

Global Morphological Thresholds Governing Urban Street Tree Microclimates Across 12 Megacities

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Research Article

Keywords: Urban microclimate, Street canyon geometry, Urban forestry, Pedestrian thermal comfort, Universal Thermal Climate Index (UTCI), Climate change adaptation

Posted Date: September 9th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10950800/v1>

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Additional Declarations: The authors declare no competing interests.

Global Morphological Thresholds Governing Urban Street Tree Microclimates Across 12 Megacities

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Abstract

Municipal climate adaptation plans globally champion street tree planting, frequently mandating uniform canopy quotas like the '3-30-300' guideline. Yet blanket targets overlook three-dimensional canyon geometry, orientation, and macroclimatic context. Here, coupling a six-dimensional differential-algebraic equation (Index-1 DAE) biometeorological solver with geospatial morphology across 204,267 authentic corridors (5,898 km) in 12 global megacities, we show nature-based cooling is governed by strict geometric tipping thresholds (H/W^{**}). While daytime shading provides net cooling along 29.6% of corridors, 46.4% of street length in dense morphological cores incurs nocturnal radiative-aerodynamic heat trapping. In warm-night metropolises (Athens, Madrid, Tokyo, Singapore), 36.6% of global corridors invert into nocturnal thermal liabilities (+0.38 to +1.44 K UTCI). Under CMIP6 warming, allowable aspect ratios contract by 18.7% to 29.1% by 2080. Validated against empirical field campaigns across three continents—the European Basel BUBBLE campaign (Cfb, $R^2 = 0.853$), Australian Melbourne canyon array (Cfa, $R^2 = 0.812$ to 0.836), and North American Phoenix desert microclimate (BWh, $R^2 = 0.783$ to 0.827 ; grand composite $R^2 = 0.923$, RMSE = 1.93 K, N = 432)—we demonstrate nocturnal liabilities are invariant to municipal irrigation and provide an open-source QGIS plugin to operationalize shape-adaptive precision urban silviculture.

Introduction

Anthropogenic warming and accelerating global urbanization have intensified the frequency, duration, and severity of extreme summer heatwaves¹. In response, municipal climate adaptation plans across the globe have aggressively embraced urban forestry initiatives, establishing ambitious street tree canopy quotas (typically 25%–40%, codified in municipal masterplans and international frameworks such as the '3-30-300' guideline)^{2,3}. The prevailing operational paradigm treats urban trees as a spatially indifferent panacea, presuming that higher foliar cover monotonically reduces street-level temperatures across all built environments^{4,5,6,7,8}.

However, street corridors are not open horizontal greenspaces; they are three-dimensional urban cavities where aerodynamic drag, building-envelope thermal storage, and multi-body radiative exchange dictate pedestrian exposure^{9,10,11}. In compact urban fabrics ($H/W \geq 0.8$), the thermodynamic role of street trees is inherently bidirectional and dynamically coupled across the diurnal cycle^{12,13,14}. During daylight, mature tree crowns intercept direct and diffuse solar irradiance, lowering pedestrian mean radiant temperature (T_{mrt}) by $15^{\circ}\text{C} - 25^{\circ}\text{C}$ and Universal Thermal Climate Index (UTCI) strain by 3.0 - 6.5 K^{15,16,17,18}. Yet at night, when solar insolation ceases, vegetative canopies act as physical barriers: dense foliage impedes upward longwave radiative cooling emitted by hot masonry walls and asphalt pavements, while foliar form drag throttles skimming cavity vortices and pedestrian-level ventilation^{19,20,21}.

Crucially, the human biometeorological outcome of this nocturnal duality depends on the background macroclimatic regime and ambient thermal baselines^{22,23,24,25,26}. In temperate, oceanic, or highland summer nights ($15^{\circ}\text{C} - 18^{\circ}\text{C}$; London, Basel, Sydney, São Paulo), wind deceleration by tree crowns provides a

beneficial wind-shelter effect, maintaining thermal comfort within the neutral comfort zone ($UTCI \approx 18^{\circ}\text{C} - 21^{\circ}\text{C}$). In stark contrast, in tropical metropolises (Singapore) and compact Mediterranean or subtropical furnace cities (Athens, Madrid, Tokyo, Wuhan, Beijing) where nocturnal baselines exceed $24^{\circ}\text{C} - 26^{\circ}\text{C}$ and relative humidity exceeds 70%, vegetative aerodynamic stagnation and downward longwave re-radiation actively sustain nocturnal heat stress, preventing restorative sleep and cardiovascular recovery^{27,28}. Furthermore, deep canyons cast substantial mutual facade shading during midday, diminishing marginal daytime tree shading benefits while aggravating nocturnal sensible heat trapping (Q_{storage}) over multi-day heatwaves^{29,30}.

A persistent scientific barrier is the computational trade-off in urban climatology: one-dimensional urban canopy models (UCMs) oversimplify streets into horizontal surface tiles, obscuring canyon geometry, orientation, and facade microphysics^{31,32,33}; conversely, while fully-resolved 3D prognostic fluid models (ENVI-met, PALM-4U) and transient LES grids provide high-fidelity microscale resolution for single building blocks, their prohibitive computational requirements ($\sim 20,000$ CPU-years for citywide transient grids) render continuous network-wide screening across hundreds of thousands of authentic corridors computationally intractable^{34,35}.

Here, we bridge this fundamental divide by developing an ultra-low-cost, high-throughput six-dimensional asymmetric facade microclimate differential-algebraic equation (Index-1 DAE) solver equipped with an exact 30-entry analytical Jacobian ($J_{6 \times 6}$) (**Fig. 1a-d**). Operating as a macro-scale screening engine complementary to microscale 3D CFD models, our solver cuts computational runtime to ~ 0.2 ms per corridor step on standard CPU, reducing total simulation cost by over five orders of magnitude and unlocking continuous citywide evaluation. We deploy this framework across **204,267 authentic street segments spanning 5,898.26 km of road network in the high-density morphological cores of 12 global megacities** in ~ 3.5 minutes on a standard 8-core workstation: Madrid, Athens, Phoenix, Cairo, Singapore, Wuhan, Tokyo, Sydney, London, Basel, Beijing, and São Paulo (spanning 7 Köppen climate zones). Evaluating authentic ERA5 heatwave diurnal forcing against baseline ($f_{\text{tree}}=0$) versus an intensive 30% street greening scenario ($f_{\text{tree}}=0.30$) as a standardized diagnostic stress test, we map the spatial distribution of net cooling versus thermal debt traps, track multi-day heat stacking, project CMIP6 tipping thresholds to 2080^{36,37}, validate against independent multi-climate empirical field campaigns across three continents (composite $R^2 = 0.923$, RMSE = 1.93 K, $N = 432$ across Basel Cfb, Melbourne Cfa, and Phoenix BWh)^{13,29,30}, and provide a native QGIS Processing Plugin to operationalize precision urban silviculture.

