Large-Eddy Simulations of Stability-Varying Atmospheric Boundary Layer Flow over Isolated Buildings

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ABSTRACT: This study explores the response of flow around isolated cuboid buildings to variations in the incoming turbulence arising from changes in atmospheric boundary layer (ABL) stability using a building-resolving large-eddy simulation (LES) technique with explicit representation of building effects through an immersed body force method. An extensive suite of LES for a neutral ABL with different model resolution and advection scheme configurations reveals that at least 6, 12, and 24 grid points per building side are required in order to resolve building-induced vortex shedding, mean-flow features, and turbulence statistics, respectively, with an advection scheme of a minimum of third order. Using model resolutions that meet this requirement, 21 building-resolving simulations are performed under varying atmospheric stability conditions, from weakly stable to convective ABLs, and for different building sizes (H), resulting in $L_{\text{ABL}}/H \approx 0.1\text{--}10$, where L_{ABL} is the integral length scale of the incoming ABL turbulence. The building-induced flow features observed in the canonical neutral ABL simulation, e.g., the upstream horseshoe vortex and the downstream arch vortex, gradually weaken with increasing surface-driven convective instability due to the enhancement of background turbulent mixing. As a result, two local turbulence kinetic energy peaks on the lateral side of the building in nonconvective cases are merged into a single peak in strong convective cases. By considering the ABL turbulence scale and building size altogether, it is shown that the building impact decreases with increasing L_{ABL}/H , as coherent turbulent structures in the ABL become more dominant over a building-induced flow response for $L_{\text{ABL}}/H > 1$.

KEYWORDS: Turbulence; Boundary layer; Large eddy simulations; Urban meteorology

1. Introduction

The fundamental understanding of flow structures over urban topography has primarily been built on laboratory experiments and direct numerical simulations (DNSs) of flow around isolated surface-mounted cubic buildings, immersed in shear-driven turbulent flow at Reynolds numbers of $O(10^3\text{--}10^4)$ (e.g., Martinuzzi and Tropea 1993; Meinders and Hanjalić 1999; Yakhot et al. 2006; Diaz-Daniel et al. 2017; Khan et al. 2018; and references therein). Despite the simple building geometry, the measurements and DNS results with such configuration have revealed characteristic features of flow response to buildings, including flow separations in the upstream and front corners of building's top and lateral faces, flow recirculation and reattachment, as well as unsteady vortex shedding in the wake region. One of the practical limitations of the wind tunnel experiments and DNS techniques is prohibitive costs that have constrained their applications for the most part to laboratory scales (i.e., low Reynolds numbers) and neutral stratification regimes. On the other hand, experimental and DNS studies have provided simulation benchmarks for relatively cost-effective computational fluid dynamics (CFD) models, such as Reynolds-averaged Navier–Stokes (RANS) models (e.g., Gorlé et al. 2010; van Hooff et al. 2017; Longo et al. 2019) and large-eddy simulation (LES) models (e.g., Shah

and Ferziger 1997; Tseng et al. 2006; Lim et al. 2009; Bazdidi-Tehrani et al. 2013; Boppana et al. 2013; Auguste et al. 2019), which are more appropriate to study building impacts on atmospheric scales, i.e., higher Reynolds numbers, and non-neutral stratification regimes.

The atmospheric boundary layer (ABL) over land is characterized by a well-defined diurnal cycle driven by radiative cooling and heating of Earth's surface, varying from the nocturnal stable boundary layer (SBL) to the daytime convective (or unstable) boundary layer (CBL), and transitions between them (Stull 1988). In addition, the heterogeneous nature of urban surfaces creates unique urban weather and climate by directly altering the dynamics and thermodynamics in the ABL (e.g., low-level winds and surface energy budgets; Collier 2006). The characteristics of atmospheric turbulence in the ABL, including coherent structures (e.g., near-surface streaks, convective rolls, and open cells) and the scales of the most energy-containing larger eddies relevant to the coherent structures, vary substantially across ABL stability regimes (e.g., Moeng and Sullivan 1994; Sullivan et al. 2016; Salesky et al. 2017). A number of LES studies have contributed to advancing the knowledge on this subject mainly for the flow over horizontally homogeneous and structure-free surfaces (e.g., Nieuwstadt et al. 1993; Andren et al. 1994; Moeng and Sullivan 1994; Kosović and Curry 2000; Kumar et al. 2010; Sullivan et al. 2016; Salesky et al. 2017). Recently, the LES scope has been expanded to include the flow over urban landscapes and/or complex terrains with improvements to the explicit representation of effects of these heterogeneous surfaces, in response to an increasing demand for microscale information of the urban flows (e.g., Bou-Zeid et al. 2009;

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Lundquist et al. 2012; Giometto et al. 2016, 2017; Gronemeier et al. 2017; García-Sánchez et al. 2018; Auguste et al. 2019; Auvinen et al. 2020; Baumann-Stanzer et al. 2020; Sauer and Muñoz-Esparza 2020; Muñoz-Esparza et al. 2020). However, the majority of these urban-resolving LES studies have focused on neutrally stratified ABL (NBL) conditions. A few building-resolving LES studies have considered nonneutral ABL flows over urban-like surfaces (Park and Baik 2014; Jiang et al. 2017; Wang and Ng 2018; Grylls et al. 2020). These studies have investigated changes of mean ABL circulations and/or turbulent statistics of the ABL by the presence of urban-like surfaces (e.g., horizontally averaged profiles of first- and higher-order turbulence statistics). However, the fundamental understanding of changes of building-induced local circulations, e.g., flow separations and vortex modes in the vicinity of buildings, by interaction between nonneutral ABLs and buildings remains poorly understood.

As a first step toward bridging this gap in the fundamental understanding of building-induced local flow structures in realistic ABL stability regimes, we explore the response of flow around isolated cuboid buildings under various atmospheric stability conditions, modulated by changing the surface heating and vertical structure of the incoming flow, which is at a quasi-equilibrium state for the surface heating. The NCAR GPU-accelerated LES model, FastEddy[®] (hereafter FastEddy) (Sauer and Muñoz-Esparza 2020), is used with explicit representation of building effects using an immersed body force method (IBFM; Muñoz-Esparza et al. 2020) and a Smagorinsky–Lilly subgrid-scale (SGS) model (Lilly 1966; Deardorff 1980) based on a diagnostic SGS turbulence kinetic energy (TKE) equation. The computational efficiency gain of the GPU-based FastEddy LES model compared to CPU-based models, 1 GPU matching 256 CPUs (Sauer and Muñoz-Esparza 2020), enables a comprehensive assessment based on a large number of building-resolving simulations: a total of 33 simulations with 21 of them at 1- or 2-m grid spacing.

