

The Dual Effect of Urban Areas on Supercell Storms

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Abstract. The effect of urban land use on convective storms with deep and persistent rotating updrafts (supercell storms) is systematically investigated using ensembles of idealized numerical simulations. A supercell is simulated over a flat domain containing a circular city surrounded by croplands. It is triggered upstream of the city so that it subsequently moves into the urban area. Twenty-five experiments with eleven ensemble members each are conducted in which city size, urban fraction, building height, and building density are varied. The results show a statistically significant weakening of the supercell with increasing city size. The weakening of the approaching storm is primarily driven by the urban dry island (UDI), which substantially reduces convective available potential energy. While the initial storm can be suppressed by the city, the urban heat island (UHI) generates a pressure minimum and horizontal convergence, which induce upward motions and can trigger a new supercell downwind of the city, in a corridor where SRH is also higher. Compared with UHI-induced vertical velocities, the building-generated vertical velocities are negligible. This study expands our understanding of the complex interactions between the urban environment and deep moist convection, emphasizing the role of the UHI and UDI in influencing storm dynamics and highlighting the potential dual effects of urban land use on supercell storms.

1 Introduction

The most severe socio-economic impacts of severe storms typically occur when they strike urban areas, where large populations are at risk of injuries, and dense infrastructure and numerous vehicles are exposed to damage (e.g., ??). This underscores the need for a thorough examination of the interactions between urban land use and severe storm behavior, with the ultimate goals of improving early warning systems, designing effective emergency plans, informing the public about associated risks, and strengthening socio-economic resilience.

It is well established that the presence of buildings and urban materials significantly modifies the Planetary Boundary Layer (PBL), leading to the Urban Heat Island (UHI; i.e., higher temperatures within cities, ?), and modifications in streamlines (?), which often result in weaker surface winds over urban areas. Urban areas also modify the moisture field: both Urban Wet Islands (UWIs) and Urban Dry Islands (UDIs) have been observed (??). UWIs are more common at night, due to enhanced evapotranspiration associated with the UHI (which is stronger at night, ?), in winter, due to anthropogenic emissions, and in

25 dry regions (?). UDIs, instead, are more frequent in the late afternoon and in spring or summer in wet regions (????), where evapotranspiration within urban areas is reduced due to less vegetation cover relative to rural areas (?).

Urban areas affect also precipitation, and the existence of an Urban Rainfall Effect (URE) was already noted more than 50 years ago (?). This phenomenon is typically characterized by enhanced precipitation downstream of both large and compact urban areas (?). Several hypotheses have been proposed to explain it, ranging from thermodynamic mechanisms (UHI-induced vertical motions that trigger convection; ??), to dynamic processes (vertical velocities induced by flow modifications caused by buildings; ??), and chemical interactions (urban aerosols affecting rainfall efficiency; ??). In particular, the dynamic explanation has received considerable attention. Various mechanisms have been proposed to explain enhanced vertical velocities resulting from building-induced flow modifications, including dynamical blocking of the flow upstream of buildings (????), flow merging downstream of cities (?), downstream wind convergence driven by a pressure minimum induced by flow bifurcation (?), and storm bifurcation via the so-called building-barrier effect (?). However, these hypotheses have generally not been tested quantitatively. While it is reasonable to expect that all these factors may influence a convective cell to some extent, it remains unclear whether one (or some) of them plays a dominant role in producing the URE phenomenon.

Moreover, most of these studies have focused on ordinary convective cells, while only a limited number have examined the effects of urban land use on local severe storms. In particular, the present study focuses on supercells, which are convective storms with a deep and persistent rotating updraft and represent the most dangerous type of local severe storm (e.g., ?). Since surface-based supercells are fueled primarily by air masses located in the lowest few hundred meters of the troposphere (?), it is reasonable to hypothesize that they may be influenced as well by urban land use (?). Indeed, some case studies have found that supercells occurring over the US Great Plains were intensified by the presence of cities (???). Similarly, ? reported a systematic increase in updraft helicity (UH) over Moscow (Russia) compared to simulations without the city. A recent study showed that even a Quasi-Linear Convective System (QLCS) can be displaced and broken up by urban land use (De Martin et al. 2025).

Attempts to generalize these pioneering case studies have been made using idealized simulations (???), which found that both supercells and QLCSs intensified when a city was included. However, in those simulations, the city was simplified as a thermal and roughness perturbation, and a realistic city was not considered in the simulation domain.

50 These early investigations suggest that even local severe storms can be modified by urban land use. Nevertheless, they either lack generality or rely on overly simplified urban representations. Therefore, the present research employs idealized simulations using state-of-the-art urban parameterizations to better assess whether urban perturbations are sufficiently strong to alter supercell behavior. Another important aspect that has been only marginally addressed in previous studies concerns the physical processes responsible for urban-induced modification of supercells. Accordingly, this research is guided by two main scientific questions:

1. Can a city modify a supercell?
2. What are the physical processes that cause such modifications?

The limitation of idealized simulations is that they rely on the outcomes of a numerical model, which must be trusted. To enhance the trustworthiness of the idealized simulations, similar model settings used for a real case study by ? are employed in the present study.

The analysis is divided into two main phases. The primary objective of the first phase is to investigate how an already developed supercell is modified by the presence of a city. To this end, the storm is initiated upstream and advected toward the city center, where an urban boundary layer has developed during the preceding hours. In particular, we aim to assess the storm's sensitivity to variations in city size, urban fraction, building height, and building density. The second phase of the analysis focuses on understanding how the pre-storm environment is influenced by different urban morphological configurations. This aspect is crucial for explaining the urban-induced storm modifications identified in the first phase.

The methodology used is described in detail in Section 2. The results of the first phase are presented in Section 3, while those of the second phase are shown in Section 4. Finally, the main outcomes of both phases are discussed in Section 5, along with comparisons with the existing literature. Tentative answers to the scientific questions posed above will be provided in Section 6.

2 Method

2.1 Numerical simulation setup

Numerical simulations are performed using version 4.6.1 of the Weather Research and Forecasting (WRF) numerical model (?). Numerical simulations are conducted in a single square domain with horizontal grid spacing of 1 km, consisting of 250×250 grid points. The same 64 vertical levels used in ? are employed, as they were shown to accurately reproduce severe storm dynamics in a real urban setting. Periodic Boundary Conditions (PBCs) are implemented. A sufficiently large domain is chosen to ensure that spurious wave interactions do not occur during the period analyzed in this study.

The simulations are initialized at 10:00 am (local time), and the storm is triggered at 04:00 pm, a typical initiation time of convection (e.g., ?). The supercell is initiated using a thermal bubble released at 04:00 pm near the bottom-left corner of the domain, at grid point (40, 40). The bubble is a thermal perturbation of +3 K released at 1800 m AGL. The perturbation relaxes to zero with a vertical radius of 1800 m and a horizontal radius of 10 km. This setup allows the storm to develop for approximately two hours before reaching the city. This numerical configuration is similar to that used by ? to investigate interactions between supercells and idealized orography.

The microphysics scheme used is ?, with hail as the prognostic rimed ice species. Longwave radiation is parameterized using the Rapid Radiative Transfer Model (?), while shortwave radiation is parameterized using the Dudhia scheme (?). Radiative forcing corresponds to conditions at a latitude of 45°N (the same as Milan) on May 31st. Noah-MP is used as the land surface model (??), while the Revised MM5 scheme (?) is employed to resolve the surface layer processes.

Several schemes are tested for the representation of PBL processes, coupled with the 1.5 TKE closure ($km_{opt} = 2$ in the WRF namelist), including the Boulac (?), Yonsei University (YSU, ?), or Mellor-Jamada-Janjic (?) schemes. Since no

90 remarkable differences are observed among the PBL schemes considered, the YSU scheme is preferred because it is widely used in severe storm studies at mid latitudes and also in urban settings (e.g., ?).

The domain is entirely flat, with a surface soil moisture¹ of $0.34\text{ m}^3\text{m}^{-3}$ and croplands as the uniform land-use category, except for a circular city centered at grid point (90,76). This location is chosen based on an analysis of the supercell evolution in the *no_urban* control run, where the land use is cropland everywhere. The goal is to locate the city such that the supercell
95 passes over its center two hours after initiation, coinciding with the time of peak intensity. Urban surface processes are resolved using the Building Effect Parametrization (BEP, ?) and the Building Energy Model (BEM, ?). In both models, buildings are not explicitly resolved; instead, their effects on the grid-averaged variables are parameterised. BEP computes the impact of roofs, streets, and walls on wind speed, temperature, and turbulent kinetic energy, also accounting for the shadowing and radiation-trapping effects induced by urban canyons. Building-height information affects the momentum, heat, moisture, and turbulent
100 kinetic energy source terms passed from the urban canopy to the atmospheric model. The model can therefore accurately represent the aggregate, grid-cell-scale effect of building height, which is the scale relevant to our simulations (?). In BEM, the exchange of momentum, heat, and radiation between indoor rooms and urban canyons is parameterised, also accounting for the heat generated by occupants and equipment and the effect of air conditioning systems. In this work, the *sea_breeze_2d*, adapted to run with the BEP-BEM scheme in a three-dimensional domain (??), was employed.

105 We chose a grid spacing of 1 km rather than a finer resolution because the BEP-BEM and PBL schemes have been extensively tested at that scale. At finer resolutions, within the 0.1–1 km grid-spacing range, a “*terra incognita*” exists (?), in which PBL schemes become unreliable (as part of the turbulence is explicitly resolved), while large-eddy simulations (LES) are also not fully appropriate (because not all coherent eddies are directly resolved at such coarse resolution). Using LES at a resolution of 100 m or finer would have been a valuable alternative; however, the computational costs were beyond our capabilities,
110 especially given the sensitivity tests and ensemble approach we implemented. Therefore, we preferred to use a well-established mesoscale modelling configuration with an advanced urban parametrization rather than adopting a finer resolution within the “gray zone,” with a potentially less reliable representation of urban processes.

2.2 Choice of the input sounding

A spin-up time is needed in the simulations to permit the generation of the urban boundary layer. During this spin-up time, deep
115 moist convection is not desired. To achieve the desired controlled experiment, the Weisman-Klemp supercell sounding profile (?) is used. Since the radiative heating during the day quickly triggers deep moist convection, an artificial thermal inversion of 4 K is added in the profile to coincide in height with the lifting condensation level (LCL, Fig. 1a). Through trial and error, an increase of 4 K is chosen as the threshold that completely suppresses the development of moist convection. The same issue was addressed similarly by ? and ?. At the LCL, the relative humidity is also reduced by a factor of 1.5, to resemble the presence of
120 an Elevated Mixing Layer (EML, see Fig. 1 of ?), a frequent feature during severe storm events both in the US (?) and in Europe (?). The denominator 1.5 is chosen in order to decrease the mid-level moisture, without drying the troposphere excessively. A

¹Lower values of soil moisture caused the development of an excessively dry PBL that suppressed deep moist convection.

thermal inversion of 4 K is compatible with real EML profiles (?)². Thus, the vertical profile of potential temperature $\Theta(z)$ of the input sounding is defined as:

$$\Theta(z) = \begin{cases} \Theta_0 + (\Theta_{tr} - \Theta_0) \left(\frac{z}{z_{tr}} \right)^{\frac{5}{4}} & z < z_{lcl} \\ \Theta_0 + (\Theta_{tr} - \Theta_0) \left(\frac{z}{z_{tr}} \right)^{\frac{5}{4}} + 4K & z_{lcl} \leq z \leq z_{tr} \\ \Theta_{tr} \exp \left[\frac{g}{C_p T_{tr}} (z - z_{tr}) \right] + 4K & z \geq z_{tr} \end{cases} \quad (1)$$

125 where g is gravity acceleration, C_p the specific heat capacity of the atmosphere, $\Theta_0 = 296$ K the potential temperature at the surface, $z_{tr} = 12000$ m the height of the tropopause, z_{lcl} is the height of the LCL, $\Theta_{tr} = 343$ K the potential temperature at the tropopause and $T_{tr} = 219$ K its temperature.