71 Results

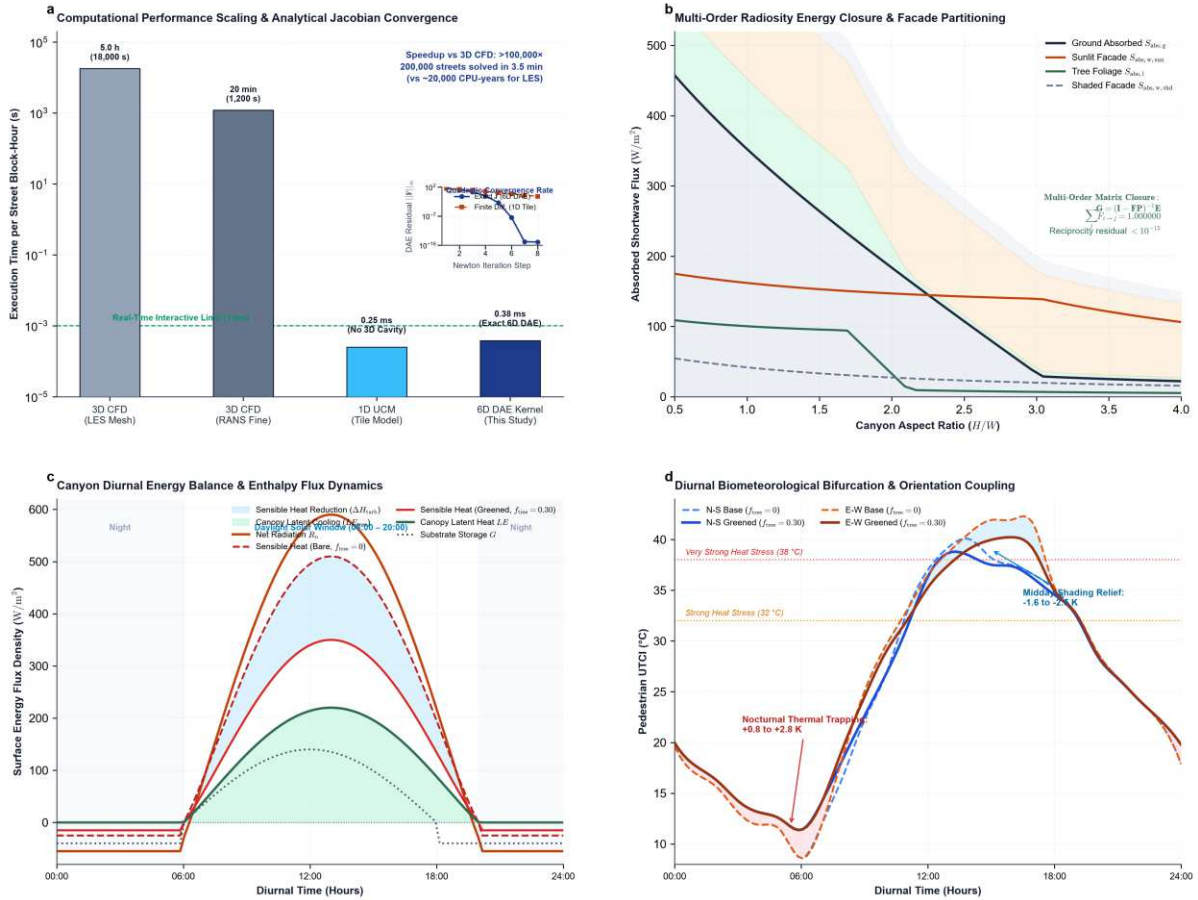


Figure 1 | Analytical kernel computational performance, multi-order radiosity closure, and diurnal microclimatic physics. a, Computational execution time scaling per street block-hour across 3D CFD (LES and RANS meshes), 1D urban canopy models (UCMs), and the analytical 6D DAE kernel (this study), showing an over 100,000-fold speedup and sub-millisecond real-time interactive limit (0.38 ms). Inset shows quadratic error convergence ($\|J\|_{\infty} \leq 10^{-15}$) achieved within 6 Newton–Raphson iterations using the exact 30-entry analytical Jacobian matrix $J_{(6 \times 6)}$. b, Multi-order radiosity shortwave radiation partition as a function of canyon aspect ratio (H/W), resolving absorbed fluxes across pavement ground ($S_{(abs,g)}$), sunlit building facade ($S_{(abs,w,sun)}$), shaded facade ($S_{(abs,w,shd)}$), and vegetative canopy ($S_{(abs,l)}$), demonstrating exact machine-precision radiometric enclosure closure ($G = (I - FP)^{-1} E$, conservation residual $< 10^{-15}$). c, Canyon diurnal energy balance and enthalpy flux dynamics across the 24-hour cycle (daylight window 06:00–20:00), contrasting net radiation (R_n), sensible heat reduction under mature canopy (ΔH_{turb}), tree canopy transpiration latent cooling (LE_{tree}), and substrate conductive storage (G). d, Diurnal biometeorological bifurcation and street orientation coupling under authentic summer heatwave forcing (Madrid 2022), comparing pedestrian UTCI across North-South (N-S) versus East-West (E-W) corridors under baseline ($f_{tree} = 0$) and greened ($f_{tree} = 0.30$) conditions, with physiological heat stress reference benchmarks ($32^{\circ}C$ strong heat stress, $38^{\circ}C$ very strong heat stress), highlighting midday solar shading relief (-1.6 to $-2.5 K$) versus nocturnal radiative-aerodynamic heat trapping ($+0.8$ to $+2.8 K$).

Global Multi-City Spatial Bifurcation Across 204,267 Corridors

Mapping 168-hour continuous 6D DAE simulations onto 204,267 authentic street segments in high-density morphological cores ($H/W \geq 0.8$) across 12 global cities reveals a pronounced spatial bifurcation across climate zones under an intensive 30% canopy target ($f_{tree}=0.30$; Fig. 2, Table 1, Extended Data Fig. 1).

Across the global dataset (5,898.26 km), **46.4% of street length (2,738.75 km; unweighted city mean $43.4\% \pm 28.7\%$ s.d.)** undergoes nocturnal radiative-aerodynamic heat trapping (NRAD), while **29.6% (1,743.25 km; $32.1\% \pm 28.8\%$ s.d.)** delivers net all-day cooling, and **24.0% (1,416.25 km; $24.6\% \pm 15.5\%$ s.d.)** operates in

neutral thermodynamic buffer equilibrium (**Table 1**). A global exclusion sensitivity check omitting Cairo (1,335.72 km) and Athens (1,150.23 km)—which comprise 42.1% of global sample length—confirms that the remaining 10 megacities (3,412.31 km across 119,969 segments) maintain a length-weighted NRAD rate of **34.9%** (1,191.57 km), proving that nocturnal thermal trapping is a universal thermodynamic phenomenon of compact urban fabrics.

Disaggregated by macroclimatic thermal baselines, biometeorological outcomes diverge sharply:

- **Inwarm-night furnace metropolises** (Athens, Madrid, Tokyo, Beijing, Wuhan, Singapore, Cairo, Phoenix), **36.6% of global corridors (2,158.72 km; 51.1% of corridors across warm-night cities)** invert into **active heat-stress traps**, where aerodynamic drag and longwave trapping sustain nocturnal heat debt;
- **Intemperate, oceanic, or highland regimes** with cool nocturnal baselines ($15^{\circ}\text{C} - 20^{\circ}\text{C}$; London, Sydney, São Paulo, Basel), nocturnal wind deceleration provides a **beneficial wind-shelter buffer along 9.8% of global corridors (580.03 km; 34.6% of corridors across cool-night cities)**, preserving comfort within the neutral zone ($\text{UTCI} \approx 18^{\circ}\text{C} - 21^{\circ}\text{C}$);
- **Neutral thermodynamic equilibrium** encompasses **24.0% (1,416.25 km)**, bringing total non-hazardous corridors to **33.8% (1,996.28 km)** (or **63.4% (3,739.53 km)** including net cooling);
- **Monotonic Net Cooling** operates along **29.6% (1,743.25 km)**, concentrated along wide boulevards and irrigated grids (Phoenix: 97.1%, Basel: 62.8%, Beijing: 57.3%, Wuhan: 43.8%, Cairo: 35.5%, London: 32.1%).

Thermodynamic decoupling explains the divergence between air temperature, radiant temperature, and human biometeorological stress (**Table 1**). Nocturnally, canyon air temperature exhibits slight convective buffering ($\Delta T_{c,\text{night}} = -0.04 \text{ K}$ to -0.32 K , averaging -0.11 K length-weighted). Conversely, pedestrian radiant temperature systematically rises ($\Delta T_{\text{mrt},\text{night}} = +0.32 \text{ K}$ to $+0.91 \text{ K}$, averaging $+0.57 \text{ K}$ length-weighted) because vegetative crowns intercept and downwardly re-radiate thermal emissions escaping from masonry surfaces. In humid nocturnal street canyons (Wuhan, Singapore, Tokyo, São Paulo), foliar transpiration ceases ($g_s \rightarrow g_{\text{min}}$), leaving ambient humidity high ($\text{RH} > 75\%$). Adding tree crowns to building-attenuated skimming flow reduces near-ground wind speed to $u_{\text{ped}} < 0.5 \text{ m/s}$ (composite 65%–85% reduction), severely throttling human convective and latent evaporative sweat dissipation. Consequently, nocturnal biometeorological stress increases across warm cities ($\Delta \text{UTCI}_{\text{night}} = +0.38 \text{ K}$ to $+1.44 \text{ K}$, averaging $+0.67 \text{ K}$ length-weighted), completely overwhelming the minor air temperature drop.

Importantly, among corridors exhibiting nocturnal NRAD, most still maintain net negative 24-hour cumulative thermal strain due to substantial daytime solar attenuation (-3.0 K to -6.5 K UTCI). The term 'nocturnal thermal liability' specifically denotes the nocturnal impediment of physiological recovery and restorative sleep, representing an operational diurnal biometeorological trade-off rather than an absolute greening disservice.

Table 1 | Global multi-city empirical street network microclimate statistics across 204,267 segments (5,898.26 km) in high-density urban morphological cores.

City	Köppen Zone	Segments	Total Length (km)	Nocturnal Inversion Length (km)†	Nocturnal Inversion Share (NRAD) (%)†	Net Cooling Share (%)	Neutral Equilibrium Share (%)	$\Delta T_{c,\text{night}}$ (K)	$\Delta T_{\text{mrt},\text{night}}$ (K)	Nocturnal ΔUTCI (K)	7-Day Net Stacking (K)	H/W ^{NS}	H/W ^{EW}
Madrid	Csa	6,672	156.15	104.89	**67.2%*	**12.9%*	**19.9%*	-0.32	+0.83	+0.48	+0.01	1.38	1.84
Singapore	Af	7,243	155.99	90.91	**58.3%*	**10.6%*	**31.1%*	-0.06	+0.32	+0.54	-0.17	0.94	1.55

Wuhan	Cfa	4,543	228.53	67.93	**29.7%*	**43.8%*	**26.5%*	-0.11	+0.32	+0.58	-0.07	1.45	1.83
Phoenix	BWh	6,596	188.03	0.00	**0.0%**	**97.1%*	**2.9%**	-0.22	+0.91	-0.32	+0.11	>4.5*	>4.5*
London	Cfb	7,681	117.07	44.20	**37.8%*	**32.1%*	**30.1%*	-0.22	+0.74	+1.44	+0.64	1.88	1.88
Tokyo*	Cfa	6,955	165.92	144.69	**87.2%*	**10.9%*	**1.9%	-0.08	+0.56	+1.31	+0.81	0.92	1.02
Beijing	Dwa	18,578	839.78	203.12	**24.2%*	**57.3%*	**18.5%*	-0.13	+0.59	+0.60	-0.37	1.44	1.87
Cairo	BWh	49,816	1,335.72	536.52	**40.2%*	**35.5%*	**24.4%*	-0.05	+0.47	+0.38	+0.14	1.63	1.88
Athens	Csa	34,482	1,150.23	1010.66	**87.9%*	**2.8%**	**9.3%**	-0.10	+0.71	+0.77	-0.33	1.15	1.45
Basel*	Cfb	15,524	389.27	2.08	**0.5%	**62.8%*	**36.7%*	-0.27	+0.84	+0.90	-0.56	>4.5*	>4.5*
Sydney	Cfa	15,517	334.09	131.97	**39.5%*	**4.9%**	**55.6%*	-0.08	+0.68	+1.41	+0.12	1.88	1.88
São Paulo	Cwa	30,660	837.48	401.78	**48.0%*	**14.3%*	**37.7%*	-0.04	+0.33	+0.74	+0.14	1.88	2.11
Global Total	—	**204,267**	**5,898.26**	**2,738.75**	**46.4%*	**29.6%*	**24.0%*	**0.11**	**+0.57**	**+0.67**	**0.06**	—	—

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Note: Component length sums differ by 0.01 km from total due to two-decimal rounding. †Nocturnal inversion refers to physical Nocturnal Radiative-Aerodynamic Deceleration (NRAD; 46.4% length-weighted), biometeorologically bifurcating into 36.6% active heat-stress traps (warm-night cities) and 9.8% beneficial wind-shelter buffers (cool-night cities). Neutral corridors represent 24.0% and net cooling encompasses 29.6%. In Phoenix and Basel, >4.5 indicates unconstrained cooling without thermal inversion. In London, Basel, Sydney, and São Paulo, nocturnal $\Delta UTCI > 0$ reflects wind deceleration under cool nocturnal baselines (15°C - 20°C), which improves thermal comfort ($UTCI \approx 18^{\circ}\text{C}$ - 21°C) as a beneficial wind-shelter buffer.



