

Effectiveness of Wall-Modeled Large-Eddy Simulation in Simulating Tornado-Like Vortices

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SUMMARY

Wall-modelled large-eddy simulation (WMLES) can provide a computationally efficient alternative to wall-resolved LES (WRLES) for high-Reynolds-number flows, but its effectiveness in simulating tornado-like vortices is uncertain as the near-ground flow region exhibit strong curvature and adverse pressure gradients that violate the equilibrium assumptions of wall-function. In this study, WMLES is used to reproduce the flow field of a tornado-like vortex generated by a tornado simulator. The major characteristics of the numerically simulated velocity and surface-pressure fields are compared with experimental measurements. It is found that while WMLES can replicate mean characteristics of the velocity and pressure fields, it falls short in reproducing fluctuating characteristics such as the standard deviation of surface pressure. For reference, WRLES is used to replicate another vortex generated by the simulator. It is shown that WRLES is much more effective in reproducing the mean and fluctuating characteristics of experimentally generated tornado-like vortices than WMLES.

Keywords: Tornado-like vortices, Wall-modelled LES, near-ground flow fields, Wall-resolved LES.

1. INTRODUCTION

Numerical studies of tornado simulators and tornado-like vortices are increasingly using large-eddy simulation (LES) to investigate the tornado-vortex dynamics. Studies have shown LES can be used to reproduce key flow features of tornado-like flows such as the radial profile of mean tangential velocity, the formation of corner flow, and the transition from single-celled to two-celled vortices with increasing swirl ratio e.g. (Ishihara et al.,2011), (Liu et al.,2020). LES has also been applied to downburst-type non-synoptic winds; for example, Aboshosha et al. (2015) simulated stationary downbursts and quantified their turbulent structure over different terrain exposures. However, resolving all dynamically important near-wall eddies in wall-resolved LES (WRLES) is prohibitively expensive for highly turbulent flows like tornado flows, so wall-modelled LES (WMLES) can be adopted as a more computationally efficient alternative (Piomelli and Balaras,2002). Bose and Park (2018) further showed that WMLES can be applied to flows over complex geometries such as airfoils, suggesting that it is also suitable for simulating tornado simulators. Nonetheless, the applicability of WMLES in simulating tornado-like vortices needs to be further examined because the near-ground tornado-like flow includes adverse pressure gradients and strong curvature, which may not be effectively modelled by equilibrium wall functions. In addition, Zhang (2024) recently showed that surface-pressure predictions can be highly sensitive to near-floor resolution and wall treatment, indicating a need for a systematic evaluation of the application of WMLES in simulating tornado-like vortices. This paper presents a WMLES aimed at replicating a tornado-like vortex generated in a Ward-type tornado simulator. The characteristics of the simulated flow are compared with those of the physically generated vortex. As a reference, a WRLES is used to replicate another tornado-like vortex to enable a comparison between the performances of WMLES and WRLES.

2. METHODOLOGY

2.1. VorTECH facility and numerical domain

The target tornado-like vortex for the WMLES is generated by the VorTECH, a Ward-type tornado simulator at Texas Tech University. Figure 1(a) shows a schematic elevation view of the simulator, which has been presented and described in Tang et al. (2018). Figure 1 (b) shows the computational domain of the numerical model, which reproduces the essential flow-controlling components of the simulator. Two turning vane angles of 25° and 30° relative to the radial directions are used in the experiments to generate vortices of swirl ratios $S=0.65$ and $S=0.83$, respectively. The WMLES model was used to reproduce the vortex of swirl ratio $S=0.83$ and the WRLES model was used to reproduce the other vortex by setting the turning vane angles in the computational domain the same as those in the experiments. In the numerical simulations, swirling velocity is applied at the inlet, which is an annular plane of the same height as that of the convergence zone. The outlet plane at the honeycomb base is modeled as an open/outflow boundary by imposing free stream pressure with zero normal-gradient to the plane while allowing intermittent backflow expected in two-celled vortices. All solid boundaries (the turning vanes, converging region walls, floor, and walls of the updraft hole) are treated as no-slip walls. For WMLES, the flow adjacent to the floor is modelled with equilibrium wall functions; for WRLES, the flow in the near-floor region is resolved. Figure 1(c), displays the WMLES fully structured hexahedral mesh with refined resolution near the walls and within the vortex core as the flow in these regions have large pressure gradients. The WMLES configuration's wall normal first-cell height is chosen as 0.005m ensuring that $y_1^+ > 30$ to place the first off-wall cell outside the viscous sublayer; in the WRLES configuration the wall-normal first-cell height spacing is refined further to 3.2×10^{-5} m with 26 inflation layers to achieve $y_1^+ < 1$ over the entire floor region.