The vertical profile of relative humidity $rh(z)$ is defined as:

$$rh(z) = \begin{cases} 1 - \frac{3}{4} \left(\frac{z}{z_{tr}} \right)^{\frac{3}{4}} & z \leq z_{lcl} \\ \left[1 - \frac{3}{4} \left(\frac{z}{z_{tr}} \right)^{\frac{3}{4}} \right] / 1.5 & z_{lcl} \leq z \leq z_{tr} \\ 0.25 / 1.5 & z \geq z_{tr} \end{cases} \quad (2)$$

130 An exponent of 0.75 is used instead of the 1.25 employed in the original version of ?, in agreement with ?. The moisture in the boundary layer is defined by fixing a maximum value for specific humidity $q_{bl} = 14.5$ g kg⁻¹.

Six hours after the start of the simulation, the solar heating deepens the PBL (Fig. 1b), eroding the thermal inversion and creating high Convective Available Potential Energy (CAPE) values, as expected by the conceptual model of ?. At this time, the convective inhibition is negligible, and convection can grow once a lifting mechanism is provided. In the previous six hours,
135 deep moist convection is suppressed by the thermal inversion, permitting the generation of the urban boundary layer.

The environmental wind profile is defined by the quarter-circle hodograph proposed by ?. The profiles of the zonal $u(z)$ and meridional $v(z)$ wind components used for the current study, and plotted in the hodograph of Figure 1a, are defined as:

$$u(z) = \begin{cases} u_1 - u_1 \cos \left(\frac{\pi z}{2h_1} \right) - \frac{u_2}{4} & z < h_1 \\ u_1 + (z - h_1) \frac{u_2 - u_1}{h_2 - h_1} - \frac{u_2}{4} & h_1 \leq z < h_2 \\ \frac{3}{4} u_2 & z \geq h_2 \end{cases} \quad (3)$$

and

$$140 \quad v(z) = \begin{cases} v_1 \sin \left(\frac{\pi z}{2h_1} \right) & z < h_1 \\ v_1 & z \geq h_1 \end{cases} \quad (4)$$

²Note that the thermal inversion and moisture decrease associated with an EML are usually located at an elevation higher than the LCL. We place them at the LCL because the daytime growth of the PBL lifts the hygrothermal discontinuity to a more realistic elevation.

Fig1.png

Figure 1. (a) Input sounding at 10:00 am; (b) simulated sounding at 04:00 pm when the storm is initiated with a thermal bubble. Temperature (red line), dew point temperature (green line), and temperature of a surface parcel lifted adiabatically (black line) are shown. The CAPE area is red shaded. The hodograph is shown in the upper-right panel (the first 6 km of wind speeds are plotted).

Acronym	Index	Value
CAPE	convective available potential energy	2740 J kg ⁻¹
CIN	convective inhibition	0 J kg ⁻¹
bulk shear 0- 6 km	bulk shear 0-6 km	32.3 m s ⁻¹
SRH 0-3 km	storm relative helicity in the 0-3 km layer	200 J kg ⁻¹
SRH 0-1 km	storm relative helicity in the 0-1 km layer	33 J kg ⁻¹

Table 1. Some relevant thermodynamic and kinematic indices computed on the simulated sounding at 04:00 pm shown in Figure 1b.

where $h_1 = 1500$ m, $h_2 = 6000$ m, $u_1 = 7$ m s⁻¹, $u_2 = 40$ m s⁻¹, $v_1 = 10$ m s⁻¹ are chosen to produce a right-moving supercell (? used similar parameters). The diurnal mixing in the boundary layer and the surface drag changes the imposed wind profiles, as can be inferred by comparing the hodographs at 10:00 am and 04:00 pm in Figure 1. This is also a consequence of the lack of a meridional thermal gradient in the domain, which hinders the presence of a thermal wind capable of maintaining the curved hodograph in long-lasting simulations.

The transient evolution of the simulated profile suggests that the optimal timing for triggering the supercell should be carefully estimated. In the first part of the simulation thermodynamic and kinematic atmospheric parameters change (as shown in Figure S1); in particular, CAPE and LCL increase, Convective Inhibition (CIN) and Storm Relative Helicity (SRH) decrease. Between 5:00 pm and 8:00 pm, these parameters reach a minimum and a quasi-steady state, before nocturnal radiative cooling again significantly modifies the atmosphere. Therefore, triggering the storm at 04:00 pm and analyzing its interaction with the urban area between 05:00 pm and 07:00 pm is an appropriate choice. Even if at the beginning the supercells are moving into a slightly less favourable environment, any difference between the numerical experiments (that includes the city) and the *no_urban* simulations (Table 3) observed in that time span can be reasonably attributed to the urban morphological parameters rather than to changes in the broader environment.

Values of selected parameters calculated from the simulated sounding at 04:00 pm, when convection is initiated, are shown in Table 1. At 04:00 pm, the atmosphere is conducive to supercell storms, since the substantial—albeit not extreme—Surface Based (SB) CAPE (2740 J kg⁻¹, virtual correction is considered), strong bulk shear 0-6 km (32.3 m s⁻¹) and moderate 0-3-km SRH (200 J kg⁻¹). The highest Θ_e in the low-levels is observed at the surface, suggesting that storms are surface-based with this profile.

2.3 The numerical experiments

The BEP-BEM model requires several urban morphological parameters to run. The thermal features of the city are kept constant: the default values (reported in Table 2) of Local Climate Zone 2 are used (?). The sensitivity of the supercell to some of the BEP-BEM parameters is investigated in this work: street width (s), building width (b), building height (h_b), and urban fraction (uf). In Table 3, a summary of the numerical experiments conducted is provided, while in Figure 2, a graphical summary is furnished. The range of parameters explored is selected by studying the mean morphological parameters of some European and

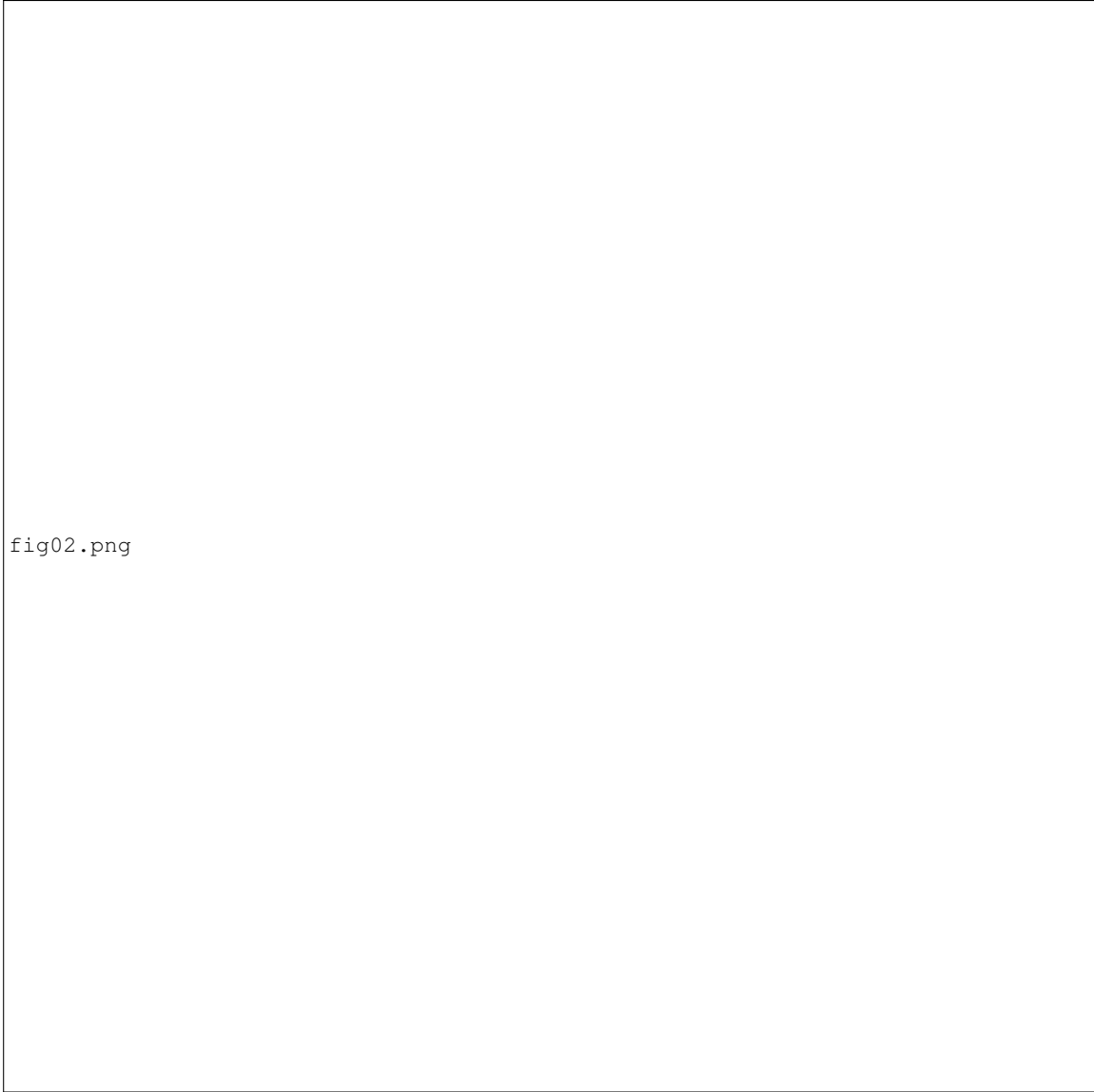


Figure 2. Schematic representation of some of the urban features explored in the idealized simulations. The *zero value* (left) and the *max value* (right) of the studied urban morphological parameters (city size, building height, urban fraction, and building density) are shown (see Table 3). In the first row, the simulation domain is depicted from above, showing croplands (green shading with plants) and the city (grey circle). In the remaining rows, the view is lateral. Grey rectangles represent buildings. d denotes the city diameter, h_b the building height, uf the urban fraction, s the street width, b the building width, and λ_b the ratio of building area to total area.

	Heat Capacity ($\text{Jm}^{-3}\text{K}^{-1}$)	Thermal Conductivity ($\text{Jm}^{-1}\text{s}^{-1}\text{K}^{-1}$)	Surface Albedo	Surface Emissivity
Ground	1.68×10^6	0.73	0.14	0.95
Walls	1.67×10^6	1.09	0.3	0.90
Roofs	1.8×10^6	1.25	0.3	0.91

Table 2. Thermal features of the idealized city.

	numerical experiments	zero value	intermediate values	max value
<i>city size</i> (km)		0 (no_urban)	5; 10; 15; 20; 25	30
<i>city size ufl</i> (km)		0 (no_urban)	5; 10; 15; 20; 25	30
<i>urban fraction</i>		0.4	0.6; 0.8	1.0
<i>building height</i> (m)		10	20; 40	60
<i>building density</i> (λ_p, λ_b)		(0.1,0.3)	(0.2, 0.6) ; (0.3,0.9)	(0.4,1.2)
<i>green roofs</i>		no_urban		green roofs over all roofs
<i>no_thermo</i>		no_urban		buildings with rural energetic balance
<i>storm_shifted</i>		no_urban		bubble shifted from (40,40) to (30,60)

Table 3. Numerical experiments conducted and parameters explored.

US cities frequently affected by severe storms (see, for example, Table S1 and Figure S2), using the GLocal Building heights for Urban Studies (GLOBUS) dataset (?). In that dataset, the plan area fraction (λ_p) and the building surface-to-plan area ratio (λ_b) are reported. These are defined as:

$$\lambda_p = \frac{b}{s+b} \quad (5)$$

$$170 \quad \lambda_b = \frac{2h_b}{s+b} + \lambda_p. \quad (6)$$

λ_p is the fraction of ground covered by buildings, it quantifies the building density in a city. Instead, λ_p quantifies the total urban area (roofs, walls, streets) exposed to the atmosphere.