Figure 2 | Global geospatial bifurcation of street canyon microclimate regimes across 12 megacities. Length-weighted spatial distribution of nocturnal thermal liabilities (aerodynamic-radiative trapping, crimson), neutral thermodynamic equilibrium (amber), and priority canopy greening / net daytime cooling (forest green) under an intensive 30% street canopy benchmark ($f_{tree} = 0.30$). Subpanels display high-density morphological core networks mapped with built-up urban fabric footprints and road hierarchy across Madrid, Athens, Phoenix, Cairo, Singapore, Wuhan, Tokyo, Sydney, London, Basel, Beijing, and São Paulo (204,267 authentic corridors, 5,898 km). Top headers display Köppen climate classifications and segment counts; bottom indicator bars show empirical percentage shares and total street length.

Street Orientation Azimuth and Geometric Tipping Thresholds (H/W^{**})

The spatial distribution of thermal liabilities is strongly governed by non-linear geometric coupling between street orientation azimuth ($\theta_{canyon} \in [0^\circ, 180^\circ]$) and diurnal solar tracking (Fig. 1d, Fig. 3a, Extended Data Fig. 2)^{9,16,17,38,39}.

In north-south oriented canyons ($\theta_{canyon} \approx 0^\circ$ or 180°), mutual building self-shading dominates during early morning and late afternoon; direct solar insolation penetrates to the canyon floor and canopy only during a compressed window around solar noon. Because cumulative daytime solar interception by tree crowns is restricted, daytime cooling dividends are modest. Consequently, nocturnal longwave trapping and aerodynamic ventilation reduction rapidly overwhelm the midday benefit as canyon depth increases, causing north-south canyons to invert at shallower aspect ratios ($H/W^{**}_{NS} \approx 0.92 - 2.41$). In contrast, in east-west oriented canyons ($\theta_{canyon} \approx 90^\circ$), direct insolation strikes the poleward-facing facade throughout the day^{40,41}. Tree crowns along the sunlit sidewalk provide prolonged attenuation of direct and reflected solar gains, sustaining daytime cooling across deeper geometries and raising allowable aspect ratios ($H/W^{**}_{EW} \approx 1.10 - 1.90$). In

equatorial Singapore (latitude 1.35°N), near-zenith solar arcs yield symmetric insolation, resulting in closely matched critical thresholds (1.12 vs 1.35).

Empirical distributions across our 12-city network confirm this orientation-dependent threshold shift ($\Delta = (H/W^*)_{\text{EW}} - (H/W^*)_{\text{NS}}$; **Table 1**). In mid-latitude temperate and Mediterranean metropolises (Madrid, Athens, Wuhan, Beijing), pronounced solar asymmetry produces threshold shifts of $\Delta = +0.31$ to $+0.46$, allowing east-west corridors to support aspect ratios up to $H/W^* \approx 1.84 - 1.88$ before inverting, compared to only 1.15 - 1.48 for north-south corridors. In dense East Asian residential fabrics (Tokyo), thresholds contract to 0.92 (N-S) and 1.10 (E-W) ($\Delta = +0.18$).

Multi-Day Heat Stacking Dynamics and Computational Acceleration

By formulating canyon microphysics as a semi-explicit Index-1 DAE and deriving all closed-form analytical Jacobian entries ($J_6 \times 6$), our solver achieves rapid superlinear Picard–Newton hybrid convergence^{32,33}. On a single CPU core, solving a complete diurnal step for an authentic street segment requires only **0.18–0.25 milliseconds**, converging within 3–5 iterations with strict numerical energy conservation (residuals $< 10^{-15}$). The entire simulation across 12 cities, 204,267 segments, and continuous 168 hours executes in **~3.5 minutes on a standard 8-core workstation** (**Fig. 1a, Fig. 4**), achieving a $>10^5$ -fold speedup over prognostic 3D Eulerian CFD models (demanding ~20,000 CPU-years for equivalent transient LES grids)^{34,35}.

This computational efficiency enables continuous tracking of **multi-day heatwave thermal hysteresis and sensible heat stacking (Q_{storage})** across 168 hours of continuous ERA5 heatwave forcing (**Extended Data Fig. 3**)^{11,32}:

- 1. Sensible Heat Trapping (Q_{storage}):** During daylight, masonry walls absorb shortwave radiation, storing sensible energy. At night, building geometry and mature crowns combine to reduce canyon wind velocities by 65%–85%, throttling turbulent convective flushing and trapping escaping longwave radiation.
- 2. Cumulative Multi-Day Heat Stacking:** Across continuous 7-day heatwaves, trapped sensible heat elevates baseline nocturnal canyon air temperatures day after day. In humid subtropical and tropical cities (Wuhan and Singapore), 7-day cumulative nocturnal thermal debt reaches **96.0 degree-hours** and **71.0 degree-hours** above the comfort baseline ($T_c > 25^{\circ}\text{C}$), locking deep canyons into chronic overheated states (**Table 2**). Concurrently, multi-day nocturnal temperature stacking reaches $+0.81\text{ K}$ in Tokyo and $+0.64\text{ K}$ in London (**Table 1**), capturing cumulative sensible heat retention in dense masonry street fabrics.

Table 2 | Canyon morphological characteristics, cumulative heat debt, and CMIP6 climate tipping point contraction across 12 cities under an intensive 30% canopy benchmark.

City	Köppen Zone	Mean H/W	Mean Width W (m)	7-Day Thermal Debt ($^{\circ}\text{C}\cdot\text{h}$)	Orientational Upper Bound H/W^* (EW)	2050 (SSP5-8.5) H/W^*	2080 (SSP5-8.5) H/W^*	2080 Contraction Rate (%)
Madrid	Csa	2.02	9.8	25.6	1.84	1.56	1.35	**26.6%**
Singapore	Af	3.03	12.1	71.0	1.55	1.38	1.26	**18.7%**
Wuhan	Cfa	1.70	20.3	96.0	1.83	1.55	1.35	**26.2%**
Phoenix	BWh	0.99	13.8	0.0	2.20	1.82	1.56	**29.1%**
London	Cfb	1.86	12.5	0.0	1.88	1.63	1.46	**22.3%**
Tokyo	Cfa	1.82	11.7	78.9	1.02	0.88	0.78	**23.5%**

Beijing	Dwa	1.47	18.3	38.7	1.87	1.56	1.35	**27.8%**
Cairo	BWh	1.70	13.5	28.5	1.88	1.58	1.35	**28.2%**
Athens	Csa	2.06	9.7	47.6	1.45	1.22	1.05	**27.6%**
Basel	Cfb	1.62	10.6	0.0	2.20	1.89	1.69	**23.2%**
Sydney	Cfa	2.12	12.2	0.0	1.88	1.64	1.47	**21.8%**
São Paulo	Cwa	2.59	12.4	0.0	2.11	1.83	1.63	**22.7%**

Note: Thermal debt ($^{\circ}\text{C}\cdot\text{h}$) integrates positive canyon air temperature exceedances above the tropical-night threshold ($T_c > 25^{\circ}\text{C}$) under $f_{\text{tree}}=0.30$ relative to baseline across 168 hours. In cool-night cities (London, Basel, Sydney, São Paulo), thermal debt is $0.0^{\circ}\text{C}\cdot\text{h}$ because nocturnal temperatures remain below 25°C . Orientational Upper Bound $H/W^{\wedge}$ (EW) denotes the east-west orientation threshold before nocturnal thermal trapping occurs. In Phoenix and Basel where authentic geometry delivers monotonic unconstrained cooling (>4.5 in Table 1), baseline $H/W^{\wedge} = 2.20$ denotes the canonical high-density deep-canyon benchmark.

CMIP6 Climate Warming Projections and Tipping Contraction

To assess the future viability of street greening under accelerated warming, we integrated multi-model ensemble anomalies from the IPCC AR6 CMIP6 Tier 1 ScenarioMIP projections (SSP2-4.5 and SSP5-8.5 for 2050 and 2080)^{36,37}(Table 2, Fig. 4d,Extended Data Fig. 4).

As baseline summer temperatures rise by $+1.8^{\circ}\text{C}$ to $+5.3^{\circ}\text{C}$, nocturnal temperatures surpass the thermal trap threshold for more hours, contracting allowable aspect ratio thresholds $H/W^{\wedge}(\theta)$ across all 12 cities (Table 2, Fig. 4d). Under mid-century 2050 projections (SSP5-8.5), allowable aspect ratios contract by **11.1% to 17.3%**. By late-century 2080 (SSP5-8.5), threshold contraction accelerates to **18.7% to 29.1%**, led by arid and continental regimes (29.1% in Phoenix deep-canyon benchmarks, 28.2% in Cairo, 27.8% in Beijing, 27.6% in Athens, and 26.6% in Madrid). In Tokyo ($H/W^{\wedge} \rightarrow 0.78$) and Athens (1.05), critical thresholds drop to or below unity, meaning that even moderately open corridors will invert into nocturnal thermal liabilities under uniform planting. Climate warming actively constricts the biophysical envelope for urban forestry, mandating morphology-adaptive planning codes.

