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Role of City Texture in Urban Heat Islands at Nighttime

J. M. Sobstyl,[1] T. Emig,[2,3] M. J. Abdolhosseini Qomi,[4] F.-J. Ulm,[1,2] and R. J.-M. Pellenq[1,2,5,*]

[1]*Concrete Sustainability Hub, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

[2]*CNRS/MIT/AMU Joint Laboratory "MultiScale Materials Science for Energy and Environment", UMI ⟨MSE⟩[2], MIT Energy Initiative, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

[3]*Laboratoire de Physique Theorique et Modeles Statistiques, CNRS UMR 8626, Universite Paris-Saclay, 91405 Orsay cedex, France*

[4]*Advanced Infrastructure Materials for Sustainability Laboratory (AIMS Lab), Department of Civil and Environmental Engineering, Henry Samueli School of Engineering, E4130 Engineering Gateway, University of California, Irvine, Irvine, California 92697, USA*

[5]*Centre Interdisciplinaire de Nanosciences de Marseille, CINaM, CNRS/Aix-Marseille Université, Campus de Luminy, 13288 Marseille Cedex 9, France*

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An urban heat island (UHI) is a climate phenomenon that results in an increased air temperature in cities when compared to their rural surroundings. In this Letter, the dependence of an UHI on urban geometry is studied. Multiyear urban-rural temperature differences and building footprints data combined with a heat radiation scaling model are used to demonstrate for more than 50 cities worldwide that city texture—measured by a building distribution function and the sky view factor—explains city-to-city variations in nocturnal UHIs. Our results show a strong correlation between nocturnal UHIs and the city texture.

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In the century of growing urbanization with 55% of people worldwide living in cities [1], there is an urgent need for establishing quantitative means for controlling urban climate [2]. One of the most substantial local climate effects [3], which has a profound impact on health [4,5] and energy consumption [6,7], is the urban heat island (UHI). While it is well known that the release of solar irradiance heat at night is the inducement of intensified temperatures in cities [8], detailed quantitative descriptions of correlations with city texture parameters are mostly limited to single street canyons [9]. Modifications in material properties [10] or geometries of infrastructure [11,12] lead to changes in physical processes at Earth's surface, which contributes to notable climate effects, such as the UHI. These processes reveal geographical and periodic (i.e., hourly, daily, seasonal) influences on the UHI [13,14]. In recent years, the UHI has been studied extensively [15] and its dominating factors have been found to include ventilation and surface materials [16], and indoor temperatures [17]. For day-time UHIs, detailed periodic hourly variations have been found to be related to changes in convection efficiency in the lower atmosphere between different climate zones [18]. At nighttime, however, the UHI is dominated by two factors: (i) the ability of materials to store solar radiation during the day, and (ii) the rate at which this energy is released at night [8]. Although additional energy may come in the form of anthropogenic heat [19], due to reduced congestion at night, it is reasonable to assume its significance to be negligible [9,20].

While all these factors have been known for several decades, studies that offer quantitative understanding of the impact that city texture has on the nighttime UHI, ΔT_{u-r}, are limited by single street canyon domains [9,20]. Therefore, they are insufficient to quantitatively capture the relationship between UHIs and city texture [9]. To study the impact of city texture on UHIs, we analyze hourly night-time peaks of ΔT_{u-r}s for twenty-two U.S. urban air temperature time series (group *A* cities [21]) for a period of multiple years—a time domain, which is large enough to provide us with statistically sufficient sample, but not too large to be influenced by global warming effects. The hourly temperature data unveil large fluctuations due to changing weather conditions that superimpose UHI. However, Fourier transformed temperature series depict distinct maximal peaks for the periods of 24 h [Fig. 1(a), [24]]. These peaks, when added to time-averaged temperatures, constitute a reliable measure of nocturnal UHIs. It is imperative to emphasize that the goal of this work is to measure and model to what extent city texture alone can describe variations among ΔT_{u-r} for different cities (all other important factors influencing nocturnal UHIs are captured by a phenomenological parameter γ, which is explained in the later part of this Letter). By observing discrepancies between measured data and our model predictions, we are able to study the role of city texture in UHIs at night, and estimate the significance of other parameters that influence the UHI.

