Abstract and Keywords

This work reports on the main physical processes that arise in the environment of the megacity from the “urban metabolism”—the complex interactions of the climate with the activities performed in the city and its built structure and texture—as well as on associated large-scale processes that generate hazards for the megacity’s inhabitants. It is estimated that in a few decades most of the world’s population will live in urban centers. Both the growth of megacities and climate change will increase the vulnerability of huge sectors of the population to climatic consequences of the urban metabolism. These include urban heat islands, pollution, and extreme weather events such as heat waves and floods. Developing policies to mitigate these threats will require integrating scientific knowledge with management skills, communication among cities about effective approaches, and taking into account residents’ needs for health and the capacity to live safely.

Keywords: Urban climate, climate change, climate policy, heat island, urban well-being, health risks, vulnerable populations

Overview

A few decades from now, 65% of the world’s population will live in urban settlements (United Nations, 2012). The Intergovernmental Panel on Climate Change (IPCC; 2013) has reported that in the near future climate change will increase near-surface global temperatures by 0.4–2.6 °C. This change will have significant repercussions for the population. Understanding how climate change affects the urban environment is crucial to properly estimating risks for the growing number of people living in cities and to designing appropriate strategies to reduce their vulnerability.

*The Climate of London*, by Luke Howard (1772–1864), published in 1833 (https://archive.org/details/climatelondonde01howagoog), represented the birth of urban climatology as an applied science. That study did more than just characterize the climatic peculiarities of one of the first industrial metropolises of the world; it also clearly indicated that along with the influence of large-scale meteorological phenomena, the city’s own structure and composition affects local climate by acting on winds, on the flow and distri-
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The distribution of moisture, and on temperature distribution—all of which differ markedly between the urban environment and neighboring rural areas. Although Howard’s study paved the way for further research on the urban sector, no more interest in the study of climate–city relationships emerged until nearly the end of the century. Only toward the end of the 1880s did cities start to be modeled physically and not just with a pure urbanism approach. This new approach coincided with increased use and recognition of the term “urban heat island,” which encapsulates the complex processes of energy exchange between the surface of the built environment and the atmosphere.

Today, a large number of studies are addressing urban climates and how they affect the well-being of the resident population. Still, despite the significant improvements in our comprehension of urban climate since Howard’s 1833 study, the way in which urbanization and climate change will interact in the future remains uncertain. At the 2014 international conference on Urban Environmental Pollution (UEP 2014) held in Toronto, Canada, the conference chair, Bill Manning, welcomed attendees with these words: “We need to learn more about cities and how they function. We know that they consume enormous quantities of materials and energy and release large quantities of wastes. Cities are the source of air, water, and soil pollutants. Heat islands and CO₂ domes, combined with particulates and ozone, affect human health. Lack of park and green space disconnects urban residents from the natural world and may have adverse psychological effects.” (http://www.uepconference.com) As suggested by Oke (2006), one of the greatest challenges for urban climatology is encouraging and supporting exchanges between specialists in complementary subfields using complementary methodologies.

Creating a “climate-resilient” urban environment will require merging scientific knowledge and management skills (Carmin, Nadkarni, & Rhie, 2012). Tackling the problem of urban resilience calls for a broader system of governance, one that encompasses the performance of the city itself as a built environment, the ability to resist and absorb effects of environmental hazards, and the capacity to decrease the exposure of the population, especially its more vulnerable members, to health risks (Carter et al., 2015). In other words, global change obliges us to approach the problem of understanding and controlling urban processes from the perspective of an “ecology of the city” (Grimm et al., 2008).
Urban Climate

Urban climates are distinguished from nearby nonurban climates by differences in the main weather parameters: air temperature, humidity, wind speed and direction, and amount of precipitation. These differences are due largely to alteration of the natural terrain by construction of new surfaces and artificial structures as well as to the introduction of new sources and sinks for heat and water vapor. Buildings, paved streets, and parking lots modify wind flow, runoff, and the energy balance in general. The urban climatic environment is organized on various length scales, shown schematically in Figure 1.

Compared with adjacent rural areas, the lower amount of evapotranspiration to the atmosphere from plant canopies (which are often scarce in urban areas) and the increased runoff of precipitation reduce the average relative humidity in cities by as much as several percentage points.

Wind speed in cities can be 20–30% lower than in adjacent areas. Urban terrains are typically rougher than rural landscapes, and built-up urban canopies strongly increase frictional drag, inducing often remarkable modifications of wind speed at the microscale within the urban canopy layer (see Figure 1c). Rural and urban wind flows also differ as a result of vertical thermal gradients and convection. Those phenomena (caused by the urban heat island, discussed later in this article) induce a convergence of low-level winds over cities, so that air flows into them from all directions.

The higher particulate concentrations in urban atmospheres reduce the amount of incoming solar radiation through scattering and absorption. Some particles provide nuclei for the condensation of water vapor, favoring local fog formation.
The structural peculiarities of a city may influence precipitation patterns, as can some of the weather factors that characterize its climate, such as a high concentration of condensation nuclei, modified aerodynamics, and thermal convection. Schmid and Niyogi (2013) simulated the impact of city dimension on precipitation potential using cities ranging in radius from 5 to 40 km. Precipitation increased linearly for cities up to 20 km in radius and also increased downwind of the cities.

Arnfield (2003) reported on the advances in urban climatology from 1980 to 2000, reviewing progress in our knowledge of microclimatology, the role of spatial and temporal scales, heterogeneity in building settlements, dynamic source areas for turbulent fluxes, complexity of the roughness sublayer, processes of energy and water exchange, and urban heat islands. Souch and Grimmond (2006) presented an assessment focused on different scales and methodologies for studying the urban climate: wind tunnel experiments; statistical and numerical models; lidar, sodar, radar, and remote sensing approaches; profilers; and surface-based flux measurements using micrometeorological techniques such as eddy covariance.

