Impacts of surface boundary layer turbulence on surface temperature measurements at different spatial resolutions

Damien Commandoire, Jean-Pierre Lagouarde, Mark Rankin M. R. Irvine, Sylvia Dayau, Didier D. Garrigou, Jean-Marc J.-M. Bonnefond

IMPACTS OF SURFACE BOUNADRY LAYER TURBULENCE ON SURFACE TEMPERATURE MEASUREMENTS AT DIFFERENT SPATIAL RESOLUTIONS

D. Commandoire, J.-P. Lagouarde, M. Irvine, S. Dayau, D. Garrigou, J.-M. Bonnefond

INRA, UR1263 EPHYSE, F-33140 Villenave d'Ornon

ABSTRACT

Surface temperature displays temporal fluctuations driven by turbulence intensity of both surface (SBL) and planetary (PBL) boundary layers. An experiment conceived to evaluate the error induced by these fluctuations on instantaneous satellite measurements at different spatial resolutions is described. It is based on the reconstruction of surface temperature time series from sequences of thermal images acquired using a TIR camera aboard an helicopter in stationary flight over 5 different surface types. It is shown that the spatial averaging performed over the pixel allows one to reduce the contribution of the high frequency SBL turbulence to the error on Ts measurements. This error rapidly decreases with pixel size, and is found to be around ±0.5°C at 50m resolution for the cases we studied. Unfortunately the experimental set up revealed not as well suited to evaluate the contribution of low frequency PBL turbulence to Ts error, and our recommendations are given for future experiments.

Index Terms: surface temperature, thermal infrared, turbulence, spatial resolution, ergodicity, satellite

1. INTRODUCTION

The present offer of TIR satellite data is not sufficiently adapted for monitoring the surface processes and developing applications in many fields of environmental sciences such as climatology, meteorology, agriculture, etc… Indeed researchers and end-users still have to face a dilemma between spatial and temporal resolution. In response to the needs expressed by the scientific community for missions combining high spatial resolution and revisit frequencies in the TIR, the French Space Agency CNES is currently developing a project, MISTIGRI combining a resolution of about 50 m with high revisit capacities of 1 or 2 days [1]. However, measurements at high resolution in the TIR pose specific problems in relation with atmospheric turbulence which until now have generally been ignored [2]. The surface temperature Ts is governed by the energy budget, and it displays temporal fluctuations driven by those of the meteorological forcing variables. A large continuum of frequencies is concerned. Leaving out the lowest ones, which correspond to the daily cycle, low frequencies which correspond to characteristic times ranging between a few tens of seconds to a few minutes are related to convective processes and induced by large eddies affecting the entire planetary boundary layer (PBL) [3]. The typical length scale of the fluctuations here corresponds to the PBL height i.e. range from a few hundreds of meters to the kilometer scale. Higher frequency fluctuations, characterized by times lower than a few seconds, are associated with the flow in the surface boundary layer (SBL), with typical length scales of a few meters. The error on instantaneous satellite measurements should therefore be related to the spatial resolution through the spatial integration performed over the pixel of the high frequency turbulent structures having a much lower typical size. It is not the case for low frequency structures which influence entirely high resolution pixels of much lower size. Contrary to high frequency turbulence no smoothing process at the pixel scale is possible here, and low frequencies unavoidably contribute to the uncertainty on Ts measurements.

We present an experimental study designed to investigate the spatial integration process (also referred to as ergodicity) of the Ts fluctuations at pixel scale, with the scope of evaluating the error on TIR measurements and providing some guidelines for specifying the resolution.

2. EXPERIMENTAL

2.1. data acquisition

The protocol of the experiment was based on the acquisition of long sequences (about 15-20 minutes) of images at high frequency (~ 4 Hz) over different surfaces using an airborne TIR camera aboard a helicopter (Ecureuil AS 350 B2) in stationary flight above the centre of each plot. A FLIR SC3000 camera[1] working in the 7.5 – 9.5 µm spectral window was used. Its cooled QWIP detector provides low thermal noise and an excellent sensitivity less than 20mK at 30°C. The camera delivers 320x240 pixels images with a ±1°C accuracy. It is equipped with 45x34° lenses and is

[1] *Trade name and company are given for the benefit of the reader and do not imply any endorsement of the product or company by the authors.*

mounted in a sphere which can be rotated along two axis, a horizontal one and a vertical one.