In order to extract geometrical patterns in cities—herein defined by the set of building footprints (most of which are residential properties) within a three-mile radius around urban weather stations [see Fig. 2(a)]—we employ a radial

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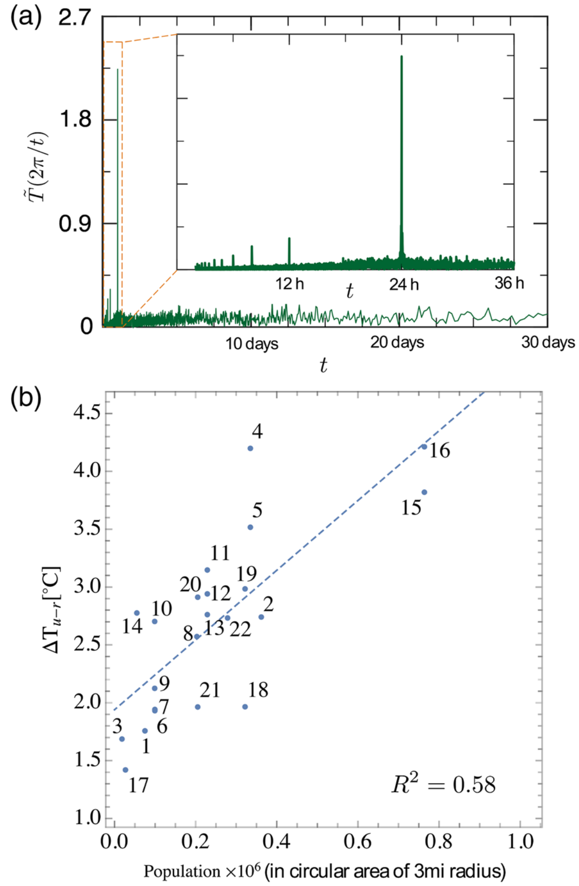

FIG. 1. Night-time UHI intensity from Fourier analysis of temperature time series and population influences. (a) Fourier transformed temperature time series for Boston, MA. (b) Relationship between ΔT_{u-r}s and the population within a 3-mile radius from urban weather stations.

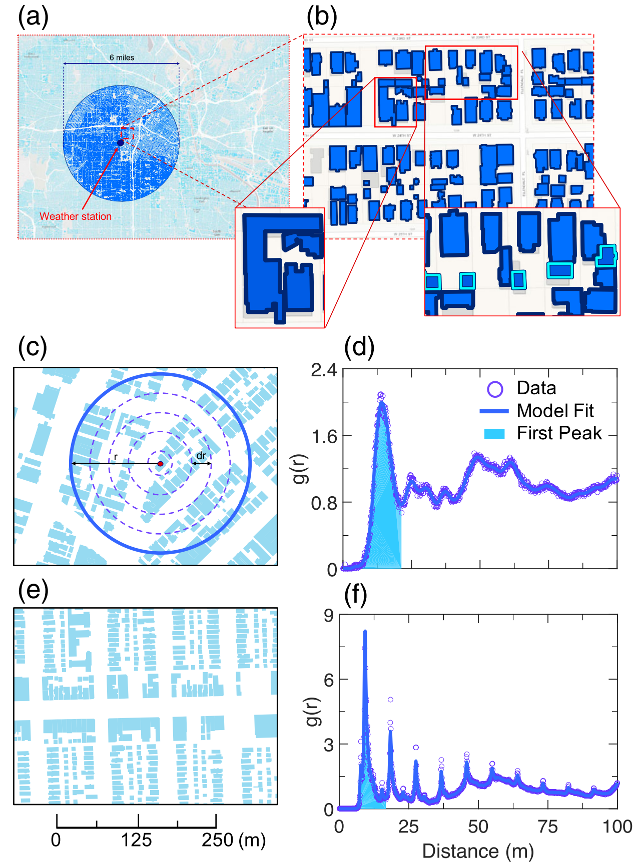

FIG. 2. Radial distribution function $g(r)$ for city texture that depicts visualization of data editing, analysis, and results. (a) Buildings within a 3-mile radius of an urban weather station are extracted. (b) Any buildings that share a wall are merged and any unoccupied buildings (i.e., garages) are removed from the sample of buildings transformed into a set of single points using buildings' 2D center of mass. (c) City texture of Los Angeles, CA showing a comparable absence of order of buildings caused by dispersed streets captured by (d) the smooth and outspread peaks in $g(r)$, which generally are characteristic properties of liquids. (e) City texture of Chicago, IL showing order of buildings and periodicity reflected in (f) the sharp and narrow peaks of $g(r)$, characteristics that are known to be the hallmark of highly ordered and stable crystalline materials.

distribution function $g(r)$, which traditionally has been used to investigate the atomic-scale structure of condensed matter. In the context of buildings, $g(r)$ is the probability of finding a building at distance r from the reference building relative to the average. Peaks in $g(r)$ appear when the local density of buildings deviates from the average density of a system. These peaks can be studied to extract information about sizes of building clusters using a function's minima. The distance at which $g(r)$ reaches its first minimum is defined as the local cluster size R. Such a defined cluster size is critical in deriving city texture parameters, namely, the number of local neighbors, average distance between them, local density, and angular distortion between buildings, which is captured with the local Mermin order parameter [25].

