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Reconceptualizing urban heat island: Beyond the urban-rural dichotomy

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ABSTRACT

Past decades have seen drastically increasing research effort and progress on the study of the phenomenon of urban heat island (UHI). Despite its simplicity, this convenient concept has promoted significant advances in scientific research and policy making processes in the urban environmental community. Nevertheless, the oversimplification and inadequacy of the urban-rural dichotomy, inherited in the UHI concept, is increasingly manifest today in the continuously urbanized world. In this study, we conduct a holistic and in-depth survey of the inadequacy of the urban-rural dichotomy intrinsic to the definition of UHI, from theoretical, technical, and practical perspectives. In addition, in the light of recent research advances, we urge to radically reconceptualize UHI by proposing a novel paradigm by treating the total urban environment as a complex dynamic system. The new framework broadens the frontier of conventional urban environmental study by utilizing advanced techniques of complex systems and data sciences, including complex network theory, machine learning techniques, causal inference, etc. The reconceptualization of UHI is also expected to foster decision making and urban planning, and to avoid the one-sidedness of the singular and often too exclusive aim of heat mitigation.

1. Introduction

The growth of civilization, from a historical perspective, proceeds by a recurrent rhythm of successful responses to continuous challenges (Toynbee, 1974), as a potentially infinite *élan vital* (Bergson, 1911). In the past decades, global climate changes emerge as an unprecedented critical challenge faced by all human societies, of which urbanization, with concomitant burgeoning anthropogenic activities, has been a primary driver (IPCC, 2014). "World history is city history", wrote Spengler, "In place of a world, there is *a city, a point*, in which the whole life of broad regions is collecting while the rest dries up" (Spengler, 2020). By the middle of 21st century, cities and towns are projected to accommodate 67% of the global population (UN, 2019). The concentration of population and anthropogenic activities in urban areas, on the bright side, positively promote the economic growth and business innovation, with urban residents having smaller *per capita* values of resource consumption, infrastructural need, and greenhouse gas (GHG) footprints (Bettencourt & West, 2011). Nevertheless, the global urbanization also imposes severe challenges to the built environment and the well-being of residents, including concentrated GHG emissions, reduced thermal comfort, and degraded air quality (Nazaroff, 2013; Wong et al., 2016; Baruti et al., 2019).

Behind the urban environmental challenges, excessive warming in cities plays a pivotal role in regulating the dynamics and interactions of diverse environmental measures, such as air pollution, GHG emission, ecosystem services, etc. The most prominent thermal phenomenon in cities is that urban cores are usually found warmer than their rural surroundings, known as the urban heat island (UHI) effect. The UHI effect has long been documented, dating back to as early as 1833 (Howard, 1833; Landsberg, 1981). But it was not until 1960s-1970s that the phenomenon received systematic research endeavor, from field observation, remote sensing, to theoretical studies (Hutcheon et al., 1967; Rao, 1972; Oke, 1967,1976). Among the earliest generation of researchers, the work of Timothy Oke, especially the one that formulated the energetic basis of UHI (Oke, 1982), has been ground-breaking with far-reaching impact till today. Built upon the pioneering work, last few decades have seen burgeoning interest and efforts, be it academic, policy-making, or practical, devoted to UHI studies, partly owing to the attractiveness of the idea of simple urban-rural dichotomy. Today, the volume of literature on the UHI study will deter even the most voracious readers or ambitious authors from conducting a comprehensive review.

The concept of UHI, capsulizing the dichotomy of artificial and natural environments, furnishes a great simplification in depicting the complexity of thermal environment along the urbanization gradient. More specifically, with simple instrumentation in early years, the UHI intensity was measured by the ambient (typically in the near-surface atmosphere, say, 2-m above the ground) temperature difference between town centers and their rural surroundings. This simple, and

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sometimes vaguely defined, urban-rural dichotomy has been *customarily* adopted up to date. The effect of this very simplicity has been double-edged: On the one hand, it has attracted tremendous research interest, promoted the search for sustainable solutions to mitigate the UHI effect. Whereas on the contrary, its inadequacy has also led to some most brutal misuse in academic research and/or one-sidedness in urban planning.

Unfortunately, this inadequacy of the urban-rural dichotomy, intrinsic to the definition of UHI, despite the fact that it has been widely recognized, has only received *patchy* refinements up to date, such as the distinction of subsurface, surface, boundary-layer UHI effects. In this study, unlike the previous ones, we conduct a more holistic and in-depth survey of the urban-rural dichotomy, from theoretical, technical, and practical perspectives, which is hitherto lacking. Furthermore, we urge for a radical reconceptualization of UHI studies by proposing a novel system-based paradigm in which all analogous urban environments are treated as a "connected" complex dynamic systems, instead of isolated built terrains. Studying urban areas as complex systems, first, enables us to break the shackle of conventional urban environmental studies that are largely process- and locality-based at the conceptual basis. Secondly, the new paradigm will be open the frontier of urban environmental study, UHI included, to admit brand new techniques, especially advanced theories in complex systems and data sciences, including but not limited to, e.g. complex network theory, machine learning techniques, causal inference, genetic optimization, etc. Some pioneering studies, as proof-of-concept along these lines, have already produced very promising results, as detailed in Section 3. Lastly, this newly proposed UHI reconceptualization will foster decision-making and urban planning for future development of more sustainable cities by, e.g. absorbing the conventional concept of UHI into broader-context urban sustainability measures such as the general liveability (Antognelli & Vizzari, 2016) and/or the compound environment impact (Wang, 2021).