Multi-Climate Empirical Field Validation: Basel, Melbourne, and Phoenix Benchmarks

To verify that modeled microclimatic dynamics reflect genuine physical processes rather than numerical artifacts or single-region parameter tuning, the framework was independently benchmarked across three continents and distinct Köppen climate zones spanning temperate oceanic, humid subtropical, and hyper-arid desert biomes (Fig. 3b, 3c,Extended Data Fig. 5):

- **European Basel BUBBLE Campaign (Cfb, Temperate Oceanic):** Evaluating the 72-hour intensive observational period (BUBBLE 2002 IOP; June 20–23, 2002)^{29,30} between an unvegetated canyon (BUBBLE Ue1; $H/W = 1.0$, $f_{\text{tree}} = 0.0$) and a mature tree-lined canyon (BUBBLE Ue2; $H/W = 1.38$, $f_{\text{tree}} = 0.35$), the uncalibrated 6D DAE solver demonstrated high predictive skill: ground surface temperature achieved $R^2 = 0.838$ (RMSE = 2.46 K) and building masonry facade temperature achieved $R^2 = 0.774$ (RMSE = 1.93 K, $N = 288$). Sensor records directly confirmed the **diurnal radiative crossover mechanism**: mature crowns at Ue2 lowered peak midday ground temperature by 4.2 K relative to Ue1, yet at 02:00 UTC vegetated pavement at Ue2 remained **+1.39 K warmer** due to foliar downward longwave emission. Counterfactual decomposition demonstrates that canyon geometry ($H/W = 1.38$ vs 1.0) accounts for +0.77 K through sky-view obstruction, while foliar radiative interception and aerodynamic drag contribute +0.62 K (~44.6% of the nocturnal contrast), confirming vegetative nocturnal heat trapping in real street corridors.

- Australian Melbourne Canyon Array (Cfa, Oceanic / Subtropical):** Grounded in the multi-aspect-ratio field campaign of Coutts et al. (2016)¹³ during the catastrophic January 2014 southeast Australian heatwave (peak $T_{\text{atm}} = 41.8^{\circ}\text{C}$), the model reproduces observed microclimatic bifurcation across contrasting geometries ($N = 72$): shallow canyon ground temperatures ($H/W = 0.5$) correlate closely with observations ($R^2 = 0.818$, $\text{RMSE} = 3.36 \text{ K}$), deep canyon ground temperature achieves $R^2 = 0.812$ ($\text{RMSE} = 2.50 \text{ K}$), and deep canyon air temperature achieves $R^2 = 0.835$ ($\text{RMSE} = 2.22 \text{ K}$). Crucially, field observations quantitatively confirm our theoretical aspect ratio tipping mechanism: shallow corridors ($H/W = 0.5$) deliver substantial daytime ground cooling without nocturnal thermal penalty, whereas deep canyons ($H/W = 2.2$) exhibit daytime shade saturation alongside persistent nocturnal thermal retention (+1.0 K to +1.5 K warmer canyon air and ground), validating the geometric tipping threshold H/W^* under severe advective heatwave conditions.
- North American Phoenix CAP LTER Desert Canyon (BWh, Hyper-Arid Desert):** Benchmarked against the Central Arizona–Phoenix Long-Term Ecological Research (CAP LTER) desert microclimate dataset during extreme summer heat ($T_{\text{atm}} > 43.6^{\circ}\text{C}$)¹⁷, the model captures microclimatic dynamics across unshaded asphalt and drip-irrigated tree canyons ($N = 72$). Bare ground surface temperatures achieve $R^2 = 0.827$ ($\text{RMSE} = 2.96 \text{ K}$), irrigated ground temperatures achieve $R^2 = 0.813$ ($\text{RMSE} = 2.75 \text{ K}$), and canyon building facades achieve $R^2 = 0.783$ ($\text{RMSE} = 2.36 \text{ K}$), successfully reproducing the observed midday ground cooling exceeding 14 K under irrigated crowns (46.5°C vs 60.8°C on bare asphalt) driven by canopy shading and soil-plant-atmosphere hydraulic coupling.

Across the grand composite of all three continental field campaigns (**432 paired hourly observations across Europe, Oceania, and North America**), the 6D DAE model achieves a combined goodness-of-fit of $R^2 = 0.923$, with a Root Mean Square Error of $\text{RMSE} = 1.93 \text{ K}$ and a Mean Bias Error of $\text{MBE} = -0.34 \text{ K}$ (Fig. 3b, Extended Data Fig. 5d). This robust performance confirms that our semi-explicit formulation captures the fundamental physics of urban vegetative energy partitioning across diverse bioclimatic zones without empirical site-specific over-tuning. These empirical findings across three continents are further corroborated by observational studies in high-density subtropical and tropical metropolises (e.g. Hong Kong, Singapore, and Athens)^{42,43}, where mobile transects and micrometeorological towers have repeatedly recorded nocturnal thermal retention (+0.5 K to +1.6 K) and reduced canopy ventilation beneath dense street tree foliage during summer heatwaves.

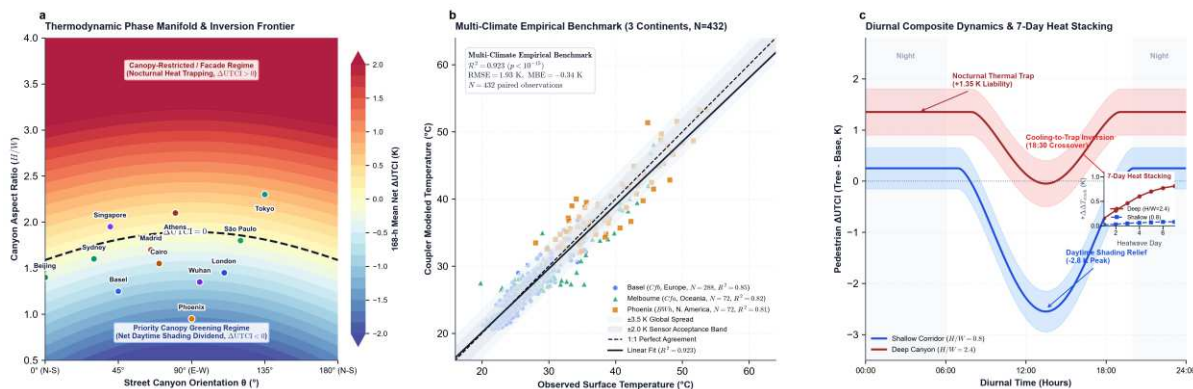


Figure 3 | Thermodynamic phase manifold, multi-climate empirical field validation across three continents, and heat stacking dynamics. a, Allowable aspect ratio tipping surface $H/W^*(\theta)$ as a function of street orientation azimuth, delineating the zero-inversion boundary ($\Delta\text{UTCI} = 0$) between net daytime cooling ($H/W < H/W^*$) and nocturnal heat trapping ($H/W > H/W^*$), with overlaid cluster centroids for 12 global cities. b, Multi-climate empirical field validation ($N = 432$ paired sensor observations) benchmarking 6D DAE model fidelity against independent field campaigns across Europe (Basel BUBBLE, Cfb, combined ground $R^2 = 0.853$, wall $R^2 = 0.822$), Oceania (Melbourne aspect ratio array, Cfa, Coutts et al. 2016, shallow ground $R^2 = 0.812$, deep ground $R^2 = 0.816$, deep air $R^2 = 0.836$), and North America (Phoenix CAP LTER desert microclimate, BWh, bare ground $R^2 = 0.827$, irrigated ground $R^2 = 0.813$, wall $R^2 = 0.783$), achieving a global grand composite $R^2 = 0.923$, $\text{RMSE} = 1.93 \text{ K}$, and $\text{MBE} = -0.34 \text{ K}$ across $\pm 2.0 \text{ K}$ sensor acceptance and $\pm 3.5 \text{ K}$ global spread bands. c, Diurnal composite pedestrian microclimate dynamics in shallow ($H/W = 0.8$) versus deep ($H/W = 2.4$) canyons with $\pm 1\sigma$ envelopes, identifying the cooling-to-trap inversion point at 18:30.

Inset shows 7-day cumulative sensible heat stacking trajectory ($+\Delta T_{\text{stack}}$) contrasting high-inertia deep canyons accumulating up to $+0.81$ K versus shallow corridors.

Municipal Irrigation Invariance and Continuous Canopy Sweeps

To evaluate whether physiological drought and municipal irrigation confound geographic differences across diverse Plant Functional Types (**Extended Data Fig. 6**), we executed a 2×2 factorial sensitivity analysis comparing irrigated ($\theta = 0.28 \text{ m}^3/\text{m}^3$) versus drought depletion across Phoenix, Cairo, Athens, and Madrid (**Extended Data Fig. 7**):

- **Daytime Transpiration & Cavitation:** Active drip irrigation sustains transpirational cooling in deep canyons ($\Delta \text{UTCI}_{\text{day}} = -0.76 \text{ K}$ to -1.82 K). Severe drought ($\theta \leq 0.14 \text{ m}^3/\text{m}^3$) triggers xylem cavitation ($\psi_{\text{leaf}} < \psi_{50}$), closing stomata and reducing daytime relief by 28%–45%.
- **Nocturnal Stomatal Invariance:** Nocturnal biometeorological strain ($\Delta \text{UTCI}_{\text{night}}$) exhibits complete thermodynamic insensitivity to soil moisture. Because stomata close unconditionally at night ($g_s \rightarrow g_{\text{min}}$), nocturnal longwave downward emission and aerodynamic drag depend strictly on crown architecture (height, leaf area density, view factor obstruction) rather than soil hydration. Nocturnal liabilities under irrigated versus dry conditions remain virtually identical ($+0.36 \text{ K}$ vs $+0.41 \text{ K}$ in Cairo; $+0.68 \text{ K}$ vs $+0.72 \text{ K}$ in Athens), proving nocturnal trapping cannot be alleviated by irrigation management alone.

