Seventeen city types define distinct pathways for climate mitigation and adaptation worldwide

Felix Creutzig[1,2], Alona Zharova[3,4]*, Simon Montfort[5], Florian Nachtigall[1]*

[1] Potsdam Institute for Climate Impact Research, Potsdam and Berlin, Germany
[2] Bennett Institute for Innovation and Policy Acceleration, Business School, University of Sussex, UK
[3] Humboldt Universität zu Berlin, Berlin, Germany
[4] University of Oxford, Environmental Change Institute, Oxford, UK
[5] EPFL Lausanne

**both authors contributed equally. Contact: creutzig@pik-potsdam.de*

Abstract. *Understanding that cities are main arenas of climate action, it remains unclear which cities should focus on what kind of action taking a global comparative lens. Recent contributions identified four different types of cities across seven world regions, while others specified a huge case study literature database on cities and climate change biased towards established, stagnant, and megacities, largely ignoring smaller, rapidly growing cities, mostly in the Global South. Here, we comprehensively assess climate issues, climate actions, and their main political entry points and feasibility challenges for 17 types of cities. For this, we rely on three different data modalities: a) a global database of >10000 cities and 16 different quantitative characteristics; b) AI assisted full-pdf analysis of >1200 pdfs on representative cities of 17 different types; and c) AI-assisted web-based analysis of representative cities and their challenges. While the first two steps enable evidence identification with medium to high confidence, the last steps allows us to fill crucial gaps and debias the analysis, albeit subject to low confidence insights. We find that smaller and poorer cities in Africa and Asia are strongly motivated to develop WASH infrastructure, that rapidly growing and megacities will need to focus on future proof urban planning, and that established cities, mostly in Europe, North America and East Asia, but also cities in small island states aim to disentangle from costly gas and oil dependence in heating and transport sectors. Cities that aim for net-zero are co-motivated by a high quality of life.*

Introduction

All cities are different. But some are more similar to each other than others. Capturing this complexity in a structured assessment for cities in the context of climate action remains a holy grail of global urban sustainability research. Home to more than half of humanity and responsible for 67–76% of global final energy consumption and a comparable share of CO_2 emissions, urban areas simultaneously concentrate both the drivers and the consequences of anthropogenic climate change[1]. By mid-century, approximately 2.5 billion additional people will live in urban areas; growth will be concentrated in smaller and mid-sized cities across Africa, Asia, and Latin America[1,2]. The decisions made now about urban form, infrastructure, and energy systems will lock in emissions trajectories and adaptation capacities for more than a century[3]. Correspondingly, the Intergovernmental Panel on Climate Change (IPCC) has elevated cities to the centrepiece of its seventh assessment cycle, commissioning a dedicated Special Report on Climate Change and Cities[4,5].

Yet the scientific foundations required to underpin such an assessment remain deeply uneven. Research priorities identified include the need to expand observations of informal settlements, understand city–climate interactions across scales, and utilize novel big data and AI technologies for evidence synthesis[6,7]. However, existing evidence concentrates overwhelmingly on wealthy, and slow-growing cities in the Global North, while the fast-growing, lower-income cities of Africa and Asia, centers of urbanization dynamics and also climate vulnerabilities, remain underrepresented[8]. Cities with development and planning challenges are hardly covered by city-specific case studies[8]. This asymmetry in literature introduces systematic bias into city assessments. It also risks producing policy guidance that is poorly calibrated to the needs of the majority of global urbanites.

Addressing this imbalance requires, in the first instance, a suitable framework for organizing the extraordinary heterogeneity of the world's cities. Urban typologies serve precisely this function, as they enable structuring shared characteristics across cities to make a complex evidence base interpretable and actionable[9,2,10]. A primary globally comprehensive quantitative typology of urban energy use demonstrates that GDP per capita, population density, gasoline prices, and climatic conditions together explain up to 88% of variance in urban transport energy demand across 274 cities[3]. To extend in scope and resolution, a novel data-driven typology of 11,000 cities based on 12 structural indicators considers demographic scale and change, socioeconomic and institutional capacity, and biophysical energy demand conditions, using an ensemble Deep Embedded Clustering pipeline to identify four statistically robust and substantively validated city types[11]. This typology is linked to the systematic evidence landscape[8] and thus enables identification of i) which cities are structurally similar, ii) where evidence is available and, iii) where critical gaps must be filled by targeted new studies or alternative data modalities.

The four-type classification, however, while statistically representative, necessarily compresses within-type heterogeneity. The policy challenges, feasibility constraints, and political entry points for climate action differ not only between a development-constrained city in sub-Saharan Africa and a high-income European metropolis, but also between established cities in North America and East Asia, or between emerging cities in South America and Africa. A finer-grained typological framework, combining city characteristics with regional context, is therefore a prerequisite for a fine-grained understanding of urban climate challenges and corresponding actions.

Meeting this need is further constrained by a severe evidence bottleneck. Manual synthesis of city-specific literature across 4 types and seven world regions and across climate-relevant and governance dimensions is challenged by i) a very rich data base of case studies on cities that is impossible to synthesize in short time scales with limited human expertise, and ii) a high bias within the literature data base[7,8]. Recent advances in artificial intelligence offer a partial solution. To address (i), large language models (LLMs) have demonstrated the capacity to support systematic evidence synthesis at scale, covering literature search, screening, and structured data extraction with precision and recall rates competitive with trained human reviewers, and at dramatically lower cost[12,13,14]. In the urban domain, LLM-based frameworks have been applied to the automated extraction of local climate policies from planning documents, achieving high agreement with manual annotation[15]. AI-assisted information extraction of pdfs, however, maintains the bias of case studies reflected in the academic literature. As a useful complement, and to address (ii), AI-assisted web scraping permits structured, traceable retrieval of grey literature, municipal reports, and practitioner knowledge that peer-reviewed databases systematically miss. AI assisted web scraping for systematic information retrieval has been demonstrated as efficient to extract structured data from complex texts[16]. In our case, this offers the opportunity to partially correct the Global South bias present in academic literature[8].

