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Wall Modelled Lattice Boltzmann Method for Atmospheric Boundary Layers

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Advancements in computational resources and numerical methods have fuelled a paradigm shift in recent years, leading to the widespread adoption of Large Eddy Simulations (LES) for applied engineering applications. In this context, the Lattice Boltzmann Method (LBM) has gained increasing popularity, driven by its inherent parallelism and scalability, particularly on graphics processing units (GPU). However, accurately capturing the viscous sub-layer is crucial in fields like urban flows, atmospheric sciences, and heat transfer, as it governs near-wall turbulent structures, which drive the production and dissipation of kinetic energy, and Reynolds stress anisotropy. Two approaches are often considered: wall-resolved LES (WRLES) or wall-modelled LES (WMLES). Choi and Moin estimate that resolving a turbulent boundary layer scales near-quadratically with Reynolds number, $N_{\text{total}} \propto Re^{13/7}$, making WRLES computationally intensive or infeasible [1]. In contrast, WMLES resolves the scales of motion at the outer layer while approximating the inner boundary layer via an appropriate wall model, with grid point dependency that is approximately linear with Reynolds number [1]. Albeit, LBM-specific wall modelling approaches have received limited attention and remain an active area of research [2,3].

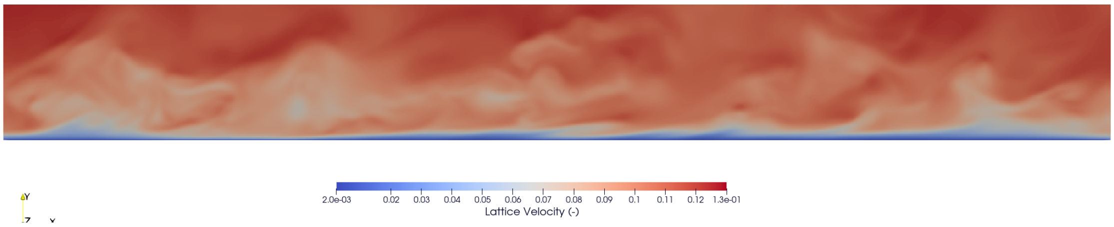

Figure 1: WMLES of turbulent boundary layer at $Re_\tau = 1000$.

In this study, we generalise the inverse momentum exchange method (iMEM) proposed by Asmuth et al. [2] and implement it within the open-source multi-physics framework *waLBerla* using its code-generation interface, *lbmpy*. The core principle of the iMEM approach is to enforce a shear stress consistent with the *law of the wall* by adjusting the slip velocity within a bounce-back boundary scheme. This scheme differs from other wall-modelling approaches in the literature, as it neither modifies the eddy viscosity nor requires reconstruction of distribution functions, whilst being extendable to non-planar boundaries [2]. The code-generation interface automates CPU/GPU portability and provides flexibility in selecting the bounce-back scheme or wall function used within the iMEM kernel. We validate the iMEM implementation by benchmarking it against DNS simulations conducted by Lee and Moser[4] for a canonical turbulent channel flow at $Re_\tau = 1000, 2000, 5200$, before demonstrating its applicability to neutral atmospheric boundary layers. All simulations are conducted using the fourth-order accurate cumulant collision operator with the Galilean correction[5, 6]. Furthermore, the distribution functions are formulated in their well-conditioned form, $f_i^{wc} = f_i - w_i$, to reduce the impact of round-off errors[5]. We analyse the flow statistics at different grid resolutions, for varying lattice dimensions, wall-functions, and bounce-back schemes, highlighting the applicability of the iMEM-based, code-generated WMLES capability in high Reynolds number flows.

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