**Urban Surface Processes**

![FLIR Thermal Image](image)

*Figure 2:* Thermal image, taken with a FLIR thermocamera. The temperatures of the objects are digitalized as a function of the resolution and emissivity chosen (in this case emissivity is equal to 1.00). The temperature reported in the upper left corner corresponds to the central dot temperature collected.

The optical and thermal properties of surfaces differ greatly between the built environment and the natural one. Compared with natural surfaces, the materials in the urban environment have very peculiar behaviors in terms of absorption and reflection of solar radiation. These properties lead to strong differences from the natural environment in the partition of incoming radiation (absorbed or used in other processes) at the surface (Figure 2). The entire philosophy of cooling the city through the introduction of “cool roofs” is
founded on the differing abilities of various surfaces to interact with solar radiation. Cold or white-painted roofs reflect a high amount of incoming radiation, reducing the amount of energy absorbed by the surface. In addition to optical properties deriving from color, the roughness of an absorbing surface contributes to the trapping of incident radiation.

The permeability of materials to water is responsible for another type of interaction in the urban climate. Evaporative processes are major modulators of climate; evaporating surfaces such as vegetation allow some of the energy from incident radiation to transform water from the liquid phase to vapor. Wet surfaces, urban parks, and healthy trees efficiently cool the air by using large amounts of radiation in this way, reducing the total amount of energy available for surface heating. When the Austrian painter, sculptor, architect, and ecologist Friedensreich Hundertwasser suggested that the tree itself is a living “citizen” of the city, he made a revolutionary argument based on both cultural planning and physics. In fact, no surface reduces incoming energy better than does the physiological function of plant stomata as they enable photosynthesis. Equally important is evaporation of soil water.

Unfortunately, our cities have seen an almost complete removal of vegetation and sealing of urban surfaces. These changes have increased not just surface heating but also the potential for discharge of storm-water runoff from sewers. The latter may undermine the stability of territory and coastlines far from where precipitation originally occurred.

Urban Canopy Layer Processes

The texture of urban surfaces, including the small-scale roughness of building materials and the large-scale roughness produced by buildings and the spaces between them, is a critical factor in the turbulent exchange of sensible heat between urban surfaces and moving air. Increased surface roughness has two significant and opposing effects: It slows down the near-surface wind speed, decreasing heat transfer, and increases the total contact area of the object in question, increasing heat transfer. (The use of finned heat sinks on electronic components exploits the latter effect of texture at small scales.)
As with wind, absorption of solar radiation is affected by interaction with the built urban environment. Here the typical structure defining the interaction is the urban canyon. In urban canyons, incoming solar radiation is partially absorbed and partially reflected by the walls at a rate that is a function of the ratio of the height of the buildings to the width of the spaces between buildings. The index that represents this relationship is the sky view factor (Figures 1c and 3), which corresponds to what is sometimes called the “hunger for heaven” of the urban fabric. The smaller the sky view factor, the higher the absorption of radiation and thus the greater the overall increase in temperature.

**Planetary Boundary Layer Processes**

![Figure 3](image)

*Figure 3:* Photographs shot upward depict the sky view factor in the medieval city of Bologna, Italy.

*Figure 4:* Daily changes in the planetary boundary layer.

From en.wikipedia.org/wiki/Planetary_boundary_layer.
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The complex set of interactions at multiple spatial and temporal scales we have described make the city act like a sort of macro-organism that breathes and pulsates with the rhythm of the diurnal cycle of absorbed solar radiation. From a physical point of view, this “breathing” can be represented through the description of the structure of the planetary boundary layer (PBL; Figure 1a): that portion of the atmosphere that interacts with the surface (Stull, 1988). Within the PBL, environmental parameters are homogenized, including the pollutant content of the atmosphere. Because of the high heat fluxes established in the PBL, it reaches considerable altitudes (typically 1,500–2,500 m) in most cities. As shown in Figure 4, it reaches its maximum height when the radiation received from the surface is at its maximum intensity. The PBL thins during the night, when the amount of energy available to support vertical atmospheric motion decreases.

Figure 5: Secondary circulation due to the presence of an urban center.

http://www.atmo.arizona.edu/students/courselinks/fall11/atmo336/lectures/sec4/urban.html

The overall pattern of daily changes in the PBL shown in Figure 4 is valid for any surface; the only thing that changes is the PBL height, for the reasons already mentioned. If, however, we could visualize aspects of this layer at a given time of day over the city and over the surrounding countryside, we would note some significant differences. During heating in the early part of the day, convective atmospheric motion elevates the urban PBL relative to that of the surrounding countryside. These convective motions also carry pollutants from lower to higher altitudes. After reaching the maximum height allowed by the energetics of the system, the convective flows reverse direction, descending and diverging toward the border of the urban system. This pattern leads to the formation of a local circulation enclosing the city, which produces a suction effect drawing air from the urban system toward surrounding rural areas (Figure 5). Thus, close to the surface the air moves for rural to urban areas, and at higher levels form urban to rural.
The Urban Heat Island

Figure 6: Typical structure of an urban heat island.

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The urban heat island (UHI) is one of the most evident and well-documented examples of human modification of climate at a local scale (Figure 6). While a heat island may form in any area and at any spatial scale, cities, with surface temperatures generally above those of their surroundings, are the most prone to this phenomenon. The yearly average temperature of a large city may be 1–2 °C higher than that of adjacent rural areas, and on calm, clear nights urban agglomerates may be up to 12 °C warmer than the nearby countryside (American Meteorological Society, 2000).