Here, we combine this novel set of methods and develop a globally comprehensive characterization of 17 types of cities and their distinct climate challenges, climate actions, and political feasibility constraints. We integrate three complementary data modalities: a quantitative global database of more than 10,000 cities characterized by 16 structural indicators from which 17 city types are derived; AI-assisted full-PDF analysis of more than 1,000 papers on representative cities of each type; and AI-assisted web-based analysis of representative cities and their climate challenges, calibrated to fill evidence gaps and correct systematic biases in the peer-reviewed literature. We also explicitly stratify confidence levels across modalities (high to medium for quantitative and peer-reviewed evidence, lower but structured for web-derived insights). The resulting product is the first comprehensive characterization of cities globally that enables prioritization of action.

Results

Quantitative subtype characterization. A full characterization of subtypes (cf.[11]) reveals distinct patterns (Fig. 1). Demographic dynamism concentrates in low-income tropical contexts while wealth- and emissions-intensity concentrates in temperate, high-income ones, including China. African emerging cities constitute the most demographically active subgroup globally (population and density growth rates roughly double the global median) with near-zero heating demand and emissions approximately 90% below the global median. African and Asian large and mega cities share explosive population size deviations (>2,700% and >3,600% above median, respectively) and rapid density growth, but diverge in infrastructure endowment. Asian rapidly growing cities present an unusual combination of high heating demand (+278%), rapidly declining density, and rising emissions, corresponding to coal-dependent mid-sized cities in northern China and Central Asia. Asian and European established cities are characterised by ageing populations, high heating demand, and above-median emissions; European established cities additionally exhibit the highest critical infrastructure scores and GDP per capita among non-North American established cities.

