International Journal of Research and Review
[Indexed, Peer-Reviewed Journal]
Volume 13; Issue: 4; April 2026
Website: www.ijrrjournal.com
E-ISSN: 2349-9788; P-ISSN: 2454-2237

Review Paper

Urban Heat Islands and Heat Waves as Compound Urban Warming: Mechanisms, Observation, Modelling, Health Risk, and Equitable Adaptation

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DOI: https://doi.org/10.52403/ijrr.20260465

ABSTRACT

Urban heat islands (UHIs) and heat waves (HWs) are no longer best understood as parallel hazards. Across diverse climates, urban forms, and development trajectories, they increasingly operate as a compound urban warming regime that intensifies thermal exposure, modifies boundary-layer processes, amplifies health risk, strains energy and water systems, and challenges urban governance. Building on the earlier systematic review of UHI–HW research and incorporating more recent literature from the supplied Scopus corpus, this review synthesizes advances in mechanisms, observations, modelling, vulnerability analysis, and adaptation. The evidence base shows that research has shifted from documenting whether UHI–HW synergy exists toward asking when, where, and why the synergy strengthens, weakens, or reorganizes across scales. Recent studies highlight the importance of urban morphology, anthropogenic heat, soil moisture, wind, humidity, vegetation structure, and background synoptic forcing in conditioning compound heat. Methodologically, the field has moved toward multi-source integration, including dense in situ measurements, citizen weather networks, geostationary and polar-orbiting satellites, local climate zone classification, high-resolution urban canopy parameterization, and coupled mesoscale–biometeorological modelling. The literature also demonstrates that compound urban warming is fundamentally unequal: exposure, sensitivity, and adaptive capacity vary sharply within and across cities, making equity-sensitive interventions essential. Mitigation studies confirm the potential of cool roofs, green roofs, trees, irrigation, and urban blue–green infrastructure, but they also reveal context-specific trade-offs involving humidity, ventilation, nighttime performance, and air quality. This review argues that the next frontier lies in integrated urban heat intelligence: city-scale systems that link urban climate science, health surveillance, fine-scale forecasting, and targeted adaptation. A future-ready research agenda therefore requires higher-resolution observations, better urban parameterization, stronger coupling of physical and social risk models, and implementation frameworks that prioritize both effectiveness and justice.

Keywords: urban heat island; heat waves; compound urban warming; heat-health risk; urban climate modelling; thermal remote sensing; equitable adaptation

INTRODUCTION

Extreme heat has become one of the most consequential climate risks for cities, not only because global warming is increasing the frequency, duration, and intensity of heat extremes, but also because urbanization modifies local energy, moisture, and momentum exchanges in ways that systematically elevate heat exposure. The combined effect is more than additive in many cases. When heat waves overlap with urban heat islands, cities can experience a compound urban warming regime in which the background meteorological extreme and the local urban thermal anomaly reinforce one another in time, space, or human experience (Cheval et al., 2024; Kong et al., 2021; Li & Bou-Zeid, 2013; Santamouris, 2020).

The earlier systematic review by Cheval et al. (2024) established the breadth of this field by synthesizing 403 studies published between 1991 and 2022 and showing that interest in UHI–HW linkages accelerated sharply after 2000, with Europe and Asia emerging as the most intensively studied regions. That review also showed that the dominant themes of the literature had shifted toward urban patterns, risk and vulnerability, impacts, causal drivers, and decision-support systems, while integrated analyses of present and future climate remained comparatively limited (Cheval et al., 2024). The present article extends that foundation by reworking the narrative around a more explicit compound-risk framing and by incorporating newer studies available in the supplied abstract corpus, especially those published in 2021–2023. This matters because the newer literature increasingly moves beyond descriptive UHI mapping and asks higher-order questions about thermal comfort, fine-scale forecasting, local climate zones, humidity moderation, equitable adaptation, and operational urban heat management (Giannaros et al., 2023; Chakraborty et al., 2022; Broadbent et al., 2022; Wang et al., 2022; Chen, Yu, Wu, & Yang, 2022).

A publication-ready synthesis now needs to do three things simultaneously. First, it must revisit the physical basis of UHI–HW interaction. The literature shows that synergy is often observed, especially in temperate and densely built environments, but not universally. In some tropical or moisture-limited settings the UHI may remain stable, reorganize diurnally, or even show weak amplification during heat waves depending on background wind, soil moisture, and heat storage dynamics (Ao et al., 2019; He, Wang, Liu, & Ulpiani, 2021; Chew, Liu, Li, & Norford, 2021). Second, it must address the rapid methodological maturation of the field. Contemporary studies rely on multi-source evidence: dense weather-station networks, low-cost sensors, crowdsourced observations, MODIS and Landsat thermal products, GOES-R geostationary land surface temperatures, Sentinel imagery, ERA5 reanalysis, LCZ classification, and coupled WRF–UCM–RayMan or analogous modelling chains (Cheval et al., 2024; Chang et al., 2021; Hersbach et al., 2020; Fick & Hijmans, 2017; Bosch et al., 2021). Third, it must foreground human consequences. The most important question is no longer whether cities are warmer. It is how compound urban warming translates into morbidity, mortality, thermal discomfort, hospital behavior, emergency service demand, and inequitable risk distribution across neighborhoods and demographic groups (Graham, Vanos, Kenny, & Brown, 2016; De Troeyer et al., 2020; Chaston et al., 2022; He, Zhao, et al., 2022).

This review therefore adopts an explicitly integrative framing. It examines the emerging evidence that UHI–HW relationships are conditioned by scale, climate background, urban form, and metric choice; it assesses how observation and modelling advances have transformed the field; it synthesizes the latest evidence on health, comfort, and vulnerability; and it evaluates mitigation and adaptation strategies not only in terms of cooling performance but also in terms of distributional justice, implementation realism, and potential unintended consequences. The article is written for a broad scholarly readership spanning urban climatology, geography, environmental health, planning, architecture, and climate adaptation.

The central argument is that UHI–HW research is entering a second phase. The first phase established the existence, relevance, and heterogeneity of the interaction. The second phase, now underway, focuses on operationalization: how cities can diagnose compound heat, forecast it at actionable scales, and target interventions where they reduce the largest absolute and relative risks. In that sense, UHI–HW research is not only a climate science field. It is increasingly an infrastructure field, a public-health field, and a governance field (Casanueva et al., 2019; Santamouris, 2020; Broadbent et al., 2022; Cheval et al., 2023).

MATERIALS & METHODS

This review builds directly on the evidence structure presented in the supplied systematic review, which searched the Web of Science Core Collection using UHI and heat-wave terms, removed duplicates and irrelevant items, and retained 403 eligible studies covering 1991–2022 (Cheval et al., 2024). That earlier synthesis already demonstrated that the field had become highly interdisciplinary and increasingly reliant on mixed data streams, with in situ measurements appearing in 86% of reviewed studies, numerical simulations in 56%, and remote sensing in 30%, while tri-source integration remained relatively uncommon (Cheval et al., 2024). It also highlighted important thematic balances: most studies focused on observed climate rather than future climate, topic clusters were concentrated in characteristics and impacts, and research gaps remained especially visible in integrated forecasting, health-risk assessment, and implementation-oriented adaptation (Cheval et al., 2024).