The remainder of the paper is organized as follows. Section 2 provides a model description and simulation setup. Section 3 establishes model resolution and advection scheme requirements for adequately simulating mean-flow features and turbulence characteristics over isolated buildings in the NBL, based on a total of 13 simulations. In section 4, we systematically analyze the effects of atmospheric stability and its interplay with the buildings size (H), leading to a total of 20 additional simulations spanning a substantial range of stability and building size configurations. Summary and discussions follow in section 5.

2. Model description and simulation setup

The NCAR GPU-accelerated FastEddy LES model (Sauer and Muñoz-Esparza 2020) used in the present study solves the fully compressible Navier–Stokes equations discretized using finite difference approximations. A third-order in time Runge–Kutta scheme and an upwind-biased fifth-order in space advection scheme on an unstaggered A grid were used unless otherwise stated. No acoustic filtering, e.g., time-splitting technique, was applied. To parameterize effects of SGS

turbulence on the resolved (or filtered) turbulent flow, a Smagorinsky–Lilly SGS model was adopted with a diagnostic SGS TKE equation (e.g., Moeng et al. 2007; Muñoz-Esparza et al. 2014b). The surface momentum and heat fluxes at ground surfaces were parameterized based on the Monin–Obukhov similarity theory (Monin and Obukhov 1954), with stability correction terms (Dyer and Hicks 1970; Dyer 1974). The reader is referred to Sauer and Muñoz-Esparza (2020) for a comprehensive description of the FastEddy model formulation, dynamical core validation, and performance benchmarks.

For the explicit representation of building effects, an extended version of the IBFM from Chan and Leach (2007) was implemented in the FastEddy model (Muñoz-Esparza et al. 2020). The IBFM from Chan and Leach (2007) was designed to reduce the momentum at inside-building grid points to zero by adding sufficiently large drag forces to the momentum equations through a discrete forcing (Mohd-Yusof 1997). Muñoz-Esparza et al. (2020) extended the IBFM of Chan and Leach (2007) in the following two aspects. First, the drag force term of the momentum equations, which was originally developed for a specific grid spacing (Chan and Leach 2007), was generalized for application of the IBFM to a wide range of spatial scales (from laboratory to atmospheric scales); refer to Eqs. (1) and (2) of Muñoz-Esparza et al. (2020). Second, a similar forcing term (i.e., diffusion of thermodynamic variables) was applied to the temperature and density equations, such that the temperature and density perturbations from predefined reference states of building temperature and density are essentially zero inside buildings; refer to Eqs. (3) and (4) of Muñoz-Esparza et al. (2020). The current version of the IBFM does not include near-wall modeling; no-slip boundary conditions (BCs) of momentum, and BCs of temperature and density at building surfaces (i.e., aforementioned reference states, which match the corresponding inflow conditions in this study) are implicitly imposed by the forcing terms of the IBFM applied to inside-building grid points. With respect to overall performance of these IBFM approaches implemented without a wall model, Chan and Leach (2007) showed that their IBFM reproduces characteristic features of the flow around an isolated cubic building in a neutral condition (e.g., horseshoe and arch vortex modes, top and side flow separations) similar to the flow simulated by explicitly resolving buildings as solid boundaries, despite the lack of a wall model; refer to Chan and Leach (2007) for more quantitative information. Our simulation of the flow around a single building in a neutral ABL confirms good performance of these IBFM-type approaches in comparison to previous studies; refer to section 3 for more quantitative information. Including a wall model is expected to further improve the results in regions close to building surfaces. These IBFM techniques are computationally more efficient than the immersed boundary method (IBM) techniques (e.g., Mohd-Yusof 1997; Mittal and Iaccarino 2005; Lundquist et al. 2012) in the following aspects. The IBM directly enforces boundary conditions on specified immersed boundaries (e.g., no-slip conditions on building surfaces), which do not necessarily coincide with computational grid points, therefore necessitating determination of a forcing term at computational grid points adjacent to the immersed boundaries and

FIG. 1. Coordinate notations, model domain with an isolated building, and a schematic of mean inflow wind (U_0).

interpolation to the boundaries (Lundquist et al. 2012). The IBFM, on the other hand, eliminates the need for an interpolation scheme, by assuming that building surfaces pass the center of computational grid volumes. This assumption is valid in case of the simulations performed in this study, which employed horizontally uniform and unstaggered Cartesian grids and cuboid buildings aligned to the computational grids. In addition, there is a coefficient representing the fraction of a cell occupied by the immersed body, and that accounts for partially intersected body boundaries (Muñoz-Esparza et al. 2020). The IBFM is computationally more efficient than the IBM; however, the accuracy in the vicinity of buildings might be slightly lower (refer to the IBFM development papers, Chan and Leach (2007) and Muñoz-Esparza et al. (2020), for more quantitative information). Nonetheless, this simplified and computationally more efficient IBFM is able to satisfactorily reproduce the relevant building-induced flow patterns, as will also be shown hereafter. Further details of the IBFM employed in this study are provided in Muñoz-Esparza et al. (2020), including its formulation and validation at laboratory and atmospheric scales, and discussions on advantages and disadvantages compared to the traditional IBM techniques.

Figure 1 shows the model domain configuration with an isolated building and a schematic of mean inflow wind (U_0). The building is configured to have the same dimensions in all three directions, $H = H_h = H_v$, where H_h and H_v are the horizontal and vertical building dimensions, respectively, except where explicitly specified otherwise. The characteristic

model domain parameters shown in Fig. 1 are set as D_u , D_d , $W = 15H$, $10H$, $12H$, in the case of the highest-resolution simulations performed in the present study. The corresponding domain extent is L_x , L_y , $L_z = 26H$, $12H$, $10H$, in the stream-wise, spanwise, and vertical directions. The domain parameters were adjusted according to the grid spacing (Table 1), as explained later. The lateral boundary conditions, which consist of mean profiles of the model prognostic variables at an equilibrium state for prescribed surface heating and geostrophic wind forcings, were obtained from a precursor LES performed under identical forcing conditions but over homogeneous surfaces and using doubly periodic lateral boundary conditions. Using such homogeneous inflow profiles at a quasi-equilibrium state for prescribed forcings reduces the initial model integration needed to reach an equilibrium state, yet it still requires the inlet flow, if unperturbed, to travel a long distance toward the interior of the model domain to transition into a fully turbulent flow. To shorten this fetch, we applied the cell-perturbation method (Muñoz-Esparza et al. 2014a, 2015; Muñoz-Esparza and Kosović 2018), which accelerates the transition by introducing stochastic potential temperature perturbations near the inflow boundaries of the domain of building-resolving simulations.

