'Heat island effects in summer or wetter winters with increased flash flooding are only a few phenomena which have great impacts on the urban living conditions. We have to face these challenges and our urban city regions must react on the effects of climate change.'

Examine the extent to which anthropogenic changes in surface geometry and composition, atmospheric composition and socio-economic activities can both exacerbate and mitigate urban climates in mid-latitude and tropical cities.

As recently as 1950, 30% of the world's population lived in urban areas. By the year 2030, it is predicted to double, with 60% of the world's population inhabiting the metropolis (UN World Population Prospects Revision Report, 2010). The city is thus becoming increasingly important climatologically, as the site in which humans and the atmosphere interact. These interactions are dynamic. The construction of every house, road or factory - urban structures in general - destroys existing microclimates and creates new ones of great complexity. Fundamentally, this paper focuses on the Urban Heat Island effect as 'the totality of [these] microclimatic changes brought about by man-made alterations of the urban surface' (Oke, 1988). It is this Heat Island Effect that accounts for why urban temperatures are generally higher than rural ones. Primarily, this paper introduces the parameters of the Urban Energy Balance equation. These parameters, and their modification by anthropogenic activity, underlie much of the subsequent narrative. The main body of this paper explores the radiative, thermal, moisture and aerodynamic processes affecting the Energy balance. The distinct urban climate is observed as a result of: (i) changes in the radiation balance due to atmospheric composition (ii) changes in the radiation balance due to the albedo and thermal capacity of urban surface materials, and canyon geometry (iii) the production of heat by buildings, traffic and industry (iv) the reduction of heat diffusion due to changes in airflow patterns caused by urban surface roughness; (v) the reduction in thermal energy required for evaporation and transpiration due to the surface character, rapid drainage and generally lower wind speeds of urban areas.

Throughout this paper, the city is regarded as having two distinct vertical layers: the Urban Canopy Layer (UCL) and the Urban Boundary Layer. The former is dominated by canyon geometry; the latter by the effects of sensible heating from the surface. With an outline of the general city, this paper progresses into exploring, with specificity, the differences between mid-latitude and tropical cities. I suggest that their dissimilar urban morphologies equate to subtly different Energy Balances and thus thermal regimes. Finally, this paper suggests that cities, have a tendency to shed their thermal surplus through the interactions of vertical and horizontal temperature-pressure gradients. Through the interactions of the canopy and boundary layer, the intensity of surface heating is dampened, a phenomenon particularly apparent when large surface heat islands generate convectional uplift and strong thermal mixing. With mind to mitigation, I suggest that there are both deliberate and inadvertent modes of reducing the heat island. With the former I briefly explore urban surface modifications such as green space-making and open-air planning. The latter refers more to atmospheric modifications such as pollution, which inadvertently may contribute to reducing the urban heat island effect. This occurs because pollutive aerosols act as strong condensation nuclei, thus facilitating precipitation and the subsequent cooling effects of a droplet upon reaching the surface.

The surface energy budget equation reveals the processes of energy exchange between the atmosphere and earth surface. As such, on a simplified un-vegetated surface the energy budget equation can be expressed as:

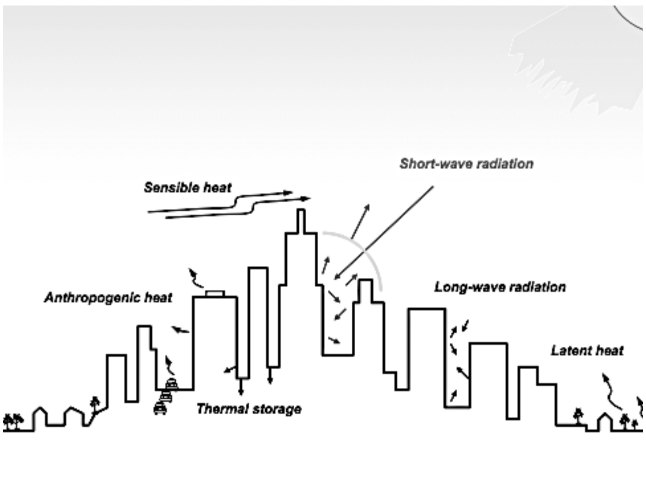
$$Rn = H + LE + G$$

where Rn, the net all-wavelength radiation = [S(1 - a)] + Ln (S = incoming shortwave radiation, a = fractional albedo of the surface, and Ln = the net (outgoing) long-wave radiation.) G = heat flux into the ground; H = turbulent sensible heat flux to the atmosphere; LE = turbulent latent heat flux to the atmosphere.