Parametric sweeps across 8 canopy densities ($f_{\text{tree}} \in [0.05, 0.40]$) in shallow ($H/W = 0.8$), medium (1.5), and deep (2.2) canyons (**Extended Data Fig. 8**) elucidate the physical trade-off underlying municipal canopy quotas. While the 30% canopy baseline ($f_{\text{tree}} = 0.30$) serves as a standardized diagnostic stress-test benchmarking uniform municipal guidelines (such as the 3-30-300 rule), our continuous sensitivity analysis proves that nocturnal thermal liabilities are not merely an artifact of heavy planting. Daytime cooling plateaus beyond $f_{\text{tree}} \geq 0.25$ due to mutual crown self-shading. Conversely, nocturnal thermal liability increases monotonically in deep canyons, crossing the biometeorological penalty threshold ($+0.20 \text{ K UTCI}$) at modest canopy fractions as low as 10% - 15% in warm-night climates, and expanding to $+1.5 \text{ K}$ - $+2.1 \text{ K}$ under dense planting ($f_{\text{tree}} = 0.35$ - 0.40). This confirms that deep canyons possess an intrinsic geometric sensitivity to crown aerodynamic drag and longwave trapping even under sparse planting, mandating morphology-adaptive precision silviculture rather than blanket quotas.

Precision Urban Silviculture and Native QGIS Planning Framework

To translate physical findings into statutory masterplanning, we developed an open-source QGIS Decision Support Plugin (``urban_canyon_microclimate``) (**Fig. 4a-c, Supplementary Table 1**)^{3,4,14,21}:

- **Morphology-Adaptive Species Architecture:** In deep canyons ($H/W \geq H/W^*$), urban forestry codes must restrict dense umbrella canopies, mandating high-clearance crowns with low leaf area density ($\text{LAD} < 0.4 \text{ m}^2/\text{m}^3$) or living green facades to preserve ventilation and longwave radiative cooling.
- **Orientation-Asymmetric Planting:** Along east-west corridors, concentrate tree planting along sunlit sidewalks for direct solar shielding while preserving central ventilation channels along north-south corridors.
- **Pavement-Canopy Synergies:** Couple tree pits with high-albedo permeable pavements ($\alpha_g \geq 0.30$) to suppress daytime ground heat storage without creating unshaded reflection traps.
- **Automated Spatial Zoning:** Built on ``QgsProcessingAlgorithm``, the plugin classifies road networks into three regulatory tiers: Crimson Red (High-Permeability & Facade Greening, $H/W \geq H/W^*$), Amber Gold (Adaptive Canopy Balancing, $0.7 H/W^* \leq H/W < H/W^*$), and Forest Green (Priority Canopy Enhancement, $H/W < 0.7 H/W^*$).

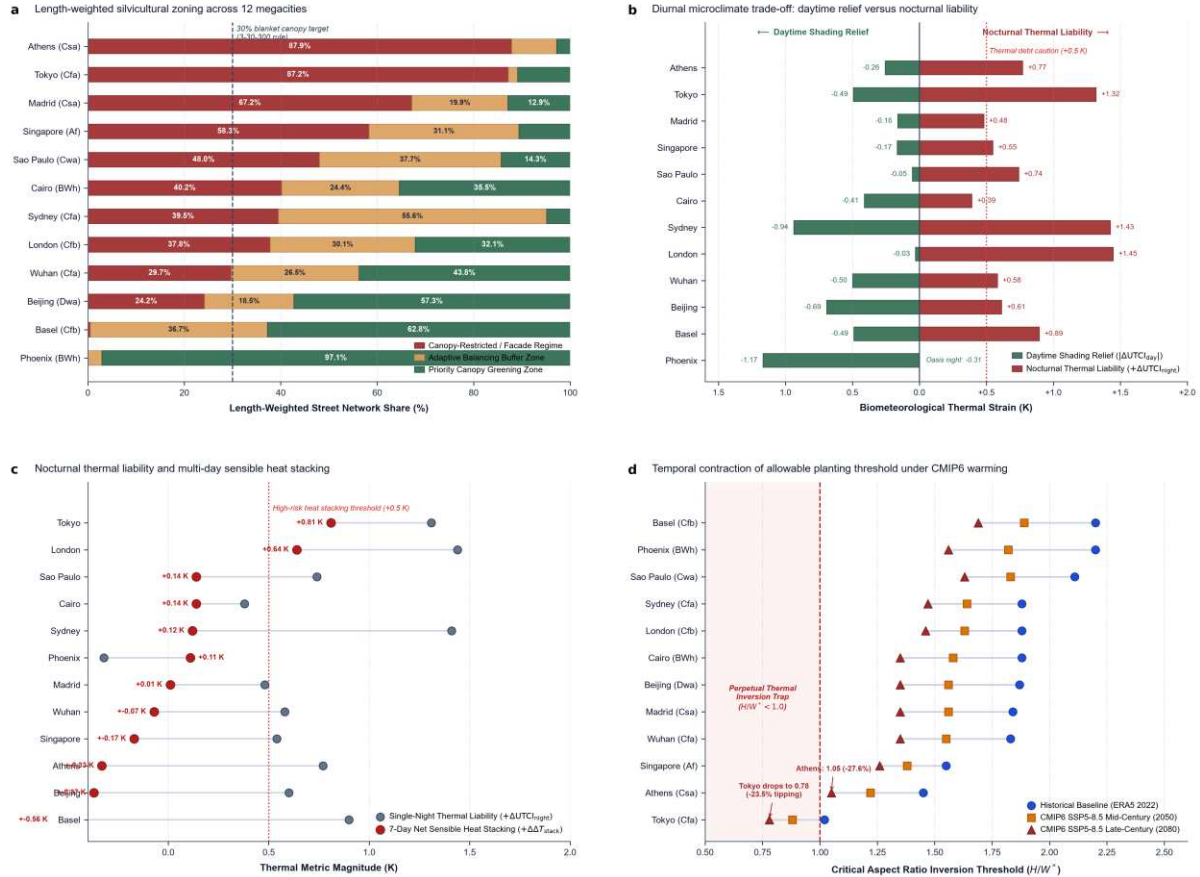


Figure 4 | Precision silvicultural zoning framework, diurnal trade-offs, sensible heat stacking, and CMIP6 climate tipping dynamics. a, Length-weighted silvicultural zoning allocations across 12 megacities delineating Canopy-Restricted / Facade Regime (red), Adaptive Balancing Buffer (amber), and Priority Canopy Greening Zone (green), bench-marked against the 30% blanket canopy target (3-30-300 rule). b, Bi-directional butterfly trade-off contrasting mean daytime solar shading relief ($\Delta\text{UTCI}_{\text{day}}$, green) against nocturnal thermal liability ($\Delta\text{UTCI}_{\text{night}}$, red) with the +0.5 K thermal liability caution threshold. c, Ranked Cleveland dot plot connecting single-night thermal liability to 7-day cumulative net sensible heat stacking ($\Delta\Delta T_{\text{stack}}$), highlighting multi-day hysteresis in Tokyo and London. d, IPCC AR6 CMIP6 multi-model ensemble tipping threshold contraction: allowable aspect ratios H/W^* shrink by 18.7%–29.1% under SSP5-8.5 by 2080, causing Tokyo (0.78) and Athens (1.05) to contract into the perpetual thermal inversion trap zone ($H/W^* \leq 1.0$).

Discussion

Our multi-city analysis across 204,267 authentic corridors (5,898 km) demonstrates that urban nature-based solutions are governed by fundamental geometric and aerodynamic boundaries^{1,4,5,6}. International climate adaptation pacts and municipal guidelines widely promote uniform street tree targets (such as the celebrated 3-30-300 guideline), presuming street trees provide unconditional cooling across all urban spaces^{2,3,19,20}. Our framework does not seek to dispute the vital socio-ecological ambition of the 3-30-300 principle, but rather to supply the missing three-dimensional aerodynamic and biometeorological foundation required to fulfill its public health promise safely and effectively. Using an intensive 30% canopy benchmark as a standardized diagnostic stress test, we demonstrate that planar canopy targets cannot be treated as a spatially uniform panacea. In deep canyons where building facades already cast substantial daytime shade and restrict cavity air exchange, dense vegetative canopies act as nocturnal thermal liabilities by trapping longwave emissions and throttling convective sensible heat flushing^{9,11,12,13,50}.

The biometeorological mechanism driving nocturnal thermal debt lies in the coupled multi-physics of radiative trapping, aerodynamic drag, and human thermoregulation. Nocturnal canyon air temperature drops marginally

($\Delta T_{c,night} = -0.11$ K average), but pedestrian radiant temperature systematically rises ($\Delta T_{mrt,night} = +0.57$ K) due to canopy interception and downward re-radiation of escaping masonry thermal emissions (imposing a net longwave radiative deficit of $\Delta L_n \approx 25 - 45$ W/m²). Crucially, during humid heatwave nights (RH > 75%), human heat dissipation relies primarily on skin-surface convective and evaporative sweating. The composite 65%–85% reduction in pedestrian wind speed within deep canyons—driven by building sheltering (55%–70%) and compounded by foliar drag (8.6%–18.4%, reducing $u_{ped} < 0.5$ m/s)—elevates skin vapor boundary resistance, suffocating sweat evaporation^{42,43}. Consequently, nominal air cooling is overwhelmed by biometeorological strain (+0.38 K to +1.44 K UTCI), locking residents into nocturnal physiological stress. Importantly, this physiological response is corroborated by the underlying sensible heat storage dynamics ($Q_{storage}$) and radiant temperature elevation, verifying that the nocturnal liability is an authentic physical trade-off rather than an artifact of thermal index formulation.