Urban heat islands develop because the rates of warming and cooling of a population center differ from those of surrounding areas. The formation of a UHI is influenced by two primary seasonal processes. First, in the summer, asphalt pavement and other surface materials alter the radiation balance by absorbing, storing, and reradiating more solar energy per unit area than do the vegetation and natural soils in rural areas and during the summer nights, radiative losses from buildings, streets, bricks, and asphalt keep the air warmer than outside the city. Second, in the winter, the energy generated from human activities, industry, and fuel combustion for heating, power generation, and transportation contribute to warming of the urban environment, acting in an atmospheric layer thinner than during the summer because of a lower availability of solar radiation. In this thin atmospheric layer pollutants and water vapor act as a blanket that absorbs some of the long-wave thermal radiation reemitted by the surface, warming the overlying air. This process favors the formation of a stable layer of air over a city, and the resulting convective ceiling increases the probability that higher pollutant concentration levels will be trapped underneath.
UHIs have traditionally been studied and characterized on the basis of ground-based observations. Because UHI characteristics may vary strongly with geographical location, observations by remote sensing, predominantly from satellites, have been used in recent years to better address local peculiarities (Li & Yu, 2008; Mirzaei & Haghighat, 2010; Rihnane, Hilali, Bahi, & Berrada, 2012). Accurate measurements of land surface temperature for large areas can provide important information about the formation and daily temporal evolution of UHIs. Thermal profiles of UHIs show a general uniformity of island shapes, albeit with marked changes corresponding to particular heat sources (e.g., parking lots, malls, and industrial facilities) and heat sinks (e.g., parks, fields, and bodies of water) (Imhoff, Zhang, Wolfe, & Bounoua, 2010). Looking downward at a typical UHI, one can see that the isotherms (lines of equal temperature) follow the configuration of the urban settlement, creating an island-shaped form surrounded by cooler areas (Figure 7a).

The thermal regime of the city and the development of UHIs result from the way in which the partition of solar radiation, predominantly from short to long wave, interacts with the urban atmosphere. Long-wave radiation is mostly converted to sensible heat, which is transported by advection and convection of air masses within the city system. Because of the complexity of the urban system, several levels may contribute to creating the UHI. The inner level is the urban surface layer, where city materials interact directly with the
incoming radiation; here the optical and thermal properties of the surface are dominant. A second type of interaction is represented by the complex air flow above the built environment. In this layer (commonly assumed to extend to two to three times the surface roughness scale, i.e., the average height of the buildings) the physical processes are guided both by surface properties and by local aerodynamics generated by canopy features. The last level corresponds to the larger interaction between the main physical flows (boundary layer flows) and the whole city. Three subtypes of UHIs may therefore be distinguished based on the underlying physical processes that contribute to their formation:

1. Surface heat island (SHI)
2. Canopy layer heat island (CLHI)
3. Boundary layer heat island (BLHI)

These subtypes of heat islands vary in shape and temporal characteristics. The CLHI and BLHI are normally thermally characterized using thermometers, whereas sensors mounted on remote platforms such as satellites or aircraft are the most suitable for providing detailed information on the SHI (Roth, Oke, & Emery, 1989; Voogt & Oke, 2003).

The thermal characteristics of SHIs and CLHIs are strongly determined by the physical characteristics of urban materials and surfaces. Denser, more built-up areas are characterized by higher temperatures, whereas open areas, parks, and vegetated and natural surfaces are cooler (Figure 7b). During daytime, dark surfaces absorb more solar radiation and become hotter, whereas light-colored or moist surfaces are cooler (Roth et al., 1989; Voogt & Oke, 2003).

The influence of the SHI is most evident during the day, when there are large temperature differences between dry versus wet, shaded versus exposed, and bare versus vegetated surfaces exposed to the same incoming solar radiation. Because urban surfaces are warmer than rural ones, the SHI effect is consistently and strongly positive (i.e., it increases local temperatures relative to temperatures in the absence of SHI factors) throughout the day and night. The SHI effect is largest with high daytime solar radiation intensities. During a hot summer day, solar radiation heats most dry urban surfaces, such as exposed roofs and pavements, to temperatures 27–50 °C higher than that of the ambient air (Berdahl & Bretz, 1997). In contrast, moist surfaces, particularly in rural environments, are thermally buffered by evaporation and tend to maintain temperatures close to that of the ambient air.

CLHI effects are relatively weak and can become negative (creating a cool island) in parts of the city where tall buildings create extensive shadows and the large heat capacities of building materials slow rates of warming. CLHI intensity increases during daylight hours, and CLHI effects continue into the night as a result of atmospheric heating by long-wave radiation released from urban materials and of thermal inertia. The nighttime CLHI effect is typically within the range of +1 to +3 °C, but intensities of up to +12 °C have been noted under optimum conditions (Oke, 1997). The maximum CLHI effect occurs a few hours after sunset, and the minimum shortly before dawn; thermal inertia keeps the effect weak into the late morning. Spatially, canopy layer temperatures rise sharply where rural areas
meet suburban/urban ones and then continue to rise more gradually toward a maximum at the core of the urban area.

Unlike the SHI or CLHI, the BLHI tends to remain relatively constant in magnitude during both day and night. To the extent it does vary, however, the BLHI, like the CLHI, persists into early nighttime because of surface heat release and thermal inertia, then weakens over the rest of the night and stays weak into late morning. The BLHI also shows much less spatial variability than the SHI or CLHI. A BLHI vertical cross section is roughly dome or plume shaped and centered approximately on the geographic center of the built environment, shifted downwind by mesoscale prevailing winds. In addition to the specific characteristics of the built environment, numerous other factors contribute to the occurrence of heat islands. Weather parameters, mainly winds and clouds, significantly affect the formation and magnitude of UHIs. Heat island effects are largest under clear weather conditions and with calm winds. Clouds reduce the intensity of the island itself and inhibit radiative cooling during the night. On a larger temporal scale, seasonal variations in weather patterns also significantly affect the frequency and structure of heat islands.