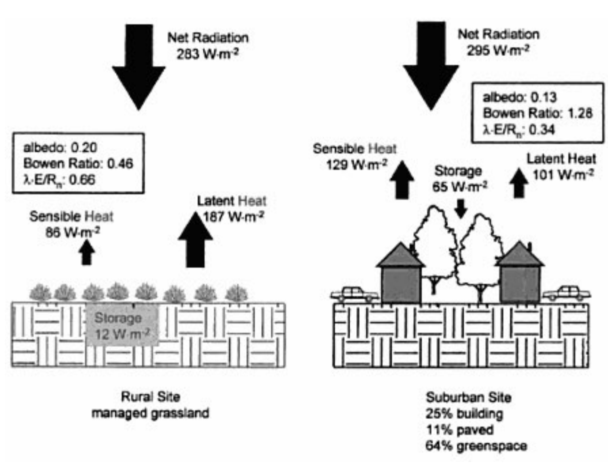
As Barry et. al posit, ‘Rn is usually positive by day, since the absorbed solar radiation exceeds the net outgoing long-wave radiation’ (Barry & Chorley, 2009). Thus at night, when S = 0, Rn is determined by the negative magnitude of Ln, a facet which largely determines the observed strong urban nocturnal heating relative to the rural. In general, daytime available net radiation is balance by outgoing turbulent fluxes of sensible heat (H) and latent heat (LE) into the atmosphere and by conductive heat flux into the ground (G). The surface energy budget equation provides a powerful framework for understanding urban climatic effects and their relations to surface material and morphology. The Urban Energy Balance involves several further parameters (however; namely anthropogenic heat flux, net storage heat flux and the net horizontal heat advection.

$$Rn + QF = QH + QLE + \Delta QS + \Delta QA$$

In this instance, the parameters Rn, LE and S remain unchanged (a slight complicating factor being that the symbol for sensible heat changes to QH). Nevertheless QF = the anthropogenic heat flux (the energy released by human activities); QS = the net storage heat flux and QA = the net horizontal heat advection (lateral movement of energy). The relative importance of each parameter varies over space and time. For instance, on a warm, clear skied day the sensible heat and storage flux parameters would dominate. Studying, a New York urban canyon system under such conditions, Oke postulated that ‘60% of the daytime radiant surplus entering is removed by the convective sensible heat flux, a further 30% conducted into storage’ (Oke, 1978). However, a day later, having rained overnight, the relative energy fluxes involved shifted to include more latent heat flux. As such moisture availability is one of the key variables in controlling the local partitioning of daytime radiant energy between the sensible and latent heat parameters. These relations furthermore exhibit distinct spatialities, Grimmond writes: ‘under low-wind conditions, storage heat flux is most significant at downtown and light industrial sites (accounting for 50% of Rn), and the sensible heat flux is most



Urban energy fluxes (Bridgeman, 2000)



Urban-Rural Differences in Sensible and Latent Transfers. The ‘waterproofed’ urban surface lacks evaporative cooling (Oke, 1976) important at residential sites (40 to 60% of daytime Rn). Furthermore in a city, green spaces - parks and gardens - dispersed intermittently between grey spaces - pavements and buildings - lead to distinctly localised heating patterns. In many urban areas of North America, up to 40% of the plan area of a city is vegetated, Central Park of New York being one such. Within these pockets of grassland, latent heat fluxes become more dominant, thus contributing to a cooling effect at the surface. This occurs due to latent heat of evaporation (state change from liquid to lower state gas) drawing energy away from the surface.

At a grander spatiality still, these latent-sensible relations can be viewed between the rural and the urban. The differences in energy fluxes of Diagram 1 are related to the different characteristics and structure of the landscapes. The built surface of the city (right) generally absorbs more solar radiation than vegetation. The surface is furthermore impervious, covering the soil and thus preventing heat dissipation from evapotranspiration, the sensible heat parameter, that which warms the air intensely, thus remains relatively large. The Bowen ratio, descriptor of the type of heat transfer in a water body is relatively high (in terms of relative dominance a higher Bowen ratio = dominance of sensible heat; lower = latent heat) The anthropogenic heat flux parameter (QF) also exhibits strong temporal and spatial variability. The average anthropogenic heat flux density (QF) depends upon the average energy use by individuals, and the city's population density. The per capita energy use is itself further dependent upon several factors such as affluence, stage of industrial development , and the need for winter space heating. These factors are evident between mid-latitude and tropical cities, and thus offer some indication as to why their respective Urban Heat Island's slightly differ. Furthermore, in several Arctic cities during polar darkness, the energy balance during calm conditions depends solely on net longwave radiation and heat production by anthropogenic activities (QF). In Reykjavik, Iceland (population, 100,000) the anthropogenic heat release is 35Wm -2 , mainly as a result of geothermal pavement heating and hot water pipelines (Barry & Chorley, 2009). The parameters of the urban energy balance are thus dynamic and fluid.

