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Momentum exchange and domain-size effects in urban-boundary layer large-eddy simulations

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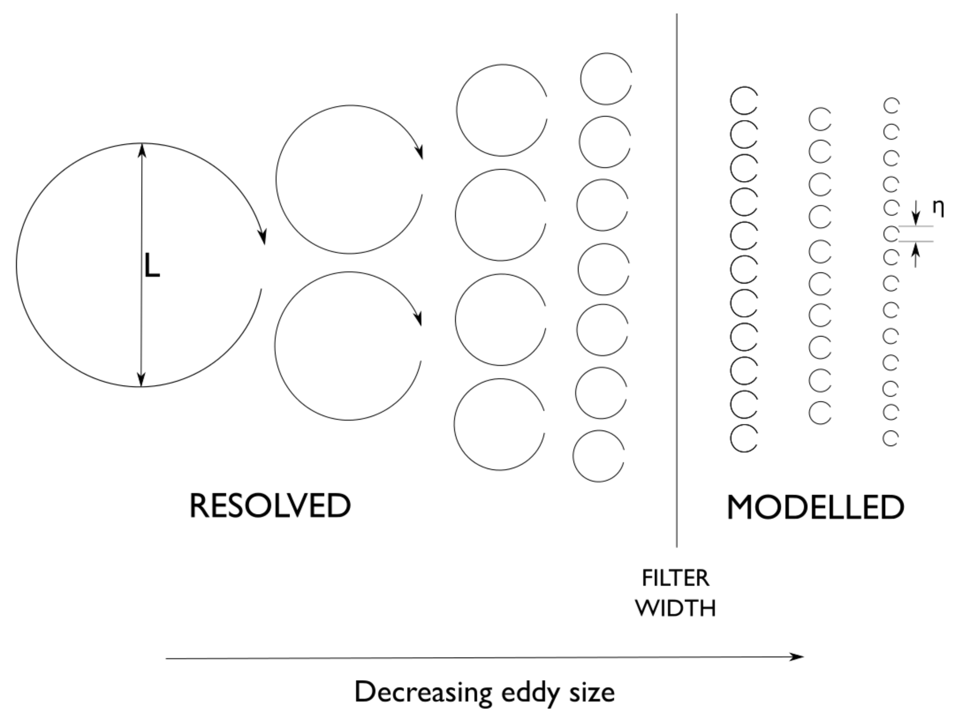
INTRODUCTION

The urban boundary layer (UBL) is the region of air above a city which is affected by the presence of the city. The aim of this study is to simulate air flow over a UBL using large-eddy simulation (LES), and in particular to understand the exchange of momentum in a UBL. Several studies have been carried out on other flow properties in a UBL, such as scalar transport and buoyancy. Furthermore, momentum transport in turbulent flows over both smooth and rough walls is relatively well-understood. However, the impact of very large roughness elements on the exchange of momentum has not been studied in detail. The key aim of the current study is to understand the interactions between the roughness elements and the rest of the flow field, and the height at which the presence of buildings (represented by large roughness elements) influences various properties in the flow.