2. Process-based UHI studies

2.1. The technical inadequacy of the UHI definition

The essence of the UHI concept, down to the root, is nothing but to quantify the degree of warming of an urban environment in contrast to its rural surroundings. The first inadequacy inherited in this concept is the definition of the UHI intensity, customarily expressed as the urban-rural temperature difference, $\Delta T_{\mathrm{u-r}}$, where the measure of standard diagnostic temperature T is lacking. As a scientific subject, the notion that urban areas are warmer than their rural surroundings needs to be more precisely quantified, viz., warming measured by what temperature and by how many degrees. When Luke Howard documented that "Night is 3.70 $^{\mathrm{o}}$[F] warmer and day 0.34 $^{\mathrm{o}}$[F] cooler in the city [of London] than in the country" (Howard, 1833), the degrees referred to the average thermometer readings at screen height (1–2 m above ground). As the measurement technique advances, soon the indicators of UHI intensity started to diversify. In the atmospheric layer lying above complex built terrains, the difference between canopy and boundary layer UHI was recognized as early as researchers attempted to correlate the UHI intensity to city sizes (Oke, 1973,1976). Meanwhile, the thermal remote sensing technique offered an attractive alternative to weather stations in observing land surface (skin) temperatures over vast areas (Voogt & Oke, 2003), leading to the measure of surface urban heat island (SUHI) at large scales (Yuan & Bauer, 2007; Tian et al., 2021). Likewise, there is nothing preventing the signal of $\Delta T_{\mathrm{u-r}}$ from "penetrating" into the soil, engendering the so-called subsurface urban heat island (Sub-UHI) (Ferguson & Woodbury, 2007; Menberg et al., 2013).

The remedy to this difficulty is seemingly a technical one as to account for the continuous variation of $\Delta T_{\mathrm{u-r}}$. We will need to expand the measure of UHI to include a vertical profile of temperature differences in the soil-atmosphere continuum (see Fig. 1), instead of using the conventional UHI intensity at a single screen height. This can be done with the help of, e.g., satellite-derived temperature data (Zhan et al., 2014; Hu & Brunsell, 2015). As shown in Huang et al. (2020), the UHI intensity determined with respect to fixed ground location, across the soil-atmosphere continuum, varies with elevation. The pattern $\Delta T_{\mathrm{u-r}}$ is somehow manifest in that it vanishes with elevation in the atmospheric boundary layer, apparently due to atmospheric mixing, while the subsurface UHI intensities all converge to a constant value at a depth of 2–4 m beneath the ground level.

But the problem is further complicated than it appears if we consider the source areas (footprints) contributing to the measurement of both urban and rural temperatures. In the urban boundary layer, footprints of $\Delta T_{\mathrm{u-r}}$ increase with elevation, and shift toward the upstream of prevailing wind (Schmid, 2002; Wang et al., 2018). Depending on the direction of urban-rural breezes, rural surroundings can contribute significantly to the source area of urban temperatures especially at high elevation, and vice versa. Thus a vertical profile of $\Delta T_{\mathrm{u-r}}$ may not faithfully reflect the actual contrast of urban-rural thermal environment unless supplemented with their corresponding source areas; the latter is by no means a trivial task. In addition, it has been found that different measures of the UHI effect in the urban canopy, surface, and subsurface do not bear a simple linear correlation. Instead, their relationship

