R120m} = a + b\mathrm{NDVI}_{120m} + c\mathrm{NDVI}^2_{120m} \tag{7}$$

For considering spatial variability due to soil moisture effects, a correction quantity ($\Delta T'_{R120m}$) is estimated by subtracting the results of applying Eq. (7) to the original values of T_{R120m}:

$$\Delta T'_{R120m} = T_{R120m} - T'_{R120m} \tag{8}$$

Finally, 30 m T_R (T_{R30m}) is computed via:

$$T_{R30m} = T'_{R30m} + \Delta T'_{R120m} \tag{9}$$

where T'_{R30m} is obtained using Eq. (7) with the previously estimated coefficients a, b, and c, but now with the original $NDVI_{30m}$ values. Regarding the correction term, $\Delta T'_{R120m}$, estimated at 120 m pixel resolution, it must be rescaled to 30 m pixel resolution by assuming the same value within the corresponding 4×4 pixels.

With this procedure, the thermal spatial resolution of the Landsat5-TM shows an increase of 75%, which can be very useful when working on areas with field lengths lower than 100 m. A similar increase can be observed by applying the disaggregation procedure to the MODIS images. In this case, the original surface temperatures, at 1 km pixel resolution, are rescaled to 250 m pixel resolution. This significant gain in surface temperature information expands the range of landscapes over which MODIS can be used to retrieve surface energy fluxes.

3 STUDY SITE AND MEASUREMENTS

This work is focused on the Basilicata southern Italian region. It has a total extension of 10045.4 km^2 and it is suitable for our study because of its large variety of landscapes. Three satellite images with different spatial resolution were selected, Landsat7-ETM+ (9/26/1999), Landsat5-TM (5/26/2004) and MODIS Terra (5/26/2004). For the Landsat images, all bands were corrected of atmospheric effects and NDVI was obtained from reflectivity in bands 3 and 4 (30 m) while T_R was estimated from band 6 (60 m and 120 m for ETM+ and TM, respectively) data using the mono-channel equation for the atmospheric and emissivity corrections. For the MODIS image, NDVI and T_R were taken directly from the MODIS11_L2 (1 km) and MOD13Q1 (250 m) products, respectively, provided by the EOS Data Gateway.

Maps of the meteorological variables required as inputs in the STSEB model were performed by the interpolation of the data registered in 40 meteorological stations distributed around the whole study area. Moreover, parameters such as vegetation height and leaf size were mapped from the land use map elaborated by the CORINE Land Cover 2000 project.

Vegetation cover and emissivity were obtained through the method described in Valor and Caselles (1996), while albedo values were estimated according to Starks *et al.* (1991).

With the aim of analyzing the influence of the length scale of the fields in the results, three targets (~14 km^2) were selected within the whole images (Figure 1):

– Fields about 100–250 m of side length.
– Fields about 250–500 m of side length.
– Forest area with a big homogeneity.