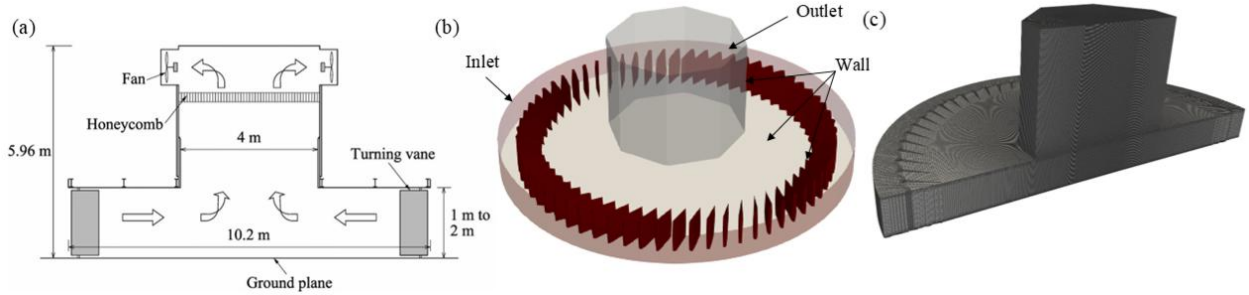


Figure 1: (a) Schematic elevation view of VorTECH (b) Computational domain and (c) structured mesh

2.2. Governing equations and turbulence modelling

The governing equations for the 3D incompressible LES are the filtered continuity equation and Navier-Stokes equations given as:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0; \quad \frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial}{\partial x_j} (\bar{u}_i) = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j^2} - \frac{\partial \tau_{ij}^{SGS}}{\partial x_j} \quad (1)$$

where, \bar{u}_i ($i=1, 2, 3$) and \bar{p} are the three filtered velocity components and pressure, respectively, ρ is air density, τ_{ij}^{SGS} denotes the subgrid-scale (SGS) stress tensor.

$$\tau_{ij}^{SGS} = \frac{1}{3} \tau_{kk} \delta_{ij} - 2\nu_t \widetilde{S}_{ij} \quad (2)$$

In LES, the governing equations are spatially filtered so that the large energy-containing motions

are resolved on the grid while the effects of unresolved sub-grid motions are modeled. The eddy viscosity (ν_t) in Eqn. (2) is the term that must be modelled, and \widetilde{S}_{ij} is the strain rate (deformation) tensor of the resolved flow field $\widetilde{S}_{ij} = (\partial \bar{u}_i / \partial x_j + \partial \bar{u}_j / \partial x_i)$. In this study, the standard Smagorinsky turbulence model is used. For this model, $\nu_t = (C_s \Delta)^2 |\widetilde{S}|$, in which $\Delta = (\Delta_x \Delta_y \Delta_z)^{1/3}$ is the effective grid scale, C_s is the Smagorinsky coefficient and $|\widetilde{S}| = \sqrt{2 \widetilde{S}_{ij} \widetilde{S}_{ij}}$ is the magnitude of the filtered strain rate tensor. The simulations are carried out in OpenFOAM and the pressure–velocity coupling is handled via the PISO algorithm with two corrector steps per time step. The physical time step was set to 1×10^{-4} s and 7×10^{-5} s for WMLES and WRLES respectively ensuring the Courant number did not exceed 1. Time-averaged statistics are computed over a statistically stationary interval of length 70s, after discarding an initial transient period of 10s. The velocity and the pressure of the flow are sampled at 625Hz.

3. RESULTS AND DISCUSSIONS

Figure 2 compares the radial and vertical profiles of normalized mean velocity components of the simulated flows with those of the physically generated vortices. The WMLES for $S=0.83$ captures the overall radial profile of the mean tangential velocity except that the numerically produced mean tangential velocity is higher in the inner-to-near-core region and decays slightly slower at locations well outside the vortex core. It is also seen that the simulation is effective in reproducing the vertical profile of the mean radial velocity observed in the experiment except over a narrow height range where the mean radial velocity is at or near the maximum positive value. Similarly, the WRLES profiles for $S = 0.65$ also included and show much closer agreement with the corresponding experimental data especially the mean tangential velocity curves, further indicating that the main vortex structure is consistently reproduced across the two swirl ratios and modelling approaches. However, the radial curves near the ground of the WMLES curve have the largest difference compared to the experiment and WRLES, this points to the sensitivity of near-floor flow to wall modelling that later manifest in the surface-pressure statistics.