LARGE-EDDY SIMULATION

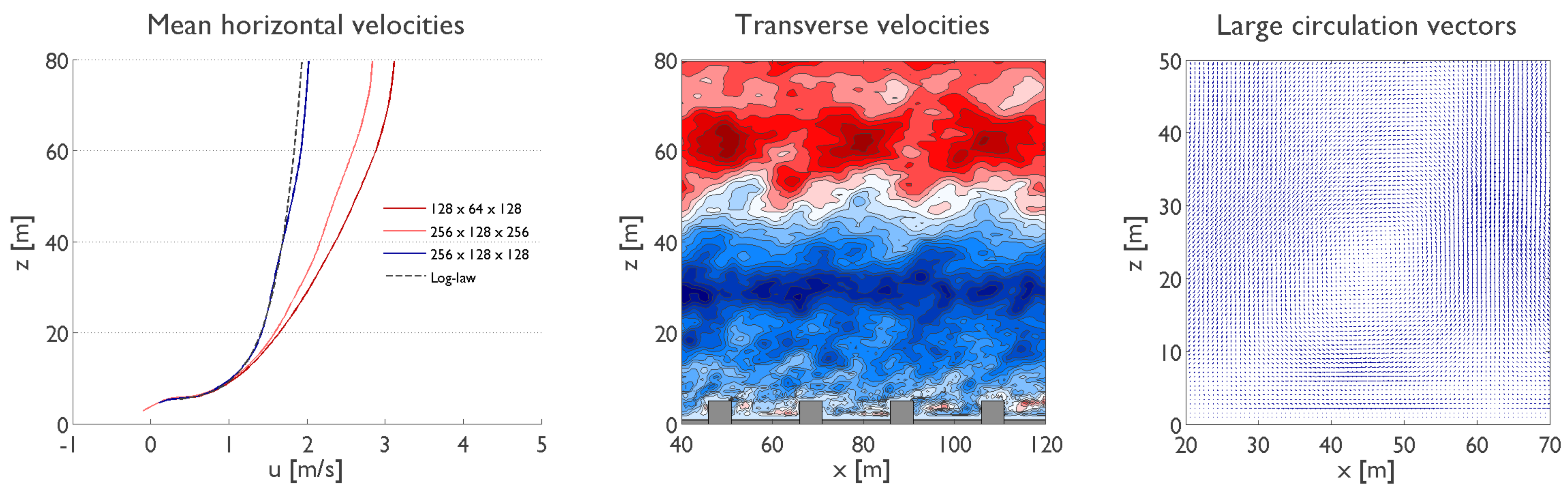
Turbulent flows can be described as a series of eddies of varying sizes. Turbulence is produced at the larger scales (governed by the geometry of the flow) and then cascades down to the smaller scales (governed by viscosity) where it is dissipated. The basic principle behind LES is that the small eddies in a flow are modelled while the larger eddies can be resolved – this is possible since the small-scale turbulence is largely isotropic, and since 90% of the energy in the flow is found in the larger scales of the turbulence.

LES is performed by solving the filtered Navier-Stokes equations, replacing the subgrid stress tensor τ_{ij} with an eddy-viscosity model. Our simulations have been carried out using DALES (Heus et al, 2010).



DOMAIN SIZE EFFECTS

Initially, the simulation was carried out in a 128 × 64 × 128 domain (8*h* × 4*h* × 8*h*, where *h* is the block height). The logarithmic profile that can typically be fitted to a turbulent flow was only valid up to 2h (see left figure, below). This was because the domain was too small, so that the largest eddies in the *x*-direction were being restricted; this interpretation was supported by performing a spectral analysis. This meant that the turbulent kinetic energy that should have been found in the largest eddies was instead resolved in the mean horizontal velocity.