Early UHI studies have established empirically a scaling of UHI for thirty-one cities (group B cities located in North America, Europe, and Australia) with population [26]—a common hypothesis for the nocturnal UHI [18]. While our obtained values for ΔT_{u-r} [see Fig. 1(b), [27]] are indeed correlated with the population [coefficient of determination $R^2 = 0.53$, Fig. 1(b)], we find that with the urban geometry encoded in $g(r)$, the correlation is more evident and it matches the robust linear scaling that has been observed between urban geometry for group B cities and the open sky view factor ψ_s [$R^2 = 0.88$, Fig. 4(a)] [20].

A relationship of this kind is consistent with the notion of reduced efficiency at which street canyons release heat at night [28]. However, our detailed analysis of building footprints supports a more complex dependence of UHIs on city texture. More specifically, utilizing $g(r)$ to quantify city texture, we find that cities have distinct textures that resemble structures of crystals, or liquids, with local Mermin order parameters ranging between 0.5–0.9 [see inset in Fig. 3(b), [27]], where the lower bound indicates a moderate disorder and the upper bound a high angular order of buildings within the local cluster of size R [25]. Although, an average nonlocal quantity "urban porosity" is known in this context, we restrict our analysis to the local city texture parameters derived using $g(r)$. We observe that the local spatial order varies from liquidlike [Los Angeles, CA, Figs. 2(c), 2(d)] to almost a perfect crystal [Chicago, IL, Figs. 2(e), 2(f)]. We discover that the position of the first local minimum of $g(r)$, R [Figs. 2(d), 2(f), [27,29]] is related to the distance at which the first local maximum of $g(r)$ occurs through the mean relation $R = 1.5d$, where d is the average distance between buildings' centers of mass. When compared to the ratio of $\Delta T_{u-r}/R^2$ we find that for

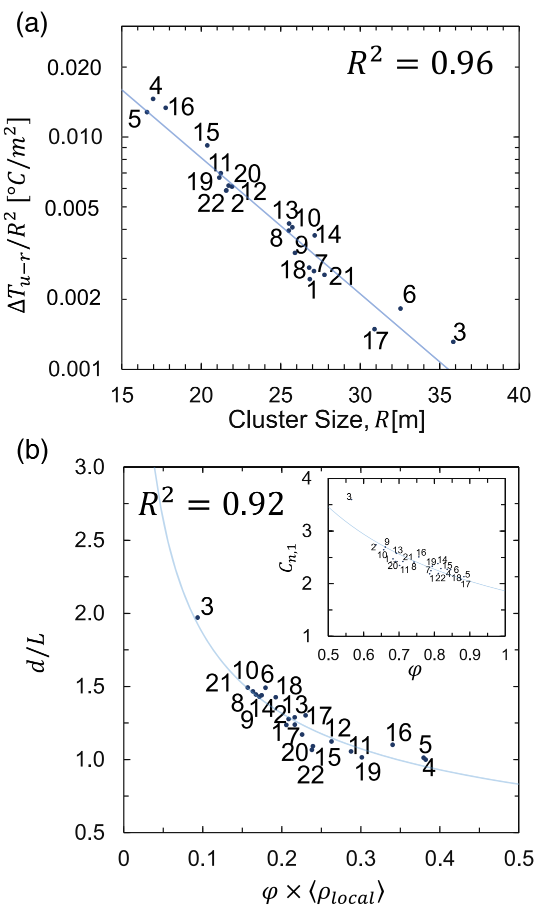

FIG. 3. City texture parameters [25] for group A cities. (a) Relationship between ΔT_{u-r} and the cluster size R. Measured and model-predicted relationship of city texture, obtained from the upper limit of the integral of the first peak of $g(r)$, shows a strong negative correlation captured with a power law. (b) Power-law correlation of the form $y = a \times x^b$, where $a = 0.59$ and $b = -0.5$, between the ratio of average distance between buildings d (obtained using $R = 1.5d$) and building size L, and the product of the local Mermin order parameter, φ, and local density $\langle \rho_{\text{local}} \rangle$. The inset shows an inverse relationship of the form $y = 1.8/x$ between the number of local neighboring buildings $C_{n,1}$ and φ.