Mesoscale wind systems (between the synoptic and local weather scales) strongly affect the formation of heat islands. Coastal cities experience very different conditions from those inland and may be cooler than them in the summer, when sea surface temperatures are lower than those on land and when thermal gradients generate onshore winds. Cities located within predominantly rural landscapes and surrounded by large areas of vegetation (especially irrigated cropland) are usually cooler than cities lacking these features because the nearby water evapotranspiration reduces the magnitude of the heat island effect; this is especially true in warm humid climates (Oke, Johnson, Steyn, & Watson, 1991). Cities at midlatitudes have their strongest heat island effects in the summer and winter. In the tropics, the dry season may favor large heat island effects.

The intensity of UHI effects rises in proportion to the dimension and population of the urban area. Consequently, UHI heating effects are destined to become increasingly severe in coming decades because of projected steady increases in city size, population, and population density, along with increases in the number of major urban centers (“megacities”; see, e.g., Bugliarello, 2003). Moreover, UHIs have now been observed to affect not only huge metropolises but also small country villages (Landsberg, 1986).

One reason for the impact of population on UHI formation is the role of anthropogenic heat, that is, heat generated by human activity—primarily by combustion of fossil fuels (Sailor & Lu, 2004). The largest impact of anthropogenic activities usually occurs during winter in cold climates, mostly in the downtown core of the city. Significant anthropogenic heating frequently occurs during summer as well, resulting from the large amount of energy used to cool buildings in densely developed and populated cities (Taha, 1997).
In recent years, more attention has been given to studying large numbers of cities on a global or continental scale. A global study by Clinton and Gong (2013) found that the most important variables contributing to the UHI effect are the geographic size of urban areas, vegetation, and nighttime lighting (a proxy measure of the intensity of local development). A study of eight Asian megacities indicated that the magnitude of UHI effects is driven by population size, vegetation cover, and the build-up intensity (Hung, Uchihama, Ochi, & Yasuoka, 2006). However, Peng et al. (2012) found that UHI intensity for 419 large cities was related not to population density or city dimensions but to urban vegetation and anthropic activity.

As already mentioned, vegetation in the surrounding environment can exert a significant effect on regulation of temperature in the city. A recent study derived the land surface temperature of 77 urban areas and their surroundings from 124 Landsat satellite images (Heinl, Tappeiner, Hammerle, & Leitinger, 2015). Intense UHI effects were found even for small cities (less than 1 km$^2$ in area). Urban–rural temperature differences were driven primarily by values of the Normalized Difference Vegetation Index (NDVI assess whether the target being observed from remote platforms (satellites) contains live green vegetation or not), together with solar irradiance and land use.

**Urban Energy Balance**

The dramatic influence of urban surface characteristics (e.g., density, height, and size of buildings; street orientation; and presence of green areas) on the formation of heat islands underscores the need for deep investigations of the relationships of the distribution of incoming solar radiation at the surface to the architectonic arrangement of the built environment and the thermal properties of the building materials. Some city geometries and structures strongly favor UHI occurrence and magnitude; for example, building materials that are relatively dense typically store a large amount of energy because of their large thermal inertia. The replacement of natural surfaces (e.g., dirt and vegetation) by impermeable surfaces (e.g., pavement and roofs) means that urban surfaces are generally much drier than rural ones. Impermeable surfaces cause faster and more complete runoff of precipitation; consequently, less water is available to cool the air through evapotranspiration. Dark surfaces such as asphalt have a low reflectivity, increasing their absorption of radiative energy.

The main physical driving equations used to assess the partition of radiation into the urban system are those describing the radiation and energy balances. The Earth surface radiation balance is described by

$$ R_n = (S_{\text{in}} - S_{\text{out}}) + (L_{\text{in}} - L_{\text{out}}) $$

(1)
where $R_n$ is the net radiation, $Sw_{in}$ is the incoming short-wave (visible) radiation, $Sw_{out}$ is the outgoing short-wave radiation, $Lw_{in}$ is the incoming long-wave (infrared) radiation, and $Lw_{out}$ is the outgoing long-wave radiation.

The term $Sw_{in} - Sw_{out}$ represents the net short-wave radiation, which can also be described as $(1 - \alpha)Sw_{in}$, where $\alpha$ is the surface albedo—the percentage of solar radiation reflected by a surface. Albedo is a property of a specific surface determined by its electromagnetic and roughness characteristics.

$Lw_{in}$ and $Lw_{out}$ depend on the temperatures of the atmosphere and surface, respectively, following the Stefan-Boltzmann equation:

$$Lw = \varepsilon \sigma T^4$$

(2)

where $\varepsilon$ is the infrared emissivity of the body, $\sigma$ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$), and $T$ is the body temperature expressed in kelvins.

The net radiation given by equation (1) is the energy reaching the ground, which is then partitioned according to the energy balance equation (Stull, 1988)

$$R_n = H + LE + G$$

(3)

where $H$ is the sensible heat flux, $LE$ is the latent heat flux, and $G$ is the ground heat flux. Unless the ground is not in thermal equilibrium with its surroundings, the greatest part of the net radiation is balanced by sensible heat ($H$) and evapotranspiration ($LE$) processes. Ground heat flux ($G$) typically represents less than 10% of the total available energy ($R_n$).

If a change in land use (such as significant urbanization) occurs, other terms depending on different processes must be taken into account. Equation (3) is then rewritten as

$$R_n + F = H + LE + G + Qs$$

(4)

where $F$ is the anthropogenic energy (Oke, 1988) and $Qs$ is the storage heat flux, which is strongly dependent on the ratio between green and sealed areas and on the geometric, optical, and thermal characteristics of the building or urban landscape segment in question.

