QUANTIFYING UNCERTAINTIES IN LAND SURFACE TEMPERATURE DUE TO ATMOSPHERIC CORRECTION: APPLICATION TO LANDSAT-7 DATA OVER A MEDITERRANEAN AGRICULTURAL REGION

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ABSTRACT

The impact of using non-coincident radiosoundings to remove atmosphere effect from thermal radiances is analyzed here. We considered 27 Landsat-7 ETM+ images acquired over a Mediterranean agricultural region, benefiting from nearby radiosoundings launched almost 2 hours later, and from the availability of a network of ground stations deployed over different types of ecosystems. We observed that, in the conditions of our images, surface temperature estimates slightly improved when considering one atmospheric profile interpolated to our particular date, time and location, in comparison with the use of non-coincident radiosoundings. However, it may imply an error up to ±2.5 K for brightness temperatures (in particular for very high temperatures and during summer when the atmosphere was warmer and the vapor pressure was higher), leading to important errors in the derivation of surface energy fluxes. The characterization of the lowest atmosphere layer appeared to be essential to improve the estimates of brightness temperatures.

Index Terms— Land surface temperature, atmospheric effect, thermal infrared, Landsat, remote sensing

1. INTRODUCTION

Remote measurement of surface temperature allows assessing surface energy balance at various spatial scales from satellite and airplane platforms or from hand-held thermal infrared radiometers. However, surface temperature cannot be directly derived from thermal measurements. Measured radiation includes not only the radiation emitted by the surface but also the radiation emitted by the atmosphere. Moreover the signal from the surface is attenuated by the transfer through the atmosphere. Correction of these atmospheric effects requires knowing the atmospheric profile in temperature and vapor pressure. The difficulty to obtain atmospheric profile at the same time and at the same position than thermal infrared measurement generates uncertainties in the derivation of surface temperature. The emissivity effect must also be accounted, since it directly affects the level of emitted radiation at a given temperature, inducing additional uncertainties. Poor knowledge in either surface emissivity or atmospheric and reflection effects results in error in the determination of surface temperature from remote sensing measurement. These effects have been recognized for a long time (e.g. [10], [17]). An error of ±0.01 on emissivity results in an error between 0.6 and 0.9 K on surface temperature [14]. This error increases if atmospheric radiation is not considered in the same spectral range as the sensor [15], which measurement is particularly complex. Further, its determination is hindered by the fact that the lowest atmosphere layers are strongly affected by the underlying land surfaces [9].

The work presented here complements the analysis presented in [15], where we analyzed the impact of surface emissivity and atmospheric conditions on surface temperatures, while here we focused on the atmospheric correction effect. In the present study we analyzed the impact of using non-coincident radiosoundings to remove atmospheric effect from thermal radiances acquired by Landsat-7. For that, we studied the sensitivity of the atmospheric parameters required to correct the temperatures top of atmosphere (i.e., atmospheric transmission, $\tau$ and upwelling radiance, $L^\uparrow$, both band-averaged for the 10.4-12.5 µm spectral range) to errors in the estimation of the air temperature ($T_a$), pressure ($P_a$) and relative humidity ($R_h$) at surface level. After characterizing land surface emissivities ($\varepsilon$), land surface temperatures ($T_s$) derived from
Landsat-7 were evaluated with their comparison with ground measurements.

We considered 27 Landsat-7 images acquired at 10:15 UTC from 2007 to 2010 over the lower Rhône Valley in France (Avignon-Crau-Camargue area; 0 to 60 m above sea level). It is mainly a flat area presenting a wide variety of land uses [13]. Ground measurements were performed at six surface energy balance stations set on different ecosystems (dry grassland, irrigated meadow, salty marshes, wheat fields and rice). At the ground, surface temperatures were estimated from pyrgeometer measurements (Kipp & Zonen CNR1 sensors) applying the following Eq. (3) to the 5-50 μm spectral range.

2. METHODOLOGY

It is possible to convert top of atmosphere radiances measured by the instrument (\(L_{TOA}\)) to top of canopy radiances (\(L_{TOC}\)), corrected for atmospheric effects but not for emissivity effects, by considering band-averaged magnitudes using [6]:

\[
L_{TOC}(Tb) = \frac{L_{TOA} - L_{\uparrow}^{\uparrow}}{\tau}
\]

(1)

where \(\tau\) is the atmospheric transmission; \(L_{\uparrow}^{\uparrow}\) is the upwelling or atmospheric path radiance; and \(Tb\) is the brightness temperature (i.e., the temperature of a black body that would have the same radiance).

