Large-eddy simulation of a diurnal cycle in a coastal urban environment

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1 INTRODUCTION

Urban areas tend to exhibit microclimates, i.e. small-scale variation of environmental conditions in the urban canopy layer (UCL), which can directly influence people's experience in terms of wind and thermal comfort [1]. The principal thermal forcing to the urban surface, which is thermally coupled with the UCL, is the diurnal cycle of solar radiation, with the surface energy balance (SEB) dictating heat transfer and storage [2]. An important factor influencing the evolution of the SEB is thermal inertia: the fact that surface temperature changes tend to be delayed and damped compared to the solar forcing [3].

This study involves simulating an urban environment with a hot, arid climate in order to provide insight into the microclimatic processes contributing to thermal comfort. The case consists of a set of buildings that are located by the coast (Fig. 1). The buildings are situated on underlying terrain, and there is a substantial section of terrain where there are no buildings. This enables a comparison of the microclimate of the built environment with that of the open terrain.

2 METHODOLOGY

The model used in this study is uDALES v2.0 [4]: a large-eddy simulation (LES) model with a two-way coupled 3D SEB scheme. The governing equations for the flow are discretised on a Cartesian computational grid, but the immersed boundary method (IBM) uses a geometry representation that is unstructured, i.e. the surface is not necessarily aligned with the grid. This is a unique feature of the model in comparison to other LES tools with SEB modelling capabilities, and it means that it can faithfully capture radiative transfer for realistic (non-grid-aligned) geometries. The geometry is specified using an STL that was obtained from a CAD model for a realistic masterplan (Fig. 1).

A precursor simulation is used to generate an inflow boundary condition that is characteristic of the marine boundary layer at the site. The main simulation uses data from a nearby weather station for the inflow air temperature and radiative forcing to the surface. The simulation is carried out for several days in order to capture the effect of thermal inertia.

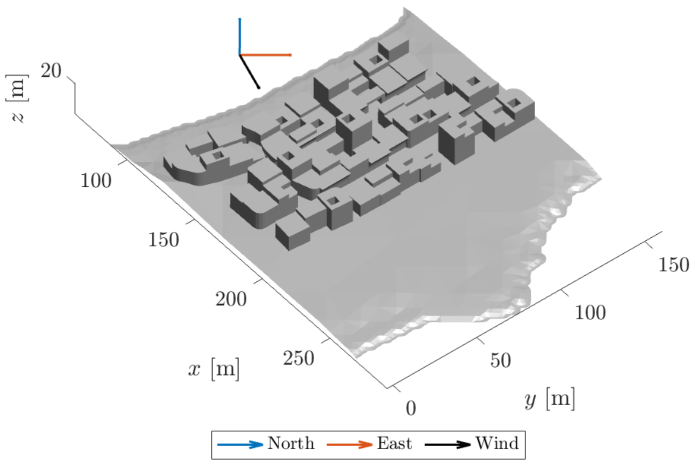

Fig. 1: Geometry used in main simulation, with North, East, and prevailing wind direction indicated.

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The study consists of the following three aspects of investigation. The first aspect involves the bulk thermal response of the whole surface in terms of the temperature and energy balance, for both the buildings and the terrain (Sect. 3.1). In the second aspect, the evolution of the net radiation, the surface temperature, and the sensible heat flux for the various surface facets (roofs, walls, streets, and terrain) are presented (Sect. 3.2). The third aspect aims to understand the behaviour of environmental quantities, including the street-level air temperature and mean radiant temperature (MRT), considering these key SEB quantities and the flow (Sect. 3.3).

3 RESULTS

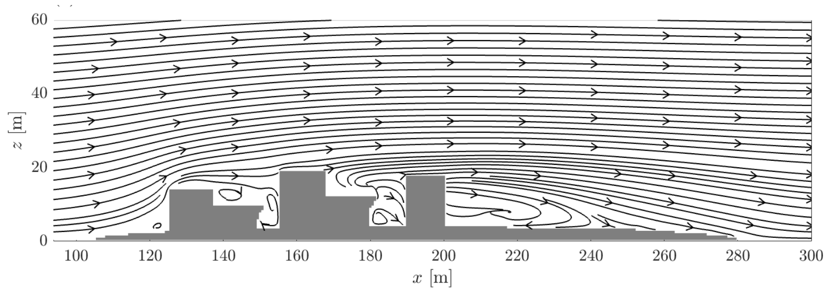

Fig. 2: Streamlines at y=50 m. Note the separation bubble behind the last row of buildings.