The model resolution requirements for the canonical simulation, which are defined as the minimum numbers of model grid points per building side ($N_{\min}$) required to resolve building-induced mean and turbulent flow characteristics, were identified by performing a total of 13 simulations with different

TABLE 1. Summary of resolution sensitivity simulations: the number of grid points per the side length of cubic building (N), horizontal grid spacing (Δ), computational domain parameters (D_u , D_d , and W ; Fig. 1), and vertical resolution parameters (vertical grid stretching, Δz and z_1 ; z_1 is the lowest vertical level height, i.e., $\sim \Delta z_1/2$).

	N	Δ (m)	D_u	D_d	W	Vertical grid stretching	Δz for $z < H$ (m)	z_1 (m)	Δt (s)
N60	60	2.0	$15H$	$10H$	$12H$	Stretched	1.4–3.0	0.7	0.0025
N40	40	3.0	$15H$	$10H$	$12H$	Stretched	2.8–3.3	1.4	0.005
N24	24	5.0	$20H$	$10H$	$12H$	Stretched	4.8–5.3	2.4	0.0125
N16	16	7.5	$20H$	$10H$	$12H$	Stretched	7.5–7.6	3.2	0.020
N12	12	10.0	$20H$	$10H$	$12H$	Uniform	10.0	5.0	0.025
N10	10	12.0	$25H$	$10H$	$17H$	Uniform	12.0	6.0	0.025
N8	8	15.0	$25H$	$10H$	$17H$	Uniform	15.0	7.5	0.040
N6	6	20.0	$25H$	$10H$	$17H$	Uniform	20.0	10.0	0.050
N4	4	30.0	$30H$	$10H$	$17H$	Uniform	30.0	15.0	0.050

FIG. 2. Time-averaged streamlines for (a) N60, (b) N24, and (c) N16 simulations: (top) in the x - y plane at $z/H = 0.05$ and (bottom) in the x - z plane at $y/H = 0.0$. In (a), the stagnation and reattachment points are marked with A and B , and front, top, side, and rear vortices are marked with F , T , S , and R . The horseshoe vortex and the two legs of the arch vortex are marked with red and blue shaded areas, respectively.

configurations of grid spacing and advection scheme. A few studies on this topic exist in the peer-reviewed literature; however, these either tested a narrow range of model resolutions (Tseng et al. 2006; Auguste et al. 2019) or employed grid refinement methods and domain interior boundaries to represent the presence of buildings (Hefny and Ooka 2008; Bazdidi-Tehrani et al. 2013). Model resolution sensitivity simulations were performed for an idealized NBL case, for a fixed H of 120 m. The NBL forcing conditions were prescribed through a constant geostrophic wind profile $(U_g, V_g) = (10.0, 0.0) \text{ m s}^{-1}$, and roughness length of $z_0 = 0.1 \text{ m}$. The initial potential temperature profile $\theta(z)$ consisted of a mixed layer with $\theta = 300 \text{ K}$ for $0 \leq z < 400 \text{ m}$, an inversion layer with a constant temperature gradient $\partial\theta/\partial z = 0.08 \text{ K m}^{-1}$ for $400 \leq z < 650 \text{ m}$, and free atmosphere with $\partial\theta/\partial z = 0.003 \text{ K m}^{-1}$ aloft. The same NBL forcing conditions were used in Sauer and Muñoz-Esparza (2020) for verification of the FastEddy simulations over homogeneous surfaces, and in Muñoz-Esparza et al. (2020) for verification of the IBFM. The model was integrated for 46 min and the last 30 min of simulations were used to calculate turbulence statistics. The initial 16-min spinup phase allowed the homogeneous initial flow state to achieve a heterogeneous, quasi-equilibrium turbulent flow state throughout the limited area domain. The 30-min analysis period corresponds to approximately 10 vortex shedding cycles, i.e., 10 times of the temporal scale of the largest structure induced by the building, and sensitivity tests to the analysis period confirmed that a statistical convergence is achieved within approximately 6 vortex shedding cycles. The simulation output was saved every 5 s, yielding 360 three-dimensional samples to be used for calculating the statistics. The model resolution was changed by varying the number of grid points per building side in all three directions: $N = H/\Delta$, where Δ is the grid spacing. We examined $N = 60, 40, 24, 16, 12, 10, 8, 6$, and 4, while keeping the advection scheme fixed as the fifth-order upwind method (Adv5) in all spatial directions. Uniform grid spacings in all three directions were used for $N \leq 12$. For $N > 12$, vertical grid

stretching was applied, with the following two constraints in order to minimize undesirable impacts that can be caused by using anisotropic grids: N is the same in horizontal and vertical directions, and the vertical grid spacing (Δz) varies within a $\pm 50\%$ range of horizontal grid spacing, i.e., Δz is approximately 0.5Δ near the surface and increases up to 1.5Δ near the model top. Table 1 summarizes simulation details. We set the upstream domain extent D_u to $15H$ for $N = 60$ and increased it with Δ up to $D_u = 30H$ for $N = 4$, for the following reason. The flow statistics in the vicinity of the building should not be affected by the upstream fetch from the inflow boundary, if the fetch is sufficiently large for the upstream background ABL turbulence to be fully developed. Since the upstream fetch required to this transition into a turbulent flow (i.e., a threshold fetch) could increase with Δ (Muñoz-Esparza et al. 2014b), we increased D_u with Δ in order to ensure D_u is sufficiently larger than the threshold fetch. The spanwise-direction domain size W is $12H$ for $N > 10$, sufficiently wide to capture the oscillating flow past the building. For $N \leq 10$, the spanwise domain was extended to $W = 17H$ in order to increase the number of grid points in the direction, to alleviate undesirable effects from lateral boundaries. The time step (Δt) of these simulations was determined to satisfy the CFL condition for acoustic modes ($\Delta t < \Delta/c$, where c is the speed of sound), and Δt varies between 0.0025 s for $N = 60$ ($\Delta = 2 \text{ m}$) and 0.05 s for $N = 4$ ($\Delta = 30 \text{ m}$).

3. Model resolution requirements for mean-flow response and turbulence characteristics

The sensitivity of time-averaged near-surface streamlines to model resolution is shown in Fig. 2. The highest-resolution simulation ($N = 60$) captures the characteristic features of the canonical flow around an isolated surface-mounted cube that are well documented in the literature based on laboratory experiments and DNS studies for relatively low Reynolds numbers (e.g., Martinuzzi and Tropea 1993; Meinders and Hanjalić 1999; Yakhot et al. 2006; Diaz-Daniel et al. 2017). The important

TABLE 2. Positions of the mean-flow features and Strouhal numbers from the simulations in the present study and the existing DNS studies. The subscripts X and Z indicate x and z coordinates, respectively. The X positions were compared at the same vertical level, $0.05H$; for low-resolution simulations, of which the lowest vertical level height (z_1) is higher than $0.05H$, i.e., N8, N6, and N4, the X positions at z_1 were used instead. Yakhot et al. (2006) does not provide the exact coordinate of R_Z (highlighted in boldface), and we estimated it from Fig. 2 therein. Up and down arrows respectively indicate increase and decrease compared to the nearest finer-resolution simulation, and similarity symbols ($\sim$) indicate changes within $\pm 1\%$. The numbers in the parentheses in the two bottom rows are Strouhal numbers from laboratory experiments that were used as benchmarks in the DNS studies.