The added value of the present review lies in how it re-synthesizes that baseline corpus together with the newer papers and abstracts contained in the supplied Scopus file. The additional studies enrich five dimensions of the earlier review.

First, they sharpen the field's understanding of localized synergy. He, Wang, Liu, and Ulpiani (2021) showed in Shanghai that UHI amplification depends on how heat waves are defined—by air temperature, wet-bulb globe temperature, or apparent temperature—and that moisture and wind can partially alleviate synergistic heat stress. Giannaros et al. (2023) demonstrated in Athens that extreme heat responsiveness varies not only across regions but within and between LCZs under the combined influence of relief, sea proximity, synoptic forcing, and urban form. Chen, Newman, et al. (2022) similarly used high-resolution modelling in Chicago to show that rural heat-wave amplification may exceed urban amplification in absolute terms, even as urban nighttime UHI remains pronounced. Together, these studies move the field beyond a binary debate about whether synergy exists.

Second, the recent literature deepens the observational turn. Chang et al. (2021) used GOES-R land surface temperature to resolve full diurnal cycles of surface UHI in Boston, showing midday maxima and nighttime minima that would be obscured in low-frequency polar-orbiting products. Chakraborty, Venter, Qian, and Lee (2022) used crowdsourced measurements from roughly 40,000 stations across Europe to reveal that lower urban humidity moderates outdoor heat stress and that surface temperature is a poor daytime proxy for intra-urban heat-index patterns. These studies collectively challenge long-standing assumptions that thermal remote sensing alone can adequately diagnose human heat exposure.

Third, the new corpus reveals a clear modelling upgrade. High-resolution urban canopy parameters now demonstrably improve heat-wave forecasts in WRF-based systems (Chen, Yu, et al., 2022), while comparisons across UCMs show that the structure of the urban representation can materially alter simulated diurnal UHI cycles and spatial patterns (Silva, Carvalho, Carvalho, & Rocha, 2021). These modelling advances are not purely technical. They determine whether forecasts and adaptation assessments are credible enough for policy use.

Fourth, the newer studies intensify the field's focus on equity, vulnerability, and behavioral response. Broadbent et al. (2022) introduced a targeted urban heat adaptation framing by showing that cool roofs strategically deployed in socio-demographically heat-sensitive areas can deliver more cooling where it is most needed. Chaston et al. (2022) showed that the mortality burden of heat waves in Sydney is substantially amplified by UHI and could be offset in part through tree cover. He, Zhao, et al. (2022) added individual-level behavioral evidence, showing that awareness, symptoms, and hospital-seeking behavior are uneven and city-specific. These insights push the literature from hazard mapping toward adaptation governance.

Fifth, the recent corpus broadens the climatic and regional scope of comparison. While Beijing, Shanghai, Paris, Athens, Berlin, and several North American cities remain anchor cases, the literature now includes more evidence from tropical coastal contexts, South Asia, Southeast Asia, and the Global South, though the imbalance in coverage persists (Chew et al., 2021; Estoque et al., 2020; Chandra et al., 2022; Dewan et al., 2021). This makes it possible to distinguish between general mechanisms and climate-specific pathways.

Conceptually, this article treats UHI–HW interaction as a compound hazard process involving at least four linked domains: physical amplification, exposure concentration, physiological translation, and adaptive mediation. Physical amplification concerns how the urban surface and canopy alter heat storage, sensible and latent heat fluxes, boundary-layer structure, ventilation, and radiative exchange under heat-wave conditions (Ao et al., 2019; He et al., 2020; Tewari et al., 2019). Exposure concentration concerns who is present, where, and under what built and social conditions, including density, housing quality, vegetation access, and nighttime thermal retention (Taylor et al., 2015; Wolf & McGregor, 2013; Chen, Ding, Yang, Hu, & Qi, 2018). Physiological translation concerns how those exposures become discomfort, illness, ambulance calls, hospitalization, or mortality (Graham et al., 2016; De Troeyer et al., 2020; Conti et al., 2005). Adaptive mediation concerns how urban form, infrastructure, behavior, institutions, warning systems, and public policy reduce or redistribute the resulting risk (Casanueva et al., 2019; Broadbent et al., 2022; Wang et al., 2022).

This framing helps explain why literature conclusions can appear contradictory while remaining scientifically consistent. A study may observe no significant amplification in average UHI intensity during a given heat wave and still find stronger human thermal stress because humidity, wind, or nighttime persistence changes the physiological burden (Chew et al., 2021; He, Wang, Liu, & Ulpiani, 2021). Another study may find that cool roofs lower air temperature but also alter breeze systems or humidity in ways that complicate comfort outcomes (Baik et al., 2022; Wang et al., 2022). The contemporary task is therefore not to seek a single universal relationship, but to identify the urban-climatic configurations under which different mechanisms dominate.

RESULT AND DISCUSSION

1. Research evolution and emerging thematic architecture.

The long-term evolution of UHI–HW research reveals a field that has become more synthetic, more policy-relevant, and more scale-aware. According to the supplied systematic review, publication counts rose almost exponentially after 2000, and approximately 63% of the sample treated UHI–HW as a main topic rather than a secondary concern (Cheval et al., 2024). Europe and Asia contributed the largest shares of studies, with Beijing, Paris, Athens, and New York repeatedly appearing as reference cities (Cheval et al., 2024). Yet the most important shift is not geographic; it is intellectual.

Earlier work often centered on proving the existence of UHI or documenting urban–rural temperature differences. More recent work increasingly treats compound heat as a city-system problem spanning meteorology, land use, health, infrastructure, and governance (Santamouris, 2020; Cheval et al., 2024). Cheval et al. (2024) identified six key research topics in the contemporary literature: urban patterns, risk and vulnerability, impacts, causes, decision-support systems, and associated complex themes. They also showed that the most common topic cluster in the broader period 1990–2021 was “characteristics of the HWs and/or UHI,” followed by health and mortality, and the influence of urban characteristics on UHI. This thematic profile reflects the field’s maturation from detection to explanation and application.

A useful way to update that architecture is to distinguish five current research frontiers.

The first frontier is conditional synergy. The question is no longer whether heat waves and urban heat islands interact, but under what conditions the interaction intensifies, stabilizes, or weakens. Observational studies in Shanghai and Beijing report amplification associated with reduced wind, altered humidity ratios, enhanced urban–rural contrast in evapotranspiration, and stronger nocturnal retention (Ao et al., 2019; An et al., 2020; He et al., 2020; He, Wang, Liu, & Ulpiani, 2021). Yet modelling work in tropical Singapore found no significant heat-wave amplification of UHI intensity, suggesting that the interaction can differ fundamentally between temperate and tropical settings where background heat, moisture, and land–atmosphere exchange regimes differ (Chew et al., 2021). This conditionality is one of the field’s defining insights.

The second frontier is metric sensitivity. Heat outcomes depend strongly on what is measured. Studies based on air temperature can produce different conclusions from those based on land surface temperature, wet-bulb globe temperature, apparent temperature, physiologically equivalent temperature, modified PET, or UTCI (He, Wang, Liu, & Ulpiani, 2021; Giannaros et al., 2023; Wang et al., 2022). Fenner, Holtmann, Krug, and Scherer (2019) showed that even heat-wave trends in Berlin and Potsdam vary materially with the choice of definition, and that inner-city regions appear more exposed when thresholds rely on minimum or mean temperature. Metric choice is therefore not a technical footnote; it shapes scientific inference and policy thresholds.