The temporal dimensions of the urban heat island are embedded in these energy fluxes. The heat island is thus not a constant condition, but rather is affected by the chameleonic, diurnal changes of energy within the system. Urban heat islands show both periodic and aperiodic fluctuations seasonally and diurnally, of which latter is particularly pronounced. In daytime the urban-rural difference even on cloudless, calm days is generally quite small. However come early sunset, the urban-rural difference becomes large, such was the case observed in Mexico City, wherein the early hours of the morning were marked by the development of a strong heat island. As such the differential cooling rates between the city and rural Mexico only came to pronounce themselves - in any strongly observable way - at night when S = 0. Furthermore these diverging rates of cooling between the urban and rural environments around sunset produce a sharp increase in heat island intensity to a maximum a few hours (typically 3 to 5) later. Thereafter slightly greater urban cooling reduces the intensity until the early daytime rural heating - the countryside not being subject to canyon shadow effects - virtually erases the heat island. As will be explored later, the relative intensity of growth and dissipation of the nocturnal heat island is inversely related to cloud cover, wind speeds and atmospheric stability. A strong wind and unstable, convective system, for example, facilitates strong boundary layer mixing between warm and cool air thus contributing to a less pronounced heat island. The intensity of the heat island is furthermore a relative phenomenon, dependent upon the rate of rural cooling, which is itself influenced by 'the magnitude of the regional environmental lapse rate' (Barry & Chorley, 2009).

The internal workings that contribute to this diurnal pattern of temperature change may be refined by using a single unit of city space. The urban canyon, that predominates in urban climate models, refers to a street or flat area bounded on two sides by buildings and open partially to the sky. On a simplified level, the canyon serves to trap solar energy during the day, and release this energy as long-wave radiation and sensible heat at night. In reality however, the absorptive and emissive behaviours involved are more complex. By day the canyon system radiative surplus is mainly dissipated by turbulent transfer, and the remaining 25-30% is stored in the canyon materials. At night with weak winds, this turbulent activity becomes negligible. The nocturnal radiative deficit is, however, almost entirely balanced by the release of subsurface heat storage. The timing and magnitude of the surface energy balances of the canyon walls and floor are strongly conditioned by the influence of canyon geometry and orientations on the radiation exchanges. As will be explored later, in a north-south canyon system, the floor becomes the most active energy site, preferentially channeling daytime radiant surplus partially into storage and dominantly into sensible heat via turbulence.

Having considered the Urban Energy Balance and its diurnal dimensions, it follows naturally to consider the five processes that accompany such fluxes. The relative importance of the first ‘suggested’ heat island cause - that of changes in the radiation balance due to atmospheric composition - is fairly minimal. The city has a marked impact upon the short and long wave components of the net radiation budget due both to the presence of radiatively-active pollutants in the air - reducing the transmissivity of the atmosphere - and to changes in the surface radiative properties. Such changes are however less pronounces as might be assumed. This is because shortwave and long-wave radiation have remarkable tendencies to offset themselves in the long run. For instance, the amount of Shortwave radiation received at the surface (direct-beam and diffuse) is typically 2-10% lower in the city. However urban albedo values, typically 0.05 to 0.10 lower than for the countryside in the mid-latitudes, tend to offset this by absorbing, as opposed to reflecting. As a result urban/rural net short-wave radiation differences are considered to be rather small (the magnitude of such differences varies depending upon the pollution attenuation and albedo factors). A similar counterbalancing occurs in the long-wave radiation budget where exchanges are perturbed by the increased pollutants and the lower surface emissivities of cities. In accordance with Wien’s law however, the higher surface temperature of the city lead to enhanced emission, thus counteracting the emissivity change in the first place. Net short and long-wave differences between urban and rural regions are thus prevented from growing unduly large. The causation of UHI thus lies in processes other than simple radiational difference. As such, differences in canyon geometry and urban material albedos and thermal capacities come to the fore.