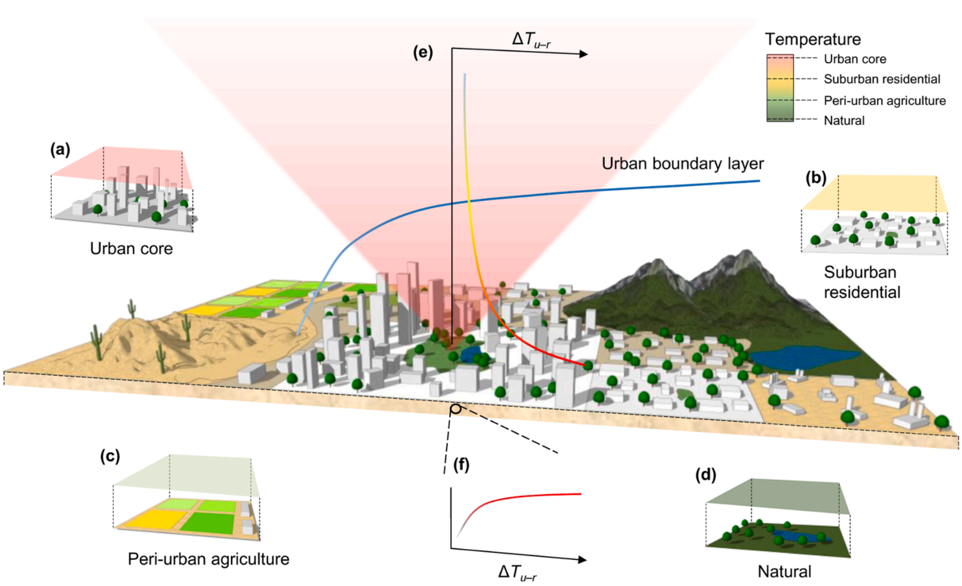


Fig. 1. Spatial heterogeneity of the thermal environment in an urban area. A horizontal transition from (a) urban core, (b) suburban residential, (c) peri-urban agriculture, to (d) natural terrains, along the urban-rural gradient; each with distinct thermal characteristics. The vertical distribution of UHI intensity $\Delta T_{\mathrm{u-r}}$ reaches the maximum at the ground surface. (e) $\Delta T_{\mathrm{u-r}}$ decreases with elevation in urban canopy and boundary layers; while its source areas in conic pink shade, increase with elevation. (f) The subsurface urban heat island reduces with the depth below the ground surface.

involves complex interactions in the solid-surface-atmosphere continuum, which manifests as the nonlinear hysteresis effect (Sun et al., 2013; Wang 2014; Song et al., 2017).

2.2. Temperature contrast at the urban-rural gradient

The urban-rural dichotomy is further challenged along the horizontal urbanization gradient, where the transition from artificial to natural environment is rather gradual. Researchers have realized the lack of clear demarcation of "urban" and "rural" landscapes (Fig. 1e). Even within the built environment, the description of urban areas can be blurred by changes of urban morphology (Wong et al., 2016; Li et al., 2021); such changes can be resulted from urban intensification, redevelopment, or even counter-urbanization (Simon, 2011). Attempts have been made to construct new classification systems, the most popular one being the local climate zones (LCZs) (Stewart & Oke, 2012). LCZs are defined by identifying local characteristics of landscape clusters, recognizing the co-existence of a spectrum of landscape characteristics along the urban-rural gradient ranging from heavily built to pristine landscape. This new classification system provides a convenient way of refining the urban-rural dichotomy by replacing the conventional UHI intensity with a set of temperature differences among LCZs, each lumped over a different scale of impervious to vegetated mosaics.

Despite the technical convenience of LCZ definition, more fundamental difficulties remain outstanding in the refined (and diversified) measure of UHI, particularly with respect to urban vegetation. In LCZs, for example, a cluster of trees has the same properties regardless of if it presents in an urban park or in a natural forest. On the contrary, mounting evidence has shown that same plant species experience different growth rate in urban environment in comparison to their rural counterparts (Gregg et al., 2003; Zhao et al., 2016). In particular, it has been observed that along the urban-rural gradient, the densely built environment often furnishes favorable conditions for plant growth and physiological functions, by providing: (1) warmer ambient temperatures (thanks to UHI) that allow urban plants to maintain a higher photosynthesis rate and a longer growing period (Lahr et al, 2018; Zhao et al, 2016; Meng et al, 2020), (2) regular maintenance practices, such as irrigation and fertilization, that relieve much of environmental stresses for plant growth (Luketich et al., 2019), and (3) the elevated carbon dioxide (CO_2) level, promoting the carbon assimilation rate (Wang et al., 2017, 2019). Should these effects be considered in the definition of UHI, we need necessarily differentiate the physiology and phenology of urban vegetation from its rural counterparts; a daunting task not yet hitherto confronted by researchers and policy makers.

Furthermore, with the recent advances in urban thermal environment studies, with UHI intensities quantified from subsurface soils to atmospheric boundary layers, it becomes increasingly clear that the patterns of UHI in many cities, be they adjacent or remotely located, exhibits striking similarity, or "analogs". A pioneering work has been conducted to map climate analogs for North American cities, involving matching the expected future climate of a city to another of potentially similar urban thermal environment (Fitzpatrick & Dunn, 2019). Hence instead of measuring and cataloging the UHI effect in each and every city individually wherever such endeavor is affordable, it is more fruitful to group and study the phenomenon comparatively in a set of various urban environments, which necessities the study of UHI in a novel paradigm at the system-based, rather than process-based, level. Here, by process-based, we mean the approaches that focus on unraveling the physics of flow and dynamics of exchange of heat, momentum, and scalars in local urban canopies, but ignore the links of these physics to like built environment at large, regional to global, scales as an *all-connected* complex system.