The third frontier is scale integration. UHI–HW literature increasingly spans the urban boundary layer, canopy layer, building scale, and neighborhood scale. Mesoscale modelling remains central, especially through WRF and COSMO-based configurations, but the operational agenda now increasingly requires downscaling to actionable microclimatic units such as blocks, streets, roofs, and LCZs (Cheval et al., 2024; Blocken, 2015; Biggart et al., 2021; Giannaros et al., 2023). The rise of LCZ-based work is especially important because it offers a common typological language linking urban form to thermal behavior.

The fourth frontier is social differentiation. Earlier work often treated the city as a thermal field. More recent studies treat it as a socially structured thermal field. Heat risk varies with age, income, housing, vegetation access, health status, and behavior; it also varies between daytime and nighttime, outdoors and indoors, and across city sectors (Wolf & McGregor, 2013; Graham et al., 2016; Buchin, Hoelscher, Meier, Nehls, & Ziegler, 2016; De Troeyer et al., 2020; He, Zhao, et al., 2022). This frontier has transformed the literature from urban climatology into urban heat-risk science.

The fifth frontier is implementation. Mitigation and adaptation strategies are now evaluated more rigorously, including their spatial equity, trade-offs, and climate-specific performance. The literature increasingly asks whether interventions should be uniform or targeted, whether they improve air temperature or only surface temperature, whether they perform differently by day and night, and whether they inadvertently worsen humidity, air quality, or ventilation (Broadbent et al., 2022; Wang et al., 2022; Baik et al., 2022; Chen et al., 2018; Zhang, Chen, Luo, & Wang, 2017).

These frontiers together imply that the field is moving from descriptive climatology toward urban heat intelligence. That transition is both scientific and institutional. It requires datasets, models, and policy frameworks that can bridge thermal process understanding and practical adaptation.

Table 1. Evolving research architecture in UHI–HW studies

Theme	Dominant questions	Typical evidence base	Main insights	Persistent limitations	Ref.
Conditional synergy	When do UHIs intensify during HWs?	In situ networks, flux observations, WRF simulations	Synergy is common but climate- and context-dependent; nighttime amplification is often stronger	Conflicting conclusions across climates and metric choices	Ao et al. (2019); An et al. (2020); He et al. (2020); Chew et al. (2021); He, Wang, Liu, & Ulpiani (2021)
Urban patterning	How do morphology, imperviousness, vegetation, and density shape compound heat?	Land-cover metrics, LCZs, urban fractions, regression, remote sensing	Urban form, imperviousness, and greenness strongly organize UHI/HW responses	Transferability between cities remains limited	Ward et al. (2016); Bassett et al. (2020); Dewan et al. (2021); Biggart et al. (2021); Giannaros et al. (2023)
Vulnerability and health	Who is most at risk and why?	Mortality data, ambulance calls, census indicators, risk indices, questionnaires	Exposure, sensitivity, and adaptive capacity are highly uneven within cities	Indoor exposure and behavioral response remain under-observed	Wolf & McGregor (2013); Graham et al. (2016); Buchin et al. (2016); De Troeyer et al. (2020); Chaston et al. (2022); He, Zhao, et al. (2022)
Observation and monitoring	How can compound heat be measured more accurately?	Weather stations, low-cost sensors, crowdsourcing, MODIS, Landsat, GOES-R, Sentinel, ERA5	Multi-source integration reveals strong diurnal, seasonal, and neighborhood heterogeneity	Surface temperature is often a weak proxy for daytime heat stress	Fick & Hijmans (2017); Hersbach et al. (2020); Chang et al. (2021); Chakraborty et

					al. (2022); García (2022)
Modelling and decision support	How can cities forecast and test interventions?	WRF/UCM, COSMO/TERRA_URB, SURFEX/TEB, ENVI-met, MUKLIMO_3, RayMan, InVEST	Urban parameterization, coupling, and high-resolution canopy data improve realism	Computational demands and validation constraints remain substantial	Blocken (2015); Garbero et al. (2021); Bosch et al. (2021); Chen, Yu, et al. (2022); Giannaros et al. (2023)
Adaptation and governance	Which interventions reduce heat most effectively and fairly?	Scenario modelling, vulnerability mapping, health-risk studies, warning-system reviews	Cool materials, greening, and targeted adaptation can reduce risk, but performance is context-specific	Many studies do not fully integrate equity, comfort, and co-effects	Casanueva et al. (2019); Tewari et al. (2019); Broadbent et al. (2022); Wang et al. (2022); Baik et al. (2022)

2. Physical mechanisms of compound urban warming.

The physics of compound urban warming are well established in broad outline but remain locally contingent in expression. At the most general level, UHIs emerge because urban surfaces and structures modify the surface energy balance, storage capacity, aerodynamic roughness, longwave exchange, and water availability relative to surrounding rural land. Heat waves, in turn, arise from large-scale meteorological conditions such as subsidence, blocking, clear skies, and warm-air advection. When the two overlap, urban and synoptic processes can reinforce one another through several pathways: stronger sensible heating, weaker evaporative cooling, altered humidity, enhanced storage and nocturnal release, reduced ventilation, or anthropogenic heat feedbacks (Li & Bou-Zeid, 2013; Ward et al., 2016; Santamouris, 2020).

A central finding of the recent literature is that urban–rural contrast in surface evapotranspiration is a major driver of daytime synergy. In Shanghai, Ao et al. (2019) showed that during heat waves latent heat flux declined slightly at the urban site but increased slightly at suburban reference sites, while sensible heat flux rose more strongly in the city. This shift in surface energy partitioning, together with increased anthropogenic heat, exacerbated urban heat island intensity. In Beijing, He et al. (2020) likewise concluded that daytime UHI enhancement during a heat-wave episode was primarily associated with increased urban–rural contrast in surface evapotranspiration, while nighttime amplification was more closely tied to anthropogenic heat and warm advection. These results align with a broader conceptual understanding that heat-wave conditions often dry rural and vegetated surfaces differently from impervious urban surfaces, modifying the relative balance between sensible and latent heat (Ao et al., 2019; He et al., 2020; Tewari et al., 2019).

Nighttime behavior remains especially important. Multiple studies report that UHI amplification during heat waves is often stronger at night than during the day, because the thermal storage accumulated in urban fabric is released under conditions of weak mixing, clear skies, and reduced cooling (An et al., 2020; He et al., 2020; Burger, Gubler, Heinimann, & Brönnimann, 2021). This matters disproportionately for human health because physiological recovery during the night is critical; hot nights extend exposure duration even when daytime maximum temperatures receive greater public attention (Founda et al., 2019; De Troeyer et al., 2020; Chaston et al., 2022). The supplied systematic review similarly notes that nighttime UHI intensification often becomes more pronounced during heat waves and that this prolongs risk through lower adaptive capacity after sunset (Cheval et al., 2024).