The measurements were performed over four natural surfaces (maritime pine, irrigated maize, vineyard, bare soil) and an urban one (Agen city center), in the South West of France during 2010 summer. For the 10 years old pine stand, the mean height of trees planted along 4 m width rows is 3.30 m, with an understory vegetation made of an evergreen gorse (*Ulex nanus).* The vineyard area is a juxtaposition of small plots with vegetation walls 1.6 m high and a stony bare soil spacing of 2 m between rows. The bare soil plot is a recent clear cut covered with sparse dry grass. For these surfaces non-homogeneities of a few tens or hundreds of meters in relation with vegetation cover or soil variability was also observed. The irrigated maize is quite a homogeneous and smooth surface, with plants about 2.5 m high. The structure of the city is rather uniform with small old buildings (2 - 4 storeys) covered with tiles, and narrow streets oriented in all directions. A flight height of 1600 m was chosen high enough to keep the studied areas about 500x500 m wide within the FOV at nadir easily, whatever possible small deviations from the stationary flight. The corresponding resolution of raw images was about 3.5 m.

Daytime measurements were performed around noon or in the beginning of the afternoon. For comparison purposes, measurements were also performed in stable atmosphere conditions just before sunrise (referred to as nighttime).

2.2. processing of data

Automatic geometrical rectifications were performed using SIFT (Scale-invariant feature transform, [4]) and RANSAC (RANdom SAmple Consensus, [5]) algorithms, to make all images of each sequence superpose over a unique reference. Atmospheric corrections were simultaneously performed using LOWTRAN 7 model, in particular to correct for the differences of path lengths between pixels within the thermal images. Emissivity was set to unity so that the contribution of the reflected ambient downward longwave radiation was not dissociated from the proper emission of the surface; Ts is therefore a brightness surface temperature [6] in our study. The time evolution of Ts at different resolutions was then generated by applying a similar grid over each image of the series and by aggregating the pixels assuming a Stefan-Boltzmann TIR radiance conservation scheme.

Unfortunately the stationary flight was not satisfactorily maintained during the experiments and the pilot let the position of the helicopter drift too much under the effect of the wind, while the operator continuously corrected for this by rotating the camera to keep the studied area in the FOV. This induced important directional anisotropy effects possibly reaching several °C as shown over forests and urban canopies [7, 8, 9]. The impact of the directional anisotropy on the Ts measurements is clearly illustrated in Fig. 1 by the similarity of the compared time evolutions of

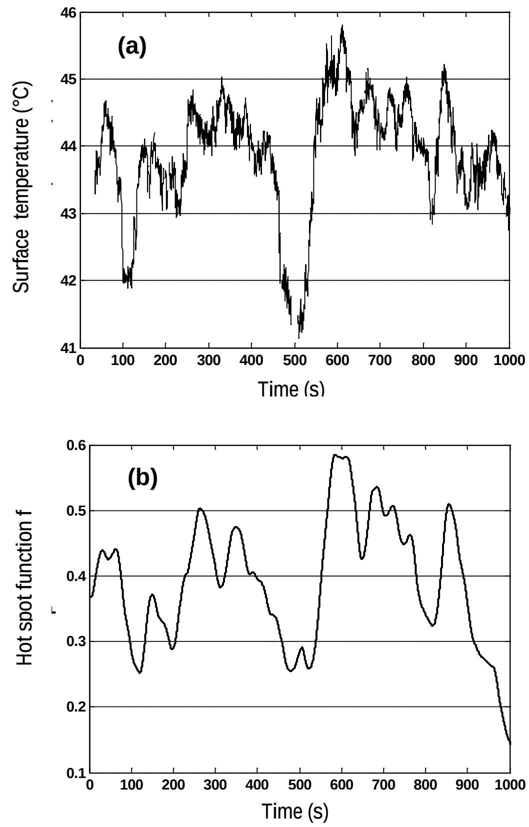

Figure 1. Temporal evolution of Ts (a) and f (b) for a given pixel of the pine stand at 50 m spatial resolution.

Ts and the hot spot function f characterizing the anisotropy defined as [10, 11]:

$$f = \sqrt{\tan\theta_S{}^2 + \tan\theta_V{}^2 - 2\tan\theta_S\tan\theta_V\cos\varphi} \qquad (1)$$

where θ_S and θ_V are the zenithal Sun and viewing angles respectively, and φ the relative angle between Sun and viewing azimuths.