	Stagnation A_X		Reattachment B_X		Recirculation R_X		Recirculation R_Z		Strouhal number St
N60	−0.51	—	2.35	—	1.35	—	0.80	—	0.116
N40	−0.66	↓	2.28	↓	1.35	~	0.87	↑	0.125
N24	−0.81	↓	2.18	↓	1.36	↑	0.87	~	0.129
N16	−0.61	↑	2.67	↑	1.66	↑	0.93	↑	0.129
N12	−0.63	↓	2.72	↑	1.76	↑	0.95	↑	0.113
N10	−0.80	↓	3.10	↑	2.10	↑	1.00	↑	0.140
N8	−0.69	↑	2.82	↓	2.36	↑	0.74	↓	0.153
N6	−0.50	↑	3.00	↑	2.00	↓	0.87	↑	0.107
N4	Not captured		2.88	↓	2.25	↑	0.77	↓	0.113
Yakhot et al. (2006)	−1.21		2.50		1.50		0.76		0.104 (0.095–0.109)
Diaz-Daniel et al. (2017)	−1.40		2.50		1.45		0.87		0.14 (0.08–0.15)

features include two primary vortex modes (the horseshoe and arch vortices; marked with red- and blue-shaded areas in Fig. 2a), a stagnation point in front of the building where the incoming flow separates (marked with A in Fig. 2a), a reattachment point on the lee side of the building (marked with B), and front, top, side, and rear vortices (marked with F , T , S , and R). The positions of these mean-flow features in N60 are in good agreement with those shown in the aforementioned DNS studies showcasing relative errors within $\pm 10\%$, except for the flow stagnation point, which is located closer to the frontal face of the building (Table 2). We attribute this to the differences in the inflow conditions. Changes of the mean-flow features with model resolutions examined in the present study can be classified into three groups. N40 and N24, in addition to N60, simulate the overall flow patterns including the small-scale top and side vortex modes in the immediate vicinity of the building (e.g., Fig. 2b). Provided all these characteristic vortices are resolved, the stagnation and reattachment points gradually move upstream with decreasing resolution, while the positions of the recirculation point do not change much. In three medium-resolution simulations, N16, N12, and N10, the small-scale top and side vortex modes are not well resolved (e.g., Fig. 2c), leading to the increase of the reattachment length and the lifting of the recirculation with model grid spacing (B_X and $R_{X,Z}$ in Table 2). Further coarsening of the model resolution does not show any systematic changes of the flow patterns.

The streamwise velocity along the building centerlines in streamwise direction ($y/H = 0.0$) and spanwise direction ($x/H = 0.5$) are compared in Fig. 3. The reversal of the streamwise velocity on the lee side of the building is resolved regardless of model resolution. As explained in the previous section, the IBFM employed in this study does not explicitly specify immersed building boundaries. Therefore, the velocity at building surfaces is not explicitly specified, as shown in Fig. 3. At $z/H = 0.25$, the intensity of the recirculating flow becomes

weaker and the peak location moves further downstream with decreasing resolution from N16 to N6. The three fine-resolution simulations, N60, N40, and N24, which unlike the coarser-resolution simulations resolve the top and side vortex modes, show an opposite resolution sensitivity. The little wiggles in the time-averaged velocity fields of N60 and N40 would be alleviated by increasing output frequency. The arch-shaped vortex on which the reverse flow depends was shown to gradually disappear with height by previous wind tunnel and DNS studies (Meinders and Hanjalić 1999; Yakhot et al. 2006), and this height dependency is more clearly seen from fine-resolution simulations (cf. Figs. 3a,b). The reverse flow near the building's lateral face is marginally resolved in three medium-resolution simulations, $N = 16, 12$, and 10 , and entirely unresolved at lower resolutions. These findings are consistent with the results of Tseng et al. (2006), who noted that a very fine grid spacing would be needed to capture the lateral flow separation, as it is dictated by the small-scale motions near the surface. The mean velocity distributions shown in Fig. 3 suggest that at least 10–12 grid points per building side are required to resolve the recirculating flow in the building's wake region and on the lateral side.

The temporal variability in velocity and contribution of different-scale motions to it can be identified from energy spectra. Figure 4 displays the temporal spectral density of spanwise velocity in the wake of the building, and the Strouhal numbers ($St = f_{\max}H/U_0$) determined from the frequency corresponding to the spectral peak ($f_{\max}$) in the spectra are presented in Table 2. The energy spectra were calculated using model output for a 30-min time span, corresponding to about 10 vortex shedding cycles. The three fine-resolution simulations, i.e., N60, N40, and N24, feature (i) a peak frequency at $f \sim 0.004$ – 0.005 Hz, which is equivalent to $St \sim 0.10$ – 0.15 , (ii) a -1 slope associated with turbulence production scales ($f \leq 0.04$ Hz), and (iii) the Kolmogorov's $-5/3$ slope at higher frequencies. N16 and N12 capture the spectral peak at

FIG. 3. Time-averaged streamwise velocity (u) normalized by the mean inflow wind (U_0) at (left) $y/H = 0.0$ and (right) $x/H = 0.5$ at two different heights: (a) $z/H = 0.25$ and (b) $z/H = 0.75$.

$f \sim 0.004\text{--}0.005$ Hz as in N60, N40, and N24, the -1 slope, and a portion of the $-5/3$ inertial range slope. These five high-resolution simulations show Strouhal numbers between 0.113 and 0.129, which are within the range found by previous DNS studies (e.g., Yakhot et al. 2006; Diaz-Daniel et al. 2017). In contrast, the two coarse-resolution simulations, N6 and N4, exhibit excessive energy dissipation across almost the entire frequency range, even around the spectral peak ($f \sim 0.004\text{--}0.005$ Hz). Nevertheless, the Strouhal numbers in these two cases are in reasonable agreement with DNS benchmarks. In these coarse-resolution simulations, the energy spectra in the building's far upstream region also show a peak frequency at around $0.003\text{--}0.005$ Hz resulting in $St \sim 0.07\text{--}0.13$ (not shown), similar to those found in the building's downstream region even though the upstream spectra are not affected by the existence of the building. On the other hand, the most reliable simulations that capture a $-5/3$ slope (i.e., N60, N40, and N24) exhibit the upstream spectral peaks at higher frequencies of