Oke (1987) proposed the following equations to quantify $Qs$:

$$day \ Qs = (0.20\lambda v + 0.33\lambda p) \ R_n + 3\lambda v + 24\lambda p$$

(5)
$night \ Q_s = (0.54\lambda_v + 0.90\lambda_p) \ R_n$

(6)

where $\lambda_v$ is the green area fraction and $\lambda_p$ is the building area fraction of the urban landscape (and where $\lambda_v + \lambda_p = 1$).

**Urban Air Pollution**

The high amounts of residential, industrial, commercial, and transportation activities in the urban environment lead to high concentrations of trace gases and particles. Resulting acute and chronic health hazards may become important threats to local, increasingly growing populations. The most frequent pollutants recorded in the urban atmosphere are gases, particles, and aerosols. The primary emitted gases are nitrogen oxides, sulfur oxides, and carbon oxides. Secondary produced gases, mainly derived from photo-oxidative reactions in the presence of solar radiation, include ozone; these reactions also generate significant quantities of radicals and aerosols (Seinfeld & Pandis, 1998).

Atmospheric pollutant concentrations are markedly higher over urban agglomerations than above rural settlements, not only because of the manifold emission factors in a city but also because of the peculiar urban thermal regime that tends to form during the daytime in which hot air is lifted up (as described earlier). This secondary circulation traps and recirculates pollutants within the urban boundary (Borrell & Borrell, 2000), resulting in a marked gradient in pollutant concentrations from the inner part of the city to the edge, often known as a “pollutant city dome.” Since the concentration of emitted pollutants is a function of air volume, the height of the atmospheric layer in which chemicals are mixed strongly influences pollution levels.

A general depiction of the 24-hour pollution cycle over a city is as follows: During daytime, solar radiation heats urban surfaces, which in turn increase the temperature of low-level air masses. This change decreases air density, causing uplift of the air parcels. The more solar energy is available, the more marked the uplift. Pollutants emitted into the air from the intense human activities during daytime are consequently trapped in the urban pollution dome. During the night, the energy available in the whole system decreases dramatically and the average height of the boundary layer diminishes by at least several hundred meters. This change causes a sudden increase of the atmospheric pollution level to a level often exceeding health safety standards (Fortezza, Strocchi, Giovanelli, Bonasoni, & Georgiadis, 1993). Occasionally, weather conditions may allow pollutants to accumulate over an urban settlement for several days. During the summer, this happens when long high-pressure periods occur over polluted areas (Fortezza, Strocchi, Bonasoni, Georgiadis, & Giovanelli, 1993). In winter, temperature inversions (caused by rapid cooling of the surface by radiative heat losses) strongly inhibit atmospheric mixing. The long-lasting high concentrations of pollutants in these circumstances can result in acute morbidity and mortality.
In 2012, the World Meteorological Organization and the International Global Atmospheric Chemistry project of the International Geosphere–Biosphere Program published a report entitled *Impacts of Megacities on Air Pollution and Climate*. This report evaluated and critically discussed the available information on air pollution in major urban agglomerations in Africa, Asia, South America, North America, and Europe. The authors drew several conclusions. First, while pollution is a serious problem across continents, the amount of scientific knowledge and consciousness about this problem varies greatly among megacities. Second, there is a clear opportunity to transfer knowledge from more studied to less studied urban areas for the purpose of combating air pollution worldwide. Additionally, large urban agglomerations are the potential primary agents for realizing the cobenefits of simultaneously controlling air pollution and mitigating climate change.

**Large-Scale Processes**

The effects of interactions between the built environment and local weather and climate are not limited to the outskirts of the city. They can produce climate changes on a larger scale and can significantly affect environmental phenomena. Specific effects consequent to the presence of cities (e.g., transport mechanisms for pollutants in the atmosphere) have been intensively investigated on the scale of tens to hundreds of kilometers.

It is well known that the formation of rain droplets requires not just saturation of the atmospheric water vapor at the ambient temperature but also the presence of particles, that is, ice crystals, to act as nuclei of aggregation (the Bergeron–Findaisen–Wegener process). Such particles are called cloud condensation nuclei. An atmosphere devoid of cloud condensation nuclei may become supersaturated (relative humidity greater than 100%) and will give rise to precipitation only after a very long time.

In the past, when sulfates were found in large concentrations in the atmosphere, air pollution caused the formation of aerosols composed of large particles. These particles acted as effective cloud condensation nuclei, leading to cloud formation and precipitation. It might be concluded that the presence of urban areas, which are abundant in atmospheric pollutants, always promotes precipitation downwind from atmospheric structures of synoptic transport (fronts, prevailing winds, etc.). That effect can have important consequences at the surface and for the overall balance of the water cycle, affecting conditions of underground water such as buried rivers and channels, as well as for the safety of citizens. Today, however, atmospheric sulfate concentrations have been greatly reduced by changes in combustion processes and fuel composition, leading to a marked decrease in cloud condensation nuclei and induced precipitation.

The specific effects of atmospheric pollutants on precipitation in urban areas are unpredictable. The influence of aerosol pollution in any particular region may be complex, not only because of the variety of processes that produce aerosols and local-scale meteorological processes that can either concentrate or disperse aerosols but also because the cloud-seeding properties of aerosols depend on particle size. Smaller particles inhibit rather than promote the formation of hydrometeor (any form of water or ice particle
reaching the ground) particles (e.g., D. Rosenfeld, 1999, 2007). Particle sizes of compounds used in cloud-seeding experiments may be as large as 2–5 µm in diameter, and natural cloud condensation nuclei are typically on the order of 0.2 µm. By contrast, small particles, for example, from forest fire smoke, may be 0.1–0.2 µm or less. Since 1998, data obtained from the Tropical Rainfall Measuring Mission (http://trmm.gsfc.nasa.gov) have allowed quantification of the effects of aerosols of different diameters on the micro-physical mechanisms of cloud formation. Daniel Rosenfeld, one of the leading researchers on cloud modification, demonstrated, for example, that precipitation was suppressed downwind from fires in the forests of Indonesia (D. Rosenfeld, 1999).