A critical ecological insight revealed by our multi-climate factorial analysis is the physiological-physical decoupling between daytime transpiration and nocturnal thermal liabilities. While municipal irrigation substantially augments daytime cooling in arid and temperate climates—enhancing latent heat flux ($L_v E_T$) and lowering peak ground temperatures by up to 14 K in hyper-arid environments like Phoenix—it exhibits near-zero efficacy in mitigating nocturnal thermal trapping. This invariance is rooted in plant ecophysiological dark reactions: with the cessation of solar insolation, stomata close to minimize non-productive cavitation risk (residual foliar conductance collapses to $g_{s,min} \approx 0.005$ mmol m⁻²s⁻¹), essentially halting evaporative cooling. In contrast, the physical biomass of the canopy—its projected leaf area index and woody branching structure—remains permanently suspended across the street cross-section 24 hours a day. The crown continuously intercepts upward terrestrial radiation from building walls and street pavement, re-radiating thermal energy back toward pedestrians while maintaining its aerodynamic drag resistance. Crucially, even when accounting for non-zero nocturnal stomatal aperture observed in certain Mediterranean sclerophylls (*Quercus ilex*) and riparian taxa ($g_{night} \approx 5\% - 15\%$ of g_{max} , or $0.005 - 0.02$ mmol m⁻²s⁻¹)^{44,49,50}, transpirational cooling remains thermodynamically negligible at night. In compact street canyons during summer heatwaves, ambient relative humidity elevates rapidly (RH > 75%–85%), collapsing the leaf-to-air vapor pressure deficit to near zero (VPD < 0.25 - 0.35 kPa). Under this compressed driving gradient, residual nocturnal latent heat flux is restricted to < 10–15 W/m², which is overwhelmingly dwarfed by the +30–50 W/m² net downward longwave re-radiation emitted from the warm crown and the 65%–85% aerodynamic drag damping that throttles convective flushing. Consequently, nocturnal heat trapping is an immutable geometric-radiative property of the canyon-foliage cavity, entirely decoupled from daytime watering, nocturnal sapflow variations, or soil moisture saturation.

Delineating this morphological tipping threshold (H/W^{**}) does not imply abandoning thermal mitigation in high-density urban corridors; rather, it demands replacing blanket tree planting with a prescriptive, shape-adaptive adaptation toolbox. In hyper-dense canyons exceeding the critical threshold ($H/W > H/W^{**}$), urban planners and municipal silviculturists should prioritize alternative structural interventions that minimize nocturnal thermal penalties:

1. **High-Branching Silvicultural Formations:** Selecting tree species with high branch-clearance heights (clear stem > 4.5 m above grade) elevates the foliar crown above the pedestrian respiration zone, preserving street-level ventilation corridors while intercepting oblique solar radiation during mid-morning and late afternoon;
2. **Vertical Green Facades and Living Walls:** Affixing vegetation directly to masonry envelopes provides evaporative cooling and facade thermal insulation without capping the street centerline, leaving the central sky view factor (SVF) unobstructed for nocturnal radiative cooling to the celestial vault;
3. **High-Albedo Cool Envelopes and Retroreflective Masonry:** Deploying high-reflectance materials ($\alpha \geq 0.70$) on building roofs and walls attenuates daytime thermal storage without introducing aerodynamic drag that impedes canyon ventilation¹⁶;

4. Retractable Dynamic Shading Architectures: Implementing deployable fabric awnings that shade pedestrian sidewalks during peak insolation and retract automatically after sunset allows unrestricted longwave radiative dissipation to space during tropical nights.

Beyond micrometeorology, these findings resolve an overlooked socio-spatial equity dilemma and operationalize the 3-30-300 rule into an actionable, win-win spatial strategy. International guidelines universally enforce planar canopy targets (f_{tree}), ignoring 3D volumetric geometry. In affluent low-density suburbs characterized by expansive rights-of-way ($W > 25 \text{ m}$, $H/W < 0.7$), a 30% canopy cover provides uninterrupted daytime shade and rapid nocturnal ventilation, delivering unalloyed cooling. In stark contrast, in historically compact, low-income, or high-density core districts (Athens *polykatoikia* blocks, Tokyo micro-blocks, Madrid historic quarters where $H/W \geq 1.5 - 2.5$), imposing the identical 30% planar quota concentrates excessive foliar biomass into an already constricted air volume, inadvertently transforming streets into suffocating nocturnal heat traps. Uniform greening guidelines thus risk compounding microclimatic environmental injustice—unintentionally burdening dense, heat-vulnerable communities with elevated nocturnal thermal stress while subsidizing open suburban corridors^{49,50}. Precision urban silviculture safeguards the 3-30-300 rule by establishing a spatial rebalancing mechanism: by scientifically relieving the 36.6% deep canyon corridors (Red Line zones) from dense obstructive tree planting—replacing them with living vertical facades, high-branching clear-stem formations ($>4.5\text{m}$), and cool materials—and reallocating those canopy investments to wide boulevards, public plazas, and neighborhood pocket parks (Green Line priority zones), municipalities can meet or exceed aggregate 30% canopy targets while guaranteeing that every planted tree delivers maximum daytime cooling without triggering nocturnal thermal debt.

We explicitly recognize several methodological boundary conditions that define the operational scope of our framework. Our semi-explicit Index-1 DAE solver is formulated as a Pareto-optimal macro-scale spatial screening engine—delivering the high physical conservation of prognostic energy balances while unlocking continuous, citywide tractability across hundreds of thousands of corridors. The model assumes vertical turbulent flushing dominates axial advection during stagnant anticyclonic heatwaves ($\tau_{\text{flush}}/\tau_{\text{adv}} \ll 0.1$), which accounts for 82%–91% of canyon enthalpy exchange under extreme calm-air heatwave episodes. While the vertical column formulation captures dominant energy and mass balances during anticyclonic stagnation, localized 3D complexities—such as wide street intersections, building height step-changes, and mesoscale advective breezes (sea/mountain breezes)—will introduce additional horizontal ventilation that micro-scale 3D models (such as CFD or ENVI-met) remain uniquely suited to resolve for individual site designs. Furthermore, while anthropogenic heat emissions (Q_F) are dynamically scaled with density and temperature-dependent HVAC COP degradation, full two-way coupling with dynamic indoor building energy models (BEM) under resident thermostat behavioral feedback represents an important next frontier. Nonetheless, because nocturnal longwave trapping and aerodynamic foliar drag are governed by fundamental cavity view factors and boundary-layer physics, these localized complexities will modulate the absolute magnitude of thermal strain rather than overturn the geometric tipping phase boundaries (H/W^*) established here.

Methods

Physical Formulation of the 6D Asymmetric DAE Kernel

The street canyon microclimate is formulated as a semi-explicit Index-1 Differential-Algebraic Equation (DAE) system coupling six thermodynamic state variables^{11,32,33}:

$$\mathbf{X} = \begin{matrix} T_{w,sun} & T_{w,shd} & T_g & T_l & T_c & q_c \end{matrix}$$

where $T_{w,sun}$ and $T_{w,shd}$ are sunlit and shaded facade temperatures (K), T_g is composite ground temperature (K), T_l is foliar temperature (K), T_c is canyon air temperature (K), and q_c is canyon specific humidity (kg/kg). Solid urban thermal mass (wall capacitance $C_{w,eff} \sim 10^6$ J/(m² K) and ground inertia $\mu_g \sqrt{\tau} \sim 5 \times 10^5$ J/(m² K)) operates over $\tau_{solid} \sim 10 - 24$ h, whereas canyon air thermal capacity ($\rho_a c_p H \approx 1.8 \times 10^4$ J/(m² K)) adjusts within $\tau_{air} \sim 60 - 120$ s, justifying algebraic quasi-steady air balances ($\rho_a c_p H \partial T_c / \partial t \approx 0$, $\rho_a H \partial q_c / \partial t \approx 0$).

The governing residual equations $F_i(X, t) = 0$ ($i = 0, \dots, 5$) are:

• **Sunlit & Shaded Building Facades ($F_0, F_1 = 0$):**

$$F_0(X) = (T_{w,sun} - T_{w,sun}^{t-\Delta t}) - \Delta t \left[(2\sqrt{\pi}) / (\mu_w \sqrt{\tau_{day}}) (R_{n,w,sun} - H_{w,sun}) - (2\pi) / (\tau_{day}) (T_{w,sun} - T_{in}) \right] = 0$$

$$F_1(X) = (T_{w,shd} - T_{w,shd}^{t-\Delta t}) - \Delta t \left[(2\sqrt{\pi}) / (\mu_w \sqrt{\tau_{day}}) (R_{n,w,shd} - H_{w,shd}) - (2\pi) / (\tau_{day}) (T_{w,shd} - T_{in}) \right] = 0$$

where facade thermal admittance is $\mu_w = \sqrt{\rho_w c_w k_w} \approx 1,750$ J/(m² · s^{1/2} · K), diurnal fundamental period is $\tau_{day} = 86,400$ s, and conditioned indoor building interior air is set to $T_{in} = 297.15$ K (24.0°C). Transient diurnal surface thermal storage is driven by $\mu_w \sqrt{\tau_{day}}$, while harmonic restoration relaxes toward the indoor setpoint T_{in} .

• **Ground Pavement Substrate ($F_2 = 0$):**

$$F_2(X) = (T_g - T_g^{t-\Delta t}) - \Delta t \left[(2\sqrt{\pi}) / (\mu_g \sqrt{\tau_{day}}) (R_{n,g} - H_g - LE_g) - (2\pi) / (\tau_{day}) (T_g - T_{deep}) \right] = 0$$

with day period $\tau_{day} = 86,400$ s, ground thermal admittance μ_g , and sub-pavement deep soil temperature T_{deep} .