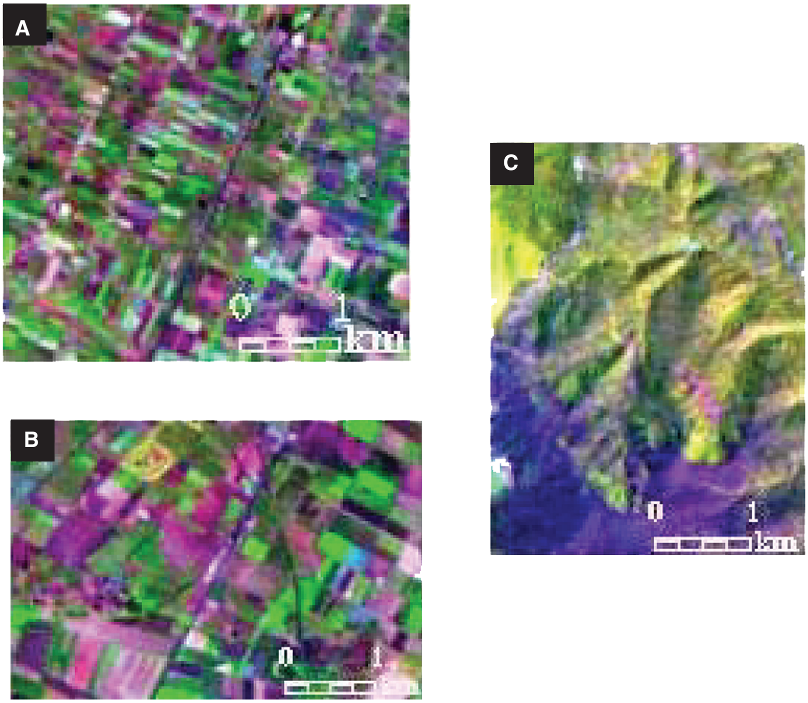

Figure 1. False color compositions (5,4,3) of the three selected targets, extracted from the Landsat5-TM image.

4 RESULTS AND DISCUSSION

As a first step, and following the line of Townshend & Justice (1988), a study of the loss of information in surface temperature variability with the degradation of the spatial resolution was made, taking the Landsat7-ETM+ image as a basis. For that, original radiometric surface temperature at 60 m pixel resolution was aggregated to simulate pixel resolutions of 120 (120), 240 (250), 480 (500), 1020 (1000), and 4980 (5000) m. Figure 2 shows the histograms of the differences between each simulated map and the original one at 60 m pixel resolution for the whole Basilicata region. As expected the standard deviation of the differences rise with the pixel resolution following a logarithmic tendency (see Table 1). According to these results, imposing a boundary in temperature accuracy, in any particular study, leads to a restriction in the spatial resolution of the used sensor.

A more exhaustive analysis of the previous differences is possible by isolating three targets with different field lengths. The standard deviations of the differences for each target are shown in Table 1. Firstly, it can be seen clearly that the lowest differences are for the forested target due to its thermal homogeneity. Furthermore, it is interesting to point out that the significant increasing of the standard deviation stops at 250 m pixel resolution

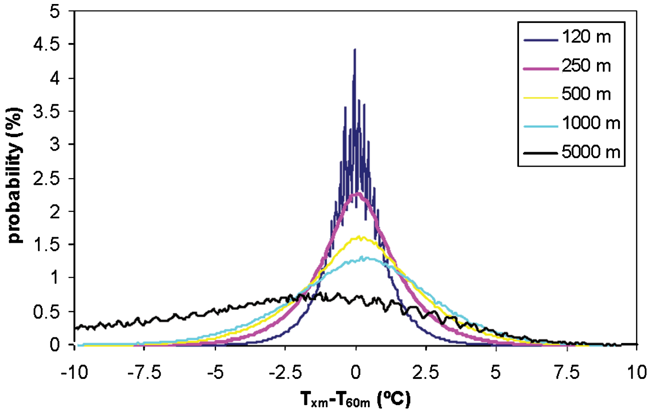

Figure 2. Histogram of the differences between surface temperatures degraded at "*x* m" pixel resolution (T_{xm}) and original one (T_{60m}) for the whole region and from the Landsat7-ETM+ image.

Table 1. Standard deviations (°C) of the differences shown in Figure 2.

Case (m)	Whole region	A	B	C
120	1.2	1.1	1.1	0.5
250	1.8	1.6	1.7	0.7
500	2.3	1.9	2.2	1.1
1000	2.7	2.0	2.5	1.4
5000	4.0	–	–	–

for the target A while it continues up to 500 m for the target B, which agrees with the scale of the maximum field length in both cases. The reason is that above those scales the field variability of the surface is lost.