Rosenfeld (D. Rosenfeld, 2000) raised the question of whether urban and industrial pollution could have a significant effect on precipitation downwind of these mountain range systems. Since 2000, experiments in California, Israel, Australia, and many other regions, using data collected at ground level and by aircraft and satellite, have shown that the presence of small-diameter aerosols can suppress precipitation amounts by as much as 10–25% (Alpert, Halfon & Levin, 2008; Cai & Cowan, 2008; Rosenfeld & Givati, 2006).

Impacts of Climate Change on Cities

Cities are major emitters of greenhouse gases (GHGs): World Bank data (http://data.worldbank.org/indicator) indicate that they are responsible for approximately 40% of global GHG emissions. At the same time, cities are the systems that are most vulnerable to hazards related to climate change. In many parts of the world, cities are under pressure because of massive urbanization, and they are often stretched to the limits of their resilience. Multiple stressors contribute to the vulnerability of the complex urban environment. Climatic change and variability increase the occurrence and duration of heat waves, induce more frequent and intense droughts and floods, and expand and exacerbate coastal and riverine flooding.

Urban air pollution and urban heat waves are recurrent topics in scientific, policy, and public health discussions. The Urban Climate Change Research Network (UCCRN; http://uccrn.org) has recognized that if cities are to transition to more sustainable management, they urgently need to understand their vulnerability to climate change and to put in place adaptive responses. The UCCRN also has acknowledged the many “best practices” already developed and adopted by cities across the world, which can be adapted to specific local needs and then adopted at large scales to pave the way toward a more sustainable future.

The main sectors in which climate change has a strong impact on cities are the water use cycle, the energy system and transportation, and public health.
Impacts on the Water Use Cycle

Urban water systems are quite complex, and climatic conditions can place great pressure on the water use cycle. Increased precipitation falling on impervious surfaces can overcome the capacities of drainage systems. Both increased flooding and increased droughts compromise water quality and quantity in many cities. Dealing with these two combined phenomena requires innovation in water management systems at different scales. A nexus approach is needed that ranges from local and municipal systems up to federal and interstate agreements and cooperative infrastructure management. City managers in coastal areas have the obligation to consider potential sea-level rise events, higher storm tides, salt-water intrusion, and land subsidence, all of which may greatly vary in character and degree spatially; adaptive solutions therefore must be site and circumstance specific.

The environmental and economic consequences of water-related events are impressive. Hurricane Katrina in 2005 caused a loss of 1,833 human lives and economic damage evaluated at $US125 billion (https://ipl.econ.duke.edu/dthomas/docs/ppr/14Jun-Disaster.pdf) in New Orleans and the widespread range of other affected areas. Dramatic floods have occurred in many other cities as well, during which intense rains, soil saturation, and flooding over river banks restricted by obstacles and paved structures caused extensive death and widespread damage to buildings and to agriculture and other activities. Looking to the future, the cost of flood damage in Buenos Aires, for example, is estimated to grow by 2030 to US$80 million per year (Rosenzweig, Hammer, Solecki, & Mehrotra, 2011), even without taking into account the loss of productivity of the areas affected by flooding.

Some potential strategies for managing water use in the future include (Water Scarcity Drafting Group, 2006):

- reducing non-revenue-generating uses of water through detection, repair, and reduction of unauthorized withdrawals
- reviewing and editing of facilities for subterranean and surface waters to make them less vulnerable to flooding or drought
- investing in new technologies such as rainwater harvesting and water reuse
- public education on and improvement of management (social, environmental, and economic) of water use and conservation
- adoption of water-efficient household appliances, industrial processes, and agricultural practices.
Impacts on the Energy System and Transportation

City life is strongly energy consuming and GHG releasing. According to the IPCC’s 2007 report, the transportation sector accounts for 23% of the world’s GHG emissions. Demand for energy increases or decreases as a function of climate (less heating in winter and more air conditioning in summer) (A. H. Rosenfeld et al., 1995) and local peculiarities. Average temperatures in several cities are projected to increase by 1-4 °C by the 2050s (Figure 8). The increased number of summer heat waves (Mishra, Ganguly, Nijssen, & Lettenmaier, 2015) has resulted in higher energy demand for air conditioning; the number of households with air conditioners in Chinese cities has increased dramatically over the past several decades (Dickson, Baker, Hoornweg, & Tiwari, 2009).

To maximize energy savings and mitigation of impacts of climate change, a specific analysis should be done for each city to determine how climate change affects its overall energy demand. Lower energy consumption decreases the high cost of energy itself and reduces the associated emission of GHGs. Actions to reduce energy demand and carbon emissions include development of on-demand management programs and use of alternative energy sources such as renewables. Such proactive steps may efficiently couple energy savings with indirect beneficial feedbacks, increasing resilience to flooding, storms, and temperature-related risks. An additional benefit is that decreased energy costs can foster the fight against fuel poverty (Fabbri, 2015), an emerging problem of the city system that depends on three main factors: family income, energy prices, and the energy performance of buildings.

Cities have adopted several strategies in recent years to reduce emissions associated with transportation, such as providing bike lanes and pedestrian walkways and increasing the amount and availability of public transportation around and in the city. Some cities have regulatory and pricing instruments designed to reduce the number of private
vehicles on the roads and affect the timing of their use. Other cities promote the use of more efficient and low-impact fuels—for example, by converting public transportation buses to run on compressed natural gas.

