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Atmospheric turbulence induced errors on measurements of surface temperature from space

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ABSTRACT

Atmospheric turbulence in both surface (SBL) and planetary (PBL) boundary-layers induce temporal fluctuations of surface temperature (T_s), with potentially important resulting errors on instantaneous satellite measurements in the thermal infrared (TIR). Several experimental studies have been performed over different surfaces (pine forest, maize, bare soil) using TIR cameras, either ground based or helicopter borne, designed to evaluate (i) how the spatial resolution operates a smoothing of the temporal fluctuations of the surface temperature measurements from space, and (ii) the resulting uncertainty on these measurements. Additionally, a simulation of instantaneous surface temperatures of a maritime pine stand, performed using a Large Eddy Simulation (LES) airflow model coupled with a canopy model, is presented for comparison. The results confirm that the impact of the SBL turbulence rapidly vanishes when spatial resolution decreases (i.e., pixel size increases) in the range of 50 to 100 m, while T_s fluctuations induced by the low frequency PBL turbulence remain. For these resolutions, the resulting uncertainty on T_s lies within a ± 1 °C interval. The implications for designing the specifications of future high spatial resolution TIR missions, in particular NeDT and revisit, are discussed.

1. Introduction

Surface temperatures (T_s) display temporal fluctuations due to the combined effects of atmospheric turbulence (Christen, Meier, & Scherer, 2012; Katul, Schieldge, Hsieh, & Vidakovic, 1998; Paw et al., 1992), radiation forcing (Gentine, Entekhabi, & Polcher, 2010; Gentine, Polcher, & Entekhabi, 2011), and soil or surface conductive storage fluxes (Christen et al., 2012). The fluctuation period induced by atmospheric turbulence is expected to be much shorter (<20 min) than the one induced by radiation forcing and surface conductive storage fluxes (Christen et al., 2012). Consequently, fluctuations induced by turbulence may lead to significant errors in interpreting satellite thermal infrared (TIR) measurements since the acquired temperature corresponds to instantaneous sampling, not necessarily in a stationary state. This means that one should be careful when injecting satellite measurements into surface flux models which have typical time steps of 15 to 30 min.

The main turbulent structures present in the surface (SBL) and planetary (PBL) boundary-layers influence the temporal fluctuations of T_s according to their spatial and temporal scales. The SBL turbulent structures have time and spatial scales of a few seconds and a few meters, respectively, depending on the atmospheric stability and on the surface roughness. A good illustration of the mechanical effect of these structures is observed in windy conditions on wheat fields through the propagation of wave-like structures, also known as honami (Dupont et al., 2010; Finnigan, 1979; Py, De Langre, Moulia, & Hémon, 2005), or on sand surfaces through the meandering of aeolian streamers (Dupont, Bergametti, Marticorena, & Simoëns, 2013). These high-frequency structures induce similar spatial variability in surface temperature, which would be likely averaged by TIR sensors with resolutions of a few tens of meters, as confirmed by Lagouarde, Commandoire, Irvine, and Garrigou (2013). On the other hand, the low-frequency PBL turbulent structures, corresponding to large convective eddies of a few hundreds of meters, typical of PBL scales (Stull, 1988), exceed the pixel size of TIR sensors and thus may induce significant temperature variations with a time scale of several tens of seconds.

Up to now little attention has been paid by the remote sensing community 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. This problem requires more research work especially as efforts are underway to propose innovative space missions combining high spatial resolution with possibly high revisit capacities in the TIR: for example, IRSUTE (Seguin et al., 1999) or MISTIGRI (Lagouarde, Bach, et al., 2013) projects proposed by CNES in France, HyspIRI project proposed by NASA in the framework of the Earth Science Decadal Survey Studies, or more recently THIRSTY (Thermal InfraRed SpaTial sYstem), a joint mission concept under study between the CNES and NASA (Crébassol et al., 2014; Hook et al., 2014). All these missions aim for resolutions between 50 and 100 m in the TIR.

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This paper addresses the problem of the uncertainty inherent to the atmospheric turbulence on surface temperature measurements from space, and its relation with the spatial resolution. In a previous study (Lagouarde, Commandoire, et al., 2013), we showed from helicopter borne TIR camera measurements that the contribution of SBL turbulence to the temperature fluctuations of various surfaces decreases with resolution, reaching ± 0.5 °C at 50 m resolution. We were, however, not able to assess the impact of PBL turbulence on surface temperature fluctuations due to the non-respect of a stationary flight by the helicopter, which indirectly induced a contamination of the data at low frequencies by directional effects. To overcome this limitation, this paper presents an analysis of new high frequency TIR imagery datasets acquired at high resolution either from masts or from helicopter stationary flights, over various surfaces (maize, bare soil, pine forest), and combined with local flow turbulence measurements (air temperature and 3D windspeed) synchronized in time. These novel measurements enable us to assess the uncertainty of instantaneous T_s measurements with degraded resolution, and to relate T_s fluctuations to the flow turbulence of SBL and PBL. Additionally, a high-resolution simulation of a convective boundary layer over a pine forest has been performed using the Large Eddy Simulation (LES) technique to illustrate the impact of large-scale convective structures on the instantaneous surface temperature fluctuations.