group A cities this cluster size scales according to a power law [Fig. 3(a)]. To reconcile this type of scaling with previously established correlations between UHIs and the sky view factor, we utilize a simple heat radiation model. The main assumption of this model is that at nighttime, only long wavelength infrared (IR) radiation emitted from urban surfaces contributes to the UHI [30]. Of course, the surface temperature at night is also partially influenced by the absorption of short wavelength radiation during the day. However, this day-time absorption is also influenced by the city texture [15]. In order to demonstrate that a simple scaling theory accounts for UHI variations with city texture measured by $g(r)$, we separate nongeometric contributions from ΔT_{u-r}. To do that, we assume that flat urban surfaces have an average temperature $T_{\text{u,flat}}$, which is different from the corresponding temperature of rural surfaces, T_r. This is due to increased sensible heat storage, decreased evapotranspiration, moisture, and increased absorption of ultraviolet (UV) radiation in the daytime [31]. The cumulative effect of the urban-rural difference between the latter processes is summarized by a phenomenological factor γ with $T_{\text{u,flat}} = \gamma T_r$ for flat surfaces. For a quantitative description of the reduced nocturnal heat release from urban areas (due to their increased "roughness"), we use an effective temperature approach T_{eff}, which is frequently used to estimate surface temperature of a body when the emissivity is unknown [22]. T_{eff} is defined as the temperature of a perfect blackbody that radiates the same power P as the actual body according to the Stefan-Boltzmann law, $P = \sigma A T_{\text{eff}}^4$, where A is the surface area of the body and σ the Stefan-Boltzmann constant [32]. By analogy, we can apply this concept to cities. Since the wavelength of IR radiation is much shorter than all relevant urban length scales, diffraction effects can be neglected and an increase in surface area attributed to buildings (when compared to rural areas) determines T_{eff}. Assuming buildings of size L, and mean height $\bar{h}$, separated by an average distance d (obtained using the relationship $R = 1.5d$), our model [32] predicts that

$$\Delta T_{u-r} = T_r \left[\gamma \left(1 + \frac{4L\bar{h}}{(L+d)^2}\right)^{\frac{1}{4}} - 1 \right]. \qquad (1)$$

This prediction can be examined with field data in different ways, which is important since the availability of geometric data for most cities is either incomplete (i.e., building heights are missing), or only sky view factors are available. For the data set A, there is no information on building heights, but there are detailed data of building footprints. Therefore, for each city we are able to compute d and L [27]. We compare these values to our theoretical model by minimizing (with respect to T_r, γ, and $\bar{h}$) the squared deviations between the data for T_{u-r} of all twenty-two cities and the corresponding predictions from Eq. (1) with obtained values for d and L. It is worth noting that while we chose to express Eq. (1) in terms of d and L, our model could be reformulated using the local Mermin order parameter, local density, and the number of neighboring buildings—city texture parameters correlated to d and L [see Fig. 3(b)]. We find a convincing agreement yielding a coefficient of determination, $R^2 = 0.77$ [see Fig. 4(b)] for the following parameters: $T_r = 20.5\,°\mathrm{C}$, $\gamma = 1.0$, and $\bar{h} = 9.5$ m. Since analyzed urban areas are mainly residential, we conclude that the result for mean building height $\bar{h}$ is reasonable. However, we have estimated correction factors for the mean buildings' heights that would yield an ideal agreement with our model. The relationship suggests that corrections of only $\pm 30\%$ of $\bar{h}$ would be needed for a perfect agreement with Eq. (1). Information on building heights would allow us to estimate the volume of the built environment and, consequently, the thermal mass which could account for these corrections. Knowing the mean height $\bar{h}$, building size L, and distances R and d for all group A cities, Eq. (1) yields a function $\Delta T_{u-r}/R^2$ that can be compared to the measured relation between ΔT_{u-r} and the cluster size R [see Fig. 3(a)]. Using T_r as the sole fitting parameter, we find a convincing agreement with $R^2 = 0.96$ for $T_r = 24.4\,°\mathrm{C}$, which is consistent with the solar irradiance values [32].