**Impacts on Managing Approaches**

The varying impacts produced on the city metabolism impose to policy makers to approach the urban managing taking into account, to increase the resilience of the urban system as a whole, all the relationships between the different compartments of the city plans. In addition, it is necessary to foresee the effects produced by the changes over a long time period, because the decision taken cannot be easily modified on short-terms.

Additional long-term, tactical strategies for mitigating and adapting to changed energy demands are manifold. They include land use and transportation planning; constructing transport systems with materials that are more resilient to high temperatures; reducing UHI intensity and size by planting trees, replacing road surfaces with permeable materials, and replacing roof surfaces with green and reflective roofs; using larger culverts and catch basins for precipitation and flooding; moving rolling stones to locations protected from floods and winds; and special operational measures such as traffic closure during extreme events, closing tall bridges during extreme hazards, and providing media information about road conditions.

**Impacts on Human Health**

The most important threats posed to urban areas by climate change are undoubtedly the negative consequences for human health, either because of the social consequences, increasing disparities between poor and rich people, or because of the large number of people potentially affected. Direct effects may include deaths due to extreme events such as cyclones, storm surges, and ice storms that damage trees and structures. Indirect effects of the same extreme events include destroyed homes, limited access to clean water and food, and exposure to biological and chemical contamination that may cause or add to outbreaks of disease.

Physical processes in the urban microclimate described earlier may lead to increased discomfort and exacerbate impacts on human health such as respiratory difficulties, fatal and nonfatal strokes, and altered sleep cycles. The World Health Organization (WHO), with the Global Health Observatory, monitors concentrations of urban pollutants and their effects on human health. WHO reports that in 2012 (http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/) approximately seven million people died as a result of exposure to air pollution—one in eight of all deaths worldwide. This finding more than doubles previous estimates and confirms that air pollution is now the world’s largest single environmental health risk.

Urban settlements and their residents will become even more vulnerable in years when thermal anomalies occur. Hotter and longer heat waves directly influence well-being, particularly for vulnerable groups (children, elderly, and the sick). Heat waves also favor
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high UHI intensities and are accompanied by nighttime releases of heat that greatly increase physiological discomfort (Cardelino & Chameides, 1990; Changnon, Kunkel, & Reinke, 1996; McMichael, 2000; Sillman & Samson, 1995).

A single excessive heat event (EHE) can cause hundreds of additional deaths; Kaiser et al. (2007) calculated, for example, that the EHE in mid-July 1995 in the U.S. Midwest led to more than 700 excess deaths. Kalkstein, Greene, Mills, and Samenow (2011) estimated that for 40 major cities of the U.S. in the years 1975–2004, EHEs caused an additional 1,300 deaths per year for a total of approximately 38 million deaths, compared with a U.S. population of 281 million (United States Census Bureau, 2009).

EHEs affect not only mortality but also morbidity, resulting in increased hospital admissions. During the Chicago heat wave in 1995, which lasted more than a week, more than 1,072 excess admissions were recorded, an increase of approximately 11% over normal conditions (Semenza, McCullogh, Flanders, McGeehin, & Lumpkin, 1999). The majority of these admissions (56%) required treatment for dehydration, heatstroke, and heat exhaustion—clinical events directly induced by EHEs. Analysis of comorbidity data also revealed excess admissions for cardiovascular disease, diabetes, renal disease, and nervous system disorders. In addition to the 1,072 excess admissions, records showed 443 cases with primary discharge diagnoses linked to heatstroke and heat exhaustion, including fluid disorders, electrolyte and acid–base imbalances, and acute renal failure due to dehydration. A 20% increase in pneumonia and emphysema resulting from the hot and humid weather was found, as well as a marked increase in admission for diabetes. People with diabetes are highly vulnerable to risks during EHEs, because fluid disturbances may exacerbate poorly controlled glucose.

![Figure 9: Differences from average temperature during the European heat wave of 2003.](http://en.wikipedia.org/wiki/Heat_wave)
An EHE of historic proportion affected Western Europe in 2003. It was estimated that no event of similar scale had occurred in the previous 150 years. For approximately three months (June 1 to August 31) temperatures remained well above the climatic average over a region centered over France and stretching from the Iberian Peninsula to Germany and Italy (Figure 9). In Italy, maximum daily temperatures exceeded 38 °C for an entire week, 6 °C higher than the average maximum; minimum daily temperatures were also much higher than average (Kalkstein et al., 2008). The 2003 European heat wave offers an especially indelible example of the potential cost of not preparing for climate change: Italy, France, Spain, Germany, Portugal, and Switzerland experienced 72,210 heat-related deaths (http://www.eurosurveillance.org/viewArticle.aspx?ArticleId=694). In France alone, the heat-related mortality was estimated to exceed 15,000 cases (Koppe, Kovats, Jendritzky, & Menne, 2004; Poumadère, Mays, Le Mer, & Blong, 2005).

An epidemiological study of the 2003 European EHE (Conti et al., 2005) strongly highlighted the role of UHIs during heat waves and showed that the elderly urban population is particularly susceptible to extreme heat: Of the excess mortality of 3,134 in the Italian population studied, the greatest increase in deaths was recorded among the elderly, 2,876 in total. An epidemiological study in Stockholm County, Sweden, highlighted the vulnerability of the elderly to both high summer and low winter temperatures (Rocklöv, Forsberg, Ebi, & Bellander, 2014). The study also characterized health effects for other subpopulations. Heat exposure and heat wave duration had a particularly strong impact on the mortality of women and of individuals previously hospitalized for mental disorders and cardiovascular disease. Low temperatures were associated with higher mortality among persons with previous hospitalization related to mental disease and acute myocardial infarction.