Humidity complicates this picture in ways that are now receiving more careful treatment. One important reason some cities exhibit strong thermal synergy while others do not is that physiological heat stress depends on both temperature and moisture. He, Wang, Liu, and Ulpiani (2021) showed that in Shanghai, the degree and timing of UHI amplification varied according to whether heat waves were defined by air temperature, wet-bulb globe temperature, or apparent temperature. Under apparent-temperature-defined events, nocturnal UHI amplification was especially visible. At the same time, their study found that air moisture and wind could alleviate synergistic heat exacerbation to the benefit of thermal comfort. At continental scale, Chakraborty et al. (2022) found that lower urban humidity moderates outdoor heat stress during the 2019 European heat wave and that urban–rural differences in heat index can be much weaker than differences in surface temperature would suggest. Together, these findings caution against equating hotter surfaces with greater human heat stress.

Wind and advection are equally central. Reduced regional wind speed is often associated with stronger UHI during heat waves because calm conditions suppress mixing and maintain stronger urban heat retention (Ao et al., 2019; Fedor & Hofierka, 2022). Yet the role of local breeze systems can be double-edged. Sea breezes, lake breezes, and urban breezes can either reduce or intensify local heat depending on timing, land–water thermal contrast, and urban morphology. Studies in Athens, Sydney, Shanghai, Seoul, and other coastal settings show that mitigation measures such as cool roofs or urban-surface changes can weaken local breezes by modifying land–sea thermal gradients, sometimes offsetting part of their cooling potential (Giannaros et al., 2023; Baik et al., 2022; Ao et al., 2019). This makes clear that the mechanistic basis of mitigation cannot be separated from mesoscale circulation.

Urban form mediates these processes through roughness, radiative trapping, sky-view factor, and the geometry of ventilation pathways. Dense canyons can trap longwave radiation and reduce nighttime cooling, while highly sealed and low-albedo surfaces elevate surface and near-surface temperature. But morphology is not reducible to density alone. The same tree intervention can cool one neighborhood while only weakly affecting another or even increasing daytime temperature if ventilation is impaired (Geletič, Lehnert, & Jurek, 2020). Giannaros et al. (2023) showed that even within nominally similar LCZ classes, significant inter- and intra-zone differences in thermal stress can arise because of relief, proximity to the sea, and background airflow. Morphology thus interacts with geography and synoptic conditions rather than acting as an isolated driver.

Anthropogenic heat remains an important but difficult-to-quantify component of compound urban warming. The literature has long recognized contributions from buildings, transport, industry, and air conditioning, and recent modelling confirms its relevance during extreme heat when cooling demand surges (He et al., 2020; Chen et al., 2018; Santamouris, 2020). One implication is that urban heat mitigation and energy systems must be considered jointly, especially in dense metropolitan areas where heat adaptation through cooling technologies can also increase anthropogenic heat emissions and electricity demand.

The most important synthesis point is therefore that UHI–HW interaction is not governed by a single master mechanism. It emerges from the balance between radiative forcing, heat storage, aerodynamic exchange, moisture availability, anthropogenic heat, and local or mesoscale advection. That is why the field increasingly emphasizes “controlling factors” rather than universal laws. It also explains why contradictory case-study outcomes are often not contradictions at all, but expressions of different climatic baselines and urban process regimes.

3. Observations, datasets, and the measurement problem.

The rapid expansion of UHI–HW literature is inseparable from a methodological transformation in urban heat observation. According to Cheval et al. (2024), in situ measurements remain the dominant data source in the field, followed by numerical simulations and remote sensing, while the combined use of all three remains relatively rare. That pattern is changing. The recent literature increasingly relies on observational pluralism, not because one dataset has become superior, but because each resolves a different part of compound heat.

In situ observations remain indispensable because air temperature, humidity, wind, and radiation are the variables most directly connected to human heat stress. The continuing relevance of weather-station records is evident in long-term trend analyses such as Fenner et al. (2019), who compared ten heat-wave definitions using records from Berlin and Potsdam over 1893–2017 and found substantial sensitivity in occurrence, duration, and trend estimates. Founda, Pierros, Katavoutas, and Keramitsoglou (2019) similarly assessed thermal-stress trends across European cities using updated historical climatic and bioclimatic indices, showing strong warming in summer in warm cities and rapid increases in heat-related discomfort in northern cities during the last decade. These studies illustrate the value of high-quality station data for long-term climatology and threshold definition.

Yet station data alone are insufficient for cities because official networks are sparse and often unrepresentative of urban heterogeneity. This has driven the rise of dense local sensor networks, low-cost devices, and crowdsourced weather observations. Burger et al. (2021) used 60 low-cost devices and land-use regression to model nighttime heat-wave patterns in Bern, showing that publicly accessible spatial predictors can meaningfully interpolate urban temperatures. The implications are practical: cities no longer need to rely exclusively on a handful of official stations to diagnose neighborhood-scale heat patterns. At still larger scale, Chakraborty et al. (2022) used crowdsourced data from approximately 600 urban clusters in Europe to show that daytime heat-index differences between cities and surroundings are often weak because humidity feedbacks offset temperature differences. This is one of the most consequential observational findings of the recent literature because it directly challenges the widespread practice of using surface temperature as a surrogate for heat stress.

Thermal remote sensing remains powerful, but its role has become more nuanced. MODIS and Landsat products were pivotal in the first generation of large-sample UHI–HW analyses, including Ward et al. (2016), who used improved-resolution MODIS data across 70 European cities to show that heat magnitude during heat waves depends not only on initial UHI size but also on regional climate and central urban green space. MODIS-based analyses have also remained valuable for long time series and day–night comparisons in Bangladesh and Romania (Dewan et al., 2021; Crețu, Ichim, & Sfîcă, 2020). Sentinel-based work has expanded the ability to analyze Andalusian cities and heat-wave-period SUHI with atmospheric co-variables such as radiation and wind (García, 2022).

The most important remote-sensing advance, however, is the move toward higher temporal resolution. Chang et al. (2021) demonstrated the value of GOES-R for resolving full diurnal cycles of SUHI in Boston, showing that urban-core maxima occur near noon and that nighttime SUHI can be weak or near-neutral depending on season and location. This matters because heat-wave management requires not just thermal snapshots but timing: midday surfaces, afternoon comfort, and nighttime relief all matter differently for risk. Geostationary systems therefore open a new observational frontier for operational urban heat intelligence.

At the same time, the literature increasingly warns against straightforward translation from land surface temperature to air temperature or physiological heat. Surface temperature remains invaluable for mapping thermal landscapes and identifying hot materials, but several studies now show that it can be a poor predictor of daytime human heat stress at intra-urban scale (Chakraborty et al., 2022). This does not make remote sensing less important; it makes interpretation more careful. Surface temperature is one layer of evidence, not the whole story.

Reanalysis and gridded climate products also play a growing supporting role. ERA5 is increasingly used to supply hourly, spatially continuous background fields for temperature, humidity, and wind, with major improvements over ERA-Interim in temporal frequency and horizontal resolution (Hersbach et al., 2020). Cheval et al. (2024) note that ERA5 has become a common driving or contextual dataset in UHI–HW research, particularly where direct urban observations are limited. WorldClim remains useful for climatological baselines and future heat-stress studies, especially when combined with geospatial urbanization analysis (Fick & Hijmans, 2017; Chandra et al., 2022). Still, the literature is clear that gridded products cannot substitute for urban-resolving measurements; they are most useful as context, forcing, or baseline rather than as direct representations of canopy-layer heat.