First, a sensitivity analysis of city size is conducted, with city diameters ranging from 0 km in the *no_urban* scenario to 30 km (numerical experiments *city size*). Table 4 presents the parameters used to define the idealized city uniformly in the control runs. These are based on the Milan, Italy, GLOBUS data (Table S1). Milan, Italy, is chosen as the reference city both because it was object of investigation in a preceding case study analysis (?), and also because its morphological parameters

	<i>no_urban</i>	<i>uf0.63_5km</i>	<i>uf0.63_10km</i>	<i>uf0.63_15km</i>	<i>uf0.63_20km</i>	<i>uf0.63_25km</i>	<i>uf0.63_30km</i>
city diameter (km)	0	5	10	15	20	25	30
urban fraction	0.63	0.63	0.63	0.63	0.63	0.63	0.63
building height (m)	20	20	20	20	20	20	20
λ_p	0.24	0.24	0.24	0.24	0.24	0.24	0.24
λ_b	0.78	0.78	0.78	0.78	0.78	0.78	0.78

Table 4. Urban morphological parameters used in the set of numerical experiments *city size* (in the first row the name of the experiments is reported).

	<i>no_urban</i>	<i>uf1_5km</i>	<i>uf1_10km</i>	<i>uf1_15km</i>	<i>uf1_20km</i>	<i>uf1_25km</i>	<i>uf1_30km</i>
city diameter (km)	0	5	10	15	20	25	30
urban fraction	1.0	1.0	1.0	1.0	1.0	1.0	1.0
building height (m)	20	20	20	20	20	20	20
λ_p	0.24	0.24	0.24	0.24	0.24	0.24	0.24
λ_b	0.78	0.78	0.78	0.78	0.78	0.78	0.78

Table 5. As in Table 4, but for numerical experiments *city size uf1*.

are relatively typical of European cities. It's characterized by urban fraction of 0.63, mean building heights of 20 m and $(\lambda_p, \lambda_b) = (0.24, 0.78)$.

The same set of numerical experiments is also performed using an urban fraction (*uf*) of 1.0 instead of 0.63 (numerical experiments *city size uf1*, Table 5). An urban fraction of 1.0 means the entire urban surface is built-up (i.e., no croplands within the city radius). However, 20% of the street surface remains covered by trees in these experiments, as a city without any trees is unrealistic. Although a mean urban fraction of 1.0 is not observed in European or U.S. cities (Table S1), this experiment is conducted to explore the impact of city size under the extreme scenario of a fully urbanized city.

A third set of numerical experiments, called *urban fraction*, is conducted to examine the supercell's sensitivity to urban fraction. Values ranging from 0.4 to 1.0 are investigated for an idealized city with a diameter of 20 km (Table 6).

The *building height* experiments, investigate the effect of building height on the simulated storm (Table 7). The building heights explored range from 10 to 60 m, representing cities from the Chicago metropolitan area to downtown New York.

Furthermore, the *building density* experiments explore the effect of building density on the simulated storms (Table 8). Since the BEP-BEM scheme uses street and building widths as input parameters (rather than the λ parameters), the building height and the building width are kept constant at 20 m, while the street width is varied from 106 m to 11.5 m. This corresponds to a range of (λ_p, λ_b) values from (0.1, 0.3) to (0.4, 1.2), representing a transition from a very dispersed to a highly compact city.

	$uf0.4$	$uf0.6$	$uf0.8$	$uf1.0$
city diameter (km)	20	20	20	20
urban fraction	0.4	0.6	0.8	1.0
building height (m)	20	20	20	20
λ_p	0.24	0.24	0.24	0.24
λ_b	0.78	0.78	0.78	0.78

Table 6. As in Table 4, but for numerical experiments *urban fraction* (uf).

	$h10$	$h20$	$h40$	$h60$
city diameter (km)	20	20	20	20
urban fraction	0.63	0.63	0.63	0.63
building height (m)	10	20	40	60
λ_p	0.24	0.24	0.24	0.24
λ_b	0.78	0.78	0.78	0.78

Table 7. As in Table 4, but for numerical experiments *building height* (h_b).

	$\lambda_b0.3$	$\lambda_b0.6$	$\lambda_b0.9$	$\lambda_b1.2$
city diameter (km)	20	20	20	20
urban fraction	0.63	0.63	0.63	0.63
building height (m)	20	20	20	20
λ_p	0.1	0.2	0.3	0.4
λ_b	0.3	0.6	0.9	1.2

Table 8. As in Table 4 but for numerical experiments *building density*.

Lastly, some additional experiments are conducted to investigate other specific questions. An experiment is carried out using the settings of numerical experiment *uf1_30km*, but with vegetation placed over all the buildings of the idealized city (?), to investigate the effect of this nature-based solution on storm dynamics (this experiment is called *green roofs*; see Table 3). A second experiment, called *no_thermo*, is conducted with the settings of the *uf1_30km* experiment and the same urban roughness, but with the urban energetic balance replaced by the rural one. This experiment serves to disentangle the dynamical (i.e., building barrier-effects) and thermodynamics (i.e., UHI and UDI) effects of the city on the storm and the pre-storm environment. An experiment, called *storm_shifted* (Table 3), is also run to test the sensitivity of the results to whether a different part of the urban plume is crossed by the storm. In this experiment, the thermal bubble is shifted from grid-point (40,40) to (30,60), while keeping the same parameters of experiment *uf1_30km* (Table 5).

2.4 Generation of the ensembles

An ensemble approach is adopted to better assess the physical signal of urban-induced storm modifications across different flow realizations, given the intrinsic chaotic variability of the atmosphere. For each numerical experiment, eleven simulations are conducted: one is the control run, and the other ten are generated using the Stochastic Kinetic Energy Backscatter Scheme (SKEBS, ?). SKEBS generates stochastic streamfunction perturbations through autoregressive processes in spectral space and injects them into regions where the model exhibits excessive systematic kinetic energy loss. In the present study, the parameters used to generate the ensemble with SKEBS are set following ?, who investigated ensemble dispersion in deep moist convective events. The only difference from their setup is the value of the maximum wavenumber of the potential temperature and streamfunction perturbation, which is set to match the number of grid points in the current simulations.

The ten ensemble members are generated using ten distinct random seeds, which are kept constant across all numerical experiments. As a result, the same members across different experiments are using the same seeds and are not fully independent (this is considered in the statistical analysis). This is done intentionally to better evaluate the influence of each parameter over the different flow evolutions (i.e., members).

2.5 Storm tracking

The Statistical and Programmable Objective Updraft Tracker (SPOUT, ?) algorithm is used to track the simulated updrafts. Fine-tuning of some user-defined parameters is necessary to achieve satisfactory tracking of the supercell updrafts. Table S2 lists these parameters and compares them with those originally employed by ?.

Further filtering of the SPOUT-detected tracks is necessary to isolate the right-moving supercell track, as the algorithm frequently splits it. This occurs because SPOUT tracks updrafts individually, and supercells may cycle, producing new updrafts. To filter out these updrafts, only the track that begins near the location where the thermal bubble is released is considered. If the track terminates at $x < 150$ (i.e., before three hours after the bubble release), a new track is searched for within a 10 km radius. If found, the new track is connected to the previous one. This process is repeated until the track reaches $x = 150$ or the storm dissipates.

Each point along the track is considered the storm center at a given time step. Storm diagnostics are extracted every 10 minutes, and the extracted variables are listed in Table 9. For each time step, the mean (or maximum or minimum, depending on the variable) is calculated within an 8-km radius around the storm center, and this value is assigned to the storm at that time step.

Then, three regions are defined using a temporal criterion to compare the storms at the same developmental stage across different numerical experiments. Those regions are defined with respect to a zero, defined as the time step when the supercell is above the city, corresponding to grid point (90,76) in the control run of the *no_urban* experiment. This time step is at 06:00 pm (see, for instance, Fig. 3d). Then, three 40-minute windows are defined (sketch in Figure 4). The first one, from -20 to +20 minutes, defines the *city region*. The *upstream region* is defined from -60 to -20 minutes. Lastly, the *downstream region* is defined from +20 minutes to +60 minutes. In these windows, the variables previously computed for each time step are averaged. Thus, considering the 10-minute output frequency, four time steps are averaged for each window.

2.6 Statistical method used to analyze the numerical experiments

Given a set of numerical experiments, a statistical analysis is conducted for each region and for each variable. The variables are normalized with respect to a reference zero value (defined case-by-case in Table 3). The normalized z_{ij} variable for the ensemble member j and numerical experiment i is given by:

$$z_{ij} = \frac{x_{ij} - x_{0j}}{x_{0j}} \quad (7)$$

where x_{ij} is the original variable and x_{0j} is the reference value for the ensemble member j . This approach is adopted because to understand how storm diagnostics vary relative to a reference case (e.g., how updraft speed changes with increasing city size compared to the *no_urban* case). A linear fit is performed using the *curve_fit* function from SciPy (?) on the normalized variables sharing the same SKEBS seed. Any null values are excluded: specifically, if a storm dissipates, the corresponding ensemble member is omitted from the fit. This exclusion is necessary because, for some variables (e.g., Θ), including a null value in the linear fit lacks physical meaning. In general, excluding such values has been observed to increase the fit's statistical significance.

We focus solely on the slope parameter of the linear fit, particularly its sign. The statistical significance of the slope relative to a null hypothesis of a zero slope is assessed using a 5–95% bootstrap confidence interval, computed from 1000 iterations using the *bootstrap* function of SciPy.

3 Results: Supercell sensitivity to the urban morphological parameters

In this section, the sensitivity of the simulated supercell to urban morphological parameters is presented. Across the different ensemble members, there are variations in the storm tracks and intensity; however, all simulations of the *no_urban* reference experiment produce a long-lasting, right-moving supercell, similar to the one shown in Fig. 3 for the *uf0.63_10km* experiment.



Figure 3. Maximum simulated reflectivity (colour shading) at a) 04:20 pm, b) 05:00 pm, c) 05:40 pm, d) 06:00 pm, e) 06:20 pm, f) 07:00 pm by the control run of numerical experiment *uf0.63_10km*. The city is shown with a grey shading. UH value higher than 100 m s^{-1} are highlighted with a black contour. The black (blue) arrow indicates the right-moving (left-moving) supercell.



Figure 4. Criterion used to define the upstream, city and downstream regions.

The right-moving supercell approaches the city from the WSW (Fig. 3c) and remains isolated and intense also one hour after
 255 hitting the city (Fig. 3f).

3.1 *City size*

In the numerical experiments *city size*, the effect of increasing the diameter of the city with the same characteristics as Milan
 on the supercell is investigated. The normalized mean value of the storm's UH in the *city region* is shown in Fig. 5a for each
 ensemble member as a function of city diameter (the same plots for the *upstream* and *downstream regions* are displayed in
 260 Figure S3). In the *city region*, there is a clear decreasing trend in UH, even with considerable ensemble spread. A similar
 pattern is observed in the *upstream region* (Fig. S4a), whereas in the *downstream region* a more consistent decreasing trend is
 seen across all ensemble members (Fig. S3c).

Table 9 presents the mean slopes for each storm diagnostic variable in the three regions. A general negative trend is observed,
 though it is statistically significant only for some of them³. The trend is particularly significant in the *city region* and for the
 265 vertical velocity and vorticity at 500 hPa, and for UH. This indicates that the supercell weakens as city diameter increases, with
 the weakening more pronounced and statistically significantly lower than zero at the mid-levels and when the storm is over the

³ Θ shows a positive trend. This is because the cold pools weaken as the storm weakens, leading to less pronounced negative Θ anomalies associated with
 downdrafts—i.e., a relative increase in Θ .

