Advances in Urban Climate Modeling

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Cities interact with the atmosphere over a wide range of scales from the large-scale processes, which have a direct impact on global climate change, to smaller scales, ranging from the conurbation itself to individual buildings. The review presented in this paper analyzes some of the ways in which cities influence atmospheric thermodynamics and airborne pollutant transport. We present the main physical processes that characterize the urban local meteorology (the urban microclimate) and air pollution. We focus on small-scale impacts, including the urban heat island and its causes. The impact on the lower atmosphere over conurbations, air pollution in cities, and the effect on meteorological processes are discussed. An overview of the recent principal advances in urban climatology and air quality modeling in atmospheric numerical models is also presented.

Key words: **urban climate; urban meteorology; urban modeling; air pollution; urban heat island**

Introduction

Cities interact with the atmosphere over a wide range of scales. A schematic view of the interactions in the urban environment and the air quality and climate change processes that occur at various scales is displayed in Figure 1 (after Ref. 1). However, a significant knowledge gap exists in relation to the interactions between the large-scale processes, which have a direct impact on global climate change (these will not be addressed here in detail), and the impact of these processes at other smaller scales ranging from the conurbation itself to individual buildings.

It is in cities where the greater part of human activity occurs; hence, an understanding of the role that cities play in global warming is of great importance. As confirmed by the Fourth Assessment Report of the United Nations Intergovernmental Panel on Climate Change,[2] anthropogenic influences, primarily from emissions of greenhouse gases (GHGs) and aerosols,[3–5] are the most significant causes of the current global warming trend. Energy production and consumption are the principal sources of GHG emissions (CO_2, CH_4, see Fig. 2), with industrial activities and transportation also making a contribution. Agricultural activities and general land use account for 22.5% of GHG emissions. In order to reduce the extent of global warming, there is an urgent need to reduce the anthropogenic emission of GHGs. The Kyoto protocol, which was signed and ratified by 174 countries (as of November 2007) has set out the reduction objectives up to 2012, with efforts to continue after this date.[6] In France, for example, a fourfold reduction of GHG is envisaged by 2050.[7] Furthermore, ozone is produced from urban pollutants (see the next

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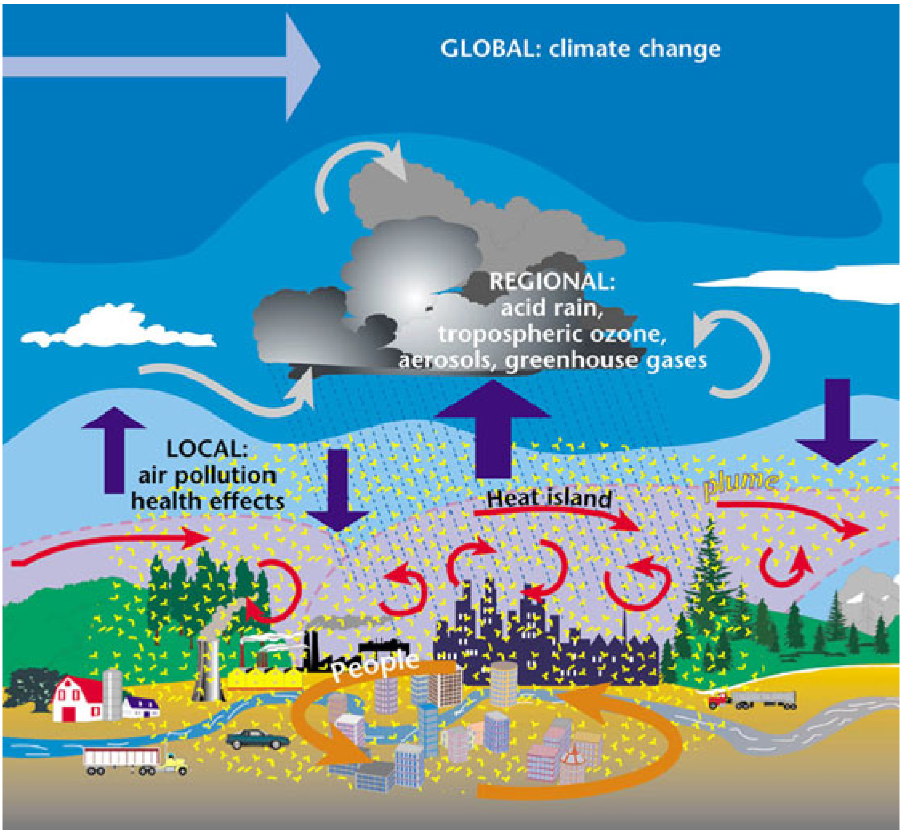

Figure 1. Schematic representation of interactions in the urban environment at various scales with regard to air quality and climate change processes (after GURME WMO[1]).

section) and concentrations are increasing in the troposphere, thereby also contributing to global warming.