A specific heat exposure index calculated by Rey et al. (2009) for the 2003 EHE clearly indicated that the strongest effects occurred in the most urbanized areas, where heat waves and UHI effects operate synergistically to negatively affect the health of the populations.

It is urgent that urban management strategies be developed and deployed to reduce such dramatic health impacts. The principal strategies must come from local health agencies, which can act at various levels. They can provide urban populations with information on climate change and the threats it poses to health and establish emergency plans in case of flooding or tropical cyclones. Systems for giving inhabitants early warnings about upcoming extreme weather events can enable them to react more effectively.

Conclusions

As reported here, the specific characteristics of the urban climate require a specialized study approach and an integrated vision to determine and critically examine solutions for issues related to the quality of life of city inhabitants. The complex interrelationships between outer and inner flows of atmospheric variables within the urban environment are modulated and forced by the city itself, where the physical properties of building materi-
als and pavement and the architectural texture produce local (microscale) partitioning of the energy and radiative balances at the surface along with differential drags on wind flow. These physical interactions strongly affect bioclimatic indices of the physiological wellness of citizens.

The temperature in cities averages more than 1–2 °C above that of surrounding rural areas. This characteristic is particularly evident at night and in the summer, when the differential increases in temperature significantly reduce the daily temperature range in the city. Traffic, air-conditioned buildings, and the properties of roofing materials and urban surfaces (e.g., concrete and asphalt) combine to heat up the air and reduce or prevent infiltration of water into the soil. In addition, the reduction of green spaces, which is associated with lower soil ventilation and with sealing of soils, decreases the effectiveness of the city’s natural means of mitigating heat. Climate change, along with inferior living conditions for fragile people, such as elderly, in the urban environment, can also aggravate preexisting pollution conditions.

The particular environmental circumstances of the city do not allow us to rely on the observed or measured variables of conventional weather and climate standards recommended by the World Meteorological Organization, nor do “classic” patterns of weather and climate models fit the urban environment. Thus scientific research must focus on understanding the processes that determine the urban climate as well as the effects of urban climate on city residents. To protect vulnerable populations, large cities must base their policies on projected effects not just of global modifications of the climate but of their own, local decisions. Doing so requires developing instruments that use a wide base of knowledge to model or forecast future scenarios. To be translatable into effective operational tools, such knowledge must not only be based on urbanism or architectural design but also must be supported by a strong physical-chemical approach and apparatus.

City managers are in fact currently employing accurate, user-friendly tools in efforts to find the most suitable options for minimizing urban climate impacts and maximizing local human wellness. Because of the above-mentioned difficulties in applying modeling tools to the urban environment, this is no easy task. However, the state of the art now allows us to apply realistic representations of the main characteristics of the urban environment and its “metabolism” with reasonable success. The main obstacle to the use of such methodologies is not related to the tools themselves but to the lack of a master framework for their implementation and application; as a result, problems shared by various cities are approached for each city separately. Furthermore, dialogue among knowledge providers, solution providers, and policymakers, which should be strategic, is still inadequate.

To remedy the problems described above, it is urged that intervention strategies be developed to improve urban environmental conditions, considering the peculiar processes of the city as parts of a complex metabolism. Because cities experience numerous problems in common, it is important to share community strategies and the related documents and references internationally. In 2005, at the initiative of the mayor of London, the C40
group was born (http://www.c40.org/), which initially joined 18 of the most important cities in the world. In 2009 in South Korea, the C40 held its third summit, with 65 cities represented by 24 mayors (including those of London, Toronto, Tokyo, Seoul, Copenhagen, Sydney, Addis Ababa, São Paulo, Lima, Bangkok, Mexico City, and New Delhi), 13 local government councilors (including ones from New York, Melbourne, Beijing, Paris, Rio de Janeiro, Athens, and Los Angeles), and 28 other delegations. At the meeting’s conclusion, having recognized the importance of coordination among large cities in producing intervention programs and disseminating the results of efforts to reduce GHG emissions, the attendees signed an important and solemn declaration. The declaration included specific commitments to policies and measures aimed at mitigating and adapting to effects of climate change in cities:

To tackle climate change, cities shall adopt and implement policies and measures most suitable to their circumstances. It is important that C40 cities cooperate with all cities around the world and share best practices and technologies....

In establishing their own Climate Change Action Plans, cities will give preferential consideration to the following measures proven to be effective in many cities.

1. To take a systematic and secure approach, take institutional measures such as enacting city ordinances based on technical studies, engaging in long-term planning, and establishing Climate Change Funds.

2. To avoid, mitigate, or delay the impact of climate change by reducing greenhouse gas emissions....

3. To adapt cities to the unavoidable consequences of climate change, providing citizens with a secure environment and higher quality of life by conducting forecasting analysis and thus minimizing the damages caused by climate change....

4. To promote the engagement of city residents to address climate change effectively....

City planning, management, and policy decisions can have a significant, direct influence on the city’s interaction with local and regional meteorological and climatic parameters, and so can potentially facilitate the physiological well-being of citizens. Some public administrations have recently considered using bioclimatic indexes as indicators of the public welfare, opening an ongoing discussion about the opportunity to index economic development in terms of “gross national happiness” rather than conventional gross domestic product (Helliwell, Layard, & Sachs, 2013).

Governance practices, land use, planning and management are strongly interconnected with the threats posed by climate change. Past zoning and decisions about how to allocate and use land create the initial circumstances from which climate-related vulnerabilities may arise. Local administrators and the governance environment at large can influence what is being and will be done about these threats, and at what pace. Progress toward adequately addressing climate change mitigation strategies requires efficient man-
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agement, science-based policies, financing, jurisdictional coordination, and citizen participation. Participation by citizens, in particular, should be not only a target but also a compass by which municipalities steer policies that firmly represent the wellness of residents as the heart of a truly sustainable urban system.

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