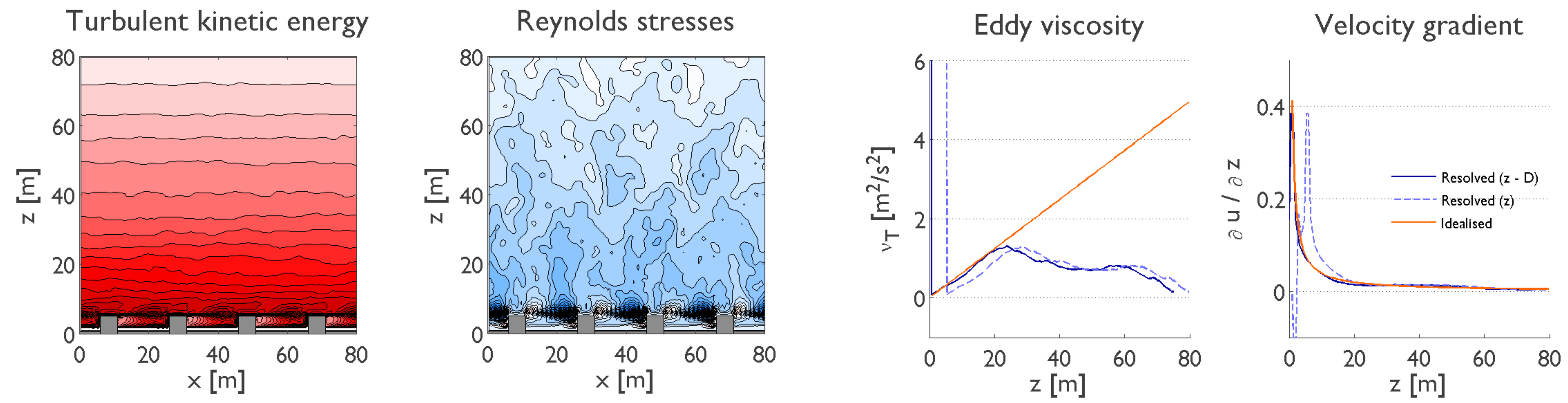


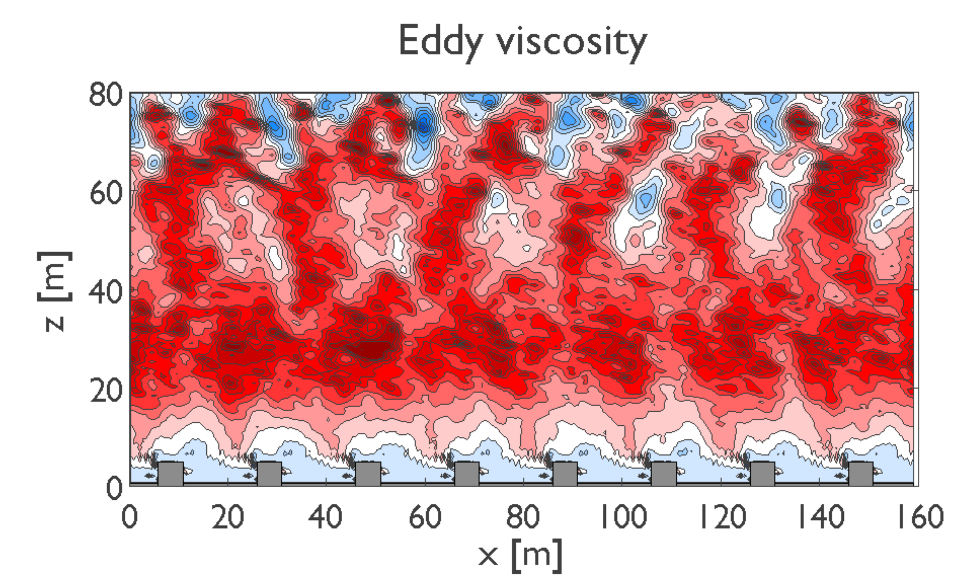
Doubling the domain size in the *x*- and *y*-directions led to the log-law being valid up to a height of 10*h*. However, this led to an imbalance between the pressure gradient driving the flow and the spatially-averaged profile of the Reynolds stresses (which would lead to unsteady acceleration of the fluid). It was found that this was due to a large circulation rotating about the *x*-axis, and therefore that assumptions made during spatial averaging were invalid. Therefore, correction terms must be included when calculating Reynolds stresses in a long, narrow domain.

EFFECT OF ROUGHNESS ELEMENTS

The presence of the roughness elements caused little horizontal variation in the mean velocities above the canopy. This was also true of the turbulent kinetic energy and the root-mean-square velocities. There was however, a noticeable variation in the Reynolds stresses in the horizontal direction, as discussed below.

In the larger domain, it was possible to fit a logarithmic profile to the mean horizontal velocity profile. It is suggested that, in an urban boundary layer, introducing a zero-plane displacement height *D* from which an effective *z*-coordinate could be measured produces a more accurate log-law than simply scaling *z* by a large roughness height *d*. *D* was calculated by plotting various log-layer identities and comparing resolved and idealised values.





MOMENTUM EXCHANGE

The eddy viscosity was calculated throughout the domain, as the ratio between the Reynolds stresses and the velocity gradient (∂u/∂z) – this is a measure of the amount of turbulent mixing in the fluid. It was found that this showed large variation in the x-direction, which may lead to regions of stagnation in the fluid.

A number of layers were identified in the flow (equivalent to the layers in smooth-wall flows which are invalid in UBL flows). These layers included a canopy layer (below z = D), a production layer (above which the turbulence shows no horizontal variation), and a momentum layer, up to which the roughness elements affect the transport of momentum in the flow.

CONCLUSIONS

Large-eddy simulations using DALES were carried out for turbulent flows over large roughness elements. It was found that a 128 × 64 × 128 domain was too small to capture the largest eddies in a flow; furthermore, long domains result in large circulations that require corrections when calculating the Reynolds stresses. Once these issues had been resolved, it was found that introducing a zero-plane displacement height *D* produced a more realistic log-profile than using a roughness height alone. Finally, it was discovered that turbulent mixing is reduced above individual roughness elements up to three-quarters of the domain height.

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