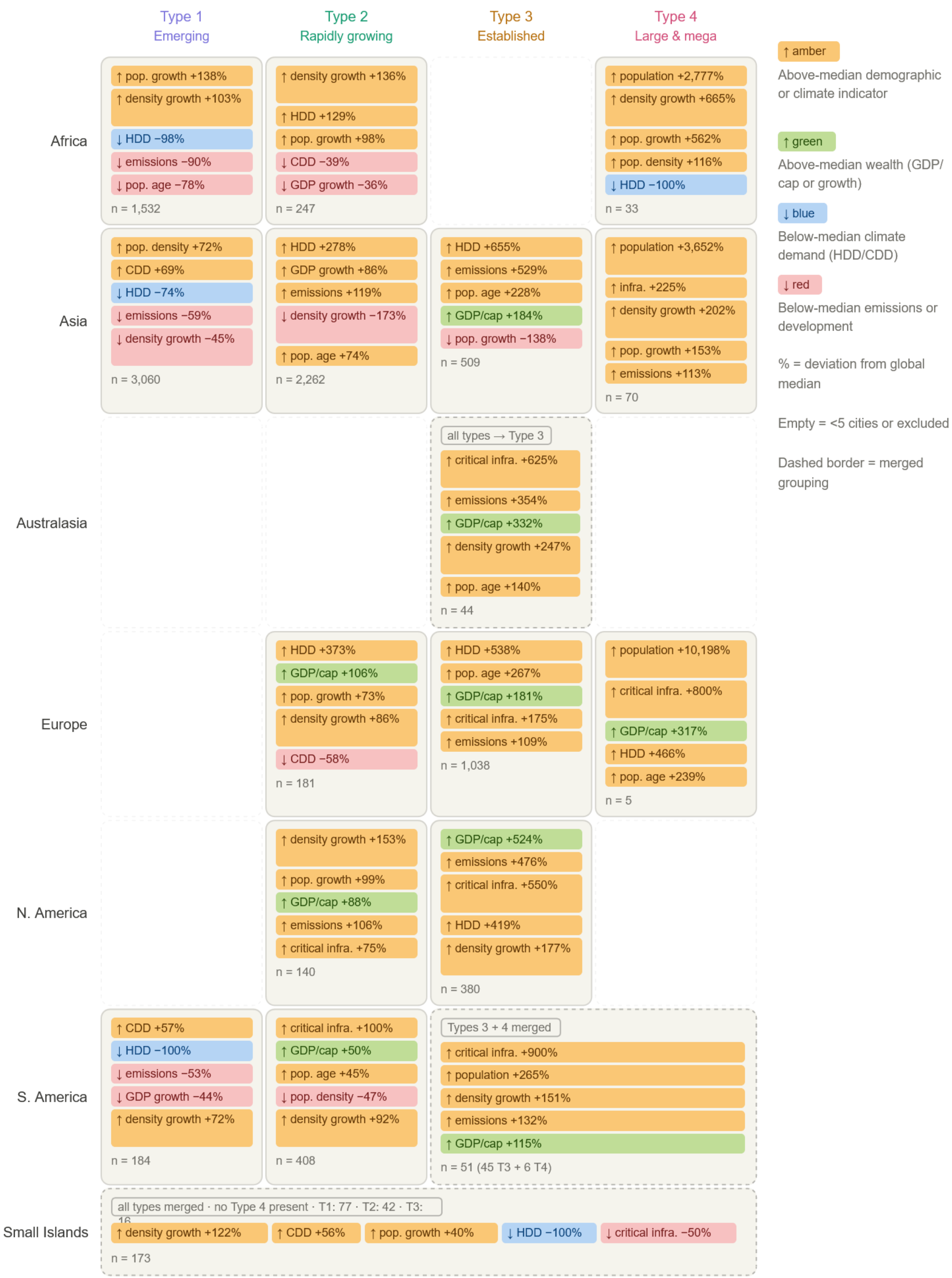

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Figure 1. Key distinguishing characteristics of global city subtypes by world region and typology. *Each cell reports the five indicators that deviate most from the global median for that region–type subgroup, expressed as percentage deviation, based on median values across all cities in the subgroup. City typology (Types 1–4) and regional classification follow Montfort et al. (2026); see Methods for indicator definitions. Three groupings are pooled due to small sample sizes or regional composition: Australasia (all types treated as Type 3), South America Types 3 and 4 (combined), and Small Islands (all types combined). Empty cells indicate fewer than five cities in that subgroup or exclusion by design. Colour coding distinguishes indicator domains: demographic and climate indicators above the global median (amber), wealth indicators above the global median (green), climate demand indicators below the global median (blue), and emissions or development indicators below the global median (red).*

North American established cities constitute the wealthiest and highest-emitting established-city subgroup (GDP per capita and per-capita emissions both exceed the global median by 470–524%). This points to high mitigation challenges in high-income, car-dependent urban systems. Australasian cities cluster almost entirely in the established type and share high GDP, high emissions, and strong infrastructure. South American emerging cities are defined primarily by intense cooling demand and low emissions; their rapidly growing counterparts show relatively low population density alongside growing infrastructure capacity. The merged South American established and large and mega city group displays high critical infrastructure scores (+900%). Small Island cities, pooled across types, present a climatically homogeneous profile of negligible heating demand, elevated cooling demand, and fast density growth. They remain severely infrastructure-deficient relative to the global median, combining climate exposure and constrained adaptive capacity.

Characterization of solutions, motivations, and feasibility based on the case study literature (summarized Fig 2). Based on 1200 full-texts of city case studies, analysis of the motivations reveals four key insights. First, GHG emission reduction strategies for solution within the literature are mostly absent in the global South, specifically in Latin America and South Asia (only 6% of Latin American papers and 9% of South Asian ones cite emissions reduction as a relevant motivation). Studies on rich Gulf cities in the Middle East cite emission reductions as motivation most often explicitly (26%). Among sectors, transport measures are most often primarily motivated by climate change (32%).

Second, health and comfort dominate across all regions (33% of papers), but for different reasons. In Europe and North America, motivations relate to indoor air quality and wellbeing framed as quality of life. In South Asia and Africa, acute concerns such as disease vectors, respiratory illness from pollution, inability to afford mechanical cooling, and flood-related health crises dominate motivations. In other words, immediate urgency dominates in the Global South, whereas long-term well-being is more prevalent in the Global North.

Third, and related to the 2nd point, flood and disaster risk drive action in South Asia and Oceania. Flood motivation appears in 31% of South Asian papers and 27% of Oceanian ones compared to only 10% in the Middle East. Recurrent flooding, displacement, cyclones, and the inability of low-income populations to relocate are existential risks in South Asia. Resilience to immediate threats is the entry point for action.

Fourth, costs are the primary motivator for energy efficiency and renewables, e.g., citing electricity bills from air conditioning, payback periods, and property value gains as a result of building scale energy efficient investments. Cost motivation is only within 21% of NbS/BGI papers, where health and flood risk matter more. An interpretation is that t*echnocentric* solutions are sold on financial returns; *nature-based* solutions are sold on liveability.

Within the co-benefit analysis, three key insights emerge. First, nature-based solutions (NbS) generate ~53% more co-benefits than other solution types. Papers studying NbS and urban green/blue infrastructure report an average of 5.8 co-benefits per paper, compared to just 3.8 for non-NbS solutions. NbS solutions also generate co-benefits across categories (Table 1). Second, case studies on African cities report the highest average co-benefit count (5.9 per paper, compared to 4.0 as median). Third, papers that report more co-benefits also tend to cover more implementation barriers ($r = 0.32$). Academic studies choosing an integrated perspective on solutions appear to investigate both directions: co-benefits and barriers.

Table 1. **Co-benefit Clusters obtained via k-means.** *Seven semantic clusters derived from 5,571 co-benefits extracted from climate solution papers (t-SNE, perplexity=100). Solution subtypes are those appearing relatively more frequently in papers associated with each cluster. City examples are drawn directly from the corpus. Note: NbS = Nature-based Solutions; BGI =*

Blue-Green Infrastructure. NbS is the dominant solution type across all clusters; secondary subtypes are more cluster-distinctive. Africa represented by Cape Town (South Africa) and Mombasa (Kenya); South America by São Paulo (Brazil) and Buenos Aires (Argentina).

Cluster	n	Solution Subtypes	Example City & Co-benefit Explanation
Social & Urban Life	1,118	① NbS ② BGI	**Copenhagen, Denmark** Urban greenspace and active mobility investments generated physical and mental well-being benefits in addition to flood regulation.
Economic	1,080	① NbS ② ToD	**São Paulo, Brazil** Blue-green infrastructure interventions increased food and water self-sufficiency; ToD counterfactually saved costs on transport infrastructures.
Air Quality	930	① NbS ② Public transport	**Cape Town, South Africa** Public transport improvements and NbS improved air quality
Heat & Energy	746	① NbS & BGI ② ToD	**Singapore, Singapore** BGI and ToD reduced cooling energy demand per housing unit and mitigated urban heat island intensity
Health & Well-being	745	① NbS ② Active mobility	**Buenos Aires, Argentina** NbS investments and active travel translated into improved public health
Water Manageme nt	519	① Flood protection ② Rainwater harvesting & NbS	**Mombasa, Kenya** Flood protection and early warning systems reduced vulnerability to flooding and helped avoid infestation by dangerous disease vectors
Biodiversit y & Ecology	433	① Ecosystem services & NbS ② BGI	**Sydney, Australia** Post-industrial site rehabilitation via hybrid NbS and BGI networks achieved ecological restoration, biodiversity enhancement, habitat recovery, carbon sequestration, stormwater cleansing, and flood risk alleviation.