As both of them generate similar low frequency variations in surface temperature, and because no anisotropy model is accurate enough and presently available for correction, it revealed impossible to discriminate the contribution of PBL turbulence itself on Ts signal from anisotropy artefacts. This led us to filter the low frequency fluctuations in the Ts signal, and to focus on the contribution of high frequency SBL turbulence on Ts fluctuations only. For this purpose a running average based on a 20 seconds window was first applied. The resulting smoothed signal was substracted from the original data and high frequency time series so derived. The 20 s duration was chosen after several tests for providing maximum consistency between the so smoothed Ts signal and the f function. Fig. 2 gives an example of the reduction of the high frequency filtered Ts fluctuations when resolution increases from 10 to 300 m for the pine stand.

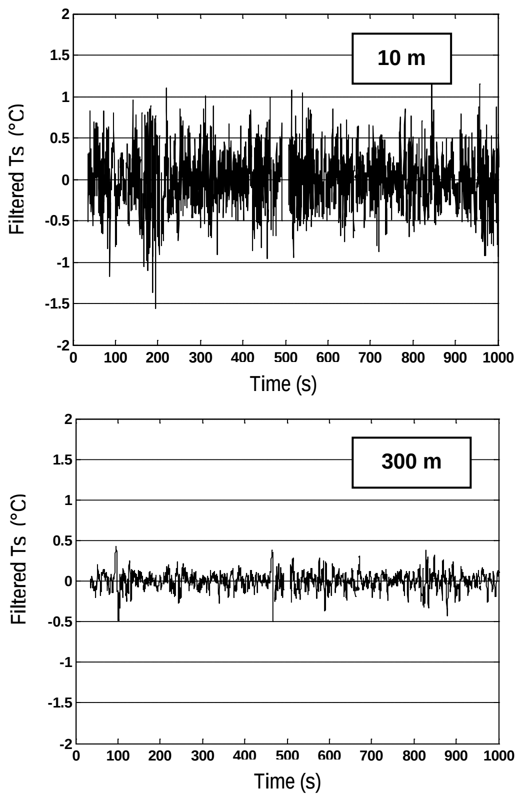

Figure 2. Examples of time series of high frequency filtered Ts over the pine stand at 10 and 300 m resolutions.

For each filtered time series, the standard deviation σ_T of the Ts fluctuations was calculated and the dependency of σ_T with spatial resolution finally analyzed. As the size of the studied areas allows one to simulate a rather large number of pixels for high resolutions, the information on the variability of σ_T was added by the mean of boxes displaying the median, and the 25% and 75 % quantiles, with a bar also indicating the 10% and 90% quantiles.

3. RESULTS

In daytime conditions σ_T rapidly decreases with the resolution up to about 50 m, and much more gently after for all of the 5 surfaces (Fig. 3 and 4). The σ_T variability for a given resolution can be related to the homogeneity of the surface: for surfaces displaying variability over a large range of spatial scales (vineyard, pine) it tends to keep important values whatever the resolution, whereas it is significantly reduced when non-homogeneities vanish with deceasing resolution, such as for Agen city. The homogeneity of the maize field resulting from intense irrigation means that there is nearly no impact of the spatial resolution on the high frequency Ts fluctuations The lower intensity of turbulence in stable conditions similarly explains the poor sensitivity of σ_T to spatial resolution. It has been checked that for a given