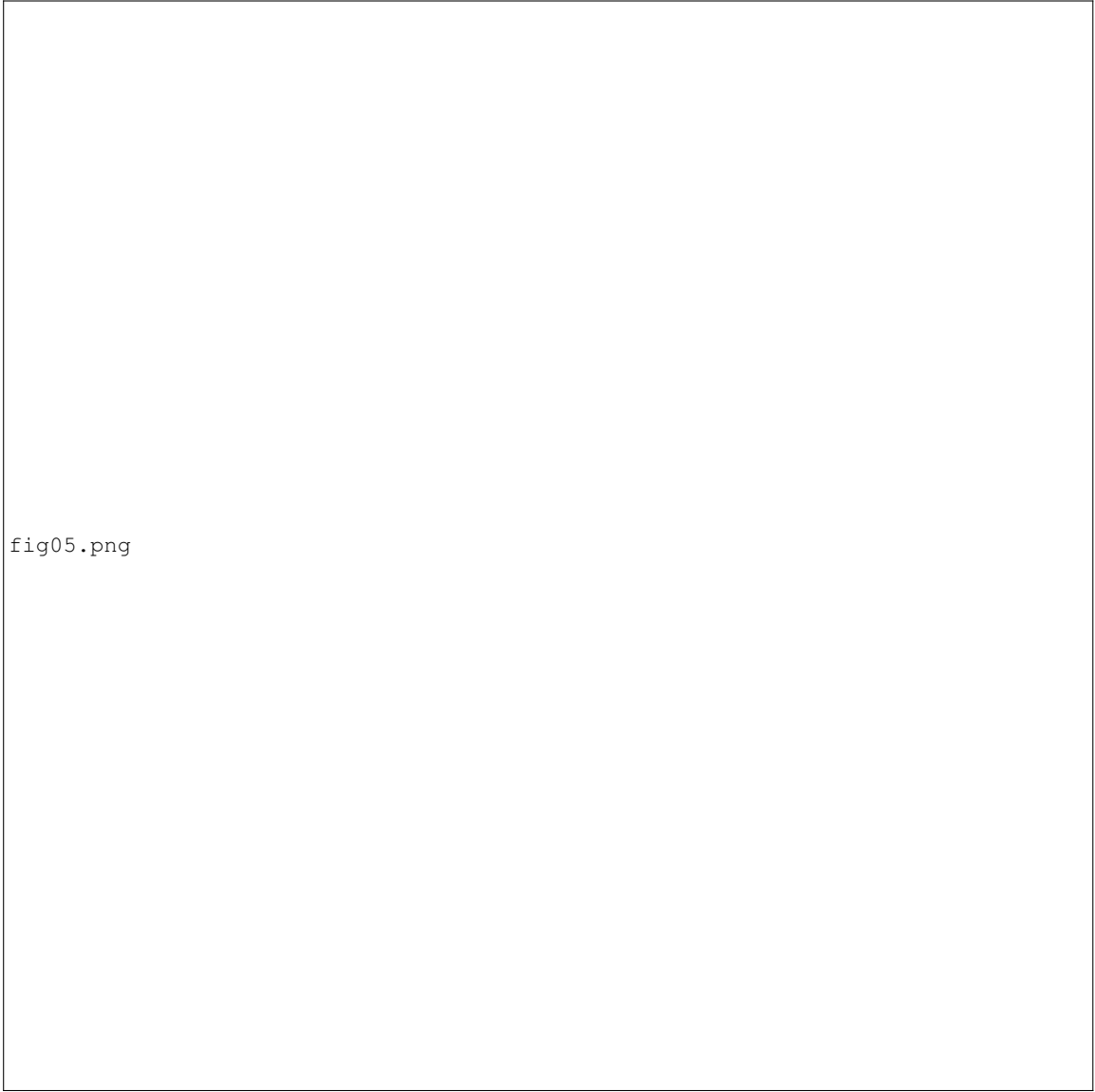


fig05.png

Figure 5. a) Normalized mean UH (z^*) in each ensemble member (black dots) of the *city size* set of experiments (Table 4) in function of the city diameter (km) in the *city region*. Ensemble members obtained with the same seed are connected. The mean linear fit is shown with a red line, while the 5-95% confidence interval is red shaded. b), c) and d) as in a) but for the *city size ufl*, *urban fraction* and *building height* set of experiments, respectively. In b), a quadratic fit is shown with a purple line.

city. The increasing trend shown by some ensemble members in Fig. S3a and 5a suggests that, even if rare, an intensification of the supercell is possible in the *upstream* and *city* regions.

variable	meaning	upstream	city	downstream
wmax	maximum vertical velocity	-2.6×10^{-3}	-2.1×10^{-3}	-1.1×10^{-3}
w500	maximum vertical velocity at 500 hPa	-6.1×10^{-3}	-3.1×10^{-3}	-1.8×10^{-3}
ζ 500	maximum vertical vorticity at 500 hPa	-3.9×10^{-3}	-2.0×10^{-3}	-2.6×10^{-3}
uh max	maximum updraft helicity in the 2-5 km layer	-3.1×10^{-3}	-4.6×10^{-3}	-3.7×10^{-4}
uh mean	mean updraft helicity in the 2-5 km layer	-3.3×10^{-3}	-4.2×10^{-3}	-5.7×10^{-3}
w700	maximum vertical velocity at 700 hPa	-1.4×10^{-3}	-1.9×10^{-3}	-2.8×10^{-4}
ζ 700	maximum vertical vorticity at 700 hPa	$+3.8 \times 10^{-4}$	-8.7×10^{-4}	-6.5×10^{-4}
w850	maximum vertical velocity at 850 hPa	-1.3×10^{-3}	-3.6×10^{-3}	-2.0×10^{-3}
ζ 850 max	maximum vertical vorticity at 850 hPa	-1.5×10^{-4}	$+2.1 \times 10^{-4}$	-5.7×10^{-4}
w950	maximum vertical velocity at 950 hPa	$+2.1 \times 10^{-5}$	-5.4×10^{-3}	-3.7×10^{-3}
ζ 950	maximum vertical vorticity at 950 hPa	-7.8×10^{-4}	-2.6×10^{-3}	-5.1×10^{-3}
Θ_e (500 hPa) max	maximum equivalent potential temperature at 500 hPa	-6.3×10^{-5}	-1.9×10^{-4}	-7.1×10^{-6}
Θ_e (500 hPa) mean	mean equivalent potential temperature at 500 hPa	-3.7×10^{-5}	-3.4×10^{-5}	-1.2×10^{-5}
Θ (5 m) min	minimum potential temperature in the first model level	-2.9×10^{-5}	$+5.4 \times 10^{-5}$	$+8.1 \times 10^{-5}$
Θ (5 m) mean	mean potential temperature in the first model level	-1.6×10^{-5}	$+4.9 \times 10^{-5}$	$+2.1 \times 10^{-5}$

Table 9. List of storm diagnostic variables used (every value is computed considering an 8-km radius following the storm track) and corresponding mean slopes (km^{-1}) of the linear fits between diagnostic variables and city diameters in the *city size* numerical experiments. Bold values are statistically significant lower (or larger) than zero.

In the *city size ufl* experiments, a similar trend of the *city size* sample is observed, but the weakening of the storm is even more pronounced (Fig. 5b). This weakening is particularly evident downstream of the city and, in this case, is statistically significantly lower than zero also for several low-level storm diagnostic variables (Table 10)⁴. In the *city region*, a quadratic fit is statistically significantly lower than zero (purple line in Fig. 5b). For city diameters up to about 10 km, the city has little effect on the storm. However, in larger cities, the storm weakens faster with city size than a linear fit would suggest.

The cumulative ensemble mean of UH clearly illustrates the effect of urban land use on the supercell. In the *no_urban* experiment, a substantial UH swath is present⁵ (Fig. 6a), which is considerably weakened as it passes over the city (Fig. 6b).

⁴Note, however, that a positive trend in vertical vorticity at 850 and 700 hPa is observed in the *city region*, with statistical significance at 850 hPa.

⁵The temporary reduction of UH over the city may be associated with a transition phase of the simulated supercell. During this stage, the storm may be more sensitive to environmental differences. However, since the only environmental differences in our experiments are urban-induced, this effect is expected to have a limited impact on the results.

The suppression becomes nearly complete in the *uf1_30km* experiment (Fig. 6c). Notably, the suppression is significantly more pronounced in the *city size uf1* sample than in the *city size* sample (Fig. 6d).

variable	upstream (<i>size uf1</i>)	city (<i>size uf1</i>)	downstream (<i>size uf1</i>)	upstream (<i>uf</i>)	city (<i>uf</i>)	downstream (<i>uf</i>)
wmax	-3.9×10^{-3}	-3.7×10^{-3}	-3.7×10^{-3}	-4.1×10^{-2}	-8.6×10^{-2}	-1.2×10^{-1}
w500	-8.1×10^{-3}	-8.7×10^{-3}	-4.1×10^{-3}	-4.8×10^{-2}	-1.6×10^{-1}	-1.8×10^{-1}
ζ 500	-4.8×10^{-3}	-4.3×10^{-3}	-4.3×10^{-2}	-3.6×10^{-2}	-7.6×10^{-2}	-7.5×10^{-2}
uh max	-4.1×10^{-3}	-6.8×10^{-3}	3.3×10^{-3}	-2.7×10^{-2}	-1.0×10^{-1}	-1.9×10^{-1}
uh mean	-6.4×10^{-3}	-7.7×10^{-3}	-9.7×10^{-3}	-4.9×10^{-2}	-4.3×10^{-2}	-2.6×10^{-1}
w700	-1.8×10^{-3}	-1.8×10^{-3}	-3.1×10^{-3}	-1.8×10^{-2}	-1.2×10^{-1}	-1.1×10^{-1}
ζ 700	-7.8×10^{-4}	$+3.45 \times 10^{-5}$	-2.7×10^{-3}	-5.8×10^{-3}	-3.4×10^{-3}	-1.6×10^{-3}
w850	-2.4×10^{-3}	-4.3×10^{-3}	-3.4×10^{-3}	$+5.0 \times 10^{-3}$	-7.2×10^{-2}	-8.7×10^{-2}
ζ 850	-8.1×10^{-4}	$+7.1 \times 10^{-4}$	-7.2×10^{-3}	$+2.2 \times 10^{-2}$	-5.5×10^{-2}	$+1.1 \times 10^{-1}$
w950	-9.1×10^{-4}	-6.1×10^{-3}	-5.6×10^{-3}	-5.1×10^{-4}	$+1.4 \times 10^{-2}$	-1.1×10^{-1}
ζ 950	$+6.6 \times 10^{-4}$	-4.7×10^{-3}	-3.7×10^{-3}	-1.6×10^{-3}	-2.8×10^{-2}	-1.8×10^{-1}
$\Theta_e(500\text{hPa})$ max	-2.6×10^{-2}	-2.4×10^{-4}	-1.3×10^{-4}	-1.0×10^{-3}	-6.3×10^{-3}	-5.9×10^{-3}
$\Theta_e(500\text{hPa})$ mean	-9.6×10^{-5}	-5.5×10^{-5}	-7.1×10^{-5}	-2.8×10^{-4}	-1.7×10^{-3}	-3.7×10^{-3}
$\Theta(5\text{m})$ min	-8.9×10^{-7}	$+1.1 \times 10^{-4}$	$+1.7 \times 10^{-4}$	-3.1×10^{-4}	$+4.0 \times 10^{-4}$	$+1.2 \times 10^{-3}$
$\Theta(5\text{m})$ mean	-1.0×10^{-5}	$+7.5 \times 10^{-5}$	$+7.2 \times 10^{-5}$	-3.7×10^{-5}	$+3.4 \times 10^{-4}$	$+5.0 \times 10^{-4}$

Table 10. Slope of fitting lines between diagnostic variables of the supercell and *city size uf1* experiments (*size uf1*, left block, units m^{-1}), or urban fraction (*uf*, right block). Bolded values are statistically significant lower (or larger) than zero.