The measurement problem in UHI–HW research is therefore not merely about data scarcity. It is about variable mismatch, scale mismatch, and exposure mismatch. Surface temperature may be spatially rich but physiologically incomplete. Station networks may be accurate but spatially sparse. Reanalysis may be synoptically coherent but too coarse for neighborhoods. Crowdsourced observations may be dense but need quality control. The most robust studies increasingly address this problem through integration.

Table 2. Main data sources, variables, and analytical uses in contemporary UHI–HW research

Data source	**Main variables/metrics**	**Strengths**	**Typical applications**	**Main caveats**	**Ref.**
Official and local in situ networks	Air temperature, humidity, wind, radiation, thermal indices	Direct relevance to canopy-layer climate and health metrics	Trend detection, threshold definition, validation, exposure analysis	Sparse coverage and siting bias within cities	Fenner et al. (2019); Founda et al. (2019); An et al. (2020); He et al. (2020)
Low-cost sensors and citizen weather networks	Fine-scale air temperature and humidity	Dense spatial coverage and neighborhood diagnosis	Spatial interpolation, local heat mapping, exposure hotspot detection	Quality control and representativeness issues	Burger et al. (2021); Chakraborty et al. (2022)
Polar-orbiting	LST, SUHI,	Strong spatial	Surface	Limited overpass	Ward et

thermal satellites (MODIS, Landsat, Sentinel)	vegetation and built-up indices	detail and long archives	thermal patterns, urban–rural gradients, city comparisons	frequency and imperfect link to human heat stress	al. (2016); Dewan et al. (2021); García (2022)
Geostationary satellites (GOES-R)	High-frequency LST	Resolves diurnal cycle continuously	Diel SUHI dynamics, operational monitoring	Coarser spatial detail than some polar sensors	Chang et al. (2021)
Reanalysis and climate surfaces	Temperature, humidity, wind, precipitation, radiation	Spatially continuous baseline and forcing data	Downscaling, boundary conditions, climatological context	Urban signal remains generalized at coarse scales	Hersbach et al. (2020); Fick & Hijmans (2017)
Socioeconomic and demographic data	Population density, age, deprivation, housing, vulnerability proxies	Links hazard to exposure and sensitivity	Heat-vulnerability mapping, equity analysis, health-risk assessment	Temporal mismatch with thermal data is common	Wolf & McGregor (2013); Chen et al. (2018); Estoque et al. (2020); Broadbent et al. (2022)

4. Modelling across scales: from explanation to operational urban heat intelligence.

If observations tell us where and when cities are hot, models tell us why, what-if, and what next. The modelling literature reviewed by Cheval et al. (2024) shows a field still dominated by WRF-based mesoscale simulations but increasingly enriched by COSMO/TERRA_URB, SURFEX/TEB, UrbClim, MUKLIMO_3, ENVI-met, EnergyPlus, InVEST, i-Tree, and biometeorological tools such as RayMan. The central issue is no longer whether modelling is necessary—it is how much urban complexity must be represented to answer the question at hand.

WRF remains the workhorse because it can nest urban domains at kilometer to sub-kilometer resolution while coupling to urban canopy schemes. Studies of Beijing, Shanghai, Singapore, Chicago, Hangzhou, Seoul, Kansas City, New York, Phoenix, and the Yangtze River Delta all demonstrate its centrality in diagnosing interactions between heat waves, urban surfaces, mitigation scenarios, and local circulations (Ao et al., 2019; He et al., 2020; Chew et al., 2021; Chen, Newman, et al., 2022; Chen, Yu, et al., 2022; Baik et al., 2022; Jeong, Millstein, & Levinson, 2021; Tewari et al., 2019; Zhang et al., 2017). But recent work also makes clear that the realism of WRF outcomes is highly sensitive to urban canopy representation and the quality of urban canopy parameters.

This is one of the most significant methodological advances in the newer literature. Chen, Yu, et al. (2022) developed high-resolution urban canopy parameters for Hangzhou using vector-format building information and showed that they improved simulation of diurnal variations and spatial distributions of air temperature, humidity, and wind speed, particularly when used with the BEP model. Similarly, He et al. (2020) found that spatial variation in urban canopy parameters improved simulation of near-surface temperature patterns in Beijing. Silva et al. (2021) further showed in Lisbon that different UCM choices and even different UHI identification methods can materially change simulated intensities and spatial structures. These findings are crucial because they show that urban heat forecasts are only as good as the morphological realism encoded into the model.

Beyond WRF, the COSMO family has advanced through TERRA_URB and related schemes. Garbero et al. (2021) showed that TERRA_URB improves air-temperature forecasts and reproduces UHI effects more realistically than simplified land-surface representations across European cities with differing morphology. The significance of this is broader than model intercomparison. It supports the argument that urban representation must move from roughness-length adjustments toward explicit building–street energy and moisture exchanges.

Microscale and neighborhood models occupy a different but complementary niche. ENVI-met and MUKLIMO_3 are often used to test design-scale interventions, assess street-level comfort, or compare land-cover scenarios under heat-wave conditions (Ambrosini et al., 2014; Geletič et al., 2020; Mohajer, Ding, & Santamouris, 2022; Alvarez, Quesada-Ganuza, Briz, & Garmendia, 2021). These models are especially useful when planners need spatially explicit guidance for blocks, plazas, roofs, and vegetation schemes. Their limitations are equally clear: boundary conditions matter enormously, validation is often difficult, and transferability from one micro-setting to another can be limited. Still, for implementation-oriented work they are indispensable.

Urban cooling models such as InVEST occupy yet another niche by translating land use and land cover into spatial estimates of cooling capacity via tree shade, evapotranspiration, and albedo. Bosch et al. (2021) made a strong case that such models can provide interpretable, scenario-friendly representations of how urban heat emerges and how planning alternatives might change it. These tools are especially attractive for planning agencies because they are less computationally intensive than fully dynamical mesoscale models and can be calibrated with available monitoring data.

The modelling frontier is also increasingly biometeorological. Giannaros et al. (2023) coupled WRF with BEP/BEM and RayMan to assess modified PET across Athens LCZs during the 2021 heat wave. Wang et al. (2022) combined WRF/UCM with RayMan to evaluate the UTCI effects of cool and green roofs in Berlin. These studies matter because they shift the modelling target from urban air temperature alone to human thermal experience. That is a fundamental advance: cities do not adapt to temperature in the abstract; they adapt to heat stress as experienced by bodies, activities, and infrastructures.

Yet modelling also reveals trade-offs that simplistic mitigation narratives overlook. Cool roofs often reduce air temperature, especially during the day, but can weaken urban breezes or alter humidity and radiation balances in ways that complicate comfort outcomes (Baik et al., 2022; Wang et al., 2022). Green roofs can improve evapotranspiration and latent cooling but may be less effective than cool roofs at city scale for nighttime air-temperature reduction (Zhang et al., 2017; Wang et al., 2022). Some tree-planting scenarios reduce nighttime temperature while slightly increasing daytime temperature in compact midrise districts by suppressing ventilation (Geletič et al., 2020). The modelling literature is therefore most valuable when it evaluates interventions as system changes rather than isolated surface manipulations.

A final point concerns validation. High-resolution urban models are now sophisticated enough to produce persuasive maps and fine-scale patterns, but their credibility depends on equally sophisticated observational constraints. This is why multi-source validation—combining station data, low-cost sensors, LST products, and in some cases flux or vertical-profile measurements—has become increasingly important (An et al., 2020; Biggart et al., 2021; Giannaros et al., 2023). The next phase of urban heat modelling will likely depend less on inventing entirely new models than on strengthening the data–model loop.