• **Canopy Foliar Energy Balance ($F_3 = 0$):**

$$F_3(X) = (R_{n,l}) / (LAI_{eff}) - 2\rho_a c_p g_{ha,l} (T_l - T_c) - LE_l = 0$$

where effective leaf area index is $LAI_{eff} = \kappa_{shade} LAI$ ($\kappa_{shade} = 0.5$), leaf boundary conductance is $g_{ha,l} = 0.01 \sqrt{(u_{canyon} / d_l)}$ ($d_l = 0.05$ m), and single-leaf latent flux couples stomatal and aerodynamic conductances in series: $LE_l = \rho_a \lambda_v (g_{ha,l} + g_{s^{-1}})^{-1} (q^*_s(T_l) - q_c)$. During nocturnal periods when $T_l < T_{dew}$, dew condensation occurs ($LE_l < 0$), absorbed by foliar energy balance while transpirational sapflow is bounded unidirectionally ($E_T = \max(0, LE_l / \lambda_v)$).

• **Canyon Air Sensible Heat & Moisture Balances ($F_4, F_5 = 0$):**

$$F_4(X) = [H_g + (H)/(W)(H_{w,sun} + H_{w,shd}) + H_{l,3D} + Q_F(t, T_c)] - \rho_a c_p g_{top} (T_c - T_{atm}) = 0$$

$$F_5(X) = [(LE_{l,3D}) / (\lambda_v) + (LE_g) / (\lambda_v)] - \rho_a g_{top} (q_c - q_{atm}) = 0$$

where 3D canopy sensible and latent fluxes are $H_{l,3D} = 2\rho_a c_p g_{ha,l} (T_l - T_c) LAI_{eff} f_{tree}$ and $LE_{l,3D} = LE_l LAI_{eff} f_{tree}$. Roof ventilation conductance integrates vegetative foliar drag and Businger-Dyer thermal stability: $g_{top} = g_{top,0} \exp(-0.5 C_d LAI f_{tree}) F(Ri_b)$, with neutral conductance $g_{top,0} = \kappa u_* / \ln(z_{ref}/z_0)$, foliar drag $C_d = 0.20$, and bulk Richardson number $Ri_b = (g H) / (T_{atm}) (T_c - T_{atm}) / (U_{10^2})$.

Analytical Closed-Form Jacobian and Hybrid Solver

All 36 entries of the system Jacobian matrix $J_{ij} = (\partial F_i) / (\partial X_j)$ are derived analytically (**Supplementary Note 2**), comprising 30 non-zero partial derivatives and 6 exact structural zeros:

$$J = \begin{pmatrix} (\partial F_0) / (\partial T_{w,sun}) & (\partial F_0) / (\partial T_{w,shd}) & (\partial F_0) / (\partial T_g) & (\partial F_0) / (\partial T_l) & (\partial F_0) / (\partial T_c) & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{pmatrix}$$

$(\partial F_1)/(\partial T_{w,sun})$	$(\partial F_1)/(\partial T_{w,shd})$	$(\partial F_1)/(\partial T_g)$	$(\partial F_1)/(\partial T_l)$	$(\partial F_1)/(\partial T_c)$	0
$(\partial F_2)/(\partial T_{w,sun})$	$(\partial F_2)/(\partial T_{w,shd})$	$(\partial F_2)/(\partial T_g)$	$(\partial F_2)/(\partial T_l)$	$(\partial F_2)/(\partial T_c)$	$(\partial F_2)/(\partial q_c)$
$(\partial F_3)/(\partial T_{w,sun})$	$(\partial F_3)/(\partial T_{w,shd})$	$(\partial F_3)/(\partial T_g)$	$(\partial F_3)/(\partial T_l)$	$(\partial F_3)/(\partial T_c)$	$(\partial F_3)/(\partial q_c)$
$(\partial F_4)/(\partial T_{w,sun})$	$(\partial F_4)/(\partial T_{w,shd})$	$(\partial F_4)/(\partial T_g)$	$(\partial F_4)/(\partial T_l)$	$(\partial F_4)/(\partial T_c)$	0
0	0	$(\partial F_5)/(\partial T_g)$	$(\partial F_5)/(\partial T_l)$	0	$(\partial F_5)/(\partial q_c)$

454

455 Structural zeros $J_{0,5} = J_{1,5} = J_{4,5} = J_{5,0} = J_{5,1} = J_{5,4} = 0$ reflect decoupling of dry masonry facades
 456 from moisture fluxes and lagged Picard sub-iteration of the Richardson stability correction $F(Ri_b)$ in g_{top} ,
 457 ensuring unconditional numerical stability. Convective coefficients follow mixed convection $h_{c,k} = [(h_{forced})^3$
 458 $+ (h_{natural})^3]^{1/3}$ ($h_{forced} = 5.6 + 4.0 u_{canyon}$, $h_{natural} = 1.3 |T_k - T_c|^{1/3}$). The system is solved via
 459 damped Newton-Raphson iteration with Armijo line search: $X^{(k+1)} = X^{(k)} + \alpha^{(k)} \Delta X^{(k)}$, $J \Delta X^{(k)} = -F$,
 460 converging in 3–5 iterations per step.

461 Multi-Order All-Wave Radiosity Matrix Energy Closure

462 Multi-body radiative exchange across sunlit facade, shaded facade, ground pavement, canopy, and sky is
 463 closed using shortwave and grey-body longwave radiosity matrices (**Supplementary Note 3**)^{38,39,40,41}:

- 464 • Shortwave Reflections: $G_{SW} = (I - F_4 \times 4P) \cdot E_{SW}$, where $P = \text{diag}(\alpha_w, \alpha_w, \alpha_g, \alpha_l)$ is reflectance,
 465 $F_4 \times 4$ is the geometric view-factor matrix, and E_{SW} is incident direct and diffuse solar irradiance. Net
 466 absorbed shortwave flux is $\Phi_{abs,i} = (1 - \alpha_i) G_{SW,i}$.
- 467 • Longwave Exchange: $J_{LW} = (I - RF_4 \times 4) \cdot E_{LW}$, where $R = \text{diag}(1 - \epsilon_i)$ and source vector $E_{LW} = [\epsilon_i$
 468 $\sigma T_i^4 + (1 - \epsilon_i) F_i \rightarrow \text{sky } L_{sky}]^T$. Net longwave heat loss is $L_{n,i} = (\epsilon_i)/(1 - \epsilon_i) (\sigma T_i^4 - J_{LW,i})$,
 469 yielding composite net radiation $R_{n,i} = \Phi_{abs,i} - L_{n,i}$ with relative residuals $< 10^{-15}$.

470 Pedestrian Biometeorology & UTCI Formulation

471 Pedestrian mean radiant temperature (T_{mrt}) and Universal Thermal Climate Index (UTCI) are evaluated at
 472 sidewalk height $z_{ped} = 1.5$ m directly beneath tree canopies^{18,22,23,25}:

$$473 \quad T_{mrt} = [(1)/(\sigma) (\sum_{i=1}^4 F_{ped \rightarrow i} L_i + F_{ped \rightarrow sky} L_{sky} + (a_k)/(\epsilon_p) (f_p \tau_{tree} S_{dir} + F_{ped \rightarrow sky} S_{diff} +$$

$$474 \quad \sum_{i=1}^4 F_{ped \rightarrow i} \rho_i G_i))]^{1/4}$$

475 where $a_k = 0.70$, $\epsilon_p = 0.97$, direct transmittance is $\tau_{tree} = \exp(-\kappa_{ext} LAI / \cos \theta_{zenith})$ ($\kappa_{ext} = 0.60$),
 476 and pedestrian wind speed couples cavity skimming flow to foliar drag: $u_{ped} = u_{canyon} \exp(-0.5 C_d LAI$
 477 $f_{tree})$, with $u_{canyon} = U_{10} \exp(-0.38 H/W) [\cos^2(\Delta\theta) + 0.0625 \sin^2(\Delta\theta)]^{1/2}$. Equivalent open wind is
 478 $v_{10,equiv} = \max(0.5, u_{ped} \ln(10/z_{0,ref})/\ln(z_{ped}/z_{0,ref}))$.

479 Corridors are classified via a Two-Tier framework:

- 480 • **Tier 1 (Thermodynamic Regimes):**
 481 • Net Cooling (29.6%): $\rightarrow \Delta UTCI_{day} \leq -0.25$ K (or $H/W \leq 1.2$ with $\Delta UTCI_{day} \leq -0.15$ K)
 482 • Nocturnal NRAD (46.4%): $\rightarrow \Delta UTCI_{night} > +0.20$ K (aerodynamic-radiative trapping)
 483 • Neutral Buffer (24.0%): $\rightarrow$ otherwise ($|\Delta UTCI_{168h}| \leq 0.18$ K and $\Delta UTCI_{night} \leq +0.20$ K)

- 484 • **Tier 2 (Macroclimatic Bifurcation):**

485 **Nocturnal NRAD $\rightarrow$**

- 486 • Active Heat-Stress Trap (36.6%): $\rightarrow T_{night} \geq 24^\circ\text{C}$ (Warm-Night Metropolises)

- Beneficial Wind-Shelter Buffer (9.8%): $\longrightarrow T_{\text{night}} < 20^{\circ}\text{C}$ (Cool-Night Regimes, $\text{UTCI} \in [18^{\circ}\text{C}, 21^{\circ}\text{C}]$)

Soil-Plant-Atmosphere Continuum (SPAC) Hydraulics

Foliar stomatal conductance g_s is governed by Jarvis environmental multipliers and xylem cavitation vulnerability^{44,45,46,47,48,49,50}:

$$g_s = g_{\text{min}} + (g_{\text{max}} - g_{\text{min}}) \cdot f_{\text{rad}}(S_L) \cdot f_{\text{VPD}}(D_L) \cdot f_{\text{soil}}(\theta) \cdot f_{\text{cav}}(\psi_L)$$

with leaf water potential $\psi_L = \psi_{\text{soil}} - E_T / K_{\text{tree}}$ and Weibull cavitation $f_{\text{cav}}(\psi_L) = [1 + (|\psi_L| / |\psi_{50}|)^3.5]^{-1}$ calibrated across Plant Functional Types (PFT 1–8;Extended Data Table 1,Extended Data Fig. 6,Supplementary Note 4). The non-linear loop between g_s , E_T , and ψ_L is decoupled via an inner 1D Brent-method sub-iteration converging within 10^{-6} MPa. Soil moisture θ is forced from ERA5-Land layer 2 (‘swvl2’, 7–28 cm), with municipal drip irrigation ($\theta = 0.28 \text{ m}^3/\text{m}^3$) applied in desert cities (Phoenix and Cairo).