3.1 Bulk surface energy balance

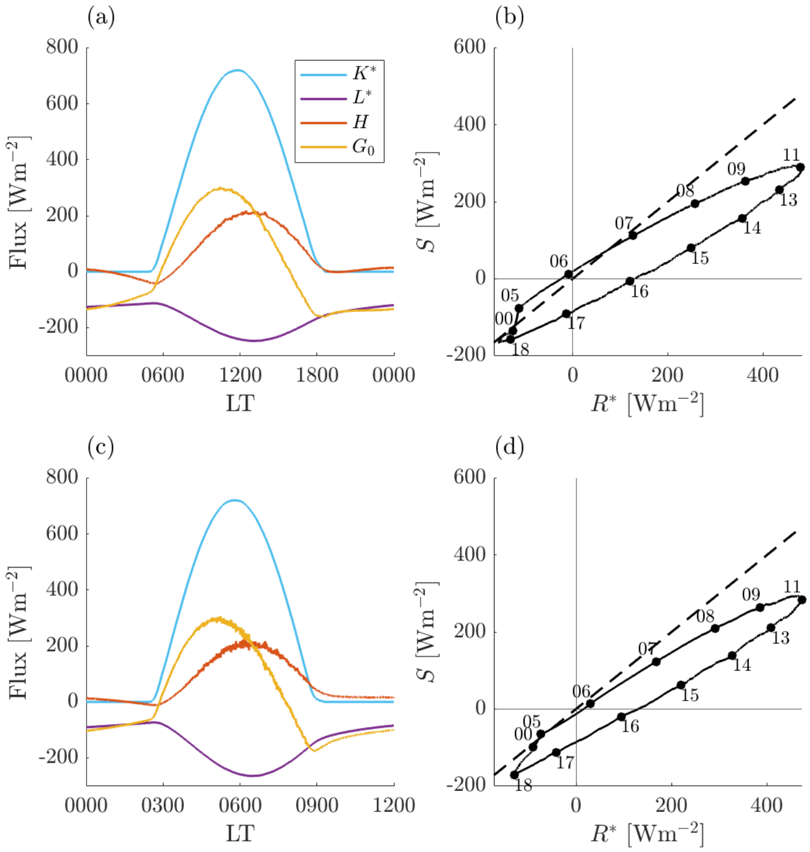

Fig 3: Surface energy fluxes (net shortwave radiation (K^*), net longwave radiation (L^*), sensible heat flux (H), and exterior conduction (G_0)) against local time (LT); and storage ($S = G_0 – G_d$, where G_d is the interior conduction) against net radiation ($R^* = K^* + L^*$) in the form of a Lissajous figure; respectively for the built environment (a,b) and the terrain (c,d).

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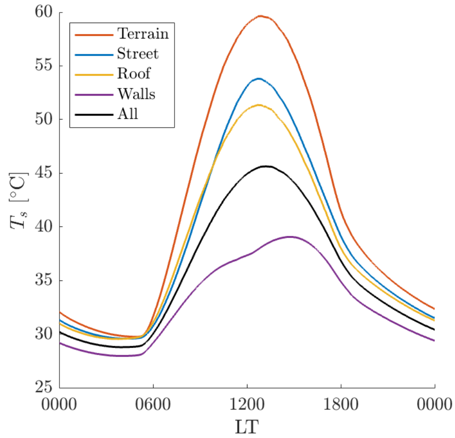

Fig 4: Area-averaged surface temperature (T_s) against local time (LT) for various facet types, where `All' includes the streets, roofs, and walls.