These results show that the temperature deviation using MODIS data, at 1 km pixel resolution, is too large so as to consider these data as inputs in models to estimate surface fluxes. Nevertheless, a significant improvement is shown if the spatial resolution of the MODIS visible bands is considered (250 m). At this point, we can take advantage of the disaggregation procedure to retrieve radiometric surface temperatures at 250 m pixel resolution from MODIS.

Figure 3 shows a plot of the NDVI-T_R relationship at 1 km pixel resolution from MODIS data for the whole Basilicata region. Applying equations (7)–(9), a new map of T_R at 250 m pixel resolution is obtained. Kustas *et al.* (2003) showed, by comparison with concurrent aircraft data, that the subpixel temperatures retrieved through the disaggregation procedure ($DisT_R$), are in better agreement with the observations than those obtained by assuming thermal homogeneity of the pixel ($UniT_R$).

Unfortunately, there was not the possibility of comparing our results with concurrent observations. However, an analysis of the deviation between $DisT_R$ and $UniT_R$ at the different scales of Landsat5-TM, Landsat7-ETM+ and MODIS Terra was carried out. Table 2 shows a summary of the comparison between $DisT_R$ and $UniT_R$ in terms of the standard deviation of the differences. As an example, Figure 4 shows the histogram of these differences for the three targets selected and for the particular case of the Landsat5-TM image. Results show that the effect of applying the disaggregation procedure is not significant upon surface conditions such as those of target C, i.e., when the field length is clearly larger than the spatial resolution of the used sensor. A similar, but not so remarkable, effect can be observed on targets A and B with the Landsat7-ETM+ (spatial resolution of 60 m). The largest differences are obtained for the Landsat5-TM image

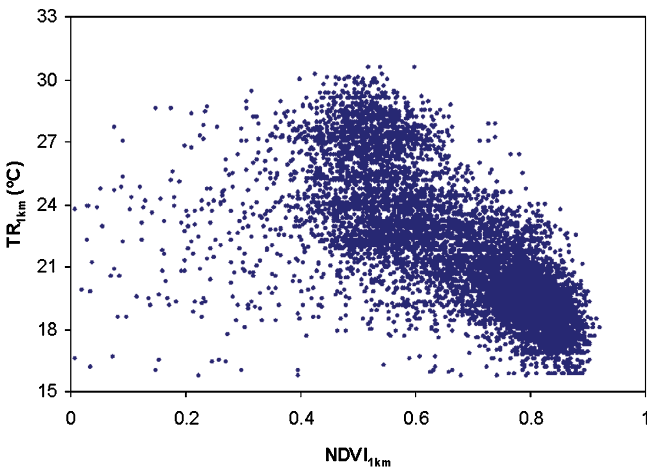

Figure 3. Plot of T_R versus NDVI rescaled at 1 km pixel resolution, for the MODIS Terra image. Data correspond to the whole region.

Table 2. Standard deviations (°C) of the differences between $DisT_R$ and $UniT_R$ for the three considered satellite images.

Case	Whole region	A	B	C
Landsat7-ETM+ (60 m–30 m)	1.1	1.3	1.1	0.4
Landsat5-TM (120 m–30 m)	2.0	2.5	2.2	0.4
MODIS Terra (1000 m–250 m)	1.2	0.8	1.2	0.2

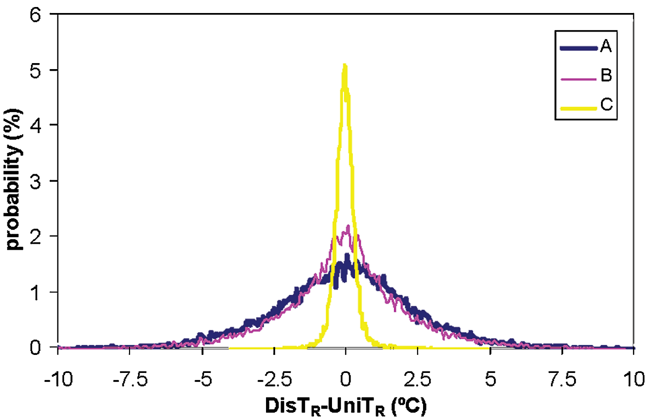

Figure 4. Histogram of the differences between $DisT_R$ and $UniT_R$ for the Landsat5-TM image and for the three selected targets.