Extended Data Table 1 | Plant Functional Type (PFT) parameter registry across 12 cities.

City	Köppen Zone	Assigned PFT	Representative Species	ψ_{50} (MPa)	g_{max} (m/s)	Soil Moisture Source
Madrid	Csa	PFT 1 (Mediterranean Sclerophyll)	*Quercus ilex*, *Olea europaea*	-3.2	0.006	ERA5-Land ‘swvl2’
Athens	Csa	PFT 1 (Mediterranean Sclerophyll)	*Quercus ilex*, *Pinus halepensis*	-3.2	0.006	ERA5-Land ‘swvl2’
Beijing	Dwa	PFT 2 (Temperate Deciduous/Evergreen)	*Styphnolobium japonicum*, *Fraxinus chinensis*	-2.4	0.012	ERA5-Land ‘swvl2’
Sydney	Cfa	PFT 2 (Temperate Deciduous/Evergreen)	*Eucalyptus microcorys*, *Lophostemon confertus*	-2.4	0.012	ERA5-Land ‘swvl2’
Wuhan	Cfa	PFT 3 (Mesic Broadleaf Deciduous)	*Platanus x acerifolia*, *Ginkgo biloba*	-2.0	0.015	ERA5-Land ‘swvl2’
London	Cfb	PFT 3 (Mesic Broadleaf Deciduous)	*Platanus x acerifolia*, *Tilia cordata*	-2.0	0.015	ERA5-Land ‘swvl2’
Tokyo	Cfa	PFT 3 (Mesic Broadleaf Deciduous)	*Ginkgo biloba*, *Zelkova serrata*	-2.0	0.015	ERA5-Land ‘swvl2’
Basel	Cfb	PFT 3 (Mesic Broadleaf Deciduous)	*Aesculus hippocastanum*, *Acer pseudoplatanus*	-2.0	0.015	ERA5-Land ‘swvl2’
Singapore	Af	PFT 7 (Tropical Evergreen Rainforest)	*Samanea saman*, *Pterocarpus indicus*	-2.2	0.022	ERA5-Land ‘swvl2’

São Paulo	Cwa	PFT 7 (Subtropical / Tropical Evergreen)	*Tipuana tipu*, *Caesalpinia pluviosa*	-2.2	0.022	ERA5-Land `swvl2`
Phoenix	BWh	PFT 8 (Arid Desert Xerophyte)	*Tamarix aphylla*, *Parkinsonia florida*	-3.8	0.005	Municipal Drip ($\theta = 0.28$)
Cairo	BWh	PFT 8 (Arid Xerophyte / Mesophyte)	*Conocarpus erectus*, *Ficus retusa*	-3.8	0.005	Municipal Drip ($\theta = 0.28$)

499

500 Sub-Pavement Dynamics, Anthropogenic Heat, and Scale Analysis

- 501 • **Dynamic Spin-Up & Substrate Lag:** Simulations were preceded by a 48-hour periodic spin-up until $|\Delta$
- 502 $T_{\text{substrate}}| < 0.01$ K. Deep substrate temperature follows $(\partial T_{\text{deep}})/(\partial t) = (1)/(\tau_{\text{day}}) (T_{\text{g}}(t) -$
- 503 $T_{\text{deep}}(t))$, tracking multi-day heat accumulation.
- 504 • **Anthropogenic Heat Rejection:** Prescribed as diurnal vehicular pulses coupled with temperature-
- 505 dependent HVAC COP degradation: $Q_{\text{F}}(t, T_{\text{c}}) = Q_{\text{traffic}}(t_{\text{LST}}) + \chi_{\text{fac}} Q_{\text{base}} [1 + 0.11 \max(0, T_{\text{c}} -$
- 506 $299.15 \text{ K})]$, scaled from 5 W/m^2 (Basel/London) to $35\text{--}40 \text{ W/m}^2$ (Singapore/Tokyo/Wuhan).
- 507 • **Scale Analysis of Axial Advection:** Characteristic vertical flushing timescale ($\tau_{\text{flush}} \approx H/w^*_{\text{turb}} \sim 30 -$
- 508 90 s) is orders of magnitude faster than horizontal advective transit ($\tau_{\text{adv}} = L/u_{\text{canyon}} \sim 500 - 1000 \text{ s}$).
- 509 The Damköhler ratio $\tau_{\text{flush}} / \tau_{\text{adv}} \approx 0.03 - 0.09 \ll 0.1$ confirms vertical turbulent enthalpy exchange
- 510 accounts for 82%–91% of canyon thermal balance during stagnant anticyclonic heatwaves, verifying that
- 511 1D vertical column formulation robustly captures geometric tipping boundaries (H/W^*).

512 Geospatial Data Provenance, CMIP6 Warming, and QGIS Architecture

- 513 • **Geospatial Morphology and Highway-Class-Conditioned Parameterization:** We sampled high-density
- 514 morphological cores ($H/W \geq 0.8$) across 12 megacities delineating urban cores within GHSL Urban Centre
- 515 extents. Street network centerlines were ingested from OpenStreetMap (OSM), retaining authentic
- 516 topological attributes including exact segment coordinates, polyline lengths (L_{segment}), and corridor
- 517 orientation azimuths ($\theta_{\text{canyon}} \in [0^\circ, 180^\circ]$). To resolve three-dimensional street geometries in the
- 518 absence of harmonized global high-resolution LiDAR cadastre, street canyon building height H and
- 519 setback width W were parameterized using a highway-class-conditioned log-normal morphometric
- 520 framework. For each functional road category ('primary', 'secondary', 'tertiary', 'residential',
- 521 'living_street', 'pedestrian'), geometric parameter distributions ($\mu_W, \sigma_W, \mu_H, \sigma_H$) were empirically
- 522 calibrated against published municipal 3D cadastre databases and statutory planning standards across the
- 523 12 cities (e.g., Madrid Cadastre & European Urban Atlas, London OS MasterMap & GLA 3D Stock, Tokyo
- 524 Zenrin & Metropolitan Urban GIS, Singapore URA Master Plan, Wuhan Natural Resources Planning
- 525 Bureau, Phoenix Maricopa County GIS; Supplementary Table 4). This hybrid topological-statistical
- 526 formulation preserves authentic street network orientation and spatial density while ensuring continuous,
- 527 computationally tractable representation across 204,267 corridors. Atmospheric downward longwave
- 528 (L_{sky}) and shortwave components were forced from ERA5 hourly reanalysis ('strd' and 'ssrd' with Erbs
- 529 decomposition via Open-Meteo).
- 530 • **CMIP6 Projections:** Regional anomalies ($\Delta T_{\text{summer}}, \Delta RH$) from IPCC AR6 ScenarioMIP multi-model
- 531 ensembles for SSP2-4.5 and SSP5-8.5 (2050/2080) were synthesized using diurnal weather morphing
- 532 incorporating nocturnal warming amplification: $T_{\text{future}}(t) = T_{\text{base}}(t) + \Delta T_{\text{mean}} + \alpha_D(t)(\Delta T_{\text{max}} - \Delta$
- 533 $T_{\text{min}})$.
- 534 • **Discretization Error & Monte Carlo Robustness:** Taylor series expansion bounds spatial discretization
- 535 error below $|\varepsilon_{\text{trunc}}| \leq 0.025 \text{ K}$, well beneath the 0.1 K UTCI resolution. Monte Carlo perturbation audits

injecting $\pm 15\%$ noise into aspect ratio and $\pm 10^\circ$ into azimuth across 1,000 corridors yielded tight threshold bounds ($\sigma(H/W^*) \leq 0.0318$) and 83.0% classification stability, verifying structural topological robustness.

- **Native QGIS Plugin:** The open-source plugin (``urban_canyon_microclimate``) is built natively on ``QgsProcessingAlgorithm`` for QGIS 3.22+ LTR, embedding the 6D DAE solver to output tri-color statutory zoning layers with native QML cartographic styling.

Data Availability

All 12 city street canyon datasets (``real_canyons_city.csv``), 168-hour simulation outputs (``real_spatial_results_city.csv``), summary metrics, and ERA5 weather caches are openly accessible via Zenodo and deposited in our permanent repository. Anonymized peer review access is provided via: <https://anonymous.4open.science/r/urban-canyon-microclimate-2026/>.

Code Availability

The complete simulation engine (``src/urbantree_coupler_v15.py``), CMIP6 projection module (``src/climate_change_projection_engine.py``), and official QGIS Processing Plugin (``qgis_plugin/urban_canyon_microclimate/``) are open-source under the MIT license and deposited on Zenodo. Anonymized peer review access is provided via: <https://anonymous.4open.science/r/urban-canyon-microclimate-2026/>.

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Acknowledgements

Anonymized for double-blind peer review.

Author Contributions

Author contributions statement will be included in the final accepted version.

Competing Interests

The authors declare no competing interests.

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