The secondary cause of urban heat islands refers changes in the radiation balance due to the albedo and thermal capacity of urban surface materials, and canyon geometry. The geometry of the urban canyon, in particular, facilitates an increase in effective surface area and the trapping by multiple reflection of shortwave radiation, as well as a reduced ‘sky view’ (proportional to the areas of the hemisphere open to the sky), which decreases the loss of infrared radiation. Its geometry further controls and complicates the spatial distribution of direct-beam solar radiation, precipitation inputs, and the mean and turbulent flow structure of winds. As a result, even for a single canyon constructed of materials possessing relatively uniform radiative, thermal, moisture and aerodynamic properties, the radiation and energy balance regimes of the component surfaces exhibit a great deal of spatial and temporal complexity. Such spatial complexity is engendered because the dry surface supports the partitioning of radiant energy predominantly into sensible heat. These localised sources of sensible heat then form the microscale advective interactions with moist areas in other regions of the city.

Complexity is further created by the multifarious forms urban buildings may take in terms of orientation and materials. In an E-W canyon, only the south-facing wall and the floor would receive appreciable solar radiation in the northern hemisphere, resulting in asymmetric wall climates. Furthermore if the canyon width-to-height ratio were significantly greater or less that 1:1 there would be changes in the ability of solar radiation to penetrate, in the trapping of outgoing longwave radiation, and in the amount of wind shelter. Construction materials of a lighter colour would further change the canyon albedo and the capacity for canyon heat storage. Storage within the urban fabric is regarded as a key cause of the urban heat island, based on the premise that the thermal conductivity and heat capacity of urban building materials are greater than for rural soils. A parameter that combines these properties is the thermal admittance. This is a measure of the thermal response of a surface to a given heat flux. Surface with large admittance readily accept energy by day into its substrate, and at night release it. This process of storage and release, when coupled with heat from combustion (QF) reduces the rate of urban cooling relative to the rural. Finally, the canyon may not always create heat surplus; shade from buildings in the urban canopy layer can create cooler local temperatures than open areas. In such an instance a cool island exists.

The release of heat due to combustion of fuels, is a heat source for city, unfounded in the countryside. As previously stated, the magnitude of QF depends upon per capita energy use and population density. Oke, in one of his seminal papers, City Size and Urban Heat Island, suggests that heat island intensity under cloudless skies is related to the 'inverse of the regional windspeed and the logarithm of the population.' Interestingly, for the same given city size observed under a North American and European context, the latter, European heat island will be smaller. He writes 'this appears surprising since European cities have greater population densities, and might therefore be expected to show more concentrated modification of the temperature field.' Oke proposes that the lower artificial energy flux densities, lower heat capacity of the urban fabric and greater evapotranspiration within Europe may account for such observations (Oke, 1988). Numerous studies of recent have shown that urban conurbations now produce energy through combustion at rates comparable with incoming solar radiation in winter. The largest QF values are found in densely inhabited cities with cold climates, wherein anthropogenic heat flux often approaches, or exceeds, the annual net radiation budget. The pollutive practices that produce this heat may not always contribute to a heat island. In extreme cases, aerosols and particulate matter may lead to a reduction in the transmissivity of the atmosphere. Such was the case of Leicester in the winter of 1945, when it was estimated that 30% of incoming radiation was lost to pollutant smogs. Spatial variability of QF within cities is considerable, such that the Central Business District often appears as the primary heat source, with localised and intense peripheral hotspots within industrial complexes. It is often assumed that for most mid-latitude cities in summer, the urban/ rural radiative and anthropogenic heat flux differences are relatively small at the surface. Thus most of the energy balance differences stem from differential storage and partitioning of heat within the urban canopy layer.

The urban heat island, as a thermal anomaly, holds horizontal, vertical and temporal compartments. Wind flow and mechanical turbulence dominate the processes forming vertically layered heat islands. Specifically, heat islands are often regarded as being the results of reduced heat diffusion caused by changes in wind speeds and direction when flowing over rough, urban surfaces. As Barry et. al write, 'city wind speeds are lower than those recorded in the

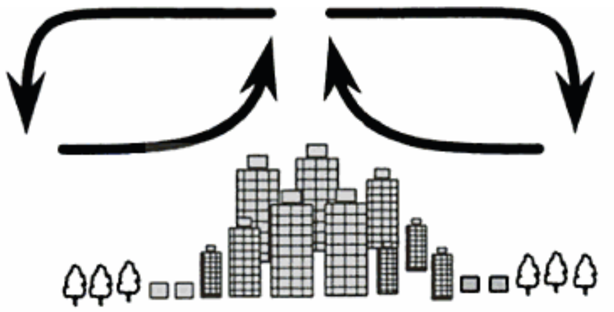


Figure 14.15. Generalized urban heat island atmospheric circulation.