Table 3. Modelling frameworks used to analyze UHI–HW interactions

Model framework	Typical scale	Major strengths	Common applications	Key limitations	Ref.
WRF with UCMs (SLUCM, BEP, BEP/BEM)	Mesoscale to neighborhood	Captures synoptic forcing and urban processes together; scenario testing	UHI–HW interaction, future climate, intervention assessment, forecasting	Sensitive to UCP quality, parameter choices, and validation density	He et al. (2020); Tewari et al. (2019); Chew et al. (2021); Chen, Yu, et al. (2022); Baik et al. (2022); Giannaros et al. (2023)
COSMO/TERRA_URB and related urban schemes	Mesoscale	Improved urban representation within operational regional models	Forecasting and evaluation across European cities	Still coarser than design-scale questions	Garbero et al. (2021)
SURFEX/TEB and UrbClim	City to regional	Strong for climate scenarios and urban land-use sensitivity	Future urban climate and adaptation scenario analysis	Less detailed for microscale comfort questions	Cugnon et al. (2019); Cheval et al. (2024)
ENVI-met and MUKLIMO_3	Microscale to neighborhood	Good for street- and block-scale design interventions	Thermal comfort, vegetation, materials, local adaptation	Strong boundary-condition sensitivity; limited transferability	Ambrosini et al. (2014); Geletič et al. (2020); Mohajer et al. (2022); Alvarez et al. (2021)
InVEST urban cooling model	Planning and scenario scale	Interpretable and relatively light computationally	Spatial planning, land-cover scenarios, policy support	Simplifies atmospheric dynamics	Bosch et al. (2021)
Biometeorological models (RayMan, UTCI workflows)	Human scale	Converts meteorological fields into physiological stress metrics	Thermal comfort and health-related analysis	Requires reliable meteorological forcing and assumptions about exposure	Giannaros et al. (2023); Wang et al. (2022)

5. Health, vulnerability, and the unequal geography of heat.

The most compelling reason to study UHI–HW interaction is not that cities are warmer than their surroundings. It is that heat risk is unevenly distributed and often magnified among those with the least capacity to avoid, buffer, or recover from exposure. The literature on health and vulnerability demonstrates this with increasing clarity.

Classic mortality evidence remains foundational. Conti et al. (2005) documented excess deaths during the 2003 Italian heat wave, especially among people aged 75 years and older, underscoring that cities are critical arenas of heat-related mortality. Hattis, Ogneva-Himmelberger, and Ratick (2012) assessed heat-related mortality in Massachusetts and found that elderly populations and African-American populations were associated with higher mortality anomalies. De Troeyer et al. (2020) showed that even nearby Belgian cities can have different heat-mortality thresholds and city-specific mortality responses above those thresholds, suggesting that local climate, air pollution, and urban structure all matter. These studies collectively show that the heat-health relationship is highly place-specific and that city-specific thresholds are more informative than one-size-fits-all warnings.

The spatialization of vulnerability has become one of the most important developments in the field. Wolf and McGregor (2013) developed a heat-wave vulnerability index for London using census proxies and showed spatial clustering of high vulnerability in central and eastern districts. Dong et al. (2014) assessed heat-health risk in Beijing by explicitly integrating hazard, vulnerability, and environmental factors, demonstrating that impervious-surface ratios were strongly correlated with risk. Chen et al. (2018) used multi-sensor remote sensing and socioeconomic data to assess heat-health risk across the Yangtze River Delta at 250 m resolution, showing that highly urbanized areas were major hotspots but that less-developed areas could also be high risk because of social vulnerability. Estoque et al. (2020) extended this risk-framing to 139 Philippine cities and showed that high hazard and exposure concentrated in Metro Manila while the highest vulnerabilities were often outside the capital region. The field has thus moved from asking where heat is high to asking where high heat coincides with high exposure and limited adaptive capacity.

Urban vegetation has emerged as a particularly important moderator of health outcomes. Graham et al. (2016) found that Toronto census tracts with less than 5% tree canopy cover had far more heat-related ambulance calls than tracts with greater canopy cover, suggesting that even marginal increases in canopy could deliver meaningful health benefits. Chaston et al. (2022) showed that in Sydney more than 90% of historical heat-wave days would not breach heat-wave thresholds in the absence of the UHI effect and argued that widespread tree planting could offset part of the future mortality burden under climate warming. Chen, Wang, Thatcher, Barnett, Kachenko, and Prince (2014) likewise estimated substantial mortality-rate reductions in Melbourne under more vegetated urban scenarios. These studies are important not only because they support greening, but because they connect greening to measurable health outcomes rather than generic cooling rhetoric.

Yet vulnerability cannot be reduced to vegetation access alone. Housing, age, indoor conditions, socioeconomic status, behavior, and service access all matter. Buchin et al. (2016) made this explicit by showing that measures that reduce outdoor air temperature do not necessarily reduce indoor hazards equally; building-level interventions and passive or active cooling can outperform classic UHI countermeasures for indoor risk reduction. Taylor et al. (2015) similarly emphasized that housing and age intersect with UHI to shape excess heat-related mortality in London. This indoor–outdoor distinction remains underdeveloped in the literature and is one of the clearest gaps in current urban heat science.

Recent behavioral evidence adds another layer. He, Zhao, et al. (2022) surveyed respondents in three Chinese cities and found that perceived urban heat severity, heat-risk knowledge, symptom profiles, and hospital-seeking behavior varied significantly by city and demography. Only a modest share of respondents indicated a strong willingness to seek hospital care, suggesting that official health statistics may under-represent heat burden and that public awareness remains uneven. This is important because adaptation effectiveness depends not only on urban design but on social cognition, communication, and institutional trust.

The literature increasingly emphasizes that vulnerability is temporally structured as well. Nighttime heat is often especially dangerous because it suppresses recovery. Founda et al. (2019) documented rising heat-related discomfort across European cities, while Chaston et al. (2022) and De Troeyer et al. (2020) linked persistent heat and UHI contributions to increased mortality burdens. Studies of tropical nights and nocturnal UHI therefore deserve greater prominence in future health risk frameworks.

Another key insight from the recent literature is that not all apparent heat metrics produce the same vulnerability geography. Since heat stress depends on temperature, humidity, wind, and radiation, the hottest neighborhoods by air temperature may not be identical to the highest-risk neighborhoods by UTCI, humidex, or heat index (He, Wang, Liu, & Ulpiani, 2021; Chakraborty et al., 2022; Wang et al., 2022). This has strong implications for equitable adaptation. Interventions designed around surface or air temperature alone may miss the neighborhoods where physiological heat burden is actually greatest.

The strongest conclusion from this body of work is that UHI–HW risk is a socially produced and physically mediated inequality. It is co-produced by land cover, urban form, housing, demographics, health status, institutional preparedness, and the temporal structure of exposure. Future research and policy that ignore this co-production will produce efficient-looking but inequitable adaptation.

6. Mitigation and adaptation: what works, where, and with what trade-offs?

The mitigation literature has grown rapidly, but its most mature conclusion is not that one intervention dominates. It is that intervention performance is context-sensitive and should be evaluated against multiple endpoints: air temperature, surface temperature, thermal comfort, mortality risk, ventilation, humidity, energy demand, and distributional equity.