Radiance to temperature conversions can be made using the inverted Planck function or the Landsat specific estimate of the Planck curve:

\[
T = \frac{k_{2}}{\ln\left(\frac{k_{1}}{L(T)} + 1\right)}
\]

(2)

where \(T\) is temperature in Kelvin; \(L\) is spectral radiance in W/m²srμm; and \(k_{1}\) and \(k_{2}\) are calibration constants equal to 666.09 W/m²srμm and 1282.71 K, respectively, for the Landsat-7 ETM+ sensor [4].

Brightness to surface temperature (\(Ts\)) conversion is possible using the approach proposed by [14]:

\[
Ts - Tb = \frac{(1 - \varepsilon)}{4\varepsilon}T_{b} - \frac{(1 - \varepsilon)}{4\varepsilon} f(Tb) \sigma Tb^{4} Ra^{\uparrow}
\]

(3)

where the spectral dependence of every parameter except \(Ts\) is obviated for simplicity. \(\sigma\) is the Stefan-Boltzmann constant. \(f(T)\) is a factor corresponding to the fraction of energy emitted in this spectral band by a black body at temperature \(T\) relative to the emitted energy over the full spectrum, defined by [11] as:

\[
f_{10.4-12.5}(T) = -0.2338 + 0.2288 \times 10^{-2}T - 0.3617 \times 10^{-5}T^{2}
\]

(4)

It varies between 0.12 and 0.13 for temperatures between -10 °C and 45 °C. \(Ra^{\uparrow}\) is the incoming atmospheric radiation in the spectral band, which can be expressed as a function of \(T_{a}\) and the atmospheric emissivity for the considered spectral band (\(\varepsilon_{a}\)) [11]:

\[
Ra^{\uparrow} = \varepsilon_{a} \cdot f(T_{a}) \cdot \sigma \cdot T_{a}^{4}
\]

(5)

\(\varepsilon_{a}\) was estimated following the empirical equation proposed by [11], modified by the hypothesis considered by [16], as follows:

\[
\varepsilon_{a} = \gamma_{10.4-12.5} \cdot 10^{-6} \varepsilon_{a} \cdot \exp(2450/T_{a})
\]

(6)

\(\gamma_{10.4-12.5}\) ranged from 1.37 (for the wettest atmosphere) to 1.63 (for the driest atmosphere). For more details see [13].

Surface emissivity (\(\varepsilon\)) is often estimated from NDVI using the relationship provided by [18]; see for example [2]. In our study, a specific relationship was derived from the analysis of the shape of the NDVI – emissivity relationship performed by [19] together with measurements of soil and vegetation canopy emissivities performed in our study area ([5], [12]). For more details see [13].

Surface temperature (\(T\)) was calculated by considering brightness temperature derived from Eq. (1) and Eq. (2), and its conversion to surface temperature using Eq. (3). Atmospheric parameters \(\tau\) and \(L_{\uparrow}^{\uparrow}\) from Eq. (1) were derived using:

- **Method 1**: The MODTRAN-4 radiative transfer code [3] and atmospheric information derived from nearby radiosoundings launched close to the Nîmes airport (20 to 40 km away; 60 m above sea level) 1 h and 45 minutes after satellite overpass, and

- **Method 2**: The operational atmospheric-correction tool available at [http://atmcorr.gsfc.nasa.gov](http://atmcorr.gsfc.nasa.gov), developed for single-band thermal infrared Landsat sensors 5, 7 and 8, which allows introducing the surface conditions (\(T_{a}, P_{a}\) and \(Rh\)) [1]. It uses atmospheric profiles from the National Centers for Environmental Prediction, interpolated to our particular date, time and location. To correct an entire image, we considered surface conditions acquired at the center of the scene at a certain time.