TABLE 2. SUGGESTED 'CAUSES' OF THE URBAN HEAT ISLAND (Not rank ordered)

Altered energy balance terms leading to positive thermal anomaly	Features of urbanization underlying energy balance changes
A. Canopy layer	
1. Increased absorption of short-wave radiation	Canyon geometry – increased surface area and multiple reflection
2. Increased long-wave radiation from the sky	Air pollution – greater absorption and re-emission
3. Decreased long-wave radiation loss	Canyon geometry – reduction of sky view factor
4. Anthropogenic heat source	Building and traffic heat losses
5. Increased sensible heat storage	Construction materials – increased thermal admittance
6. Decreased evapotranspiration	Construction materials – increased 'water-proofing'
7. Decreased total turbulent heat transport	Canyon geometry – reduction of wind speed
B. Boundary layer	
1. Increased absorption of short-wave radiation	Air pollution – increased aerosol absorption
2. Anthropogenic heat source	Chimney and stack heat losses
3. Increased sensible heat input-entrainment from below	Canopy heat island – increased heat flux from canopy layer and roofs
4. Increased sensible heat input-entrainment from above	Heat island, roughness – increased turbulent entrainment

surrounding open country owing to the sheltering effect of buildings. As the air flows over the very irregular surface of a city, friction with the buildings retards the wind in the lowest layers. Ideal conditions for maximum urban heat island intensity occur under weak winds and cloudless sky, wherein convective and advective thermal mixing is minimised. Whilst slower wind speeds is the norm, there are several situations in which wind speeds may increase. The first occurs when faster moving upper air layers are either deflected downwards by relatively tall buildings or channelled into 'jets' along streets oriented in the same direction as the flow. The formation of convective turbulence in such a manner facilitates the vertical transport of sensible heat to the urban boundary layer. The interactions between the canopy and boundary layer are not however limited to these abrupt, atypical winds. As Bridgeman posits, 'when synoptic conditions are calm or very weak, a local urban heat island circulation (UHIC) can form, controlled by the horizontal urban-rural temperature gradient. As such a low-level breeze, similar to that of a sea breeze, is drawn into the city along a pressure gradient. Once it reaches the UHI centre, the increased heating and turbulence causes it to rise. At the boundary layer inversion, it then spreads outward, back to the countryside, where it cools adiabatically and sinks. The critical point in this convective cell occurs in the deep zone of frictional influence at the heat island's core. The increased drag and turbulence of the urban canopy leads to the local slowing of air and subsequent convergence and uplift.

Thermal modification of the urban boundary layer is thus facilitated by mechanical turbulence in wind flows. The depth of this mixed layer is fluid, and tends to increase in depth with increased heat flux convergence from below. This transfer of heat upwards tends to dampen the intensity of the urban heat island by preventing stagnation from occurring within the canopy. Buoyant, moisture-holding thermals often coalesce in the boundary layer with abundant condensation nuclei - in the form of pollutants, aerosols and dust emitted as QF - to form precipitation clouds. In Summer, intense thunderstorms may lead to a dampening of the surface heat island through the cooling influences of water droplets. However, these same, intense precipitation events may lead to flooding, particularly when combined with an impervious, concrete surface and inefficient sewage system. Such is the case is many developing tropical cities, and their heat island-driven convective cells. The capacity for the heat island canopy to shed its excess heat is however dampened by return downward flows of sensible heat from the upper boundary inversion layer. These downward fluxes of warm air often occur when urban-generated turbulence eats away at the base of the inversion and mixes this warmer air downwards in a process called penetrative convection (this process when involving pollutants is called fumigation).