The systematic extraction of 1,230 urban climate solution papers confirms a highly uneven geographic distribution, as Europe (26%) and East and Southeast Asia (19%) account for nearly half of all the underlying literature (Africa only 2% of cases). We find that European and North American cases (Types 2–4) emphasize mitigation, and specifically energy efficiency, heat pumps, active mobility, and long-term planning. Asian cities (particularly Asia Types 2 and 3, together n=309) exhibit a stronger emphasis on coal phase out and renewables, urban planning, and household technologies; they document flood protection and resilient design as adaptation responses. Nature-based Solutions (NbS) and Blue-Green Infrastructure (BGI) emerge as the single largest solution category across the full corpus (24% of all 2,316 coded solution instances), relating both to mitigation and adaptation, and having the highest rate of co-benefit reporting (5.8 co-benefits; see above). BGI solutions perform strongest (mean 7.1 co-benefits), which indicates that integrating nature-based with grey infrastructure is understood to bring out the broadest range of co-benefits. Most solutions remain at pilot scale (Likert scale 1 (scaled from 0 to 3), 55% of instances), with only 25% reaching city-wide deployment (rated 3).

Institutional barriers dominate all other barriers. Governance and regulatory barriers appear in 84% of papers, higher than finance (52%), technology (41%), and socio-cultural obstacles (23%). This finding is mostly identical for both Global North (87%) and Global South (86%) contexts. Finance barriers are cited in 74% of renewable energy papers versus only 40% of

NbS papers (χ^2=29.5, p<0.0001). Renewable energies and related technologies require upfront investments, whereas NbS require maintenance costs and community engagement. African papers (all types combined, n=40 figure rows) focus on health, environmental safety, and economic constraints as motivations, and they demonstrate the highest average bundling of solutions (2.57 per paper). Here, resource constraints might imply a practical necessity of integrating interventions in high-exposure urban contexts.

Region / Type	N	Motivations	Solutions Mitigation	Solutions Adaptation	Barriers	Co-benefits
Africa Type 1	17	Economic constraints Urban growth Health/comfort	Efficient cookstoves Microgrids Renewables	NbS Resilient design Flood protection	Finance	Health improvements
Africa Type 2	8	Socio-economic Enabling impl. Health/environment	Renewables Urban planning Public transport	NbS Flood protection Resilient design	Finance	Economic/social
Africa Type 4	15	Health/safety Env. sustainability Public awareness	Waste management Renewables Thermal comfort	NbS Flood protection BGI networks	Institutions	Health improvements
Asia Type 1	45	Health/safety/QoL Economic motivations Env. protection	Renewables Waste management Circular economy	NbS Resilient design BGI networks	Institutions	Environmental sustainability
Asia Type 2	170	Health/comfort Env. protection Flood/disaster risk	Renewables Urban planning Household technologies	NbS BGI networks Flood protection	Institutions	Ecosystem benefits
Asia Type 3	139	Thermal comfort Env. sustainability Cost/affordability	Renewables Urban planning Household technologies	NbS Flood protection Resilient design	Institutions	Health/comfort
Asia Type 4	123	Health/safety Economic drivers Environmental quality	Renewables Urban planning Waste management	NbS Flood protection BGI networks	Institutions	Health/safety
Australasia Type 3 (all types merged)	44	Health/wellbeing Env. sustainability Cost/affordability	Active mobility Renewables Public transport	NbS Flood protection Resilient infrastructure	Institutions	Health/wellbeing
Europe Type 2	4	Green space recr. Env. awareness	Long-term planning Lifestyle change	NbS Flood protection	Institutions	Ecosystem quality
Europe Type 3	489	Health/safety Health/safety Climate change	Renewables Heat pumps Active mobility	NbS BGI networks Flood protection	Institutions	Health/wellbeing
Europe Type 4	33	Health/safety Economic concerns Env. sustainability	Efficient building Urban planning Active mobility	NbS Resilient design Flood protection	Institutions	Energy savings
N. America Type 2	6	Energy costs Urban heat Community oppos.	Natural ventilation Urban planning Renewables	NbS Thermal mass BGI networks	Technology	Energy savings
N. America Type 3	127	Financial access Health/wellbeing Climate change	Renewables Transit-oriented dev. Public transport	NbS BGI networks Flood protection	Institutions	Energy savings
S. America Type 1	2	Affordability Energy affordability	Efficient technology Heat pumps Renewables	Drought management	Finance	Health/wellbeing Benefits
S. America Type 2	12	Env. protection Risk/hazard Economic access	Demand management Public transport Active mobility	NbS Flood protection BGI networks	Institutions	Environmental quality
S. America Types 3+4 merged	67	Health/wellbeing Env. risks Urban NbS	Public transport Renewables Urban planning	NbS BGI networks Flood protection	Institutions	Quality of life
Small Islands All types merged	8	Env. risks Economic wellbeing Health/pollution	Long-term planning Electrification Low-carbon fuels	Flood protection Resilient infrastructure Drought management	Institutions	Economic resilience

Fig 2. Results of AI-assisted evidence extraction from 1230 case studies (out of a body 50,000 case studies) of 97 cities representative of 17 subtypes of cities. *Line of evidence and sources are provided in Methods and SI.*