3. Toward a novel system-based paradigm of UHI studies

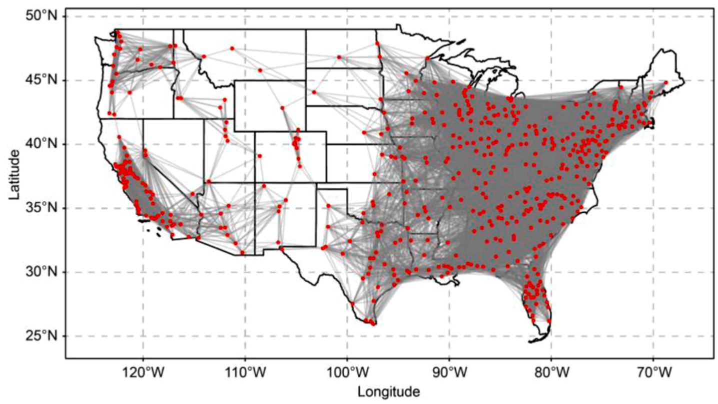
The dynamic process of UHI and its mitigation strategies, in a broader sense, run on top of substrates of heterogeneous topology that entails complex interplays of human activities and the built environment. For example, one popular UHI mitigation strategy, viz. the use of cool roofs in local cities, is found to be capable of generating adverse warming in the regional hydroclimate (Millstein & Menon, 2011). Some prominent features of structural heterogeneity, e.g. clustering and hierarchical organization, hold the key to the unravel the fundamental governing urban dynamics (Wang et al., 2020a). More importantly, the complex topology of Earth's system dynamics, urban environment included, entails connectivities over long spatial distance, known as *teleconnections* (Tsonis et al., 2008; Zhou et al., 2015; Boers et al., 2019). In particular, Seto et al. (2012) identified the land surface teleconnection in urban areas and its implications to sustainable urban development.

The effect of structural heterogeneity on the long-term evolution of the thermal environment in cities, however, cannot be adequately addressed using process-based methods alone (Bozza et al., 2015; Apreda et al., 2019). Instead, the fundamental understanding the phenomenon of UHI requires more holistic representation of the interplays between human and natural systems across different scales (Masson, 2006; Grimmond, 2007). Moreover, complex urban system dynamics, such as the existence of potential feedback mechanisms (Hall, 2004; Orlowsky & Seneviratne, 2010), nonlinearity of urban heat responses to atmospheric forcings (Good et al., 2015; Song & Wang, 2016), etc., present formidable challenges to both scientific and policy communities. Therefore, there is an imperative need of developing novel system-based toolkits, by integrating instrumental observation, modeling techniques, and urban planning (Groffman et al., 2017; Bai et al., 2018; Apreda et al., 2019), to improve the capacity of detecting and predicting emergent patterns and trends of future evolution of UHI of cities worldwide, as well as to foster decision-making processes for sustainable mitigation strategies.

3.1. Complex urban heat network

To investigate the topology of urban areas with spatial teleconnection, on top of which the longterm temporal trend of UHI emerges and evolves, one can resort to the complex network theory (see, e.g. Boccaletti et al., 2014; Kivela et al., 2014; Newman, 2018 for comprehensive reviews of network theory). A network, mathematically represented as a *graph*, is defined as a collection of nodes joined by edges (links). While the characteristics of UHI effect in cities can be highly localized and site-specific, their influence on the regional hydroclimate via land-atmospheric interactions can be well synergized to generate extreme heat events under external forcings, such as a prevailing synoptic-scale blocking high pressure system (Charney and Devore, 1979; Jiang et al., 2019). This connectedness, manifest as climatic analogs (Fitzpatrick & Dunn, 2019) among various cities that can be spatially distant from one another, can be essentially described as complex climate networks. Pioneering applications of network theory to Earth's climate systems were first explored in the last decade (Tsonis and Roebber, 2004; Tsonis et al., 2006; Donges et al., 2009). Some prominent topological features of complex networks, e.g. *teleconnection*, are found to hold the key to unraveling the spatiotemporal characteristics and regional/global patterns of hydroclimate (Tsonis et al., 2008; Runge et al., 2015; Zhou et al., 2015; Boers et al., 2019).

More recently, the application of complex network analysis has been extended to urban climate system to study the connection and hierarchical topological structure of thermal environment in the contiguous United States (CONUS) (Wang and Wang, 2020; Wang et al., 2020). Fig. 2 shows an urban heat network in CONUS constructed based on the time series of $T_{\max}$ anomalies as the nodal attribute from 1948 to 2016 (69 years), obtained from the TopoWx database (Oyler et al., 2015). The results are informative: for instance, the large value of clustering coefficient ($C = 0.744$) indicates that urban areas within the same climate regions are highly connected. It is also clear from the graphic mapping in



Network parameters	Value
Mean degree c	75.31
Total # of edges m	18113
Degree density ρ	0.157
Clustering coefficient C	0.744
Modularity Q	0.37
Average pathlength L	4.07

Fig. 2. The CONUS urban heat network with the geographic distribution of 481 U.S. cities (red nodes) and their connectivity (grey lines), and structural parameters of the network.

Fig. 2 that all CONUS cities are grouped into different regional clusters (e.g. Southwest, Northwest, and the east continent as a giant one), with mega-cities as most connected hubs. In addition, the CONUS urban network has a strong modular (assortative) organization among cities predominated by their geographic and climatic conditions (with high modularity Q) (Newman & Girvan, 2004) and a manifest small-worldness (large clustering with small pathlength L) (Watts & Strogatz, 1998).