A noteworthy feature in the *uf1_30km* experiment is the emergence of a new UH swath north of the city (Fig. 6c). To better understand this behavior, the same time steps showing maximum reflectivity from ensemble member 1 of the *uf1_30km* experiment (Fig. 7) are compared with those from the control run of the *uf0.63_10km* experiment (Fig. 3). In the *uf1_30km* experiment, the initial supercell is suppressed very early, already by 05:00 pm (Fig. 7b). However, a stripe of vertical velocities exceeding 0.5 ms^{-1} extends from the city toward the northwest. Just east of this stripe, new convective cells begin to develop between 05:40 pm (Fig. 7c) and 06:20 pm (Fig. 7e). By 07:00 pm, a new right-moving supercell forms from these earlier convective initiations (Fig. 7f). Thus, in this simulation, the original supercell is suppressed, while a new, urban-induced supercell develops. This behavior occurs in 8 out of 11 members of the *uf1_30km* experiment and is not observed in any of the other experiments (see Figs. 6 and 8). Additional evidence supporting the urban origin of the second supercell initiated at 07:00 pm will be presented in Section 4.

3.2 Urban fraction

In the *urban fraction* experiments, most storm diagnostic variables decrease as a function of the urban fraction (Table 10). However, only some of these trends are statistically significantly lower than zero in the *upstream region*. By contrast, no statistically significant trends are observed in the *city* and *downstream region* (except for $\Theta_e(500 \text{ hPa})$ in the *downstream region*). In the *upstream region*, the ensemble spread is relatively small (Fig. S5a), which leads to statistically significant

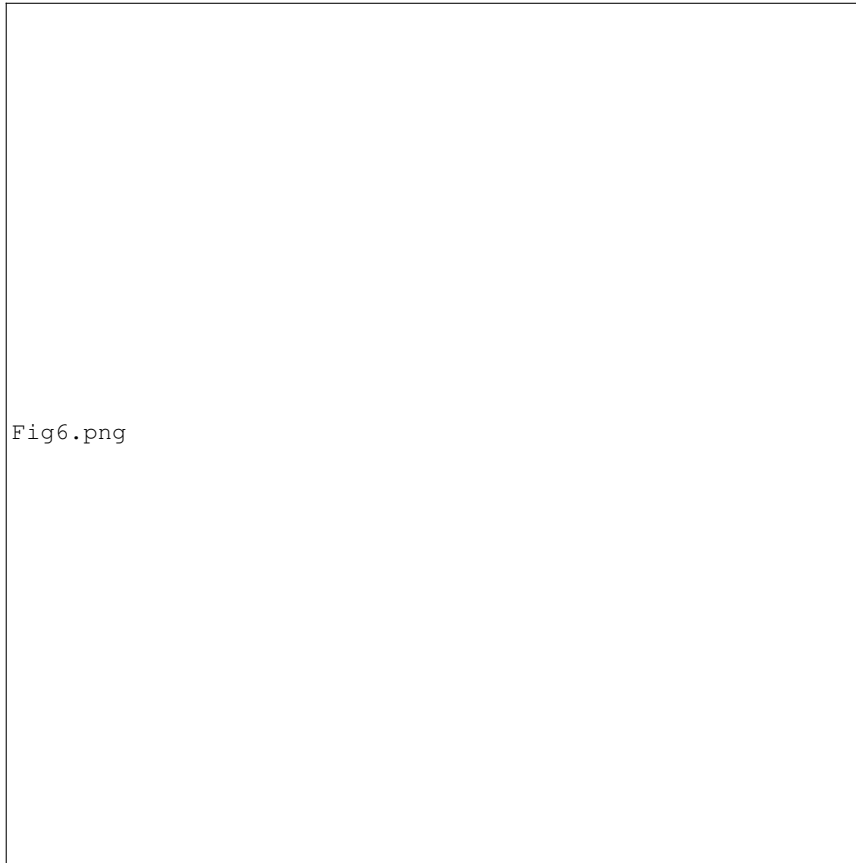


Figure 6. Cumulated UH ensemble mean in a) the *no_urban* experiment (Table 5), b) in the *uf1_20km* experiment, c) in the *uf1_30km* experiment, d) in the *uf0.63_30km* experiment (Table 4), e) in the *uf0.4* experiment (Table 6), f) in the *uf1.0* experiment. The city is highlighted in grey shading. In a) the city of the *20km* experiment is shown just for reference, in the experiment there are croplands everywhere.

trends—even though the slope of the mean linear fit is smaller than in the other two regions. Nevertheless, examining the ensemble mean of the UH swath in the *uf0.4* and *uf1.0* experiments (Figure 6e,f) reveals a visible weakening of the storm. We conclude that the supercell weakens with increasing urban fraction, although this trend is not statistically significant lower than zero.

3.3 Building height

An opposite trend is observed in the supercell’s sensitivity to building height. In all three regions, the mean UH increases with increasing building height (Fig. 5d and S6). The positive trend in mean UH is statistically significantly larger than zero across all three regions studied (Table 11). Other mid-level storm diagnostic variables exhibit a similar positive trend; however, these trends are statistically significantly larger than zero only in the *upstream* and *city regions* for some variables (e.g., w500 and



Figure 7. As in Fig. 3, but for the ensemble member 1 of the *uf1_30km* numerical experiment. Vertical velocities at 950 hPa higher than 0.5 m s^{-1} are plotted with red contours. The blue arrows indicate the triggering of the urban-induced right-moving supercell.

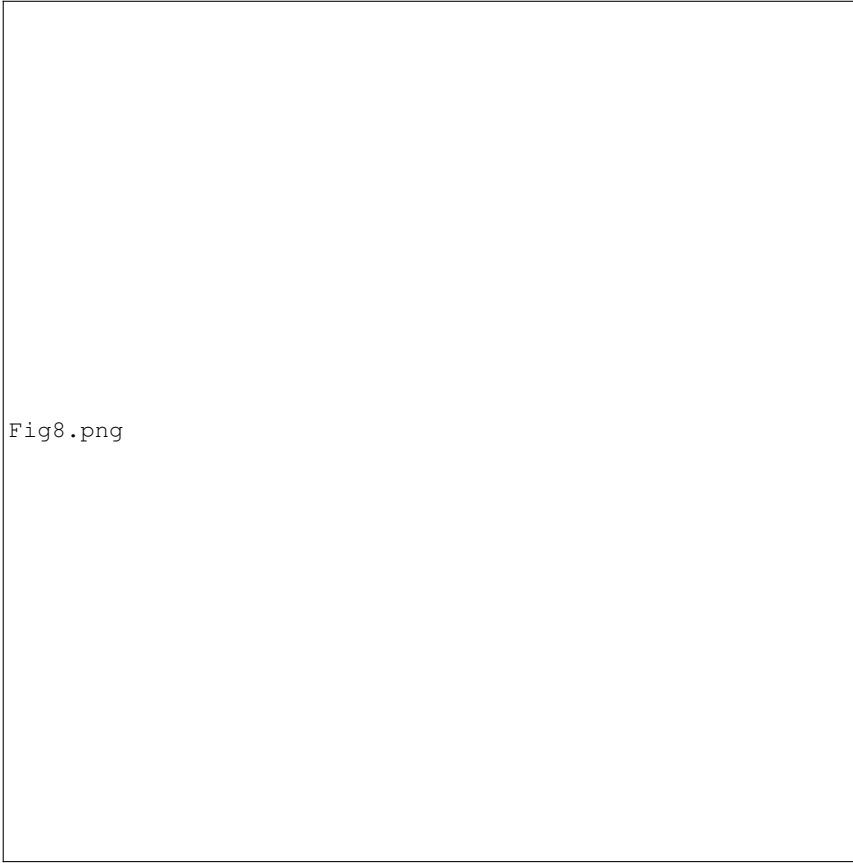


Figure 8. As in Fig. 6, but for a) *h10* experiment (Table 7), b) *h60* experiment, c) $\lambda_b 0.3$ experiment (Table 7), d) $\lambda_b 1.2$ experiment, e) *green roofs* experiment (Table 3) and f) *no_thermo* experiment (Table 3).

w700). In agreement with this result, the ensemble mean of the UH swath in the *h60* experiment (Fig. 8b) is higher than in the *h10* experiment (Fig. 8a).

In contrast, low-level storm diagnostic variables show a decreasing trend with increasing building height (Table 11), and this trend is statistically significantly lower than zero for some variables (e.g., w_{950} in the *city region*). This result is surprising and interesting, as it contrasts with the storm behavior aloft and also with the hypothesis that taller buildings should enhance vertical motions due to the building-barrier effect and mass conservation (e.g., ?).

3.4 Building density

Variables describing the storm's mid-level characteristics show a general weakening trend in the *upstream* and *city regions* with increasing building density (Table 11). However, this trend is statistically significantly smaller than zero only for some variables (e.g., w_{500} and ζ_{500} , Table 11). The mean UH does not exhibit a clear trend with increasing building density (Fig.

variable	upstream (h_b)	city (h_b)	downstream (h_b)	upstream (λ_b)	city (λ_b)	downstream (λ_b)
wmax	$+6.8 \times 10^{-4}$	$+9.4 \times 10^{-4}$	$+1.3 \times 10^{-3}$	-1.2×10^{-2}	-3.5×10^{-2}	$+2.1 \times 10^{-3}$
w500	$+8.0 \times 10^{-4}$	$+8.6 \times 10^{-4}$	$+1.1 \times 10^{-3}$	-8.0×10^{-3}	-4.3×10^{-2}	$+7.5 \times 10^{-3}$
ζ 500	$+8.1 \times 10^{-4}$	$+3.2 \times 10^{-4}$	-1.2×10^{-3}	-1.6×10^{-2}	-2.2×10^{-2}	-3.8×10^{-2}
uh max	$+5.2 \times 10^{-4}$	$+1.8 \times 10^{-3}$	$+7.7 \times 10^{-4}$	-1.1×10^{-2}	-3.8×10^{-2}	$+4.6 \times 10^{-2}$
uh mean	$+5.1 \times 10^{-3}$	$+2.0 \times 10^{-3}$	$+6.3 \times 10^{-3}$	-9.2×10^{-3}	-6.2×10^{-2}	$+5.4 \times 10^{-2}$
w700	$+3.2 \times 10^{-4}$	$+6.3 \times 10^{-4}$	$+3.7 \times 10^{-4}$	-9.2×10^{-4}	-3.4×10^{-2}	$+1.9 \times 10^{-2}$
ζ 700	$+5.0 \times 10^{-5}$	-8.1×10^{-4}	-9.0×10^{-4}	$+4.3 \times 10^{-3}$	$+1.1 \times 10^{-2}$	$+7.4 \times 10^{-3}$
w850	-4.6×10^{-5}	-2.7×10^{-4}	-4.1×10^{-4}	$+2.9 \times 10^{-3}$	-1.8×10^{-2}	-2.1×10^{-3}
ζ 850	-5.6×10^{-4}	$+6.6 \times 10^{-5}$	-1.4×10^{-3}	$+2.2 \times 10^{-2}$	-3.2×10^{-2}	$+1.0 \times 10^{-1}$
w950	$+2.1 \times 10^{-4}$	-3.2×10^{-3}	-2.2×10^{-3}	-1.1×10^{-2}	-5.1×10^{-2}	-4.2×10^{-2}
ζ 950	-1.6×10^{-4}	-3.1×10^{-3}	-2.2×10^{-3}	$+1.3 \times 10^{-2}$	-5.9×10^{-2}	$+4.0 \times 10^{-2}$
Θ_e (500 hPa) max	$+1.1 \times 10^{-5}$	$+5.5 \times 10^{-5}$	$+9.5 \times 10^{-5}$	$+1.2 \times 10^{-4}$	-2.6×10^{-3}	$+1.9 \times 10^{-3}$
Θ_e (500 hPa) mean	-3.6×10^{-6}	$+3.4 \times 10^{-6}$	$+4.3 \times 10^{-5}$	$+7.8 \times 10^{-5}$	$+1.5 \times 10^{-5}$	$+1.3 \times 10^{-4}$
Θ (5 m) min	$+3.3 \times 10^{-5}$	$+3.4 \times 10^{-5}$	-1.3×10^{-5}	$+5.6 \times 10^{-5}$	$+1.7 \times 10^{-3}$	-2.4×10^{-4}
Θ (5 m) mean	-1.6×10^{-7}	-8.0×10^{-6}	-5.1×10^{-6}	$+7.2 \times 10^{-6}$	$+6.9 \times 10^{-4}$	-8.8×10^{-4}

Table 11. Slope of fitting lines between diagnostic variables of the supercell and building heights (h_m , left block, units m^{-1}), or building density (λ_b , right block). Bolded values are statistically significant lower (or larger) then zero.