Region / Type	N	Motivations	Solutions Mitigation	Solutions Adaptation	Barriers
Africa Type 1		Flooding/coastal hazards Food/livelihood risk Health/WASH risks	Low-carbon energy/buildings Clean cooking/energy Flood/coastal protection	Early warning systems Flood/coastal protection Urban greening/EbA	Institutions
Africa Type 2		Water scarcity/drought Flooding/inundation Livelihood/poverty risks	Utility-scale renewables Urban NbS/greening	Coastal protection Water security/sanitation Climate-smart agriculture	Institutions
Africa Type 4		Flooding/drainage failures Conflict/instability Food/livelihood risk	Renewables deployment Clean cooking transition Solid waste management	Flood risk/drainage Erosion/slope control Monitoring/early warning	Finance
Asia Type 1		Water scarcity Disaster recovery Livelihood/food risk	Solar PV deployment	Early warning systems Water supply/irrigation Climate-smart agriculture	Finance
Asia Type 2		Urban greening/livability Water scarcity/hydro risk Economic/green growth	Building efficiency	Water management Heat/flood risk reduction	Finance
Asia Type 3		Green growth/investment Adaptation/risk reduction Health/heat/pollution	Demand-side energy mgmt. Coal phase-out/renewables Emissions MRV systems	Climate risk assessment	Institutions
Asia Type 4		Coastal flood/SLR Extreme heat/health Urban flooding	Energy transition Building standards Climate accountability	Heat risk/early warning Climate data/capacity Flood forecasting/EWS	Finance
Australasia Type 3 (all types merged)		Extreme weather/disaster Urban heat/livability Low-carbon urban form	Grid/storage/microgrids Emissions inventories Low-carbon buildings	Climate risk assessment Infrastructure upgrades Urban greening/canopy	Finance
Europe Type 2		Climate hazards/resilience Decarbonisation/renewables Coastal erosion/SLR	GHG inventory Fossil-to-renewables	Flood/weather risk mgmt. Coastal protection Water conservation	Institutions
Europe Type 3		Flooding/SLR Urban heat/health Climate neutrality targets	Building efficiency/std. Mobility decarbonisation Clean energy transition	Flood/stormwater resilience Urban greening/cooling Climate governance	Institutions
Europe Type 4		Heat/extreme weather Equity/vulnerability Economic risk reduction	Low-carbon energy/budgets Building/urban efficiency	Adaptation planning Flood/stormwater mgmt. Building and urban resource efficiency measures	Finance
N. America Type 2		Water scarcity/drought Ecosystem degradation Extreme heat/health	Risk/emissions monitoring	Heat risk preparedness EbA: forests/coasts Water security	Institutions
N. America Type 3		Extreme heat/inequity Flooding/SLR Emissions/air quality	Carbon budgets/policy Building retrofits CCS deployment	Flood/green infrastructure Climate-smart land use Building retrofits for efficiency and heat resilience	Financing availability and funding mechanisms
S. America Type 1		Food insecurity Climate migration Disaster risk/EWS	Forest protection	National adaptation plan Risk governance/EWS	Finance
S. America Type 2		Wildfire/disaster Drought/water scarcity Mining pollution, children's health, and environmental justice	Low-carbon energy/transport Climate governance/MRV Ecosystem restoration	Early warning systems Coastal adaptation Ecosystem restoration and nature-based resilience	Finance
S. America Types 3+4 merged		Flooding/storm surge Extreme heat/health Water scarcity/equity	Electrification	Early warning systems Flood/stormwater mgmt. Urban greening/GI	Institutions
Small Islands All types merged		Coastal inundation/SLR Water security/drought Equity/displacement	Renewables/mitigation Waste/sanitation Climate finance/MRV	Coastal protection/retreat Early warning systems Resilient urban planning	Institutions

Fig. 3. Results of web-based search (municipal documents, international agency sources, other web-based sources) for 97 cities representing 17 subtypes of cities on motivations, solutions, and main barriers. *All sources are documented and lines of evidence with quotes are provided (see Methods and SI).*

Grey-literature based assessment (summarized in Fig. 3). The web-based search of municipal documents, international agency sources, and other publicly accessible materials across 97 cities in 83 countries and stratified into 17 subtypes, sources that are closer to real-world issues but less reliable, result into findings similar to but distinct in fineprint from those of the academic literature. Flood, disaster risk, and sea-level rise constitute the single largest motivation category overall (462 entries; 39% of all coded motivations), concentrated in Small Island States (130 of that region's entries), Africa (106), Asia (69), and South America (38). Europe and North America are more motivated by urban heat and UHI concerns (71 and 33 entries respectively) and by carbon/mitigation framing, which appears as the third-ranked motivator in Europe (55 entries) and Asia (36 entries) but is hardly mentioned in Africa or the Small Island States. Clearly, carbon-neutrality narratives appear primarily in high-income urban contexts, whereas climate action in lower-income and small-island settings is driven by immediate physical exposure, such as storms, floods, water scarcity, and food insecurity. Consistently, food, livelihood, and equity concerns rank second in Africa (67 entries) and South America (30 entries); in the Small Island States, economic concerns (74 entries) are tightly coupled to disaster exposures. Solution gaps identified across the 97 cities are dominated by adaptation (35% of 292 coded gap solutions) over pure mitigation (23%). 81% of all identified solution gaps are rated as high urgency, with Africa (86%, infrastructure deficits) and North America (93%, heat equity and emission reductions) as the extremes.

