Remote Sensing of Environment 138 (2013) 189–198

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Atmospheric boundary-layer turbulence induced surface temperature fluctuations. Implications for TIR remote sensing measurements

J.-P. Lagouarde *, D. Commandoire, M. Irvine, D. Garrigou

INRA, UR1263 EPHYSE, 71 avenue E. Bourlaux, F-33140 Villenave d'Ornon, France

ARTICLE INFO

Article history:
Received 4 June 2012
Received in revised form 23 April 2013
Accepted 6 June 2013
Available online 22 August 2013

Keywords:
Thermal infrared
Surface temperature
Turbulence
Ergodicity
Spatial resolution
Satellite
Accuracy

ABSTRACT

Atmospheric turbulence in both surface (SBL) and planetary (PBL) boundary-layers govern rapid temporal fluctuations of the surface temperature (Ts), with potentially important resulting errors on instantaneous satellite measurements in the thermal infrared (TIR). An experiment designed to evaluate the error, and its reduction with spatial resolution (expected from ergodicity properties), of Ts is described. It is based on the analysis of time series of Ts at different resolutions reconstructed from sequences of images acquired at high frequency using a helicopter borne TIR camera over 5 different surfaces in the south-west of France, in the 2010 summer. Unfortunately the non-respect of a stationary flight resulted in a contamination of the data by directional effects; the filtering process developed to correct for this also eliminated the signature of low frequency PBL turbulence related to Ts measurements, and made only possible the study of high frequency turbulence impact on Ts. For decreasing resolution (i.e., increase in pixel size), the contribution of the SBL turbulence to error rapidly decreases with resolution (i.e., pixel size increase); it reaches ±0.5 °C at 50 m, the resolution selected for recent spatial mission projects, with only little variations thereafter. Recommendations are made for future experiments to evaluate the overall error induced by atmospheric turbulence on satellite Ts measurements.

1. Introduction

The present offer of thermal infrared (TIR) data is not satisfactorily adapted to the monitoring of the surface processes and to develop applications in many fields of environmental sciences such as climatology, hydrology, meteorology, agriculture, etc… Indeed researchers and end-users still have to face a dilemma between spatial and temporal resolution: systems such as MSG and GOES geostationary satellites or AVHRR and MODIS provide daily (and even hourly with MSG and GOES) observations with low (e.g., kilometric at least) spatial resolution, whereas satellites such as Landsat or ASTER provide high spatial resolution, about 100 m, with poor revisit capabilities of 16 days, much too long to develop applications requiring accurate temporal monitoring of the evolution of the vegetation. In response to these needs expressed by the scientific community for spatial missions combining high spatial resolution in the TIR and higher revisit frequencies, several projects have been studied by the French Space Agency CNES, such as IRSUTE in the past (Seguin et al., 1999) or more recently MISTIGRI (Lagouarde et al., 2013) in cooperation with Spain. In the United States the HyspIRI (Hyperspectral Infrared Imager) has been proposed by NASA in the framework of the Earth Science Decadal Survey Studies. The definition of the mission specifications conducted in the initial phase of these projects is primarily governed by scientific requirements, but they must also cope with technical constraints, and several tradeoffs finally have to be made. In this process, little attention has been paid to the temporal fluctuations of surface temperature in response to the turbulence of the atmospheric flow above the surface whereas these fluctuations may represent an important source of uncertainty on satellite measurements.

Indeed the surface temperature is governed by the energy budget, and it displays temporal fluctuations driven by those of the micrometeorological forcing variables, wind speed in particular (Katul, Schieldge, Hsieh, & Vidakovic, 1998). A large continuum of frequencies is concerned. Leaving out the lowest ones corresponding to the daily cycle, those referred to as low frequencies in what follows and corresponding to characteristic times ranging between a few tens of seconds to a few minutes are related to convective processes and are induced by large eddies affecting the entire planetary boundary layer (PBL). Higher frequency fluctuations, characterized by typical times of a few seconds, are mainly associated to the turbulent flow in the surface boundary layer (SBL). The corresponding turbulent structures above the canopy depend on wind speed and canopy height in particular; they display typical sizes of a few meters, and a good illustration is given by the wind-induced wave-like structures, also known as honami, which can be observed on wheat fields (Dupont et al., 2010; Finnigan, 1979; Py, De Langre, Moulia, & Hémon, 2005).

As the flight speed of low orbit (between 500 and 800 km) satellites is around 7.5 km^{-1}, it results that in practice each surface temperature measurement on a pixel corresponds to a unique instantaneous sampling of a randomly fluctuating signal. Most models used to derive

* Corresponding author. Tel.: +33 05 57 12 24 32; fax: +33 05 57 12 24 20.
E-mail address: lagouarde@bordeaux.inra.fr (J.-P. Lagouarde).

0034-4257/$ – see front matter © 2013 Published by Elsevier Inc.
http://dx.doi.org/10.1016/j.rse.2013.06.011

fluxes from surface temperature assume stationary conditions over time steps typically ranging from 15 to 30 min. The retrieval of such fluxes is therefore prone to errors induced by the departure between the instantaneous measurements of Ts from space and their average value <Ts> over the time steps of models. Reducing this error can only be possible by working at a sufficient spatial resolution for which an ergodicity assumption is respected (i.e., equivalence between a local time integration of temperature measurements at an instantaneous spatial integration). In practice this condition is difficult to meet for systems currently being defined in the TIR at resolutions between 50 and 100 m. Indeed if the surface temperature footprints of the high frequency turbulent structures are much smaller than the pixel size they are likely to be averaged by the integration process at the pixel scale; it is not, however, the case for low frequency turbulence structures. When sweeped by such structures having a typical size of a few hundred meters, pixels of much lower size are affected as a whole, which results in temperature variations possibly important both in amplitude and duration.