S7). Low-level storm diagnostic variables do not show a consistent trend. In general, in the *downstream region*, no clear trend is observed either aloft or near the surface, and none of the studied variables exhibit statistically significant trends.

The ensemble mean of the UH swath shows slightly lower values *downstream* of the city in the $\lambda_b 1.2$ experiment (Fig. 8d) compared to the $\lambda_b 0.3$ experiment (Fig. 8c). Overall, we conclude that the storm does exhibit some sensitivity to building density; however, this parameter appears to be the least influential in determining storm dynamics among the previously studied parameters.

3.5 Additional experiments

Comparing Fig. 6c with Fig. 8e, it is evident that the weakening of the storm as it passes over the city is much less pronounced when the roofs are covered with vegetation (*green roof* experiment). Furthermore, using the rural energetic balance in the *no_thermo* experiment (Fig. 8f) results in a UH swath that is very similar to that of the *no_urban* experiment (Fig. 6a). Thus, the greater the amount of vegetation in a city, the less effect the city has on the approaching storm.

4 Results: Sensitivity of the pre-storm environment to the urban morphological parameters

To understand the urban effects on the simulated storm, we examine how urban morphological parameters influence near-surface variables, CAPE, SRH, and w950 at 04:00 pm (the time of convective initiation). This analysis compares ensemble-mean differences between simulations using the highest values of the morphological parameters (“max value” column in Table 3) and those using the lowest values (“zero value” column in Table 3).

4.1 Near-surface variables

The *uf0.63_30km* simulations produce a weak UHI of about 1.5 K over the city (Fig. 9a), in good agreement with typical daytime UHI magnitudes (e.g., ???). A pronounced UDI is also reproduced (peak of -2 g kg^{-1}), corresponding to a relative humidity difference of about 13% between the city and the surrounding rural areas, consistent with several other studies (????). A wake of higher temperatures and lower humidity extends downwind (with respect to the southeasterly surface wind) up to 80 km from the city. Within this wake, a wind convergence is induced by the urban land use, while winds over the city are significantly reduced by increased drag. In the *uf1_30km* simulations, the UHI and UDI are slightly stronger, but the spatial pattern is similar (Fig. 9b).

The impact of urban fraction on UHI and UDI is much smaller than that of city size, about 0.5 K and -1.0 g kg^{-1} , respectively (Fig. 9c). The downwind wind convergence is also weaker. A more compact city does not significantly alter the UHI or UDI but does reduce surface winds over the city (Fig. 9e).

An interesting result is that taller buildings reduce the UHI by about 1 K and increase moisture by 0.5 g kg^{-1} (Fig. 9d). Wind speeds are weaker in simulations with taller buildings, as well as the wind convergence downwind of the city. The reduction in temperature and increase in moisture in the urban canopy are likely due to reduced ventilation and consequent moisture stagnation (?). Our simulations begin with high moisture in the PBL, which decreases during the day due to mixing. In deeper urban canopies, drying is slower due to building shade, resulting in lower temperatures and higher moisture (?).

Finally, in the *no_thermo* experiment, the UHI and UDI are eliminated, as expected, while maintaining the wind reduction over the city (Fig. 9f). This experiment can be interpreted as preserving the city’s dynamic perturbation on the atmosphere (the building-barrier effect) while suppressing its thermodynamic effect (the UHI and UDI). Overall, city size is the factor with the most decisive influence on the UHI, consistent with previous studies (?).

To understand the urban-induced flow perturbations, the sea level pressure field is investigated. A weak minimum (about -0.5 hPa) is generated downwind of the city (with respect to the surface winds) by the urban land use (Fig. 10a). The downwind pressure minimum coincides with the wind convergence. With a higher urban fraction, the pressure minimum is stronger (about -1.0 hPa ; Fig. 10b), as also suggested by the comparison between the *uf1.0* and *uf0.4* experiments (Fig. 10c). On the other hand, with taller buildings, the pressure minimum is slightly weaker (about 0.2 hPa ; Fig. 10d), while a more compact city plays only a marginal role in intensifying it (Fig. 10e). Lastly, in the *no_thermo* experiment, the pressure minimum is absent (Fig. 10f).

A relationship between the UHI and the mean sea-level pressure is evident: in simulations with a stronger UHI (e.g., *uf1_30km* experiment), the pressure minimum is also stronger, whereas when the UHI is weaker (*h60* experiment) or absent

Fig9.png

Figure 9. Ensemble mean of temperature (color shading) and specific humidity (contours every 0.5 g kg^{-1} , blue negative, red positive) in the first model level (about 5 m AGL), and 10-m wind difference (vectors) at 04:00 pm between a) *uf0.63_30km* and *no_urban* experiments; b) *uf1_30km* and *no_urban* experiments; c) *uf1.0* and *uf0.4* experiments; d) *h60* and *h10* experiments; e) $\lambda_b 1.2$ and $\lambda_b 0.3$ experiments; f) *no_thermo* and *no_urban* experiments. The city is shown with grey shading.

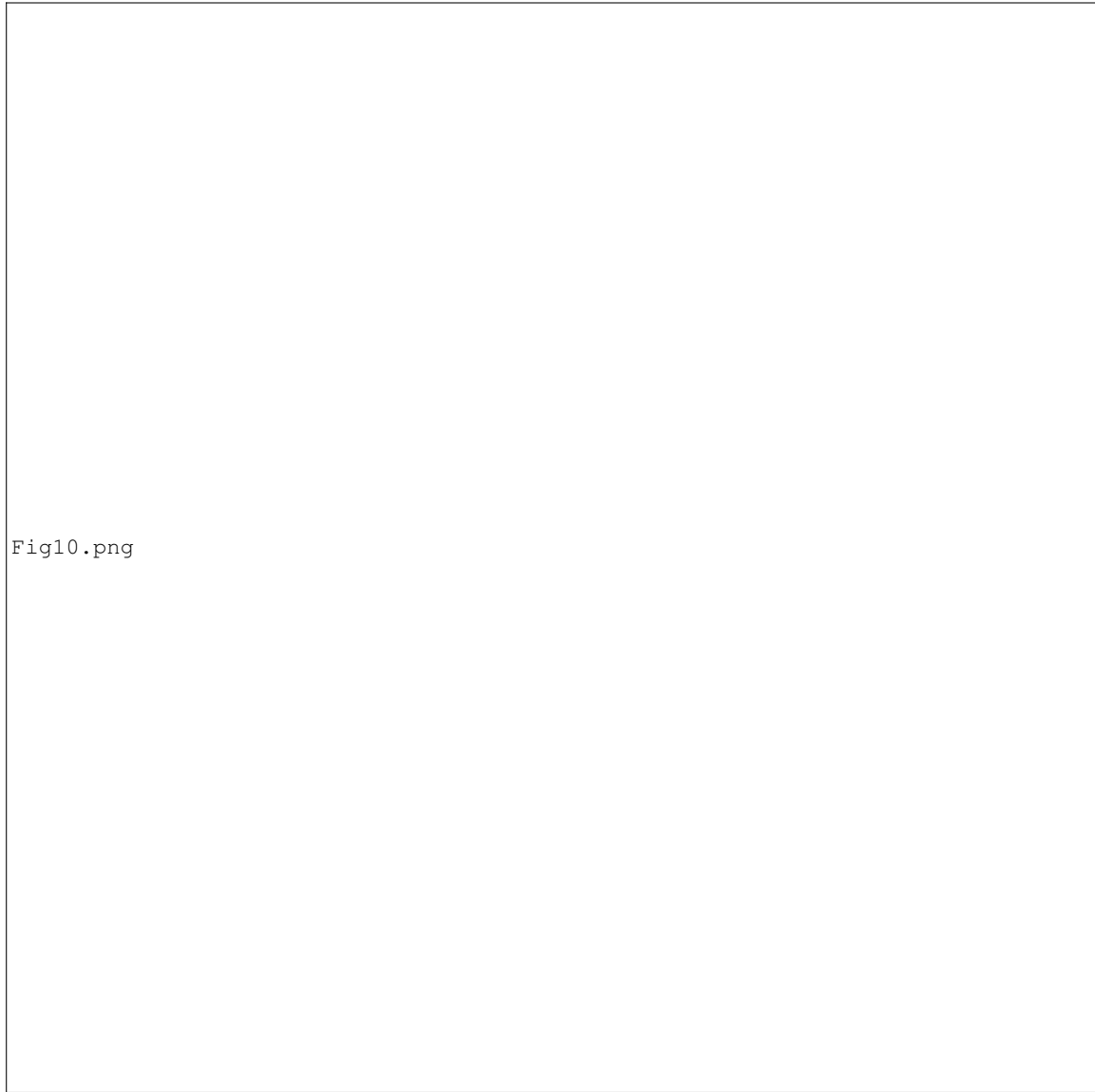


Figure 10. Ensemble mean of mean sea level pressure difference at 04:00 pm between a) *uf0.63_30km* and *no_urban* experiments; b) *uf1_30km* and *no_urban* experiments; c) *uf1.0* and *uf0.4* experiments; d) *h60* and *h10* experiments; e) $\lambda_b 1.2$ and $\lambda_b 0.3$ experiments; f) *no_thermo* and *no_urban* experiments. The 10-m wind of the minuend simulation of the subtraction is shown with vectors. The city is shown with grey shading.

(*no_thermo* experiment), the pressure minimum is weaker or absent. Thus, it appears that the pressure minimum is thermodynamically induced by the UHI (i.e., it is a consequence of the buoyancy and not of the dynamical modification of the flow by the buildings). To further support this hypothesis, an additional analysis is carried out. The dynamic p'_d and buoyancy p'_b pressure perturbations are computed for the ensemble mean of the *uf1_30km* simulations. The elliptic partial differential equations that
 360 define p'_d and p'_b are solved using a Gauss–Seidel iterative method. The reference p_0 value is taken from the ensemble mean of the *no_urban* experiment. Figure 11 shows the results at the 10th vertical level (about 300 m AGL). Buoyancy pressure perturbations p'_b clearly dominate the generation of the downstream pressure minimum, consistent with the previously noted sensitivity between the pressure minimum and the intensity of the UHI. The contribution of the dynamic pressure perturbations p'_d is negligible. This outcome is also valid for the *h60* experiment (Fig. 11d,e,f): tall buildings have a marginal effect on the
 365 generation of the downwind pressure minimum with respect to the thermodynamic modification of the PBL induced by urban land use.

4.2 SB CAPE

Surface Based Convective Available Potential Energy (SB CAPE) is markedly reduced by urban land use along a wake downstream of the city (Fig. 12a,b). The simulated storms cross the southern lobe of the urban plume with reduced SB CAPE (Fig.
 370 12a). Note that the spatial spread of the supercell tracks over the city is about 5 km, and all tracks pass through areas with similar urban-modified environmental characteristics. The reduction in SB CAPE reaches up to 1000 J kg^{-1} and coincides with the wake of higher temperature and lower moisture observed in Fig. 9. Urban fraction contributes to a decrease in SB CAPE of about 200 J kg^{-1} (Fig. 12c), while taller buildings increase SB CAPE by up to 400 J kg^{-1} (Fig. 12d). Building density has no significant effect on SB CAPE (Fig. 12e), consistent with the results previously discussed for other near-surface variables.
 375 In the *no_thermo* experiment, SB CAPE is unaffected by the presence of the buildings (Fig. 12f).

The same sensitivity of SB CAPE to urban morphological parameters observed for moisture suggests that the decrease in moisture more than offsets the temperature increase. Indeed, the Skew-T comparisons among the *uf1_30km* and *no_urban* experiments in Fig. 13 show that the drier, deeper and warmer PBL in the urban simulations (dashed lines) drives a reduction of CAPE area. While the UHI drives the generation of the downwind pressure minimum, the UDI drives the formation of the
 380 wake with reduced SB CAPE.

