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Experimental characterization and modelling of the nighttime directional anisotropy of thermal infrared measurements over an urban area: Case study of Toulouse (France)

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ABSTRACT

The measurements of surface temperature are prone to important directional anisotropy in relation to the structure of the urban canopy and the radiative and energy exchanges inside it. Following the work of Lagouarde et al. 2010 that describes the daytime conditions, this paper focuses on the experimental analysis and modelling of the nighttime directional anisotropy. An extensive data set of airborne thermal infrared (TIR) measurements was collected over the city of Toulouse, France in the framework of the CAPITOUL project (Masson et al., 2008). The TIR measurements use a pair of thermal cameras equipped with wide angle lenses installed aboard a small aircraft. Three flights were made between 21:45 and 23:15 UTC, one in autumn and 2 in winter during 2004 and 2005 intensive operation periods (IOPs). The experimental results show that (i) the nighttime TIR directional anisotropy remains lower than 1°C for zenithal view angles up to 50°, and (ii) the nighttime anisotropy is insensitive to the azimuthal viewing direction. A modelling approach that combines a simplified 3D representation of the urban canopy with 2 energy transfer models, TEB and SOLENE, is then proposed. It confirms the experimental results quite well. Possible uncertainties on the geometry of the canopy and on most important thermo-radiative surface parameters are shown to have only little impact on the modelled TIR directional anisotropy. The time evolution of TIR anisotropy throughout night is simulated: for the fall and winter conditions studied the effects of thermal inertia completely vanish about 3 to 4 h after sunset, and the anisotropy never exceeds 2°C up to 60° zenithal view angles.

1. Introduction

The surface temperature is a key signature in the assessment of the surface energy budgets. This makes thermal infrared (TIR) remote sensing an important tool for monitoring surface processes occurring in urban areas and their practical applications (Voogt and Oke, 2003). Applications include monitoring the surface urban heat islands (SUHIs, tightly related to the air temperature UHIs), building related alert systems and improving aspects of urban planning in which the surface temperature plays a significant role. These applications are particularly important in the context of larger scale climate change that will increase the frequency and intensity of heat waves combined with increased anthropogenic fluxes derived from industrial activity, air conditioning or heating of buildings, and other urban activities such as transportation. Remotely sensed surface temperatures are also important for assessing evapotranspiration and for monitoring surface moisture and the water status of vegetation in urban areas. Improved monitoring of the surface temperature of vegetation can lead to a better assessment of the water budgets of urban watersheds (Carlson and Arthur, 2000). Vegetation is strongly related to the welfare and health of inhabitants (humidification of air, shading effects and reduction of temperatures). Evaluation of the surface temperature is also an important element for the validation of urban atmospheric flow models used for forecasting the extent of pollution plumes and improving information systems on diffusion of pollutants and air quality.

These applications require accurate measurement of the urban surface temperature. Atmospheric absorption and emission between the sensor and the surface, temperature-emissivity separation, and directional anisotropy effects all can represent an important source of error that needs specific correction. Directional anisotropy is defined here as the variation with viewing angle of the observed surface temperature Ts. It can be expressed as the difference $Ts_{\text{off-nadir}} - Ts_{\text{nadir}}$ between off-nadir and nadir observations of temperature in a given zenith/azimuth viewing direction. This anisotropy, also referred to as effective anisotropy by Voogt (2008), is defined for spatial scales larger

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than the dominant surface structure (e.g. building dimensions) so that it represents the effects of the three-dimensional surface rather than the non-lambertian behaviour of individual surfaces (Voogt, 2008). The surface temperature Ts can be defined in several ways, resulting in different possible characterizations of the anisotropy. In this paper we shall unequivocally consider the directional brightness, or simply 'brightness' temperature, according to the definition of Norman and Becker (1995), when dealing with the measurements. The definition of the modelled temperatures is not so clear: they are computed solving energy budget equations, and therefore appear as 'equilibrium' temperatures. This will be discussed in detail in the text.

During daytime, because of thermal contrasts between shaded and sunlit facets within canopies, differences between oblique and nadir measurements may reach up to 10°C depending on the relative positions of the Sun and sensor: the directional anisotropy displays characteristic patterns with intense 'hot spot' effects (maximum temperature when the surface is observed in the anti-solar direction), as described by several authors (Lagouarde et al., 2010; Lagouarde and Irvine, 2008; Soux et al., 2004; Voogt, 2008).

The presence of nighttime urban anisotropy, forced by cooling differences associated with urban surface structure and materials was first suggested by Roth et al. (1989) and briefly illustrated in Voogt and Oke (2003; Fig. 4) but no detailed study of the nighttime directional anisotropy has been performed until now. The distribution of the temperatures of the facets within the urban canopy depends on coupled energy and radiative transfer processes. At night, heat conduction processes that depend on thermal inertia of materials and internal heating of buildings, together with the processes governing the net loss of longwave radiation are expected to govern the anisotropy. This marks a substantial difference from the daytime case that is dominated by differences in the solar loading on particular facets of the urban surface. This paper focuses on nighttime anisotropy and follows our previous work devoted to daytime anisotropy in the same city (Lagouarde et al., 2010). The research was performed as part of the CAPITOUL project over the city of Toulouse in 2004–2005 (Masson et al., 2008). In this paper we briefly review the observational protocol used with the airborne TIR imager, the details of which are provided in Lagouarde et al. (2010), and then present the results obtained during 3 nights in autumn and winter conditions. An anisotropy modelling approach is then described: it is based on the combination of a 3D model providing the actual urban structure with canyon street energy models computing the distribution of the temperatures of the canopy facets. The results of the simulation are evaluated against the observations and the sensitivity of the modelled anisotropy to possible uncertainties arising from the urban canopy geometry and radiative and thermal surface parameters are discussed. An extension of the results is finally proposed using the model to assess the time evolution of the anisotropy throughout the entire night.