$\sim 0.007\text{--}0.027$ Hz. N4, in particular, exhibits the spectral peak at $f = 0.004$ Hz and the energy dissipation beyond this peak frequency at both $z/H = 0.25$ and $z/H = 0.75$ (and also at $z/H = 0.5$, not shown), indicating that the spectral peak of N4 in Fig. 4 is a consequence of numerical diffusion associated with the upwind advection scheme. In fact, this is expected given the effective resolution of the fifth-order advection scheme used (Adv5), which is $\sim 6\text{--}7\Delta$ (Skamarock 2004; Sauer and Muñoz-Esparza 2020). In addition, the coarsest resolution, N4, does not properly simulate the horseshoe vortex (e.g., A_x in Table 2, and the lateral flow in the right panel of Fig. 3), which plays an important role in forming the vortex shedding. The horseshoe vortex carries the vorticity, which is eventually entrained into the two legs of the arch vortex, alternatively from one leg to the other, generating the unsteady vortex shedding (Yakhot et al. 2006). This suggests that N4, which does not capture the horseshoe vortex, is not sufficient to resolve the vortex shedding, despite the reasonable prediction of St .

FIG. 4. Temporal energy spectra of spanwise velocity (v) on the downstream side of the building ($x/H = 2.5$ and $y/H = 0.0$): (a) $z/H = 0.25$ and (b) $z/H = 0.75$. The dotted and dashed lines correspond to -1 slope associated with turbulence production and Kolmogorov's $-5/3$ slope, respectively.

The resolution requirements discussed thus far are based on simulations using a fifth-order upwind advection scheme. The order of numerical accuracy used in a simulation affects the effective resolution, i.e., the wavelength beyond which spectral energy is not damped by numerical diffusion (Glendening and Haack 2001; Skamarock 2004; Sauer and Muñoz-Esparza 2020). To identify the influence of choice of advection scheme on $N_{\min}$ and confirm the robustness of the proposed resolution requirements, four additional advection schemes were tested for a marginal resolution, $N = 12$, from the highest to the lowest order of accuracy, Adv5Hyb (a hybrid fifth-order scheme that combines the upwind-biased fifth-order and the centered sixth-order schemes, featuring a reduced level of numerical diffusion compared to the upwind-biased fifth-order scheme), Adv3Hyb (a hybrid third-order scheme), Adv3 and Adv1 (upwind-biased third- and first-order schemes). The N12 simulation is renamed Adv5 here. Results are provided in Table 3 and Fig. 5. As expected, the first-order advection scheme induces excessively detrimental numerical diffusion. In fact, the Adv1 simulation is more dissipative than the N4 simulation using Adv5 despite the 3-times-finer resolution used in the Adv1 simulation (cf. Figs. 4a, 5b). Decreasing the order of advection scheme from fifth to third also increases the numerical diffusion; however, the positions of the mean-flow features differ by less than 10%, except for the recirculation length (refer to σ/m in Table 3). To our knowledge, there are no previous studies that assessed the impact of advection

schemes to this canonical flow, but it was found that the impact of decreasing the order of numerical accuracy revealed in this study is very similar to the change of the flow pattern with decreasing Re (Khan et al. 2018). For example, the reattachment length and the magnitude of the reverse flow on the lee side of the building gradually increase with decreasing Re (Khan et al. 2018), similar to the impact of decreasing the order of advection scheme shown in Fig. 5. This is not surprising as both implicit filtering by the discretization of the advective term and viscous force act as sources of diffusion to the flow. The time-averaged streamwise velocity presented in Fig. 5a confirms that the impact of changing the order of advection scheme from fifth to third is smaller than that of decreasing N from 12 to 10, and the key conclusions drawn for the minimum resolution requirement hold. These results suggest that using a third-order scheme might be an optimal choice for this type of building-resolving simulations, considering accuracy against computational cost.

The minimum resolution requirements proposed in the present study are summarized in Table 4, together with those identified in a few previous LES studies for comparison. The present study agrees with the existing literature that the vortex shedding requires the coarsest minimum resolution, $N_{\min} = 6$, while more than 20 grid points per building side are needed to simulate the small-scale top and side vortices. These findings stress that in applying LES models for urban-resolving simulations, the guidance on adequate model resolution needs to be addressed in the context of specific applications (i.e., particular

TABLE 3. As in Table 2, but for advection sensitivity simulations. Relative spread defined as the ratio of the standard deviation (σ) to the mean (m) of the simulations is listed in the bottom two rows, one for all five simulations and the other without the outlier Adv1.

	Stagnation A_X	Reattachment B_X	Recirculation R_X	Recirculation R_Z
Adv5Hyb	-0.67	2.85	1.75	1.00
Adv5 (= N12)	-0.63	2.72	1.76	0.95
Adv3Hyb	-0.67	3.02	2.50	0.87
Adv3	-0.63	3.02	2.40	0.83
Adv1	-0.75	4.44	3.50	0.78
σ/m (all)	0.07	0.21	0.30	0.10
σ/m (Adv1 excluded)	0.03	0.05	0.19	0.08

FIG. 5. As in (a) Fig. 3a and (b) Fig. 4a, but for advection-scheme sensitivity simulations for $N = 12$.

variables of interest). In this regard, the present study provides robust guidance on adequate model resolution over a wide range of N and choice of advection scheme, yet is limited to a shear-driven NBL. In the next section, the simulation of the canonical flow delineated in this section is extended for varying incoming turbulence scales (L_{ABL}) and buildings sizes (H).

4. Interplay between atmospheric stability and building size

In addition to the highest-resolution simulation shown in the previous section, i.e., the NBL simulation using $N = 60$ ($\Delta = 2$ m), 20 additional simulations were performed using the same or smaller grid spacing for varying ABL turbulence scale (L_{ABL}) arising under different atmospheric stability conditions and for different buildings sizes (H) (Table 5). To explore the impact of L_{ABL} on the flow response, four additional simulations were designed by changing atmospheric stability while keeping the building dimension the same as $H = 120$ m: one SBL and three CBL cases. The SBL was driven by constant surface cooling of 0.25 K h^{-1} , which corresponds to a surface heat flux of $\sim -0.01 \text{ K m s}^{-1}$, and a constant geostrophic wind profile $(U_g, V_g) = (8.0, 0.0) \text{ m s}^{-1}$, the same as in the first Global Energy and Water Cycle Experiment Atmospheric Boundary Layer Study (GABLS) intercomparison case (Beare et al. 2006). The three CBL cases, i.e., weak, strong, and extreme CBL cases, were driven by constant surface heat fluxes of 0.01,