4.3 Vertical Velocities at 950 hPa

To assess the city’s capacity to trigger convection, the differences in ensemble means of vertical velocity at 950 hPa are analyzed at 4.00 pm, before storm initiation. Upstream and over the city, no remarkable vertical velocities are induced by urban land use (Fig. 14a,b). In contrast, downstream of the city, a line of intensified vertical velocity extends up to 60 km from
 385 the city. In the *uf1_30km* experiment, the intensified vertical velocity reaches locally up to 1 m s^{-1} . This line coincides with the surface wind convergence. A higher urban fraction produces stronger vertical velocities (Fig. 14c), while taller buildings reduce their intensity (Fig. 14d). A more compact city slightly intensifies vertical velocities downstream (Fig. 14e), whereas vertical velocities are not produced in the *no_thermo* experiment (Fig. 14f).

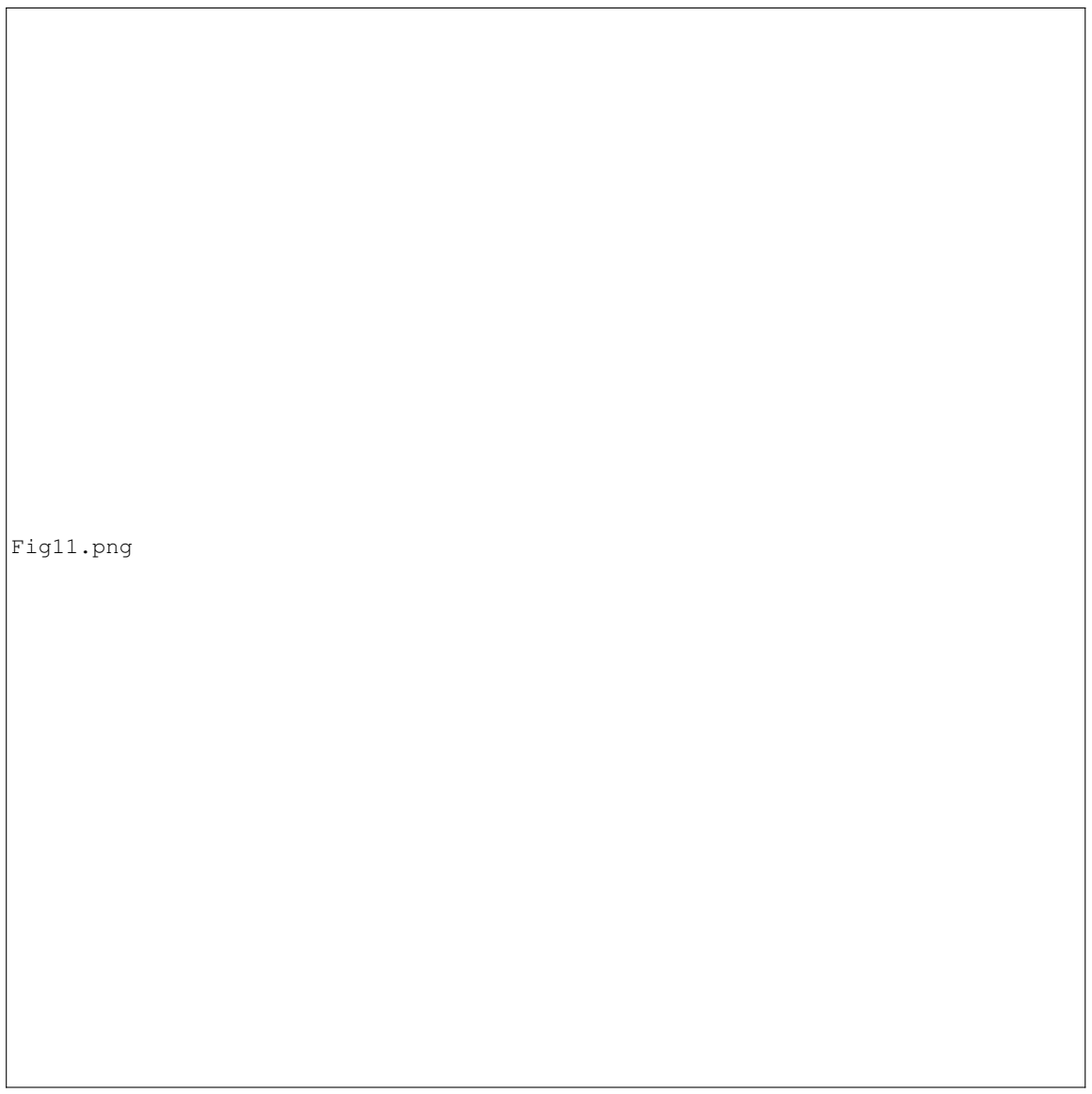


Fig11.png

Figure 11. Ensemble mean of a) total pressure perturbations p' at 300m AGL in the *ufl_30km* experiment at 04:00 pm; b) as in a) but for buoyancy pressure perturbations p'_b ; c) as in b) but for dynamic pressure perturbations p'_d ; d), e) and f) as in a), b) and c), respectively, but for the *h60* experiment.



Figure 12. As in Fig. 10, but for CAPE. In (a) the storm tracks of the *uf0.63_30km* experiment are plotted.



Figure 13. Ensemble mean Skew-T profile taken over the city center in the *uf1_30km* experiment (dashed lines) and in the *no_urban* case (solid lines) at 5.30 pm (right before the storm hit the city). Red lines are temperature, green lines are dew point temperature and black lines are surface based parcel profiles. In the upper-right part of the figure the ensemble mean hodograph in the *uf1_30km* experiment is shown. A spatial average considering grid-points within 5 km from the urban center has been performed.

The intensification of vertical velocities is related to the intensity of the UHI. A stronger UHI leads to a deeper pressure minimum, more vigorous surface wind convergence, and stronger vertical velocities. For example, in the simulation with taller buildings, vertical velocities are weaker (Fig. 14d) because both the pressure minimum (Fig. 10d) and the UHI (Fig. 9d) are weaker. In the *no_thermo* experiment, vertical velocities are absent (Fig. 14f) because neither a pressure minimum (Fig. 10f) nor a UHI (Fig. 9f) develops. Furthermore, building heights do not induce significant vertical velocities. In the *no_thermo* experiment 20 m tall buildings are present but there are no vertical velocities (Fig. 14f). Moreover, in the experiment with 60 m tall buildings (h60) vertical velocities are weaker along the convergence and more positive, i.e., closer to zero, where there is subsidence in the edges of the urban plume (Fig. 14d). This result explains why low-level vertical velocities in the simulated supercell do not increase with increasing building height, as discussed in Section 3.3 (Table 11).

4.4 Wind Shear: SRH 0-3 km

In the *uf0.63_30km* and *uf1_30km* experiments, SRH 0–3 km is reduced by up to 100 J kg^{-1} (about 50 % less than in the *no_urban* simulations) south of the convergence line discussed in Section 4.3, and increased north of it with a similar magnitude



Fig14.png

Figure 14. As in Fig. 10, but for vertical velocities at 950 hPa.



Fig15.png

Figure 15. As in Fig. 10 but for SRH 0-3 km.

(Fig. 15a). The increase (reduction) of SRH north (south) of the convergence line is due to the greater (smaller) veering of the wind caused by a stronger (weaker) surface easterly wind component (Fig. 9a) and a stronger pressure minimum. Thus, the modifications of SRH are ultimately induced by the pressure minimum generated by the UHI. An higher urban fraction amplifies this SRH pattern (Fig. 15c). In contrast, taller buildings cause the opposite pattern, i.e., higher SRH values south of the convergence line, due to the weaker pressure minimum. In the *building density* and *no_thermo* experiments, the SRH is almost unperturbed, except for slightly higher values over the city (Fig. 15e,f). The increase of SRH over the city results from reduced surface winds (Fig. 9e,f), consistent with the findings of ?. The spatial patterns in SRH 0-1 km are similar to those exhibited in SRH 0-3 km.

4.5 Further insights into the storm-urban plume interaction

The thermal bubble that initiates the storm was positioned to steer the storm toward the urban center (Fig. 6). However, the wind profile pushes the urban plume northwestward, so that the strongest urban perturbations are not located over the city, but downwind of it (Figs. 12, 15, 14), as previously observed. Thus, the storm is not interacting with the most intense urban perturbations in the simulations discussed so far.

To verify the effect of a more direct interaction between the storm and the urban plume, the *storm_shifted* experiment was run, in which the storm is shifted 22 km northwestward and the city considered is 30 km wide with an urban fraction of 1.0. The results are displayed in Fig. 16a. In that case, the storm dissipates even more quickly, and the generation of new convective cells is observed northeast of the city. Hence, the results are not different from those obtained in the *uf1_30km* experiment. Even though the storm interacts with a stronger positive perturbation of SRH, the negative perturbation of CAPE is even more pronounced, causing the storm to dissipate faster.

Another interesting observation is that, in some ensemble members (e.g., Fig. 7b), storm dissipation occurs before the storm actually reaches the negative SB CAPE perturbation, raising doubts as to whether this is the actual mechanism driving the dissipation. Investigating the urban-induced perturbations along a cross-section taken along the storm's path (line AB in Fig. 16a) reveals that the area of low equivalent potential temperature (Θ_e) over the city, driven by the moisture reduction, extends upstream (with respect to storm motion, i.e., toward point A) at the top of the boundary layer (around 1500 m, Fig. 16b). In that area, an increase in potential temperature Θ is also present (Fig. 16b), associated with regions of subsidence (Fig. 16c). These features suggest enhanced inhibition (due to higher Θ), entrainment of more stable air (due to lower Θ_e), and subsidence at the top of the boundary layer upstream of the city; this likely promotes early storm dissipation. The early dissipation occurs only in a few ensemble members, where CAPE was already reduced in the *no_urban* experiment due to ensemble stochasticity. Hence, storm dissipation is primarily driven by the UDI, which reduces CAPE and Θ_e , but regions of subsidence associated with UHI-induced vertical motions may favour this process.

fig16.png

Figure 16. (a) Ensemble mean of UH values exceeding 80 Jkg^{-1} in the uf1_30km simulations (black shading), and the storm_shift experiment (blue shading). The ensemble mean difference in CAPE smaller than -300 Jkg^{-1} (red contour), in SRH bigger than 20 Jkg^{-1} (green contour) and in w950 greater than 0.2 ms^{-1} (magenta contour) between the storm_shifted experiment and the no_urban experiment is indicated with a red contour. The ensemble mean of 10 m wind field from the uf1_30km experiment at 04:00 pm is shown with grey arrows. The city location is outlined with a black contour. (b) the ensemble mean of the difference in equivalent potential temperature Θ_e (colour shading) and of potential temperature Θ (contour lines) between the uf1_30km experiment and the no_urban one along the cross section AB in (a) is shown. (c) as in (b) but the ensemble mean Θ (contour lines) and the ensemble mean differences in vertical velocities (colour shading) are shown.