It is noteworthy that the modular structure found in real-world networks is commonly the result of a growth (dynamic) process, or emergent as adaptive mechanism generated by, e.g. temporal synchronization (Barahona & Pecora, 2002; Arenas et al., 2008). Synchronization in complex networks holds a key to understand many *critical* phenomena in complex dynamic systems (Dorogovtsev et al., 2008; Munoz, 2018). In particular, network synchronization is potentially responsible for generating climatic extremes such as extreme heatwaves (Wang et al., 2021c), interacting synergistically with the UHI effect in local cities (Jiang et al., 2019). For example, it has been found that many mega heatwaves (the European heatwave in 2003, Russian in 2010, and U.S. in 2011, to name a few) would be highly unlikely or not as devastating, without resonant amplification (viz., periodic synchronization) of planetary waves and thermal extremes (Petoukhov et al., 2013). The system-based network analysis in urban environment will therefore enable us to unravel how the dynamic evolution of UHI can be regulated by the substrate of topological heterogeneity, as well as to disentangle the climatology of UHI from meteorological-scale heat extremes susceptible to network synchronizability (Benedetti-Cecchi, 2021; Mondal & Mishra 2021).

3.2. Critical transition of UHI

In the context of global climate changes, it is natural to ask the question if the dynamics of UHI will evolve towards a critical, and often catastrophic, state of transition. And if yes, by what drivers (i.e. tipping elements)? Critical transitions (aka *tipping points*), in this context, are defined as the conditions at which the complex urban system will *run away* from the current equilibrium states and evolve towards emerging dynamic attractors (Lenton, 2008; Strogatz, 2018). The presence of tipping elements covers a wide spatio-temporal spectrum ranging from, e.g. local land-atmosphere interactions to global scale circulations, which in turn leads to emergent patterns of hydroclimatic extremes such as mega heatwaves (Wang et al., 2020b) or switch between patterns of the thermohaline circulation (Ghil & Lucarini, 2020). Despite the almost ubiquitous presence of tipping elements in climate systems (Held & Kleinen, 2004; Lenton et al., 2008), nevertheless, the underlying mechanisms remain notoriously obscure (Lenton & Williams, 2013).

More specifically, global urbanization has the potential to induce irreversible changes in multiscale components in the Earth system, e.g. heat and moisture cycles between land surface vegetation and the overlying atmospheric boundary layer, and pushes their evolution passing from normal modes into critical states of operation. Last decades have seen drastically increasing anthropogenic influence that contributed to the underlying tipping elements that involve complex interplays between human-induced landuse dynamics and the natural environment through positive feedback loops. One such positive feedback mechanism associate with UHI is well known: the elevated ambient temperature in cities increases the use of air conditioners in hot seasons, which in turn engenders more waste heat and is held accountable for further exacerbating thermal conditions in cities. Fig. 3 shows one plausible pathway that leads to tipping of urban environment via positive land-atmosphere feedback in heat and moisture transport. Due to the nonlinear nature of hydroclimatic responses to long-term forcing (Good et al., 2015), positive feedback loops in land–atmosphere interactions near critical transitions (Miralles et al., 2014) are likely to induce bifurcation across equilibria between wet/cool and dry/hot patterns, activating worsened UHI and/or water scarcity the new norm in the urban environment system.

The underlying mechanisms of catastrophic temperature changes near critical transitions involve complex interplay between anthropogenic stressors and natural environments (Song & Wang, 2015) associated with the emergence of phase transition, self-organized criticality, and changes in ecosystem patterns (Rietkerk et al., 2004; Kriegler et al.,

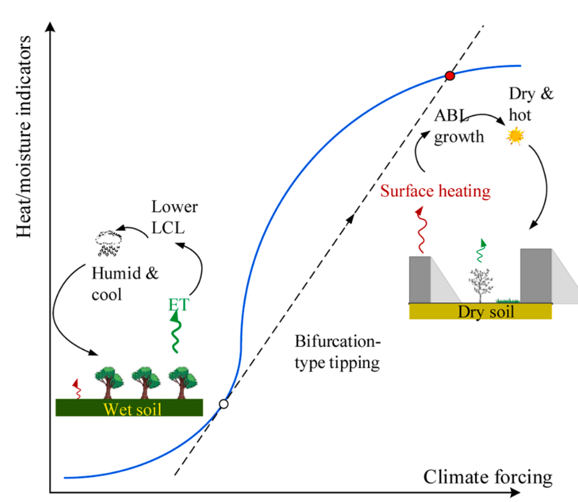


Fig. 3. Possible pathways of positive feedback loops via pavement-heat and vegetation-moisture interactions that can potentially lead to bifurcation-type tipping in regional urban hydroclimate systems.