Further credibility of our model is obtained by its application to the previously collected data of group B cities [33], providing insight into ΔT_{u-r} dependence on building height. We express the ratio $\bar{h}/d$ in terms of the sky view, ψ_s, assuming a canyon geometry [20], which leads to $\bar{h}/d = \frac{1}{2}\tan[\arccos(\psi_s)]$. Our model then predicts that

$$\Delta T_{u-r}(\psi_s) = T_r\left[\gamma\left(1 + \frac{2\frac{L}{d}\tan[\arccos(\psi_s)]}{(1+\frac{L}{d})^2}\right)^{\frac{1}{4}} - 1\right], \quad (2)$$

where T_r, γ, and L/d are determined from field data. Contrary to the empirical linear relation between ΔT_{u-r} and ψ_s, Eq. (2), our model provides an expression that is derived from the fundamental principles of heat radiation. Comparison to measured field data results in fitting parameters $T_r = 40.4\,°\mathrm{C}$, $\gamma = 1.024$, and $L/d = 1.0$ [see Fig. 4(a)], which yield a coefficient of determination of $R^2 = 0.88$, similar to what has been observed for a linear relation [33]. Our analysis thus suggests that city texture plays an important role in determining its response to heat radiation phenomena and points to urban design parameters that can be regulated to mitigate UHIs in planning and retrofitting of cities [6,34,35]. In a broader context, our work suggests that tools and methods from statistical physics at the right scale can provide means to quantitatively address the response of cities to climate. Our results complement previous studies on factors influencing day-time UHIs [18]. Observation that the causes of day- and night-time UHIs are fundamentally different corroborates that ΔT_{u-r}s at daytime and nighttime are uncorrelated [36]. According to our findings, the increase of the radiating surface area of cities is the main contributor to nocturnal UHI. While large scale changes to already existing urban textures appear unrealistic, efforts of UHI mitigation in the development of future urban structures should aim at minimizing the enveloping surfaces of urban structures. The resulting reduction in the release of stored heat during nighttime is expected to have a positive impact on energy consumption and health [4].

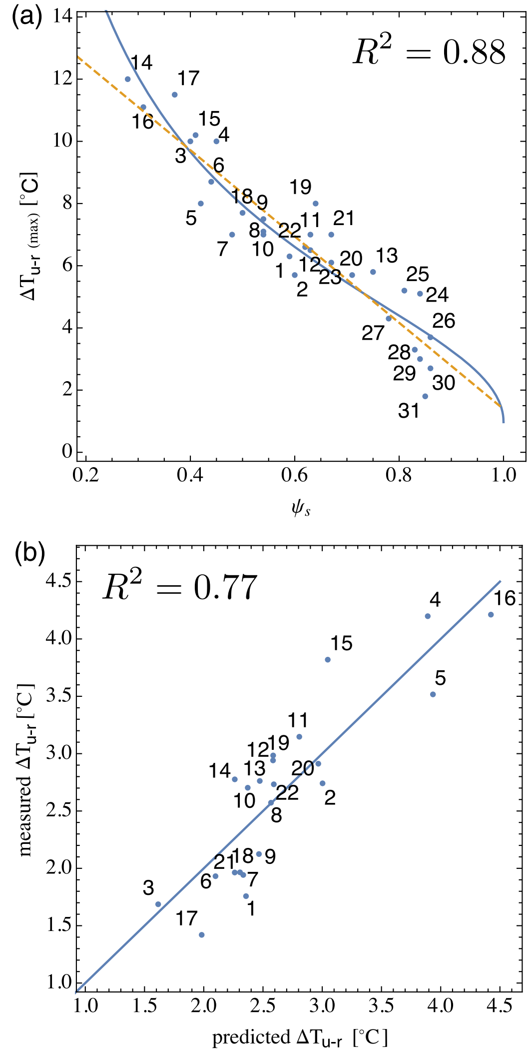

FIG. 4. Relationship between measured and model-predicted ΔT_{u-r}. (a) Maximal ΔT of group B cities as a function of the sky view factor ψ_s from Oke [33], together with the linear fit of Oke (dashed line) and the fit to our model (solid curve), from Eq. (2). Numbers in the figure correspond to cities analyzed by Oke [33]. (b) Comparison of measured and predicted ΔT_{u-r} for group A cities using Eq. (1).

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*Corresponding author.
pellenq@mit.edu

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