since its spatial resolution (120 m) is on the order of the length of the fields in target A, and in a small part of target B. Low differences (around 1 °C) over these targets are also obtained for the MODIS image. In this last case, differences are larger for the B target since the spatial variability of the NVDI (250 m) is too coarse so as to discern the field boundaries on the A target.

$DisT_R$ and $UniT_R$ values were used with the STSEB model described in Section 2.1 to estimate R_n, H, and LE_d fluxes. A study of the differences between the flux results from the two T_R configurations was performed. This work was focused on the Landsat5-TM image because it will allow us to analyse the largest differences in surface fluxes since, as shown before, the largest differences between $DisT_R$ and $UniT_R$ are obtained for this particular case.

Figure 5 shows the histograms of the surface flux differences over the three described targets. The standard deviations of these differences are collected in Table 3. As it can be seen, differences for the A site are the largest of the three targets for all the studied fluxes, while differences for the target C are almost negligible. These results are in agreement with those shown in Table 2 for the surface temperatures. It is interesting to point out that the effect of using the $DisT_R$ seems to be more important in the net radiation estimation than in the sensible heat flux retrieval, even though the small biases obtained in this last case.

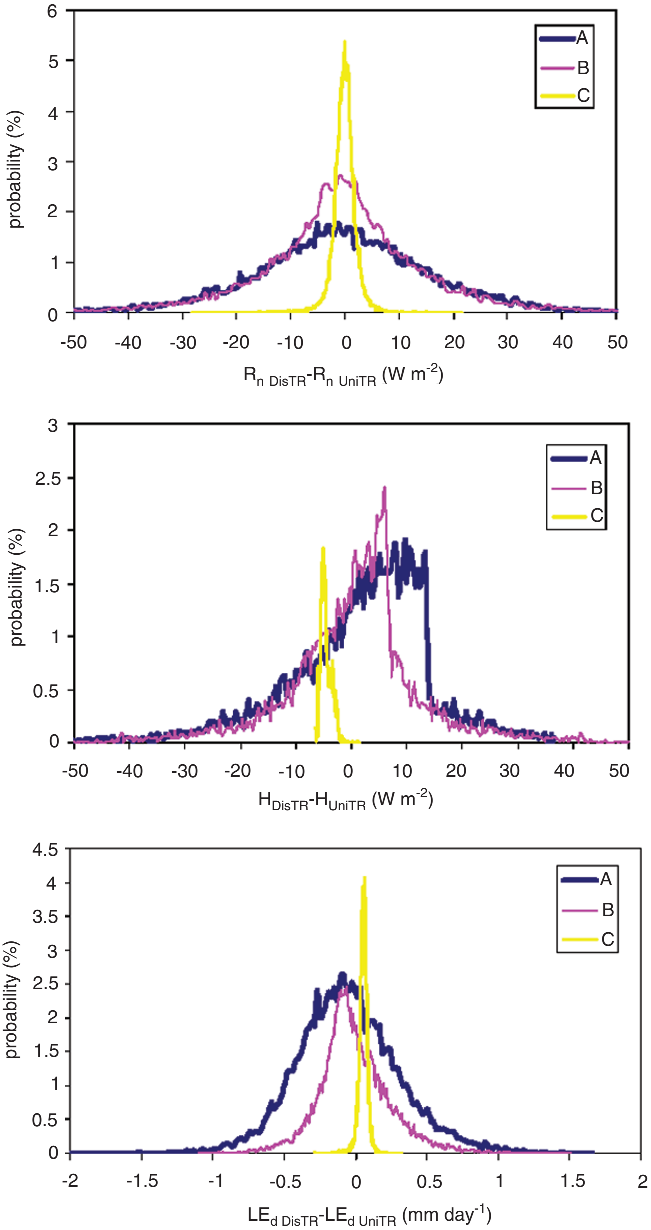

Figure 5. Histograms of the differences between the surface fluxes estimated from $DisT_R$ and $UniT_R$ by using the STSEB model. Results are shown for the three selected targets within the Landsat5-TM image. a) R_n, b) H, and c) LE_d.