3.2 Spatial variation of surface energy balance

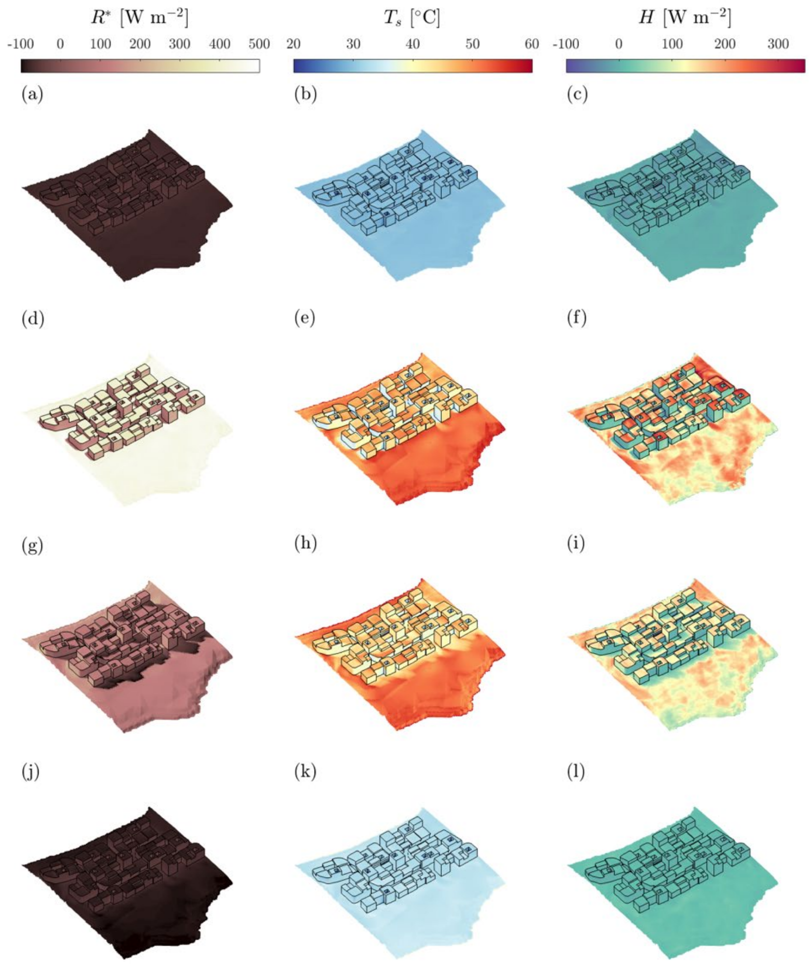

Fig. 5: 3D visualisation of facet net radiation (R^*), surface temperature (T_s), and sensible heat flux (H), respectively at 0400 LT (a-c), 1600 LT (d-f), 1600 LT (g-i), and 2200 LT (j-l).

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3.3 Atmospheric quantities

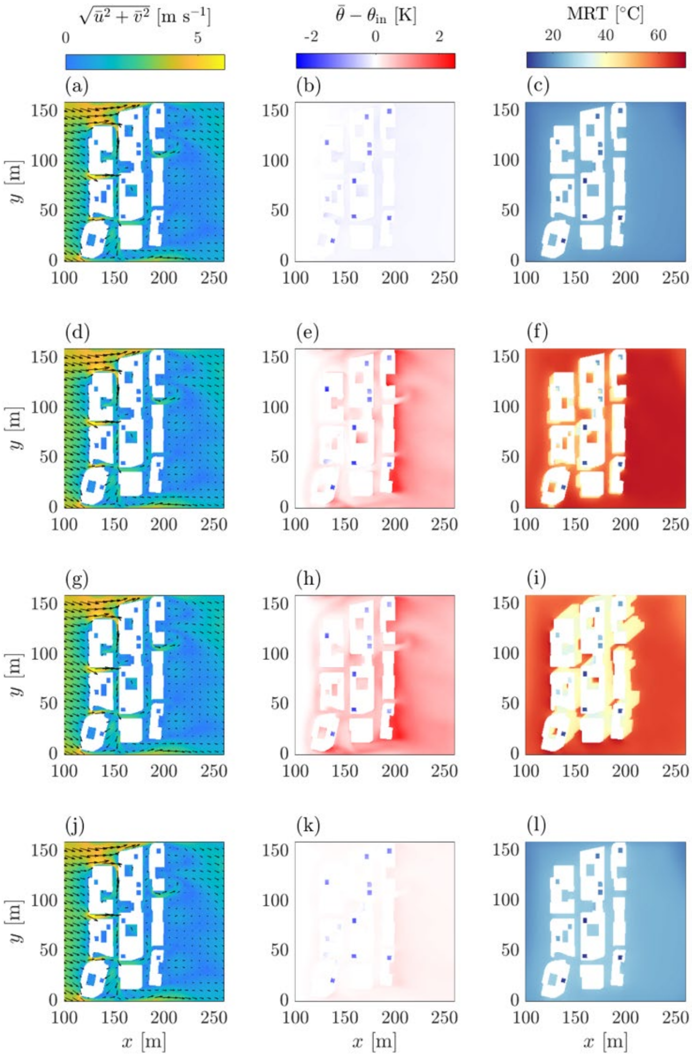

Fig. 6: Street-level wind speed and velocity vectors, and air potential temperature with respect to inflow ($\theta - \theta_{in}$), averaged during time interval: 0300-0400 LT (a-b), 0900-1000 LT (d-e), 1500-1600 LT (g-h), 2100-2200 LT (j-k); and MRT at 0400 LT (c), 1000 LT (f), 1600 LT (i), 2200 LT (l).

4 DISCUSSION

The bulk SEB for the built environment is similar to that of the terrain (Fig. 3), despite the terrain having a higher surface temperature (T_s) throughout the day on average than the built environment, and indeed than any of the facet types that make it up (Fig. 4). This is likely because their effective albedo is similar, resulting in approximately the same shortwave radiation.

The net radiation (R^*) has a strong influence on T_s (Fig. 5) and mean radiant temperature (MRT) (Fig. 6). In particular, the shading of streets results in them having a substantially lower T_s than the terrain, despite having the same material properties. Thermal inertia is important for the evolution: while R^* decreases in the afternoon, T_s does not to the same extent (Fig. 5).

The area of the domain with the highest air temperature is immediately in the wake of the buildings (Fig. 6), even though the local T_s and sensible heat flux (H) are relatively low. This is caused by flow behaviour: there is a separation bubble resulting in recirculation of air from the hot terrain (Fig. 2).

These results have implications for the ability of built environments to provide thermal comfort in hot climates and demonstrate the importance of considering microclimatic processes over a diurnal cycle.

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