2. Experimental

2.1. Experimental protocol

Details of the experimental protocol have already been described in previous papers (Lagouarde et al., 2010; Lagouarde and Irvine, 2008); its main features are summarised here for clarity. The TIR directional measurements were performed using 2 airborne TIR cameras placed aboard a small twin-engine aircraft Piper Aztec PA23 flown by the SAFIRE group (http://www.safire.fr/ Service des Avions Français Instrumentés pour la Recherche en Environnement). The 2 cameras, M740 (INFRAMETRICS [1]) and SC2000 (FLIR [1]), were equipped with 75×59° wide angle and 24×18° lenses respectively and placed aboard the aircraft with backward inclinations of 9.5 and 50°. After having installed an additional filter on the SC2000 camera with a band pass cut off at 13 µm, both instruments had quite similar spectral responses between 7.5 and 13 µm. The flight altitude was 2000 ft (above sea level), which corresponds to about 460 m above ground for the centre of Toulouse. The spatial resolutions ranged between 2.5 m (nadir) and 6.2 m (50° zenith viewing) for the M740 and between 1.5 and 3.0 m for the SC2000 (for 48 and 62° zenith viewing angles respectively). The sizes of the images are 257×370 and 240×320 pixels for the M740 and SC2000 respectively. Fig. 1 shows the corresponding areas seen at ground. The aircraft speed was 70 ms^{-1} and the images were acquired at 1 Hz (M740) and 4.3 Hz (SC2000). Each pixel of the images corresponds to particular viewing zenithal and azimuthal angles θ_v and φ_v (whose computations can be found in Lagouarde et al., 2000). The partial overlapping of the FOV of the two instruments is used for intercalibration of the recorded images.

The protocol of measurements consisted of a set of several short flight lines flown in opposite directions all crossing at the city centre. For nighttime, the flight lines were oriented N↔S, W↔E, NW↔SE and NE↔SW. Radiosoundings were simultaneously performed by Météo France to provide atmospheric profiles of temperature and humidity for use with the LOWTRAN 7 model (Kneisys et al., 1988) to determine atmospheric corrections for the thermal measurements. Measurements of surface temperature at ground level were also collected simultaneously to the flights by three groups using hand-held TIR radiometers (Minolta/Land Cyclops Compac 3 [1]) along 2 streets close to the central site, viewing walls, streets and pavements. A few measurements over roof samples were also collected.

The reader is referred to the papers of Lagouarde et al. (2000, 2004) which describe the data processing in detail. Combining all the images acquired along the 8 flight lines allows one to generate the anisotropy $T_{b\ \text{off-nadir}} - T_{b\ \text{nadir}}$ averaged by 1° steps on and in all azimuthal viewing directions φ_v (referred to North) and for zenithal view angles θ_v (referred to nadir viewing) up to 60°. No correction for pitch and roll angles of the aircraft were performed, but the excellent flight conditions at night led us to consider the accuracy on the θ_v and φ_v angles as being within ±2°. The same (θ_v, φ_v) viewing geometry

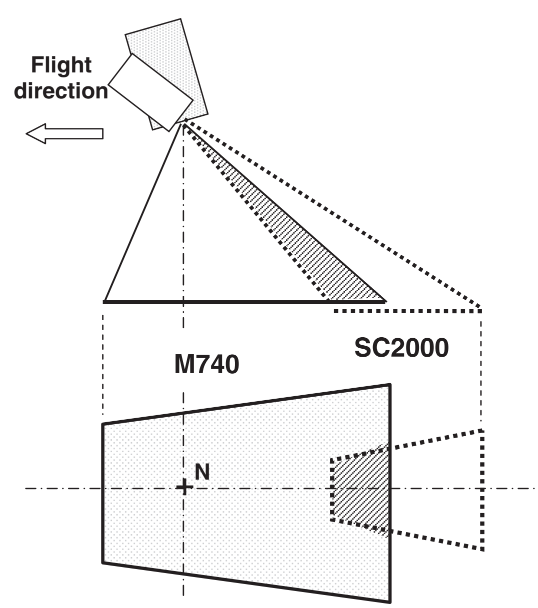

Fig. 1. Principle of angular measurements: schematic of instrumental setup aboard the aircraft with corresponding areas seen at ground level. For a 460 m flight height above ground, the approximate size of the areas is 720×440 to 570 m and 490×180 to 300 m for the M740 and SC2000 cameras respectively. The dashed areas indicate the overlapping of the FOV of the 2 cameras and the corresponding area at ground. N corresponds to the nadir of the aircraft.

[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.