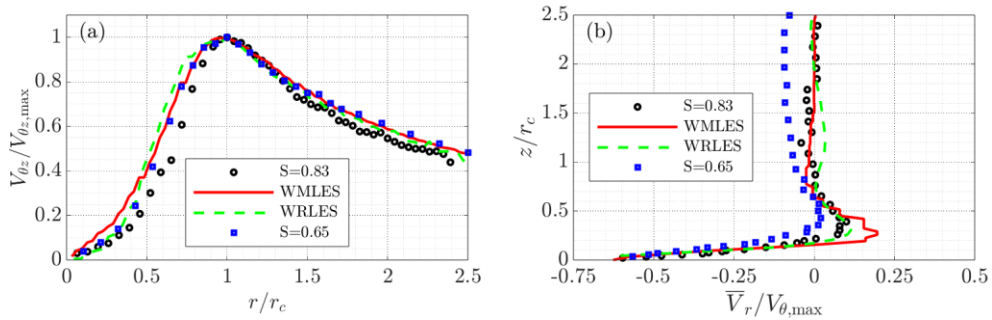


Figure 2: Comparison between mean characteristics of flow: (a) Radial profiles of mean tangential velocity, (b) vertical profiles of mean radial velocity at core radius

Figure 3 compares the mean and fluctuating characteristics of the surface-pressure resulting from the WMLES and WRLES with those from experimental measurements. It is evident that the numerical results from the WRLES match the experimental data much more closely than the results from WMLES. This is particularly true at radial positions near the center of the vortices, where the normalized standard deviation of the surface pressure resulting from WMLES can be much larger than the experimental results while the results from WRLES are much closer to the experimental

measurements. This can be due to the large adverse pressure gradient in this region. Figure 3 also suggests that results from neither WMLES nor WRLES can match the standard deviation of surface pressure measured in the experiments at locations well beyond the core radii of the vortices. This can be attributed to the fact that the numerical models assume the floor to be perfectly smooth, while the surface of the physical simulator floor has some roughness. Regardless, Figure 3 indicates again the limitation of WMLES with equilibrium wall functions in reproducing tornado-like vortices.

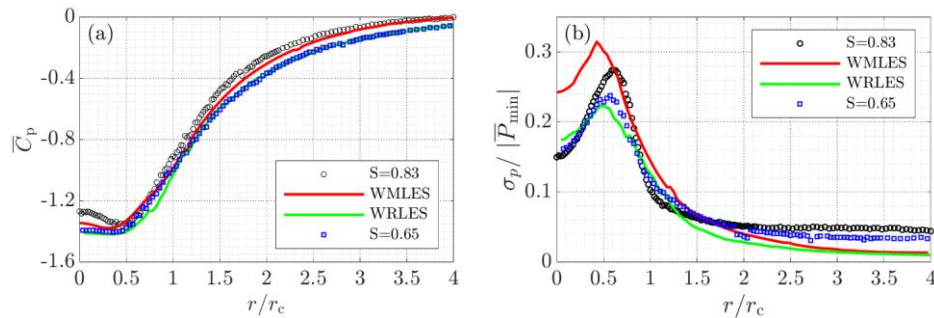


Figure 3: Comparison of radial profiles of surface-pressure resulting from numerical simulations and experimental measurements: (a) Mean value and (b) standard deviation of surface pressure coefficient

4. CONCLUSION

This study evaluated the effectiveness of WMLES with equilibrium wall function in reproducing tornado-like vortices generated in a Ward-type simulator. The WMLES was able to recover the overall vortex structure and capture the main trends of the mean velocity and surface-pressure fields. However, noticeable discrepancies were found in the surface-pressure statistics, especially in the near-ground core region. In contrast, the WRLES results showed much closer agreement with the experimental data for both mean and fluctuating quantities. These findings indicate that WMLES with equilibrium wall functions have limitations in representing the strongly non-equilibrium near-ground physics of tornado-like vortices, whereas WRLES can be much more effective for accurately reproducing the velocity and pressure fields in such flows. This highlights the need for wall functions that could account for non-equilibrium effects in near-ground tornado-like flows.

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