Cool roofs remain one of the most widely studied and generally effective strategies. Fallmann, Emeis, and Suppan (2013) showed in Stuttgart that reflective properties had stronger impacts on near-surface temperature than increases in green areas or reductions in building density. Zhang et al. (2017) found in the Yangtze River Delta that cool roofs and green roofs both reduced skin and near-surface temperature, with comparable benefits under certain coverage/albedo combinations and measurable regional effects when implementation exceeded 50% of roofs. Baik et al. (2022) showed in Seoul that cool roofs lowered daytime 2-m temperature, wind speed, and boundary-layer height during the 2018 heat wave, though their cooling benefit weakened with increasing heat-wave intensity and could interact with sea-breeze dynamics. Broadbent et al. (2022) extended the cool-roof discussion by demonstrating that targeted deployment in socio-demographically heat-sensitive neighborhoods can deliver more cooling where it is most needed than uniform deployment. This is a major conceptual advance because it reframes cooling infrastructure as an equity instrument.

Green roofs and urban greening strategies remain central, though their performance varies with climate, irrigation, and scale. Zhang et al. (2017) found green roofs effective in the Yangtze River Delta, especially when coverage was extensive. Wang et al. (2022) showed in Berlin that both cool and green roofs reduce UTCI, but cool roofs outperform green roofs in reducing urban temperatures, especially at night. Tewari et al. (2019) found that irrigated green roofs could almost completely offset projected future heat-index amplification in Phoenix and partially in New York City, underscoring the importance of water availability. These findings suggest that greening is most powerful when well-maintained, appropriately irrigated, and understood as part of a broader surface-energy strategy rather than a symbolic embellishment.

Street trees and urban canopy expansion are more complex than their widespread popularity sometimes implies. Their benefits through shading and evapotranspiration are well documented (Graham et al., 2016; Chaston et al., 2022; Chen et al., 2014), but performance depends on species, arrangement, irrigation, and urban geometry. Geletič et al. (2020) found that increasing tree numbers by 30% in Prague and Brno often cooled nighttime conditions but could yield little or even adverse daytime effect in compact midrise neighborhoods. In Athens, shading trees produced clear reductions in surface temperature but weaker mean ambient-temperature reductions than cool/reflective roofs and roads under heat-wave conditions (Athens scenario study in supplied Scopus corpus). This does not reduce the value of trees; it means trees should be planned as microclimatic devices rather than generic green symbols.

Urban irrigation and blue–green infrastructure also deserve more attention. Jeong et al. (2021) evaluated cool roofs and urban irrigation in Kansas City, indicating that combined mitigation pathways can lower urban temperatures during both typical summers and strong heat waves. The broader review literature summarized by Cheval et al. (2024) likewise highlights water bodies and blue infrastructure as important moderators of urban heat, while also noting their slower nocturnal response because of thermal inertia. This is an important reminder that daytime and nighttime mitigation performance may diverge.

One of the clearest messages of the recent literature is that mitigation must be evaluated against human thermal comfort rather than air temperature alone. Wang et al. (2022) show that the combined effects of temperature, humidity, wind, and radiation determine UTCI outcomes, and that both cool and green roofs alter several of these variables simultaneously. Mohajer et al. (2022) similarly show in Sydney that combinations of high-albedo streets, pavements, rooftops, and greening can substantially reduce peak heat-wave temperatures and improve PMV-based thermal comfort, though large layouts may still remain hot. Giannaros et al. (2023) reinforce this by demonstrating how relief, sea proximity, and urban form interact to shape mPET responses in Athens. Adaptation therefore needs to move from thermal simplification to thermal physiology.

Trade-offs are equally important. Chen et al. (2018) found that increasing urban albedo in Beijing reduces UHI intensity but can worsen urban air quality under heat-wave conditions by altering boundary-layer dynamics and pollutant concentrations. Baik et al. (2022) show that cool roofs can weaken sea breezes. Zhang et al. (2017) show that large-scale roof interventions alter vertical temperature profiles and stability. These studies demonstrate that “cooling” is not a universally benign intervention; it is an atmospheric modification whose side effects must be considered.

Adaptation also includes governance, warning systems, and emergency response. Casanueva et al. (2019) reviewed 16 European heat-health warning systems and argued that trigger variables must be clearly linked to impacts and that pre-alert levels, long-term planning, communication, and education are critical. Cheval et al. (2024) similarly emphasize the need for urban heat emergency response plans and stronger integration of scientific evidence into long-term urban adaptation. This literature indicates that built-form mitigation and public-health preparedness should not be treated as separate sectors.

The strongest synthesis point is that adaptation should be multi-layered and targeted. High-albedo materials, roofs, greening, street trees, irrigation, ventilation corridors, warning systems, and social outreach are not substitutes for one another. They reduce different components of risk, on different timescales, for different populations. The most advanced studies increasingly recognize this and evaluate adaptation portfolios instead of isolated interventions.

Table 4. Adaptation and mitigation strategies for compound urban warming

Intervention	**Main cooling mechanism**	**Typical evidence/outcome**	**Major trade-offs or limits**	**Implementation implication**	**Ref.**
Cool roofs	Higher albedo, lower heat storage	Consistent reductions in air and surface temperature; strong daytime effects; can reduce UTCI	Can alter breeze systems; may affect humidity and air quality; benefits vary by heat-wave intensity	Strong option for dense built areas, especially when targeted to vulnerable districts	Fallmann et al. (2013); Zhang et al. (2017); Broadbent et al. (2022); Baik et al. (2022); Wang et al. (2022)
Green roofs	Evapotranspiration and added insulation	Lower skin and near-surface temperatures; can reduce UTCI	Requires water/maintenance; often weaker nighttime air-temperature benefit than cool roofs	Best combined with irrigation and building-scale adaptation plans	Zhang et al. (2017); Tewari et al. (2019); Wang et al. (2022)
Urban trees and canopy expansion	Shade and evapotranspiration	Lower ambulance calls and mortality risk; local comfort improvement	Effects depend on geometry, species, and ventilation; possible daytime adverse effects in compact forms	Should be spatially targeted and integrated with wind-path analysis	Graham et al. (2016); Chen et al. (2014); Geletič et al. (2020); Chaston et al. (2022)
Irrigation and blue–green infrastructure	Added moisture and evaporative cooling	Can reduce urban temperatures under hot conditions	Water demand and slower nocturnal response may limit performance	Promising where water availability and governance capacity exist	Jeong et al. (2021); Cheval et al. (2024)
LCZ- and neighborhood-specific design	Form-sensitive adaptation and ventilation optimization	Stronger local fit between urban type and intervention package	Requires detailed diagnostics and urban data	Essential for moving from city-average to place-based adaptation	Giannaros et al. (2023); Biggart et al. (2021); Bosch et al. (2021)
Heat-health warning systems and targeted response	Early warning, communication, preparedness	Can reduce impacts when linked to meaningful metrics and action plans	Often under-integrated with neighborhood-level urban heat patterns	Must be linked with local thresholds, outreach, and vulnerable-population mapping	Casanueva et al. (2019); Cheval et al. (2024)

7. Deep synthesis: toward a next-generation research agenda

The literature now contains enough evidence to move beyond descriptive synthesis and articulate a sharper research agenda. Six priorities stand out.