0.30, and 0.90 K m s^{-1} , and $(U_g, V_g) = (10.0, 0.0) \text{ m s}^{-1}$ as in the NBL case. The surface heat flux of 0.01 K m s^{-1} is characteristic of morning/evening boundary layer transitions (e.g., Svensson et al. 2011), and the strong and extreme heat fluxes of 0.30 and 0.90 K m s^{-1} are representative of what can be found in fair-weather CBLs over bare soil or grassland (e.g., LeMone et al. 2013) and over asphalt roads (e.g., Yang et al. 2019), respectively. Inflow temperature conditions of these five ABL cases, which were also used to prescribe building temperature, are presented in Table 6. The variations in the ABL stability result in the integral length scales of the low-level ABL turbulence at/below the building height ranging roughly between 70 and 200 m (Table 5). Specifically, the L_{ABL} was calculated by taking the larger value between the spectral peak scales of horizontal and vertical velocity components and then vertically averaging it over $z/H = 0.5$ – 1.0 . To compute the spectral peak scales, temporal energy spectra calculated at an upstream point ($x/H = -2.5$ and $y/H = 0.0$) were used. This type of approach, which uses energy spectra for computing L_{ABL} has been adopted by a number of ABL LES studies (de Roode et al. 2004; Honnert et al. 2011; Shin and Hong 2013; Zhou et al. 2014). For each L_{ABL} , the flow around three different-sized cubic buildings, $H = 24$, 120, and 240 m, was simulated, except for the weak CBL case. The weakly unstable ABL was simulated for $H = 120$ only, because the turbulence length scales of the weakly unstable and the neutral ABLs are fairly similar, therefore adding the weak ABL case for different H does not expand the range of L_{ABL}/H .

TABLE 4. Minimum resolution requirements (N_{min}) identified in the present study and the previous LES studies, with — indicating not resolved.

	Horizontal advection	Vertical advection	N	Variable	N_{min}
Present study	Fifth-order upwind	Fifth-order upwind	4–60	Vortex shedding	6
				Side and downstream reverse flow	10–12
				Top and side vortices	24
Auguste et al. (2019)	Not mentioned	Not mentioned	10–40	Vortex shedding	10
				Top vortices (Fig. 14 therein)	20
Tseng et al. (2006)	Pseudo spectral	Second-order centered	4–8	Vortex shedding	6–8
				Downstream reverse flow (Fig. 4 therein)	6–8
				Side reverse flow (Fig. 4 therein)	—

TABLE 5. Summary of ABL cases: surface kinematic heat flux ($\langle w'\theta' \rangle_0$), geostrophic wind (U_g), the inverse Obukhov length (L_O^{-1}) and integral length scale of the ABL (L_{ABL}), horizontal and vertical building dimensions (H_h and H_v) and building aspect ratio ($A = H_v/H_h$), model grid spacing (Δ), and ratio between the turbulence and building scales [L_{ABL}/H_h and $L_{ABL}^2/(H_h H_v)$]; rounded off to three decimal places]. The smallest and largest ratio values tested in the present study are highlighted in boldface. Marker colors and types used in Fig. 9 are listed in the last column.

	$\langle w'\theta' \rangle_0$ (K m s ⁻¹)	U_g (m s ⁻¹)	L_O^{-1} (m ⁻¹)	L_{ABL} (m)	H_h (m)	H_v (m)	$A = H_v/H_h$	Δ (m)	L_{ABL}/H_h	$L_{ABL}^2/(H_h H_v)$	Marker	
											Color	Type
SBLC0.01	-0.01	8	0.020	71.70	24	24, 120	1.0, 5.0	1	2.988	8.925, 1.785	Blue	-, -
					120	120	1.0	2	0.598	0.357		●
					240	240, 120	1.0, 0.5	2	0.299	0.089 , 0.179		+, +
NBL	0.00	10	0.0	92.09	24	24, 120	1.0, 5.0	1	3.837	14.72, 2.945	Green	-, -
					120	120	1.0	2	0.767	0.589		●
					240	240, 120	1.0, 0.5	2	0.384	0.147, 0.294		+, +
CBLH0.01	0.01	10	-0.008	100.44	120	120	1.0	2	0.837	0.701	Yellow	●
CBLH0.30	0.30	10	-0.080	155.70	24	24, 120	1.0, 5.0	1	6.486	42.09, 8.418	Orange	-, -
					120	120	1.0	2	1.298	1.684		●
					240	240, 120	1.0, 0.5	2	0.649	0.421, 0.842		+, +
CBLH0.90	0.90	10	-0.133	193.43	24	24, 120	1.0, 5.0	1	8.060	64.96 , 12.991	Red	-, -
					120	120	1.0	2	1.612	2.598		●
					240	240, 120	1.0, 0.5	2	0.806	0.650, 1.299		+, +

The evolution of flow structures around the cubic building with changes in atmospheric stability is displayed in Fig. 6. Compared to the NBL case, the two primary vortex modes on the windward and leeward sides and the small vortices in the immediate proximity of the building's top and lateral faces are enhanced in the SBL case, leading to locally elevated TKE levels. (As will be discussed in more detail with Fig. 9, the strength of building-induced circulations in the ABL depends on which process between the background ABL turbulence and building-induced local circulation is more dominant.) The SBL case presented in Fig. 6a, $L_{ABL} < H$ (Table 5). Therefore, the impact of building on the surrounding flow predominates, and the strength of building-induced vortices is enhanced because the interactions between the building-induced local circulations and the atmosphere decrease due to the weaker background turbulent mixing in the SBL (Fig. 6a). On the other hand, the characteristic vortex features gradually disappear with the increase of L_{ABL} , as the coherent structures generated by the vigorous turbulence in the convective ABLs dominate over the building-induced local circulations. The upstream horseshoe vortex and the downstream arch vortex gradually weaken with increasing surface heating in the CBL simulations (Figs. 6c–e). The flow reattachment from the top and lateral flow separations in the vicinity of the building plays a role in forming the arch vortex, and the vorticity entrained from the horseshoe vortex enhances the arch vortex. These two processes forming and intensifying the arch vortex weaken with increasing L_{ABL} , in particular in the two strong convective cases in which $L_{ABL} > H$, resulting in the vortex in these two cases confined in a smaller area than other cases.

Figure 7 confirms that the overall building impacts decrease with L_{ABL} , in both its magnitude and spatial extent. The SBL, NBL, and CBLH0.01 simulations feature two local peaks in TKE on the lateral side, one relating to the horseshoe vortex

and the other one representing the side vortex. However, the distance between the two TKE peaks decreases with increasing ABL instability. These three simulations also feature two local peaks in u , a dominant mode located between the two vortex modes and a weak mode at the lateral edge of the horseshoe vortex. Similar to TKE, the distance between the two peaks of u also decreases from the SBL to the CBL case. On the other hand, two strong CBL simulations exhibit a single peak in TKE as the horseshoe vortex and the side vortex are merged, therefore lack a prominent peak in u . Such large sensitivities in

TABLE 6. Inflow potential temperature profiles of five ABL cases. These profiles were also used to prescribe building temperature.