Table 3. Standard deviations of the differences plotted in Figure 5.

	A	B	C
R_n ($\mathrm{W\,m^{-2}}$)	17	15	2.2
H ($\mathrm{W\,m^{-2}}$)	12	9	1.0
LE_d ($\mathrm{mm\,day^{-1}}$)	0.4	0.3	0.0

Differences shown in Table 3 are well within typical uncertainty in modelled and measured surface fluxes. Nevertheless, these differences are not negligible for targets A and B (i.e., for fields with length $\leq$500 m), and they must be taken into account. For the Landsat7-ETM+ and the MODIS images, differences are supposed to be lower and therefore not significant enough, according with Table 2.

Therefore, a study on the subpixel energy fluxes, with the STSEB model, should deal with the disaggregration procedure to estimate subpixel T_R, when using a sensor with a thermal spatial resolution on the order of the length of the monitored fields. This result is consistent with the conclusions of Kustas *et al.* (2003) work, with the difference that these authors showed a more utility of the disaggregation procedure with MODIS images since the typical dimensions of the agricultural fields in the US Southern Great Plains, in which their study was carried out, are larger than those considered in this work.

5 CONCLUSIONS

The loss of information in surface temperature variability, associated with the decreasing in spatial resolution of the satellite data, yields to a loss in surface fluxes variability when energy balance models are applied. Besides, this effect depends highly on the field pattern size of the considered area.

By progressive degradation of the surface radiometric temperature of Landsat7-ETM+ image to different pixel resolutions, differences of more than 2 °C were shown at the spatial resolution of the thermal band of MODIS over targets with field lengths <500 m. However, this differences decrease at the spatial resolution of the MODIS visible bands ($\sim$1.5 °C). The disaggregation procedure, allows us to take advantage of the relationship NDVI-T_R to estimate more reliable subpixel temperatures. Comparison of these temperatures with those obtained by assuming thermal homogeneity of the pixel showed the most significant differences (more than 2 °C) in the case of the Landsat5-TM image, and, particularly, upon the target with field lengths <250 m. These results are consistent with other works showing that the disaggregation technique should be applied when using a sensor with a thermal spatial resolution on the order of the length of the monitored fields. Surface energy flux estimations over the Landsat5-TM image by the STSEB model showed differences of about $\pm$15 $\mathrm{W\,m^{-2}}$ in R_n, $\pm$10 $\mathrm{W\,m^{-2}}$ in H, and $\pm$0.4 $\mathrm{mm\,day^{-1}}$ in LE_d, using $DisT_R$ values as inputs, and targets with field length <500 m. On the other hand, it has been also checked that the effect of applying the disaggregation procedure on extensive homogeneous targets, such as forest areas, is not significant at the scales of neither Landsat nor MODIS.

ACKNOWLEDGEMENTS

This work was supported by the Spanish Education and Science Ministry (Project CGL2004-06099-C03-01/CLI and research contract of R. Niclòs). During this study J. M. Sánchez had a research grant "V Segles" from the University of Valencia.

The authors express their thanks to ALSIA (Agenzia Lucana per lo Sviluppo ed Innovazione in Agricoltura) for providing field data and to IMAA (Istituto di Metodologie per l'Analisi Ambientale) of CNR (Consiglio Nazionale delle Ricerche) of Tito Scalo (PZ, South-Italy) for providing the base elaborations of satellite images.

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