The barrier and enabler structure of the web-based evidence is balanced (141 barriers versus 147 enablers across 288 coded entries, c.f. dominance of barriers in the academic literature). In rank order similar to the academic literature, web-based research also finds institutional barriers as the most frequently coded category overall (98 entries), followed by finance (86), technology (63), and socio-cultural factors (41). However, finance appears in grey sources as the leading barrier in Small Island States (41% of their barrier entries), Australasia (50%), and South America (35%), while institutions lead in Africa (39%) and are co-equal with finance in Europe and North America. The African statistics can be partially explained by sourcing: in Africa, only 11% of barrier-evidence entries derive from municipal sources, compared to 39% from international agencies. In contrast, Australasia (67% municipal, 0% international) and Europe (37% municipal, 20% international) are less documented by international donor literature. As African and Small Island State contexts are mediated by international reporting rather than indigenous and local voices, globally more visible solutions (e.g., flood protection) may dominate in written documents, understating locally prioritised interventions that may lack English-language documentation. Together, the two datasets (academic corpus and grey literature) agree on institutional barriers as the most universal constraint on urban climate action. Key findings across motivations, solutions, and barriers are summarized in Figure 4.

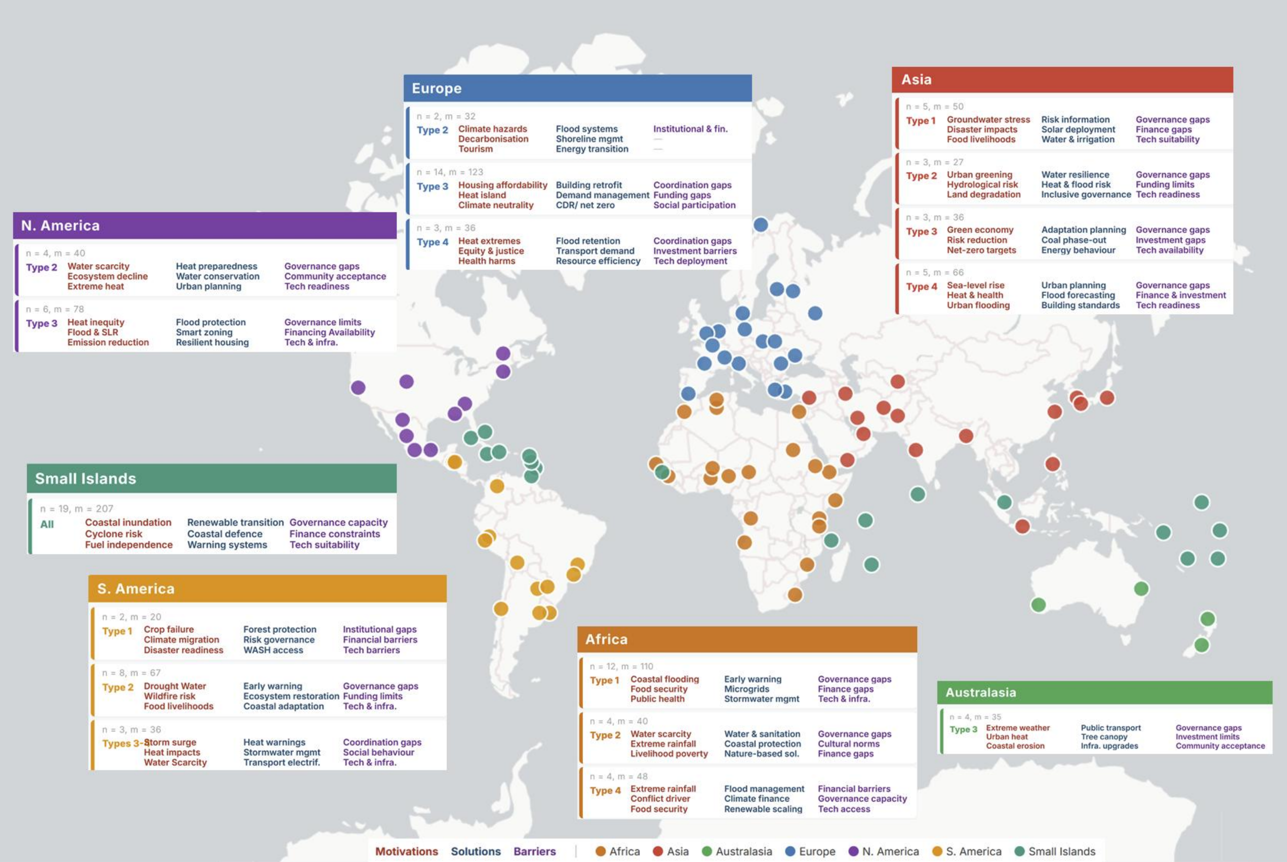

Fig. 4. Global synthesis of urban climate solution contexts across 17 region-type clusters (n = 97 cities, m = motivations/solutions/barriers coded per cluster). Points on the map specify individual case study cities colour-coded by world region (Africa, orange; Asia, red; Australasia, teal; Europe, blue; North America, purple; South America, yellow; Small Island States, green). For each region-type cluster, three columns summarise the dominant motivations (left), priority solution gaps (centre), and principal barriers (right) as derived from web-based searches of municipal documents, international agency sources, and local media. City types represent emerging, rapidly growing, established, and large and mega cities types. Sample sizes (n = cities, m = coded entries) vary across clusters, from n=2 in Europe Type 2 and South America Type 1 to n=19 across all Small Island States. Barrier categories follow a standardised taxonomy of governance, finance, technology, and socio-cultural constraints. The figure integrates evidence from the grey and academic literature and should be read alongside the underlying synthesis (Fig. 2 and Fig. 3).