Inflow temperature profile		
SBLC0.01	263.02 K	$z = 0$ m
	$\partial\theta/\partial z = 0.0107$ K m ⁻¹	$0 < z < 149.5$ m
	$\partial\theta/\partial z = 0.0251$ K m ⁻¹	$149.5 \leq z < 202.5$ m
	$\partial\theta/\partial z = 0.0104$ K m ⁻¹	$z \geq 202.5$ m
NBL	300 K	$0 \leq z < 400$ m
	$\partial\theta/\partial z = 0.08$ K m ⁻¹	$400 \leq z < 650$ m
	$\partial\theta/\partial z = 0.003$ K m ⁻¹	$z \geq 650$ m
CBLH0.01	300.5 K	$0 \leq z < 430$ m
	$\partial\theta/\partial z = 0.0886$ K m ⁻¹	$430 \leq z < 650$ m
	$\partial\theta/\partial z = 0.003$ K m ⁻¹	$z \geq 650$ m
CBLH0.30	305.4 K	$0 \leq z < 510$ m
	$\partial\theta/\partial z = 0.1042$ K m ⁻¹	$510 \leq z < 650$ m
	$\partial\theta/\partial z = 0.003$ K m ⁻¹	$z \geq 650$ m
CBLH0.90	313.9 K	$0 \leq z < 630$ m
	$\partial\theta/\partial z = 0.0485$ K m ⁻¹	$630 \leq z < 770$ m
	$\partial\theta/\partial z = 0.003$ K m ⁻¹	$z \geq 770$ m

FIG. 6. Time-averaged streamlines (contours) and TKE ($\text{m}^2 \text{s}^{-2}$, shaded) in the x - y plane at $z/H = 0.05$ and in the x - z plane at $y/H = 0.0$, from the simulations with varying L_{ABL} as the result from changing atmospheric stability for the same building with $H = 120$ m.

flow response to an isolated building to quite modest variations in the atmospheric forcing merit more expansive attention and research, particularly in that real atmospheric boundary layers are far more frequently either weakly stable or weakly unstable as opposed to perfectly neutral.

Time-averaged streamlines and TKE around three isolated cube-shaped buildings, all immersed in the identical neutral boundary layer but different in building size (H), are compared in Fig. 8 to investigate now the impact of building size. All three simulations were performed using model resolutions that have at least 24 grid points per building side, based on the resolution requirement established in the preceding section. Therefore, Δ is fixed as 2 m for $H = 120$ and 240 m, while $\Delta = 1$ m is used for $H = 24$ m. The streamlines from the three simulations resemble each other, particularly in the positions of the mean-flow features. H024 shows a slightly different behavior, e.g., the reattachment on the lee side is observed closer to the building, presumably because of the model resolution. The value of N ($= \Delta/H$) is 24 for H024, while it is 60 and 120 for H120 and H240, respectively. The similarity between H024 ($H = 24$ m) in Fig. 8a and N24 ($H = 120$ m) in Fig. 2b, the two simulations that

used the same N for different H , supports this hypothesis. While the streamlines remain similar, the intensity of the building-induced turbulence increases with H . It can be reasonably assumed that the impact of the building on the surrounding atmosphere depends on the relative scale of the building-generated flow structures, $\sim H$, compared to the inflow turbulence scale, L_{ABL} . For example, the ratio L_{ABL}/H is larger than 1.0 in H024 ($L_{\text{ABL}}/H \sim 3.8$) where the background turbulence dominates over the building-induced local circulations leading to the relatively small flow disturbances by the building. Also, it is worth mentioning that the integral length scale of turbulence, L_{ABL} , is a convenient choice to describe this interplay or dependency, given that larger L_{ABL} values are normally associated with enhanced TKE levels in the background atmospheric boundary layer, and vice versa.

The building impact on flow around isolated buildings as modulated by the interplay between the incoming turbulence and building scales is synthesized in Fig. 9. A scaling parameter, $L_{\text{ABL}}^2/(H_h H_v)$, is employed to quantify the interplay between the incoming turbulence and building scales. This parameter describes the relative scale of the background ABL

FIG. 7. Time-averaged (a) streamwise velocity (u) and (b) turbulence kinetic energy (TKE) normalized by the inflow values, from the simulations with varying L_{ABL} (see Table 5) for $H = 120$ m: (left) $y/H = 0.0$ and (right) $x/H = 0.5$ at $z/H = 0.05$.

to size of the building in both horizontal (L_{ABL}/H_h) and vertical (L_{ABL}/H_v) directions. The building impact is defined as TKE averaged over the reverse flow area ($u < 0$), related to horseshoe and arch vortices, and normalized by the upstream ABL TKE. This normalized TKE highlights well differences

between the cases (Fig. 7) and, therefore, can be a good indicator of the building impact. The parameter space explored herein includes a total of 21 building-resolving simulations: 13 simulations with cubic buildings having building aspect ratio $A = H_v/H_h = 1$, and 8 simulations with cuboid buildings having

FIG. 8. As in Fig. 6, but for the simulations with varying H for the NBL case.

FIG. 9. Scatterplots of building impact against $L_{ABL}^2/(H_h H_v)$ for (a) horseshoe and (b) arch vortex areas. Building impact is defined as TKE averaged over the reverse flow area ($u < 0$) normalized by upstream TKE ($TKE_{reverse}/TKE_0$). Different marker types indicate different building dimensions, and markers are colored according to stability (refer to Table 5). Four tall building cases with $A = 5$, marked with $-$, do not show the upstream reverse flow, implying no or little building impact; we set $TKE_{reverse}/TKE_0$ to 1.0 (i.e., no building impact) for these four simulations.

$A = 5.0$ or 0.5 and square footprints (Table 5). The data do not exactly converge into a single monotonic line for neither the horseshoe vortex nor the arch vortex. Nonetheless, it is of great importance that changing either L_{ABL} or H while the other is fixed exhibits monotonic trends, indicating that the interplay between the ABL turbulence scale and building size plays an important role in the resulting building-induced flow disturbances and vortex structures, an aspect that until now lacked emphasis or in-depth consideration. Both the building impact and the scaling parameter employed in the present study exhibit uncertainties since they do not consider all the possible building and ABL turbulence parameters that might influence the flow in the vicinity of isolated single buildings, and better correlations might be achieved by refining them. For example, the scaling parameter does not consider the building aspect ratio. The value of L_{ABL} was determined by using an algorithm based on the upstream energy spectra calculated at/below building heights; therefore, it could be sensitive to the LES resolution—for example, if the resolution is not fine enough to resolve energy-containing large eddies near the surface. Sensitivity tests of the NBL and CBLH0.30 cases performed using a larger upstream fetch indicate that the aspects discussed in this section on the interplay between the ABL turbulence scale and the building size are not changed by the upstream fetch, even for the strong convective case where the shorter upstream fetch did not allow a full development of turbulence at levels above building height.