The creation of Urban Heat Islands is in large part due to the combined, exacerbating influences of each of the above parameters. The coalescing forces of urban geometry, wind speed, and socio-economic activity, for instance, lead to the partitioning of energy into sensible heat. Surface energetics of the sort are, however, manipulable. Various recent studies have proposes three primary mitigation strategies that serve to dampen the heat island: (i) urban forestry, (ii) cool roofs and (iii) cool pavements. Urban forestry is touted as a means to increase evapotranspiration while providing daytime shading (McPherson et al., 1999). Examples of its application include direct shading of housing to provide shade. Additionally, many jurisdictions within North America are incorporating urban tree planting in parking lots to reach a 50% canopy coverage eventually. These green beds would provide a surface for interception and infiltration of rainfall, increasing the latent energy flux. Through transpiration plants further facilitate evaporative cooling at the surface. Reflective paving has also recently been introduced into the mitigation hierarchy. Two mechanisms for creating a cool pavement are increased surface reflectance, which reduces the solar radiation absorbed by the pavement, and increased permeability, which cools the pavement either through increased convection, lower thermal storage or evaporation of water. Cool roofing, as a mitigation response, formed within major policy circles after intensive research on the rooftop-atmosphere albedo relationship. Research found that black roofs typically have a 6% rate of reflectivity and low emissivity values while highly reflective white roof membranes can have reflectivity and emissivity values greater than 80%. The benefits of such mitigation are however offset when observing at the meso-scale. For instance the subsequent decrease in UHI temperatures and wind speeds - facilitated by greater latent heat flux - may lead to a lower Urban Boundary Layer, potentially creating more frequent air pollution episodes within the canopy layer.

Having explored the micro-spatial dimensions of Urban Heat Islands, this paper concludes on the macro-spatial, examining the subtle differences between the tropics and the midlatitudes. The thermal characteristics of tropical cities differ from those in mid-latitudes because of dissimilar urban morphology (building density, materials, geometry, green areas) and because they have fewer, and more uniform sources of anthropogenic heat. Land use in tropical cities differs from that in higher latitudes; it is commonly composed of high-density, single-storey buildings with few open spaces and poor drainage. In such a setting, composition of roofs becomes more important than that of walls in terms of thermal energy exchanges. As such the concept of the urban canyon becomes less significant. Furthermore the production of anthropogenic heat is more uniformly distributed and less intense than in European and North American cities. The convective cell introduced above is thus often less pronounced in tropical cities because there is no single zone of intense, localised convergence. The urban structure within the tropics differs in terms of individual buildings. Tropical abodes tend to have a relatively high thermal mass to delay heat penetration. This combined with the low soil moisture in the surrounding rural areas, makes the ratio of urban to rural thermal admittance greater than in temperate regions. Oke posits the existence of an 'oasis' effect' in tropical cities surrounded by arid regions.

Through surface moisture processes of latent heat exchange and evaporation, temperatures are maintained at relatively low levels within the city. This greater partitioning of energy into the latent heat flux contributes to tropical heat islands being on average weaker than those of temperate cities. Typically, the nocturnal maximum in the urban tropics is 4°C, however in the mid-latitudes this rises to 6°C. There are also differing timings for temperature maxima between the latitudes. Urban areas in the tropics tend to have slower rates of cooling and warming that do their surrounding rural areas, and this causes the nocturnal heat island effect to develop later that in mid-latitudes. Topography often complicates in the tropics. In Quito, Ecuador (2851m) a maximum heat island effect by day is followed by weaker night-time effects - the opposite of the common mid-latitude city. Barry et. al posit that the nocturnal drainage of cold air from the nearby volcano Pichincha cause this. Thus, tropical cities do tend to have heat islants, but the large diurnal phase tends to be delayed, or even reversed, relative to mid-latitude ones.

The city-atmosphere system is inherently complex. As this paper attempts to have shown, the atmospheric state of the heat island may be observed as a response to exchanges of energy, mass and momentum covering a wide range of space and time scales; in urban areas the sources and sinks for these exchanges are located in an extremely heterogeneous fashion and involve significant anthropogenic as well as natural factors. In summary, urban construction materials have different thermal conductivities and capacities; the geometry of buildings and their spatial arrangement trap radiation and pollutants and create a very rough surface that influences air flow and dispersion; the heat released by human activities from vehicles, industry supplements natural sources of energy; and engineering structures remove water from the surface and modify natural topography and drainage networks, thereby altering runoff and humidity regimes.The net effect is profound changes to the radiative, thermal, moisture and aerodynamic characteristics from the pre-existing landscape, which alter natural budgets of heat, mass and momentum, resulting in the development of the distinct urban heat island.

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