2009; Lenton, 2011). On the other hand, system bifurcations, with potential catastrophic consequence, usually carry generic *early-warning* signals (Scheffer et al., 2009). One noticeable feature is the critical slowing down with reduced rate of recovery from perturbation, presaging a shift in stability regime in the dynamic system that can be statistically captured as changes in autocorrelation or standard deviation of temporal variation (Dakos et al., 2008; van Nes & Scheffer, 2007).

Recently, early-warning signals have been detected in urban thermal environment associated with extreme heat using conventional statistical measures (Wang et al., 2020b). It is anticipated that such signals will also exist in the urban network topology (detailed in Section 3.1) that presages the critical transitions in future trend of UHI evolution. For complex climate systems involving big dataset, deep learning algorithm has been lately applied to detect its tipping and early warning (Bury et al., 2021). The finding of early-warning signals, be it statistical or topological, will be practically useful, given the fact that implementing large-scale countermeasures of UHI often lags behind of the occurrence of critical transition. Early-warning signals in dynamic UHI evolution will help to inform us to: (1) anticipate critical transition, (2) develop rapid assessment capacity, and (3) encourage positive tipping. One particular strategy that can be used is urban greening as promote reverse (positive) tipping from hot/dry patches back to the old attractor of cool/humid conditions (see Fig. 3). It is anticipated if the feedback mechanisms are strong and the nonlinearity in temperature response high, a partial greening with adequate irrigation will suffice to promote reverse tipping.

In summary, the longterm evolution of UHI in the future, from local to global scale, entails considerable risks of critical transitions in the face of emergent climate changes, with potentially catastrophic consequence. The understanding of possible feedback and bifurcation mechanisms, identification of early-warning signals (at both process- and system-based levels), and the seeking of solutions to reverse the trend of tipping, albeit seems far-reaching at the moment, are all integral parts for establishing a systematic framework (detailed in Section 3.3 below), to completely reconceptualize the conventional paradigm of UHI studies. In addition, finding critical transitions in the complex urban system will shed new lights on seeking sustainable solutions to future development of cities at the global scale, as a connected network.

3.3. *A system-based framework for future UHI studies*

In the light of promising advances in recent urban heat studies, by treating cities as complex systems clustered as regional networks of analogous thermal environment, in this section, we venture to propose a novel system-based framework to further future UHI studies. The proposed framework is illustrated in Fig. 4, using the urban areas in CONUS as an example grouped by their regional geographic and climate conditions (Fig. 4a). The CONUS thermal network can therefore be constructed using the extensive and appropriate UHI measures as discussed in Section 2.2. To understand if the thermal conditions in these cities represents truly climatic analogs (Fitzpatrick & Dunn, 2019), or if their teleconnections are genuine, it is of crucial importance to check the causality between a pair of regions (or a pair of cities, depending on the resolution of interest). Causality inferences can help to determine spurious links (especially teleconnections across regions) between a pair of cities with apparently similar UHI evolution (e.g. Boston and Miami, see Fitzpatrick & Dunn, 2019) that are caused by strong coupling due to dominant low frequency climate variability such as El Niño–Southern Oscillation (ENSO) (Ghil & Lucarini, 2020) (Fig. 4b). The detection of causal inference also helps us in identifying potential tipping elements and their early-warning signals prior to critical transitions via characteristic system slowing down (Figs. 4c, detailed in Section 3.2) or, if left unattended, catastrophic tipping via bifurcation of the dynamic climate system (Fig. 4d).

Some practically useful causality inference algorithms that can be used for the complex Earth system, systematic UHI studies in specific, have been developed in the past decade including:

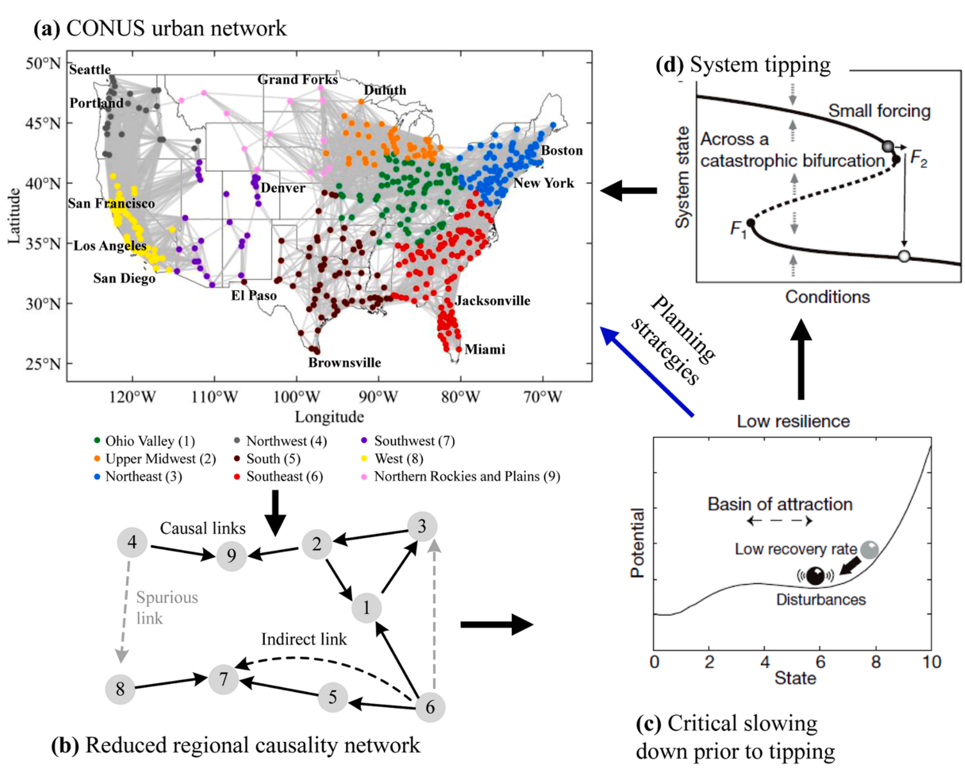


Fig. 4. Schematic representation of a systematic framework for UHI study in CONUS with 9 regional climate zones: (a) urban network construction of all CONUS cities, (b) reduced network of causality among the 9 climate regions, (c) detection of early-warning signals to critical transitions using characteristic system slowing down, and (d) potential dynamic bifurcation that leads to tipping of the complex climate system.

(i) The convergent cross mapping (CCM) method (Sugihara et al., 2012). This method explicitly addresses system non-separability variables and is most suitable for complex systems with weak to moderately coupled variables (e.g. temperature and precipitation in hydroclimate). In particular, CCM is capable of disentangling interactions among variables subject to common external forcing that give rise to spurious links without true causality relation (c.f. Fig. 4b). This is especially useful for identifying the genuine causality in UHI networks under, e.g. mega heatwaves, where most cities are under the influence of prevailing synoptic-scale blocking high pressure system (Charney & Devore, 1979; Perkins, 2015).

(ii) The recently developed multivariate causal method PCMCI (Runge et al., 2019a,b). The PCMCI method has been developed specifically for Earth system sciences to detect causality among atmospheric gateways in climate networks. This algorithm tests the causal influence between two processes, e.g. meteorological heat extremes and climatological UHI, given observed time series data. More specifically, it will help to address key questions such as "how do a high subtropical high-pressure system in Florida remotely influence synergistic UHI and heatwave interactions in Arizona via long-range causal network connection?"

4. Implications to urban planning and policy making

On the process level, the conventional UHI serves as an actionable handle for practitioners and policy makers to get hold of quickly, such as in designing heat mitigation and adaptation strategies. It is noteworthy that the UHI effect *per se* is not always a negative phenomenon that needs to be "mitigated". In some circumstances, the UHI effect can be beneficial; examples include that it can compensate the heating penalty by improving building energy efficiency for the built environment in cold seasons or climate zones (Zinzi & Agnoli, 2012; Virk et al., 2015; He et al., 2020; Berardi et al., 2020), or promoting the growth of urban vegetation (Gregg et al., 2003; Zhao et al., 2016).

Nevertheless, the conceptual simplicity of UHI is evocative of an overwhelmingly negative impression of "urban heat" and, not on rare occasions, leads to one-sided focus in urban planning. Examples include white-washing building roofs with highly reflective materials (aka "cool roofs") (Akbari et al., 2012). The use of engineering materials with high reflectivity (albedo) has lately been extended to building walls and ground pavements (e.g., roads, car parks, and pedestrian walkways), and credited in green building and construction codes (Wang et al., 2021a,b). The purpose is rather singular as to reduce the urban temperature by reflecting radiation into the atmosphere. More recently, the advocates of high-albedo materials have pushed the concept to the extreme by introducing the "super-cool" materials (Santamouris & Yun, 2020). For instance, a super-cool rooftop with surface albedo greater than 0.96 is even capable of maintaining its surface temperature below the ambient air temperature throughout the year in all climates (Baniassadi et al., 2019).

In contrast, mounting evidence shows that excusive urban planning objectives, such as UHI mitigation by reflective pavements, often leads to severe compromise of other environmental qualities (e.g., carbon emissions). Such one-sidedness in urban planning strategies, largely promoted by the obsession of UHI mitigation, has practically gained upper hand in policies of some local municipalities. However, besides the cooling effect of reflective materials, their use also leads to many unintended physical consequences in the real world (Yang et al., 2015), including heating penalty (Berardi et al., 2020), increasing of air pollution, especially the level of particulate matters (PM) (Epstein et al., 2017; Zhang et al., 2019), and human health risks (Rossi et al., 2018), to name a few. It is therefore of utmost importance that urban planner and practitioners should bear in mind the potential trade-offs or unintended consequence of this kind of single-minded design, and more sustainable urban planning strategies should account for the interactions of diverse urban system dynamics, instead of trying to minimize UHI while degrading other critical indicators of urban environmental quality (Wang, 2021).