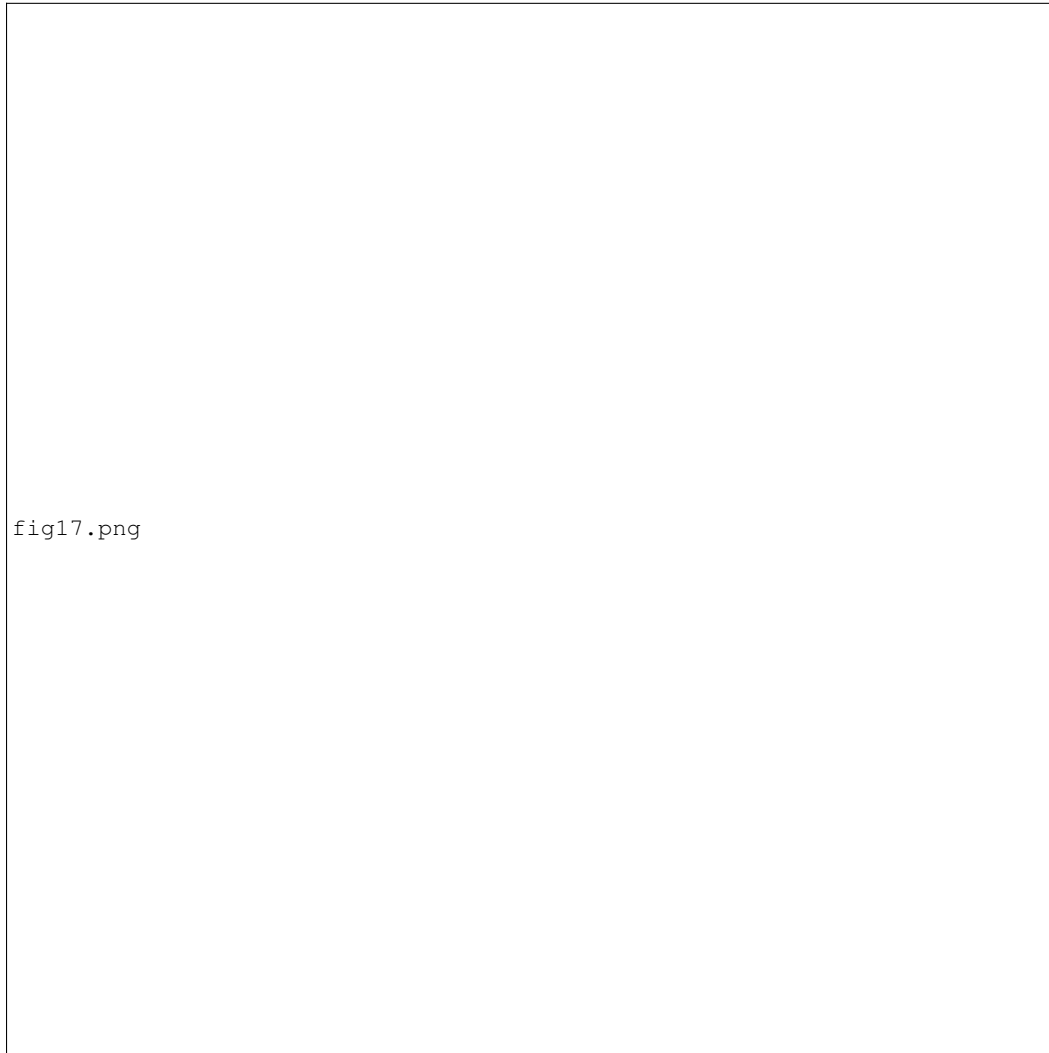


Figure 17. a) Summary of the results obtained in this study regarding the interaction between supercell storms and a city: the UHI and UDI (red shading), city (black histogram), supercell (yellowish-reddish shading with hook-echo shape), pressure minimum (letter L) and wind convergence (red arrows) are shown. b) as in a), but for a weak flow situation without supercells.

5 Discussion

In the current study, the ensembles of idealized numerical experiments consistently show a weakening of a supercell moving into a city due to the urban land use, especially down-track of the city. This weakening is significant primarily in medium- to large-sized cities with a high urban fraction (Fig. 5). For smaller cities, the effect is less evident and not statistically significant, with some ensemble members showing that the supercell is even intensified. The weakening of the supercell is caused by the UDI, which drives a substantial reduction in SB CAPE ~~of up to 1000 J kg^{-1} in the presence of a large city (Fig. 12).~~ This reduction occurs in the wake downstream of the city (relative to the surface winds, Fig. 17a). ~~The reduction of CAPE might be a little overestimated by the choice of relatively high soil moisture needed to avoid an excessive drying of the boundary layer in the afternoon.~~ Some previous studies found higher CAPE values in urban areas (?), while others noticed that urban land use can reduce CAPE (e.g., ???), with reduced moisture availability suggested as a possible explanation (?). To the authors' knowledge, this is the first time that an urban-induced reduction of CAPE has been directly linked to an urban-induced weakening of storms. Our conclusions differ markedly from those of ??, who did not consider the UDI in their idealized setup. This factor proves crucial in shaping supercell dynamics in our simulations. ~~While UDIs are not observed in all cities around the world and may have a diurnal and seasonal cycle (?), they are most common in the warm season in the late afternoon (?), when severe storms are more frequently.~~

With a sufficiently large city and a high urban fraction, a new urban-induced supercell develops in 8 out of 11 ensemble members downstream of the city, while the initial incoming supercell is dissipated by the UDI (e.g., Fig. 7). This new urban-induced supercell is triggered by a convergence line downstream of the city, generated by a pressure minimum of about 1 hPa (Fig. 17a). The UHI thermodynamically induces a pressure minimum, as it was already suggested by ?, which in turn produces the convergence line (Fig. 10). The connection between the pressure minimum and the UHI is supported by a quantitative analysis of pressure perturbations (Fig. 11) and by an *ad-hoc* experiment called *no_thermo*. Although in our experiments the generation of the urban-induced supercell occurs only with a 30-km-wide city and an urban fraction of 1.0, it could also occur with smaller cities and lower urban fractions. The key requirement may simply be a sufficiently strong UHI combined with an environment conducive to supercells. In our numerical simulations, the threshold for the development of an urban-induced supercell corresponds to a UHI of 1.5 K, which is not particularly high.

The urban-induced reductions in moisture and CAPE obtained in our simulations are larger than those published so far. The simulated reduction of relative humidity (13%) is in line with the annual mean reductions observed in Moscow (9%, ?) and Beijing ($\sim 12\%$, ?), whereas the reduction of specific humidity ($\sim 2 \text{ g kg}^{-1}$) is about 0.6 g kg^{-1} larger than the peak summer reduction of 1.4 g kg^{-1} found by ? over 1089 stations worldwide and 29 years. The difference is larger for CAPE: our reduction of up to 1000 J kg^{-1} is about twice the $\sim 450 \text{ J kg}^{-1}$ obtained by ?, and one order of magnitude larger than the $40\text{--}100 \text{ J kg}^{-1}$ reported by simulations averaged over several summers (??) or over a 4-day period (?). A plausible explanation is that most previous studies consider seasonal or multi-year averages, which smooth out the diurnal and seasonal cycles of UDIs (?); in terms of specific humidity, UDIs are strongest in the warm season and in the late afternoon (?), when severe storms are more frequent, so that individual events may exhibit larger moisture reductions than long-term averages. In addition, our

465 idealized city was designed to represent an extreme case (30 km wide, with a high urban fraction and no water bodies), whereas
Dallas–Fort Worth, the city considered by ?, includes several rivers and lakes that may attenuate the UDI. Finally, we cannot
exclude that BEP-BEM contributes to enhancing the urban drying.

The analysis was conducted under a fixed environment. We cannot exclude the possibility that a wide variety of interactions, some of which may include storm invigoration, could occur in different environments, depending on the trajectory of the storm, the topology of the city-induced perturbations, and the ground-relative flow. For instance, with a strongly veered environment that leads to a southeastward propagating storm, a storm may traverse the lobe with positive SRH perturbations, potentially leading to a storm intensification. Interestingly, this seems the case of ?, who found a supercell intensification induced by the urban land use. Looking to their Fig. 8 seems that the supercell is initiated in the region with urban-induced wind convergence north of town, as in our case (Fig. 14a). Their supercell storm could be the equivalent of our idealized urban-induced supercell (Fig. 7), but with a southward propagation.

There is some observational evidence supporting these numerical results. The radar-based climatological study of ? found that, for four Great Plains cities in the United States, reflectivity values of approaching storms were higher upwind than downwind. The opposite pattern was observed, however, when selecting an urban-favorable subset of nonsupercells occurring during summer under weak synoptic forcing. Similarly, the radar-based study of ? found that storms striking Berlin, Germany, were more frequently weakened than intensified. Thus, in strongly forced environments, it is not uncommon for approaching storms to be dissipated or weakened by cities, as is observed in our numerical simulations. This scenario has received relatively little attention in the literature, as most studies have focused on the potential of cities to generate urban storms and enhance precipitation (e.g., ??). The latter outcome is likely common in weakly forced synoptic environments and can also occur at times under strongly forced conditions, with the generation of severe storms downstream urban areas (e.g., ??). However, the weakening of approaching severe storms by urban land use is an equally important outcome that should be highlighted.

An additional relevant difference from previous studies is that the effect of building height on storms is negligible in our experiments, even with 60-m tall buildings. In these cases, the pressure minimum is still induced by the UHI (Fig. 11), and the vertical velocities generated by 60-m tall buildings are much weaker than those associated with the UHI-induced pressure minimum (Fig. 14d). Furthermore, building height is not correlated with higher values of low-level vertical velocities in the simulated supercell (Table 11). These results are consistent with the recently published work of ?, who found that the enhanced vertical velocities observed over some real cities in their simulations were primarily driven by thermodynamic processes rather than by dynamical roughness effects. Thus, there is growing agreement that the dynamical influence of buildings on convective storms may be marginal in a strongly synoptically forced environment. Nevertheless, the building-barrier effect could still play a role in other strongly forced situations not explored in these idealized simulations, such as QLCS events with intense outflows (e.g., ?) or tornadic events with more intense surface flows. In general, under such conditions, the influence of buildings may be more significant.

The marginal effect of buildings on convective storms is likely valid for most atmospheric environments (?). If building height has little impact on storms under moderate surface flows, its influence should be even less relevant in weakly forced environments. For this reason, we argue that our conceptual model can be extended to such environments. Under weak flow

500 conditions, the UHI-induced pressure minimum is not advected downstream but remains centered over the urban area, as also suggested by some recent case study analysis (????). Consequently, storms can be triggered over the urban area in such situations.

6 Conclusions

505 The simulations carried out in this work permit to provide a tentative answer to the questions originally posed in the Introduction.

Question 1: Can a city modify a supercell?

A statistically significant weakening of the approaching supercell is observed. In contrast, in some ensemble members, a new supercell is triggered downstream when a sufficiently large city is included in the domain, highlighting the dual effect of cities on supercell storms.

510 *Question 2: What are the physical processes that cause those modifications?*

Most of the observed modifications are attributed to thermodynamic changes in the PBL induced by urban surfaces. The UDI weakens an approaching storm by reducing CAPE. At the same time, the UHI generates a pressure minimum, capable of inducing downstream wind convergence that can trigger a new urban-induced supercell when the UHI is sufficiently intense. The effect of building heights on supercell dynamics is negligible.

515 Even though these results were obtained from a specific atmospheric profile, they are consistent with radar climatologies of urban storms (??). A further interesting outcome of this work is the simulated supercell's sensitivity to surface conditions. Relatively small differences in temperature (1 K) and moisture (1 g kg^{-1}) are sufficient to alter supercell behavior markedly. A direct implication of this result is that operational weather-forecasting models must be driven by up-to-date land-use data. For instance, changes in vegetation caused by drought, if not assimilated into the models, can lead to significantly inaccurate
520 forecasts (see also ?).

Several limitations remain that should be addressed in future work. Although the building parametrization employed is highly sophisticated (?) and has been shown to be reliable (?), it does not explicitly resolve the effect of buildings on the atmosphere. This approach remains appropriate for the mesoscale focus of this study; however, small-scale urban processes—which may, in some situations, strongly influence urban storms (e.g., under shallow surface-based inflow layers)—are not
525 explicitly represented. Large Eddy Simulations (LES) should be conducted (as done by ? for hurricane winds) to assess the importance of these processes for convective storms and to test whether the results of this study hold under that approach. Furthermore, some studies showed that urban aerosols can significantly influence storm development (???), suggesting that the effect of urban aerosols on idealized supercells may be worthy of investigation. Another aspect not considered here includes the effects of urban land use on nocturnal events: while the UHI is stronger during the night, nocturnal storms are usually elevated,

530 suggesting that urban-storm interactions may differ from those during the daytime. More generally, exploring the sensitivity of these results to other environmental conditions is a relevant direction for future work. Lastly, idealized simulations of a QLCS, rather than a supercell, interacting with a city should also be carried out to evaluate whether building effects on the gust front may dominate over the UHI and UDI in such cases.

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Competing interests. The authors declare that they have no conflict of interest.