These detailed examinations of the interaction between the ABL turbulence scale and building size have interesting implications for the modeling of urban flows in more realistic environments where stability effects are present most of the time. For $L_{ABL}/H > 1$, the flow over buildings is largely affected by the background ABL turbulence, while relatively small buildings compared to the ABL turbulence scale do not effectively change the surrounding flow (unless stratification effects warrant very reduced eddy sizes, e.g., very stable ABL

conditions). In contrast, large-size buildings having $L_{ABL}/H < 1$ significantly alter the flow around them, against the ABL turbulence having relatively small scales compared to buildings. Therefore, a model grid spacing properly resolving L_{ABL} (i.e., LES resolutions) is sufficient to resolve dominant processes governing the urban flow, either for $L_{ABL}/H > 1$ or $L_{ABL}/H < 1$. This leads to the conclusion that the minimum resolution requirements established for the NBL case in the present study, in which the ABL turbulence and building have comparable scales (i.e., $L_{ABL}/H \sim 1$) are valid regardless of the atmospheric stability and building size. Note that the model grid spacing properly resolving L_{ABL} depends on atmospheric stability, i.e., $O(0.1)$ m for very stable conditions (Couvreur et al. 2020), $O(1)$ m for weakly stable and neutral conditions (Beare et al. 2006; Berg et al. 2020), and $O(1\text{--}10)$ m for convective conditions (Sullivan and Patton 2011); therefore, the grid spacing that is required to resolve dominant processes of the urban flow also depends on the stability.

5. Summary and concluding remarks

Numerical simulations and wind tunnel studies upon which the basic knowledge about urban flows has primarily evolved have concentrated on neutrally stratified boundary layers, while the atmospheric boundary layer over land undergoes a pronounced diurnal cycle. Motivated by this, we investigated the impact of the background atmospheric boundary layer stability on the canonical flow around an isolated cubic building using building-resolving large-eddy simulations. For the interactions between the turbulence and building scales to be resolved at a sufficient level of detail, the model spatial resolution, which is defined as the number of model grid points per building side, and the order of numerical accuracy required for the simulation of turbulent flow were identified first. For this purpose, nine resolutions ranging from 60 to 4 grid points per building side were tested. We showed that in order to capture

the largest structures generated by the building, which correspond to vortex shedding, a minimum of 6 grid points per building side is needed, while at least 12 and 24 grid points are required for an accurate simulation of the mean-flow and turbulence characteristics, respectively. These minimum resolution requirements proposed herein were shown to be comparable to those suggested by previous LES studies but not exactly the same, at least in part due to differences in advection scheme and numerical discretization errors, SGS model, etc. Four additional simulations using different advection schemes demonstrated that the sensitivity of the building-induced flow to the order of advection scheme is not significant for schemes that are at least third-order accurate, indicating that using a third-order scheme might be an optimal choice for this type of building-resolving simulations, considering accuracy against computational cost.

Using model resolutions that enable an accurate representation of turbulence characteristics, a total of 21 building-resolving simulations were performed under varying atmospheric stability conditions: one stable, one neutral, and three convective boundary layer cases. For each case, three different building sizes were tested, resulting in L_{ABL}/H approximately between 0.1 and 10. It was found that the building-induced flow structures gradually weaken with the increase of L_{ABL} , due to enhanced turbulent mixing in the background ABL. In addition, spatial distributions on the lateral side of the building show no prominent peak in u and exhibit a single peak in TKE in the presence of strong surface heating, whereas two local peaks, one relating to the horseshoe vortex and the other one representing the side vortex, are observed in the neutral, weakly stable and weakly unstable ABL cases. In contrast, surface cooling reinforces the presence of building-induced vortices as a result of the reduced background ABL turbulence. These significant sensitivities to atmospheric stability, even considering our simplified setup consisting of an isolated building, point to the relevance of atmospheric stability effects and associated turbulence scales in building environments, which needs to be included for realistic modeling of urban environments.

Considering the background turbulence and building scales together, it is demonstrated that the influence of an isolated building decreases with L_{ABL}/H , as the coherent turbulent structures induced by the background turbulence dominate over the building-induced circulations for $L_{ABL}/H > 1$. We employed the parameter $L_{ABL}^2/(H_h H_v)$ as the nondimensional scaling parameter that dictates the impact of flow around isolated buildings, quantified as the TKE averaged over the reverse flow area for the horseshoe and arch vortex regions. Overall, scatterplots of our 21 building-resolving simulations demonstrate quasi-linear relationships between the building impact and the scaling parameter, showing a decrease of the building impact with $L_{ABL}^2/(H_h H_v)$. While the data do not perfectly converge into a single monotonic line, changing either L_{ABL} or H while the other is fixed exhibits monotonic trends, indicating that the interplay between ABL turbulence scale and the building size plays a major role in the resulting building-induced flow disturbances and vortex structures, an aspect not addressed previously.

Because of the interplay between the two scales, we suggest that the minimum resolution requirements established for the

neutral boundary layer case hold regardless of atmospheric stability and building size. This is a consequence of the ABL turbulence effects dominating for $L_{ABL}/H > 1$, and therefore, small buildings compared to the integral length scale of the ABL turbulence have a minor contribution in effectively altering the background ABL flow. In contrast, where $L_{ABL}/H < 1$, building effects are dominant, but the LES resolution has to be sufficient to resolve the building effects provided the LES properly resolves the ABL turbulence.

This study provides an expansive assessment of the impact of atmospheric thermal stability on the flow over isolated buildings, using 33 large-eddy simulations with 21 of them at 1- or 2-m grid spacing, enabled by the accelerated nature of the resident-GPU FastEddy model. To further extend the investigation on the balance between equilibrium ABLs and thermal stability introduced herein to a more realistic urban environment, a follow-up study based on building-resolving simulations utilizing urban landscapes for a real city and inflow conditions obtained from local weather forecasts under varying stability conditions is underway. The present study focused on the thermal effects in the urban flows caused by surface-driven convective instability in nonneutral background ABLs, complementing a few other studies that have shown local thermal effects forced by differential heating of building's walls to significantly alter flow around buildings in neutrally stratified conditions (e.g., Park et al. 2012; Boppana et al. 2013). To consider these two aspects together and explore interactions between the background ABL stability and local thermal effects by buildings, we plan to implement a building-energy model into the FastEddy.

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