This paper addresses the important – but generally ignored – problem of the uncertainty inherent to turbulence within the atmospheric flow at the surface on Ts measurements from space and of its relation with the spatial resolution. Contrary to a number of efforts devoted to atmospheric corrections and temperature emissivity separation (see a review in Kerr, Lagouarde, Nerry, & Ottlé, 2004), or TIR directional anisotropy (Lagouarde, Ballans, Moreau, Guyon, & Coraboeuf, 2000; Lagouarde et al., 2004, 2010; Voogt & Oke, 2003), this question has been only addressed to our knowledge in the framework of the above-mentioned IRSUTE project (Lagouarde, Dubreton, Moreau, & Guyon, 1997).

The paper presents an experimental study designed to evaluate (1) how the spatial resolution operates a smoothing of the temporal fluctuations of the surface temperature measurements from space, and (2) the resulting uncertainty which affects these measurements. The idea consists in acquiring time-series of high frequency TIR imagery at high resolution over large fields from a helicopter during stationary flights; spatial aggregation techniques are then applied to simulate time-series at a degraded resolution, on which the uncertainty of instantaneous Ts measurements is finally assessed. The experimental protocol and the study sites are first described. The data processing is then presented in detail. The difficulties met in flying the helicopter are also mentioned: the non-respect of the stationary flight above the field sites resulted in a contamination of the data by directional anisotropy effects which made extracting the PBL turbulence contribution impossible in the signal and led us to focus on the small scale SBL turbulence impact on Ts only in this paper. Finally the results are presented and discussed, and recommendations to help specify a resolution for future TIR missions are given.

2. Experimental

2.1. Experimental protocol

The measurements were performed using a FLIR SC3000 camera[1] aboard a helicopter (Ecureuil AS 350 B2/Eurocopter). The camera was mounted in a sphere which can be rotated along two axes, a horizontal one and a vertical one.

The technology of the SC3000 camera is based on a cooled QWIP detector which provides low thermal noise with an excellent NEDT (noise equivalent differential temperature) of 20 mK at 30 °C. Its absolute accuracy is ±1%, i.e., ±0. 3 °C at this temperature, and it delivers 320 × 240 pixel images. Measurements are performed in the 7.5–9.5 μm spectral range. The camera is equipped with 45 × 34° lenses. The image acquisitions were made using the FLIR ThermaCAM software at a rate of 4 Hz.

The protocol initially defined was to maintain the helicopter in stationary flight vertically above the studied plots. Given that atmospheric turbulence and the wind were expected to make this difficult for the pilot, and thus to induce unavoidable small uncontrolled displacements of the helicopter, the area seen at the ground had to be large enough to keep the studied areas within the FOV all along the observations: the flight height was therefore set at 1600 m above ground level, which leads to a 1320 × 980 m FOV large enough compared to the maximum 500 × 500 m size of the studied plots (see next section), and to a resolution between 3.9 m at nadir and 4.6 on the edges of the images. The duration of measurement sequences was set to 20 min for daytime measurements, which were performed around noon or in the beginning of the afternoon. This duration was chosen to statistically observe a few convective events having periods of a few minutes (typically between ~2 and ~5 min depending on PBL activity). For comparison purposes, measurements were also performed in stable atmosphere conditions just before sunrise. In this case, the duration of sequences was shorter and reduced to 10 min.

Turbulence measurements at the ground were performed simultaneously with the flights using 3D sonic anemometers (Young 8100V) situated into the studied areas.

Unfortunately the stationary flight protocol appeared not to be easy, and the pilot allowed important drifts in the position of helicopter, which were compensated for by the operator aboard using a continuous action on the rotating sphere to keep the studied plots in the FOV. The requirement of continuity in the sequences of observations was there so satisfied, but at the cost of introducing critical viewing angular effects (see Section 3.3.1). As detailed further, this made impossible the characterization of the signature of PBL eddies on the surface temperature signal, and led us to focus on the contribution of SBL turbulence on surface temperature fluctuations only.

2.2. Sites

The main characteristics, location, size and surface type, of the 5 studied areas are given in Table 1. Images recorded during the flights using a video camera are provided in Fig. 1a to d to allow the reader to evaluate the different types and scales of non-homogeneities which can be found in each plot.

The maritime pine stand (Fig. 1a) is a 10 year old stand planted on humid moorland. The mean height of trees was 3.30 m. The rows are oriented ENE–WSW with a 4 m spacing, and the density of trees was 1800 stems/ha, leaving the understory vegetation of an evergreen gorse (*Ulex nanus*) partly visible. As part of the CarboEuropeIP/Fluxnet network, this site is equipped with a micrometeorological tower continuously providing atmospheric flow measurements and surface fluxes at a 6.4 m height.

The vineyard area (Fig. 1b) is made of a juxtaposition of smaller plots having similar characteristics: the vegetation walls are about 1.7 m high with a stony bare soil spacing of 2 m between NNE–SSE oriented rows. A sonic anemometer had been placed at 3.4 m above the rows in the framework of a pesticide dispersion experiment.

For the pine stand and the vineyard different scales of variability can be observed ranging from a few meters for rows, up to several

Table 1
Location and size of the studied areas.

Surface type	Plot size (m)	Latitude	Longitude
Maritime pine stand	510 × 580	44° 29′ 37.17″ N	0° 57′ 23.20″ W
Bare soil	340 × 320	44° 28′ 06.55″ N	0° 57′ 42.20″ W
Irrigated maize	480 × 450	44° 30′ 10.11″ N	0° 57′ 29.31″ W
Wineyard	440 × 520	44° 39′ 46.87″ N	0° 25′ 02.74″ W
Urban	500 × 500	44° 12′ 14.60″ N	0° 37′ 16.25″ E

[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.