Conclusion

This paper closes a crucial gap: the missing systematic evidence base on climate solutions, their motivations, co-benefits, and barriers, for cities worldwide based on representative academic and grey literature sources. The underlying AI pipeline complies with high traceability and reproducibility standards, allowing for documentation of all underlying sources, and lines of evidence (quotes within documents). The method allows for evidence synthesis and assessment where scientific literature is scarce and/or biased.

Our assessment reveals, unsurprisingly, that the literature reflects climate risks as regionally differentiated: coastal flooding dominates Africa and Small Islands, heat extremes define Europe and Australasia, water scarcity drives concern in N. America and Asia, and compounding food, water, and livelihood stresses characterise S. America. Nonetheless, adaptation solutions converge around early warning systems, nature-based solutions, and building retrofits. Technology readiness and suitability appear as disproportionate barriers in the Global South, while sea-level rise and urban flooding define mega cities in AsiaI.

Mitigation efforts are similarly uneven: decarbonisation and net-zero are explicit goals only in Europe, whereas lower-income regions frame mitigation instrumentally, e.g., as renewable energy access, transport electrification, or fuel independence. In Global South cities, emissions reduction is treated as a co-benefit of resilience rather than a primary objective. Feasibility findings demonstrate that institutional and financial capacity remain the binding constraints globally, while technology and socio-cultural dimenions are less relevant.

Overall, our assessment results will be useful for assessment of cities and climate change. Additionally, the AI-pipeline, specifically for grey literature, may be useful for similar efforts in other domains.

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Methods

Subtype characterization.

For each of the 11,422 cities in the global dataset (Montfort et al., 2026), 13 structural indicators were extracted: population size, population growth rate, population density, density growth rate, age structure, GDP per capita (PPP), GDP growth rate, critical infrastructure index, heating degree days (HDD), cooling degree days (CDD), human development index (HDI), female gender index, and per-capita GHG emissions. Cities were grouped by the four-type typology and six world regions defined in Montfort et al. (2026), yielding up to 28 region–type subgroups; subgroups with fewer than five cities were excluded. For three groupings — Australasia (all types collapsed to Type 3, reflecting the near-absence of Types 1, 2, and 4 in that region), South America Types 3 and 4 (merged due to small sample sizes), and Small Islands (all types merged) — cities were pooled prior to analysis. For each subgroup, the median value of each indicator was computed and expressed as a percentage deviation from the global median across all valid cities. The five indicators with the largest absolute deviation from the global median were identified as the most distinguishing characteristics of that subgroup and reported in the figure. Deviations are colour-coded by domain: demographic and climate indicators above the global median (amber), wealth indicators above the global median (green), climate demand indicators below the global median (blue), and emissions or development indicators below the global median (red).

Four additional changes were applied:

- Australasia (the correct region label in the data): all 44 cities lumped into the Type 3 column, with a "all types → Type 3" badge. In practice, 41 of 44 were already native Type 3. The profile is striking — highest GDP/cap and emissions in the established-city tier, alongside very strong infrastructure and an aging population.
- North America Type 1: left empty as instructed (the 12 cities are too few and geographically anomalous).
- S. America Types 3 + 4: merged into a single cell spanning both columns, with combined statistics from all 51 cities. The dominant signal is exceptionally high critical infrastructure, which is the key distinguishing feature of larger South American cities relative to the global median.
- Small Islands: merged across all four type columns into a single wide cell, with composition noted (77 / 42 / 16 across Types 1–3, no Type 4). The profile is dominated by warm-climate signals — near-zero HDD, elevated CDD and density growth — alongside infrastructure deficit.

Identification of PDF documents

To identify scientific case studies documenting climate solutions in the selected 200 cities spanning the four types and seven world regions globally, we first train a binary relevance classifier to predict relevant articles containing climate solutions and then download the relevant full-text studies from OpenAlex, the largest open source bibliographic database.

First, we trained a state-of-the-art ClimateBERT binary classifier on the article abstract and title on a sample of 1,012 manually annotated article abstracts from Montfort et al (2026). The labels were iteratively refined over two rounds: confident false positives and false negatives identified were corrected and merged back into the training data before final model training to improve the quality of the annotations. We used a nested cross-validation setup with 3 inner and 3 outer folds to avoid leakage between the training and the test data for hyperparameter tuning. This allows for a conservative estimate of the models' performance. In the outer loop, we used 3-fold stratified cross-validation and in the inner loop, we used a 4-fold stratified CV used as the objective within an Optuna Bayesian optimisation study (20 trials per outer fold). In the inner fold, we tuned the following Hyperparameters: learning rate (log-uniform, 1e-5–1e-4), batch size (8 or 16), number of epochs (3–6), weight decay (0.05–0.15), and focal loss gamma (0.5–3.0). The hyperparameter tuning was optimised on the F1 score, the harmonic mean between precision (intuitively speaking, the share of irrelevant articles predicted to be relevant) and recall (the share of truly relevant studies that are falsely predicted not to be relevant). Additionally, we optimized the prediction probability. Rather than using the default 0.5 probability threshold, an optimal decision threshold was selected per outer fold by training on the outer training split with a nested 4-fold CV and searching thresholds from 0.25 to 0.85 (step 0.02) to maximise F1 on out-of-fold predictions. The threshold used on the held-out outer test set was thus derived entirely from training data, avoiding leakage. We achieved F1 scores ranging from 0.81-0.82. Given the difficulty of identifying climate solutions due to the relatively fuzzy nature of the concepts, we deem these performance scores as adequate for initial preselection of relevant studies on the study abstract level for further in-depth analysis based on full-texts. The final hyperparameters were then selected by aggregating across outer folds (median for continuous, mode for categorical), and the median of per-fold optimal thresholds. We then retrained the final model on the full annotated dataset using aggregated hyperparameters. This model was then applied on the 28,943 case studies covering the 200 cities in our sample. Of these 9,144 were identified to be relevant by the classifier.