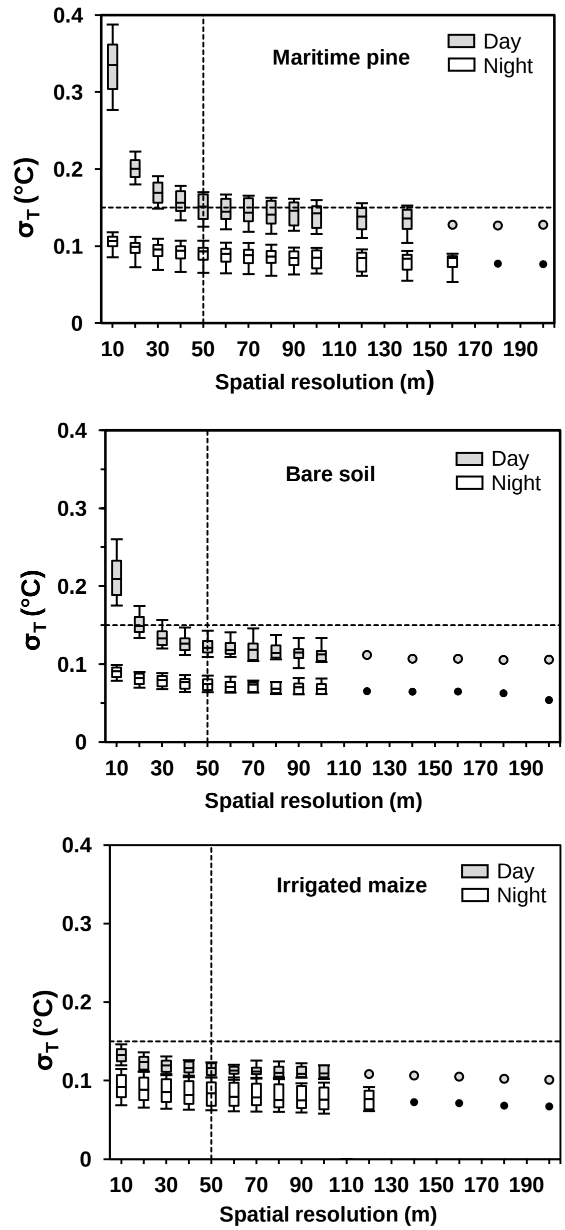

Figure 3. Relationship between σ_T and spatial resolution for 3 of the studied surfaces, both in unstable (daytime) and stable (nighttime) conditions. The lines corresponding to the 50m resolution and to a 0.15 K standard deviation σ_T (i.e. ~ ±0.5 K error) have been indicated for guiding the reader.

resolution, σ_T was displaying near normal distribution, which makes the $\pm 3\sigma_T$ interval a good indicator of the error. At 50 m resolution, σ_T do not exceed 0.15 °C for all of the studied cases, which means that the contribution of SBL turbulence to the error on satellite measurement remains below ±0.5 °C. Nevertheless it must be pointed out that the contribution of PBL turbulence to the overall error on measurements is likely to be dominant. As a matter of fact eddy correlation measurements performed simultaneously to

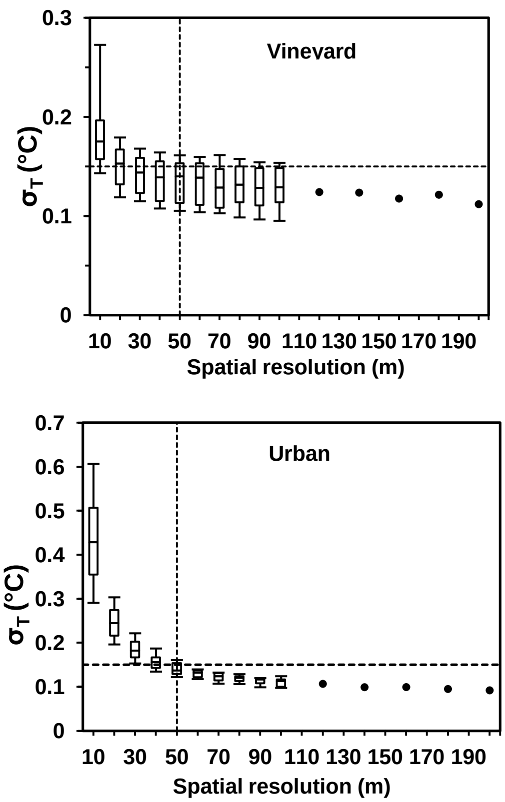

Figure 4. Same as Fig. 3 for the vineyard and the urban area in daytime conditions only.

the flights revealed standard deviations of air temperature varying between 0.7 and 1.3 °C in daytime conditions. Ts being partly governed by air temperature, one might expect similar variations in Ts, and a resulting contribution on the error much larger than the ±0.5°C previously found for SBL impact. In the same idea Katul et al. [3] attributed large skin temperature perturbations (>2°C) over grass to PBL eddies.

4. CONCLUSION

Our results clearly illustrate the impact of resolution on the spatial averaging process of high frequency Ts fluctuations induced by SBL turbulence. The contribution of the latter on the error on Ts is found to be ±0.5°C at 50m resolution for the cases we studied. However, they need confirmation for other turbulence conditions and other vegetation structures; this seems to confirm the ability of a 50m resolution to significantly reduce the impact of SBL flow on Ts measurements.

Nevertheless it has been underlined from both previous literature [3] and standard deviation of air temperature measured during the experiments, that the contribution of the PBL turbulence is likely to have an even larger impact on Ts overall accuracy. Urgent work is needed here, in particular to help designing future spatial missions.

For the future, we strongly recommend experiments to be based on fixed TIR cameras mounted on masts to capture the signature of PBL eddies unequivocally. Such a set up was successfully recently tested at the laboratory. If using a helicopter for surfaces of high vertical extension (forests, urban canopies), oblique measurements perpendicular to Sun direction should minimize the impact of directional anisotropy [9].

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