Unlike the cool materials, urban greenery, when carefully planned and implemented, is capable of harvesting co-benefit of cooling, reduction of GHG (carbon in particular) emission, and improvement of air quality as well as human health. But again the key here is not to over-emphasize the objective of UHI mitigation alone. This caveat, unfortunately, has been put behind all too easily, when we shop around for sustainable urban strategies but can hardly escape the attraction by (or even obsession to) the price tag of "heat mitigation". Thus in reality, it is found that poor planning, implementation, and maintenance practices of urban greenery sometimes lead to degraded air quality (e.g., see Vos et al., 2013; Churkina et al., 2017; Hewitt et al., 2020) or detrimental health impact (Ren et al., 2017).

It might be unfair to charge these omissions fully to the simplicity of UHI concept. Nevertheless, is the impression of urban-rural dichotomy, stamped on the subconscious thinking of researchers, urban planners, and policy makers alike, still largely responsible for treating urban *heat* as the original sin to be atoned for via *mitigation* strategies? This single-mindedness in urban planning severely hampers the integration of the measure of UHI into the context of more holistic framework of urban liveability inclusive of issues such as air pollution, energy-water nexus, and degradation of ecosystem services (Howells et al., 2013; Antognelli & Vizzari, 2016).

Nevertheless, we are fully aware that the incorporation of the new paradigm of UHI study to the existing policy-making framework will be challenging, as it involves radical transitions in the current system where policy and technology are often developed in isolation (Degirmenci et al., 2021). For example, the effect of path dependencies and lock-ins on the governance and transition of urban planning and decision-making processes needs to be carefully studied (Yang et al., 2016; Hein & Schubert, 2020). In particular, it was found that urban policy makers must take a strategic and integrated approach to lock into more sustainable future development (Ürge-Vorsatz et al. 2018), as well-intended mitigation/adaptation strategies are often confounding each other, such as in the cases of waste incineration (Corvellec et al., 2013), building block growth (Reyna & Chester, 2015), or carbon lock-in (Seto et al., 2016).

Here we propose a possible, and by no means exclusive, pathway to carry out the adaptation to the new framework in a stagewise manner. Firstly, it should be endeavored to standardize, or at least to reach consensus of, the measurement of UHI intensity by considering the thermal heterogeneity and footprints in the built environment (c.f. Fig. 1). Secondly, the new framework should take into account of the complex dynamics and interactions of human-natural environments, a prominent example being the uniqueness and evolution of urban vegetation dynamics in comparison to their natural counterparts. With the prior steps accomplished, we can then proceed to the novel system-based framework, as proposed in Section 3.3 (c.f. Fig. 4), that runs on the realistic and heterogenous topology of networks of urban environments. The new system-based paradigm, in the place of the conventional UHI concept, will have some major advantage in the development more holistic urban decision-making processes by: (1) the embedment of thermal condition in more holistic urban environmental indicators (e.g. liveability), (2) putting planners of local cities into broader contexts informed by the development of decision-making processes historically and spatially (e.g. by climate analogues from other cities), and (3) avoiding one-sidedness of urban planning in segregated departments, e.g. exclusive heat mitigation strategies such as cool or super-cool pavements without considering their unintended consequence.

5. Concluding remarks

To recapitulate, in this study, we discussed the intrinsic inadequacy associated with the concept of UHI, in the hope that this extremely useful measure of urban thermal environment will continue to evolve to serve as the handle for sustainable urban planning and policy making. To break free from the shackle of urban-rural dichotomy, UHI needs to be re-conceptualized as to:

(i) Admit more standardized measure of diagnostic temperatures reflecting the continuous transition of thermal environment along the urbanization gradient, vertically and horizontally. One plausible way is illustrated in Fig. 1 by defining a vertical profile of urban-rural temperature difference while the horizontal source areas of temperature measurements at different elevation should be clearly described.
(ii) Differentiate ecosystem dynamics and services in different environments. This means that the definition of UHI needs to embrace the complexity of human and environmental factors contributing to the scale variability in urban thermal conditions and microclimate in general; such variability includes, e.g. changes of the urban to rural gradient in different locations and urban fabric characteristics. In addition, full awareness and consideration need to be taken with respect to the longterm evolution of the dynamics of inorganic (e.g. morphology) and organic (e.g. vegetation phenology) elements in the built environment.
(iii) Adapt to new urban system science and open to integrate the compound environmental impact in broader context. One promising candidate for system-based framework of urban environmental studies is the construction of urban environment networks, together with the analysis and characterization of their topological structure (e.g. teleconnections). Furthermore, the study of UHI in the complex network setting can readily make use of most recent advances in system sciences such as causal inferences or tipping of the Earth system: Breaking through in these frontiers will shedding new lights in urban system dynamics. More specifically, on the system-based urban networks, the conventional UHI measurement and its mitigation strategies can be incorporated into more holistic and compound measures of urban sustainability. Such measures include, but are not limited to, thermal comfort, air and water quality, human health, ecosystem services, and community resilience.

Towards this end, we need to synergize research advances, management practices, and policy-making processes. Together, all stakeholders need to look critically on the continuous evolution in urban airsheds, watersheds, soils, ecosystems, and anthroposphere as integrated systems in the context of global environmental changes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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