Outer fold	F1	Recall	Precision
1	0.82	0.82	0.81
2	0.82	0.87	0.77
3	0.81	0.83	0.79

Table 2: Binary machine learning classifier performance on three outer folds.

Second, we downloaded all available full-text PDFs, from OpenAlex and Unpaywall using the Application Programming Interfaces (APIs) of the providers to facilitate downloading large number of PDFs. A minimum file size check filtered out error pages.

LLM-assisted data extraction from scientific literature and web sources

We developed two complementary, purpose-built automated pipelines to extract structured evidence on urban climate solutions at scale: a scientific literature pipeline and a web-based evidence pipeline. Both pipelines are designed to meet the reproducibility and traceability standards required for IPCC assessment contributions, and both use GPT-5.2 (OpenAI) as the extraction model, called via the OpenAI Responses API at temperature 0.0 to maximise determinism. LLMs are used not to generate findings but to read and extract structured information from existing texts, with each answer required to be grounded in a verbatim quote from the source document. [All code, extraction prompts, and run manifests are archived and will be made available].

Scientific literature pipeline

Of the 9,144 paper identified as relevant by the classifier, XXXX available as open-access full texts were downloaded. Full-text PDFs were processed using a multi-extractor parser (pypdf as primary extractor, with PyMuPDF and pdfplumber as fallback layers) to maximise text recovery across varied PDF encodings.

For each paper, six structured extraction questions were submitted to GPT-5.2 in a single API call with the complete PDF uploaded as context. The questions asked the model to identify: (Q1) whether the paper empirically investigates an urban climate solution; (Q2) the case study city or cities; (Q3) up to three climate solutions from a controlled 57-item taxonomy, with a 0–3 Likert scale of implementation intensity; (Q4) co-benefits of climate actions; (Q5) the most relevant enabling or barrier conditions (finance, institutions, socio-cultural, technological); and (Q6) local actor motivations driving political action (full questions are available in Supplementary Material). All answers were constrained to information explicitly present in the PDF, with verbatim quote support required for each finding. Responses were returned as structured JSON enforced by a strict output schema.

To ensure traceability, each extraction record stores the model name and version, a SHA-256 hash of the system prompt, the exact prompt text, raw and parsed API responses, total token consumption, and computation time. A three-tier automated verification layer checks that each verbatim quote cited by the model exists in the source document: exact substring matching, fuzzy matching (SequenceMatcher similarity ≥ 0.82), and semantic similarity using sentence-transformer embeddings (cosine similarity ≥ 0.88). Records failing all three tiers are flagged for human review. The pipeline supports incremental resumption from partial runs, ensuring crash safety, and saves intermediate outputs every ten documents.

City-level web evidence pipeline

To complement the literature-derived evidence and improve coverage of city types and world regions that are under-represented in the peer-reviewed literature, we developed a second pipeline that retrieves and processes publicly available web sources. For each city, a structured web search query of the form "{City} {Country} climate change solutions" was submitted to the Tavily search API (search_depth = "advanced"), returning up to 30 web sources per city. Retrieved sources were classified by type (municipal website, international agency document, local news, or other) based on domain and title heuristics. The full text of each source was archived locally with a retrieval timestamp.

Sources were formatted as numbered SOURCE_ID blocks carrying pre-filled URL and publication year metadata and injected into city-specific prompts. Five structured extraction questions were then submitted to GPT-5.2 for each city as independent API calls: (Q1) local actor motivations for climate action; (Q2) up to three climate solutions from a controlled 57-item taxonomy, with a 0–3 Likert scale of implementation intensity; (Q3) solution gaps - urgently needed but unimplemented solutions; (Q4) co-benefits of climate actions; and (Q5) the most relevant enabling or barrier conditions (finance, institutions, socio-cultural, technological) (full questions are available in Supplementary Material). The same 57-item solution taxonomy used in the literature pipeline was applied throughout, ensuring cross-pipeline comparability. Source URLs were pre-populated from the search API response and the model was explicitly instructed not to generate or modify them.

A two-stage verification protocol was applied to each web extraction record. Stage A checks whether the cited URL remains live and whether the retrieved live content matches the archived content (classified as exact, partial, drifted, or unreachable; stable documents such as PDFs are exempt from drift detection). Stage B applies the same three-tier quote verification cascade as the literature pipeline. All provenance metadata (i.e., prompt text, prompt hash, raw API responses, run configuration, model version, and token consumption) are stored per record in a JSONL archive.

Both pipelines produce output in a common schema (city, solutions, Likert scores, barriers, motivations, co-benefits, source provenance), enabling joint analysis across evidence sources.

Both pipelines were purpose-built to meet the requirements of IPCC assessment processes. Four dimensions of methodological rigour are addressed. **Provenance**: every extracted finding is linked to a specific archived source via a pre-populated URL or a pdf document, a verbatim supporting quote, and a retrieval timestamp; a machine-readable run manifest records the exact model version, prompt formulation (SHA-256 hash), query identifiers, and input file specifications for the full run. **Traceability**: the three-tier automated verification checks that each cited quote exists in the archived source text. **Reproducibility**: the model was called at temperature 0.0 throughout; all prompts are versioned and hashed; source texts are archived at retrieval; and pipeline code, run manifests, and extraction prompts are deposited at [add link to GitHub later]. **Quality control**: extraction errors are fully documented by type and city, and affected observations are excluded from all analyses (see details in Supplementary Materials).