Field and numerical experiments are first presented and discussed. Then, a comparison between the time series of T_s and turbulent variables is performed to highlight the impact of wind fluctuations on the surface temperature fluctuations. The magnitude of the errors that would potentially affect future measurements from space, is investigated through the analysis of T_s fluctuations at different spatial resolutions. Finally, recommendations are given to define specifications for future TIR missions.

2. Experimental data

Four field experiments and one numerical experiment have been performed. Three of the field experiments are based on ground based experimental setups, the TIR camera being placed on masts or towers. These experiments have been performed over a dry maize field, a bare soil, and a pine forest. They are hereafter referred to as MA_{GR}, BS_{GR}, and FO_{GR}, respectively, where the first two capital letters refer to the surface type and the index GR to ground-based. The fourth field experiment was conducted using a helicopter borne camera over a pine forest and is referred to as FO_{HEL} with similar notation. The numerical experiment was performed over a pine forest and is referred to as FO_{LES}.

2.1. MA_{GR} and BS_{GR} experiments

2.1.1. Measurements

MA_{GR} and BS_{GR} experiments were performed on September 29, 2011 on two adjacent fields located on the INRA test site of Bilos (44° 30′ 03″N, 0° 57′ 20″W) in Southwestern France. The first field extended over 700 × 470 m and was covered with dry maize of about 2 m tall. The second field extended over 1170 × 470 m and was a bare soil with shallow wheel tracks.

Measurements were successively performed on each field using an A40-M FLIR thermal infrared camera installed at the top of a 5.40 m

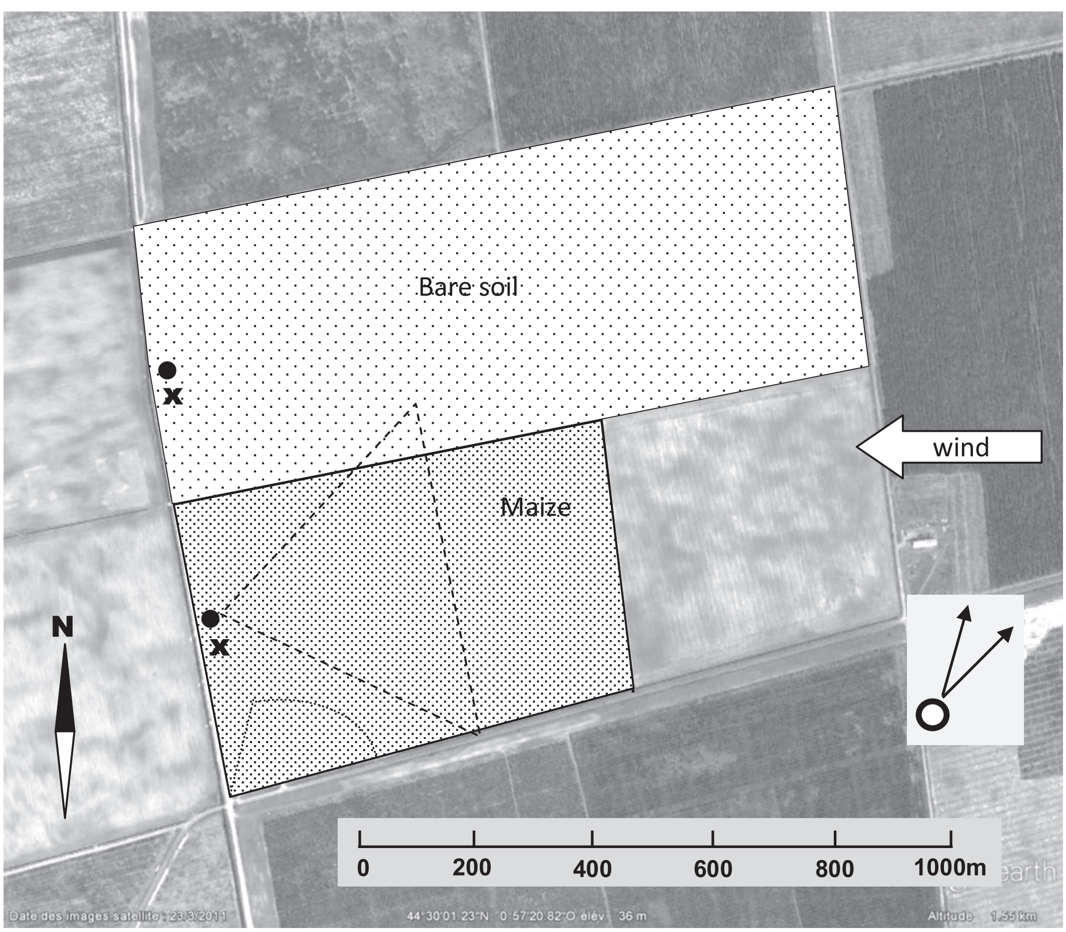

Fig. 1. MA_{GR} and BS_{GR} experimental field setup. The black circles (resp. cross) indicate the position of the TIR camera (resp. eddy correlation measurements). The doted area illustrates the field of view of the camera over maize. The mean wind direction is also indicated. The circle and the 2 arrows (low right corner) are for the Sun azimuth at the beginning and the end of the MA_{GR} and BS_{GR} experiments.