3. RESULTS

The spatial and temporal variability of \(T_{a}, P_{a}\) and \(Rh\) along the 27 considered dates was analyzed and summarized in Table 1. The effect of local topography (i.e., the land use heterogeneity of the study area) and the atmosphere spatial and temporal variability into atmospheric parameters \(\tau\) and \(L_{\uparrow}^{\uparrow}\) were analyzed and results summarized in Table 2. These uncertainties may lead to errors up to ±2.5 K and to a systematic underestimation up to 0.4 K for \(Tb\) (see Table 2), in particular in summer when the atmosphere was warmer and the vapor pressure was higher (values from a simulation study by considering TOA temperatures ranging from 0 to 40 °C, the usual range observed in our images, and the atmospheric conditions from the 27 considered days).
Table 1. Uncertainties in air temperature ($T_a$), pressure ($P_a$) and relative humidity (Rh) at surface level due to atmosphere spatial and temporal variability along 27 days. Spatial variability is calculated by considering values collected at the six meteorological stations and values from the lowest layers of the radiosoundings, both at 12:00 UTC. Temporal variability comes from comparisons between ground measurements at 10:15 and 12:00 UTC. RMSE$_A$ is the absolute Root Mean Square Error.

<table>
<thead>
<tr>
<th>Spatial variability at 12:00 UTC</th>
<th>Temporal variability (between 10:15 and 12:00 UTC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta T_a$ (K)</td>
<td>$\delta P_a$ (hPa)</td>
</tr>
<tr>
<td>1.6</td>
<td>2</td>
</tr>
<tr>
<td>Bias</td>
<td>-0.16</td>
</tr>
</tbody>
</table>

RMSE$_A$ 0.06 0.4 1.3 0.6 1.0 1.8 2.5
RMSE$_R$ 7% 31% 4.9
Bias 0.012 -0.08 0.15 -0.009 -0.15 -0.3 -0.4

However, from the analysis of all pixels of our images, and particularly for completely clear sky days, there was a good correlation between $T_b$ retrievals from Method 1 and Method 2 (absolute Root Mean Square Error, RMSE$_A$ and bias <1 K). The omission of surface atmospheric conditions (which characterize the lowest atmosphere layer) for the atmospheric correction following Method 2 implied higher errors into $T_s$ than considering those acquired at 12:00 UTC (the error in $T_b$ is almost double, while the bias is smaller), confirming what Jacob et al. (2003, 2008) claimed.

As noted in Figure 1a, an underestimation of $T_b$ implies an underestimation of $T_s$ of about the same order or slightly higher, for any temperature, emissivity and atmospheric downwelling radiance (results from the analysis of Eq. 6 from [14]). However, an emissivity error of +0.01 implies an underestimation of $T_s$ significantly increasing with temperature and the decrease of atmospheric downwelling radiance, and slightly decreasing with emissivity (Figure 1b). For an emissivity error of +0.02, the error in $T_s$ is almost doubled (Figure 1b).

Consequently, the use of a temporal and spatial interpolated atmospheric profile together with surface conditions at satellite overpass (Method 2) for correcting for atmospheric effects, instead of using data from a nearby radiosounding launched almost 2 hours later (Method 1), just resulted in a decrease of 0.1 K for the RMSE$_A$ of $T_s$ (and the bias remained the same). Figure 2 shows the comparison between satellite estimates and ground measurements of $T_s$ over each land use site. $T_s$ are estimated with a bias of +0.3 K and an error of about ±1.7 K, mostly due to larger scatter at high temperatures (probably caused by wrong characterization of emissivity over salty marshes) and the heterogeneity of the wheat field at Landsat scale. A deeper analysis is presented by [13].

4. CONCLUSIONS

Our study shows that in the conditions of our images, the effect of local topography and the atmosphere spatial and temporal variability could be considered as negligible into the estimation of $T_s$. However, the effect is much more
important for \( Tb \) and consequently for the derivation of surface energy fluxes (particularly the sensible heat flux, and exceptionally negligible for net radiation [13]). The procedure presented in this study is currently being implemented in a processing chain developed for mapping evapotranspiration (EVAP tool, [7]). This work was performed through different projects funded by the CNES (TOSCA) and the European SIRRIMED FP7 project, and the CNES postdoctoral contract from M. Mira.

![Figure 2. Comparison, over four measurement sites, between Landsat-7 retrievals from 22 days corrected for atmospheric effects using Method 2 (see Section 2) and considering surface conditions at satellite overpass, and concurrent ground based measurements of surface temperature, \( Ts \). Error bars show standard deviation of averaged data (i.e., 6×6 pixels 60-m resolution), only significant over the wheat field. RMSE, absolute Root Mean Square Error.](image)

**5. REFERENCES**