First, compound heat must be measured in human-relevant terms. The field still over-relies on air temperature and especially land surface temperature in contexts where physiological burden depends on humidity, wind, and radiation. Studies by He, Wang, Liu, and Ulpiani (2021), Chakraborty et al. (2022), and Wang et al. (2022) strongly suggest that future research should use multiple heat metrics by default rather than as occasional supplements. A city that appears thermally extreme in SUHI terms may not be the same city, district, or time window that is most extreme in heat-index or UTCI terms.

Second, urban heat science must strengthen the indoor–outdoor interface. The health literature repeatedly indicates that outdoor cooling does not automatically translate into safer indoor conditions (Buchin et al., 2016; Taylor et al., 2015). Yet a large share of urban populations, especially the elderly or mobility-limited, experience heat primarily indoors during dangerous periods. Research that couples neighborhood climate, building physics, and household vulnerability remains underdeveloped relative to its societal importance.

Third, the field needs better attribution of local drivers. Many studies identify correlations between heat and land cover, vegetation, density, or morphology, but fewer robustly partition the relative contributions of anthropogenic heat, heat storage, evapotranspiration deficit, and synoptic forcing across different climates. He et al. (2020), Ao et al. (2019), and Chen et al. (2018) show what is possible when models and observations are combined to attribute mechanisms more explicitly. This should become more standard.

Fourth, observational systems must become both denser and smarter. The rise of crowdsourced and low-cost networks is a major opportunity, but these systems need quality control, metadata standards, and linkage to health and planning applications. The combination of official stations, dense local sensors, crowdsourced data, geostationary satellites, and high-resolution urban morphology datasets could support urban heat intelligence platforms capable of real-time diagnosis and short-term forecasting. The underlying studies already exist; what is needed is system integration (Chang et al., 2021; Chakraborty et al., 2022; Chen, Yu, et al., 2022).

Fifth, equity must become a core performance criterion in mitigation studies. The most innovative recent work is not simply about cooling magnitude; it is about where cooling happens, for whom, and relative to what baseline inequality. Broadbent et al. (2022) point clearly in this direction. Future adaptation studies should routinely report distributional effects across vulnerable populations and neighborhoods rather than citywide averages alone.

Sixth, adaptation portfolios should be evaluated under future compound conditions, not only present climatology. Heat waves are projected to intensify, and some studies already show that future urban heat stress may rise faster in cities than in surrounding rural areas (Wouters et al., 2017; Tewari et al., 2019). It is therefore insufficient to test adaptation strategies only for present-day summertime averages. They must be stress-tested against compound extremes, nighttime persistence, infrastructure demand, and social vulnerability trajectories.

These priorities imply a broader conceptual shift. The field should move from “urban heat island mitigation” toward “compound urban warming governance.” The former often centers on thermal anomalies as physical targets. The latter recognizes that the ultimate policy objective is to reduce unequal heat burden under changing climate and urbanization. That requires coupling urban climate science with public health, housing, energy, water, and social policy.

This shift also clarifies how the apparent contradictions in the literature can be productively resolved. For example, studies that find no strong increase in average UHI intensity during heat waves in certain tropical contexts are not outliers to be dismissed; they are essential for understanding the climatic limits of temperate-derived assumptions (Chew et al., 2021). Likewise, studies showing that cool roofs can worsen certain air-quality outcomes or weaken breezes do not undermine mitigation; they refine it by showing which combinations of measures and settings are more robust (Chen et al., 2018; Baik et al., 2022). A mature field does not seek universal positive effects. It seeks conditional knowledge that can support better decisions.

A top-tier research agenda should therefore focus on three forms of integration: integration across variables, integration across scales, and integration across institutions. Variable integration means measuring temperature, humidity, wind, radiation, surface conditions, and social vulnerability together. Scale integration means linking synoptic forcing to neighborhood exposure and household response. Institutional integration means designing adaptation systems in which planners, meteorological agencies, public-health authorities, and community organizations operate from shared evidence.

CONCLUSION

The contemporary UHI–HW literature leaves little doubt that cities face a compound warming challenge. Yet it also shows that the interaction between urban heat islands and heat waves is neither uniform nor reducible to a single mechanism. In some cities, especially dense and temperate metropolitan environments, heat waves clearly intensify UHI effects through reduced wind, enhanced urban–rural evapotranspiration contrast, stronger sensible heating, and greater nocturnal retention (Ao et al., 2019; An et al., 2020; He et al., 2020). In others, especially tropical settings, average UHI amplification may be limited even when heat stress rises sharply for residents (Chew et al., 2021; He, Wang, Liu, & Ulpiani, 2021). This conditionality is not a weakness of the field; it is its most important insight.

The evidence base also shows that the science has become methodologically richer. In situ observations remain central, but they are now joined by crowdsourced sensor networks, high-frequency geostationary thermal data, remote sensing of urban surfaces, reanalysis products, LCZ frameworks, and increasingly realistic urban canopy parameterizations (Cheval et al., 2024; Chang et al., 2021; Chakraborty et al., 2022; Chen, Yu, et al., 2022). These advances have made it possible to resolve the timing, geography, and physiological relevance of urban heat with far greater precision than was possible even a decade ago.

Most importantly, the field now understands that compound urban warming is fundamentally unequal. Mortality, ambulance calls, hospitalization behavior, vulnerability indices, and exposure trajectories all show that heat burden is concentrated where thermal hazard intersects with social disadvantage, poor housing, low canopy cover, and weak adaptive capacity (Graham et al., 2016; De Troeyer et al., 2020; Estoque et al., 2020; Chaston et al., 2022; He, Zhao, et al., 2022). For that reason, adaptation cannot be judged by average cooling alone. It must be judged by whether it reduces unequal heat burden.

The mitigation literature offers grounds for cautious optimism. Cool roofs, green roofs, tree canopy, irrigation, blue–green infrastructure, and neighborhood-sensitive design can all reduce heat under many conditions. But no measure is universally optimal, and the best-performing portfolios are those that acknowledge trade-offs involving humidity, ventilation, air quality, maintenance, and social targeting (Tewari et al., 2019; Broadbent et al., 2022; Wang et al., 2022; Baik et al., 2022). Heat-health warning systems and emergency response plans further reinforce the need to integrate atmospheric metrics with urban and health realities (Casanueva et al., 2019; Cheval et al., 2024).

The next phase of research should therefore aim not merely to map hotter cities, but to build integrated urban heat intelligence systems. Such systems would combine dense observations, urban-resolving models, local climate zones, social vulnerability data, and impact-linked warning thresholds to support targeted, just, and operationally feasible adaptation. That is the standard toward which the field is now moving, and it is the standard cities will increasingly need as compound urban warming becomes a defining challenge of twenty-first-century urban life.

Declaration by Authors

Acknowledgement: None

Source of Funding: None

Conflict of Interest: No conflicts of interest declared.

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How to cite this article: Marcellino Christofel Mambu, Weny J.A. Musa, Marike Mahmud. Urban heat islands and heat waves as compound urban warming: mechanisms, observation, modelling, health risk, and equitable adaptation. *International Journal of Research and Review*. 2026; 13(4): 623-645. DOI: *https://doi.org/10.52403/ijrr.20260465*

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