The scope of this paper encompasses the impact of urbanization at the smallest scales. A wide range of urban features can influence atmospheric flow, its turbulence regime, and the microclimate, and can accordingly modify the transport, dispersion, and deposition of atmospheric pollutants both within and downstream of urban areas (e.g., acid rains). Key examples include the following:

- The heterogeneity of building distribution, and more generally of all rough elements of the earth's surface, affects the turbulence regime of the flow.
- The massive use of impervious materials and the scarcity of vegetation in urban areas affects the hydro–meteorological regime and pollutant deposition.
- The release of anthropogenic heat fluxes by human activity affects the thermal regime.
- The release of pollutants (including aerosols) affects the transfer of radiation, cloud formation, and precipitation.
- The street geometry ('street canyons') affects the flow regime and the exchanges of heat between different surfaces (e.g., roads and walls).

In this paper, the impacts of urban areas are described (section A) focusing on: (i) the Urban Heat Island (UHI) and its causes, (ii) the observation of the UHI and its main characteristics, (iii) the impact on the lower atmosphere (below 1 or 2 km), (iv) the city's impact on the

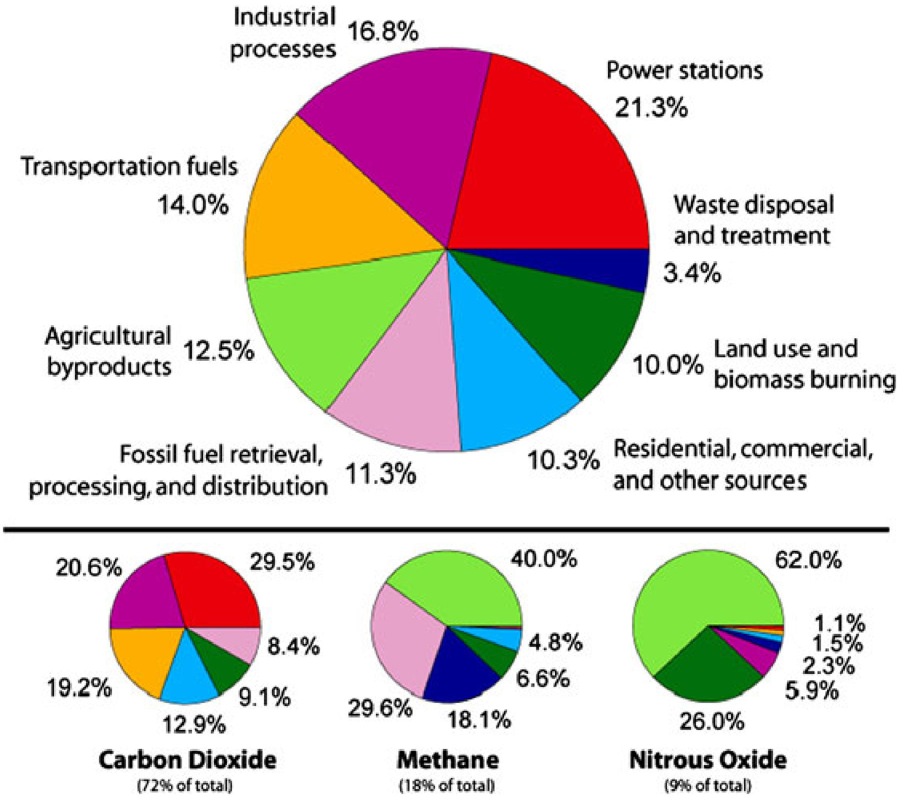

Figure 2. Annual greenhouse gas emissions by sector. Relative contributions of man-made greenhouse gases for the year 2000 as estimated by the emission database for the Global Atmospheric Research fast track 2000 project (http://www.globalwarmingart.com/wiki/Image:Greenhouse_Gas_by_Sector.png).

precipitation pattern, and (v) air pollution in cities. State-of-the-art techniques to simulate each of these topics in atmospheric numerical models are presented in section B. Some of these models are, or soon will be, used to perform operational weather forecasts over urban areas.

Description of Urban Microclimate

The Urban Heat Island and Its Causes

The most striking characteristic of the urban microclimate is the UHI. This phenomenon is generally experienced by an observer traveling between a city center and its less urbanized surroundings. The UHI effect causes the temperature to be warmer in the city center than in the surrounding area. The difference in temperature can reach up to 10°C for large conurbations under certain weather conditions.[8] Even though the effects of the UHI phenomenon are not usually catastrophic, as they are for hurricanes, tornadoes, or some thunderstorms, they can nevertheless intensify heat-related stress, especially at night during heat waves, and can lead to tragic consequences for public health. This was the case in 2003 when a strong heat wave affected Europe and caused more than 70,000 casualties, with a higher percentage of victims in urban areas, e.g., in France.[9] The UHI phenomenon has been observed in cities in a wide range of locations, from mid-latitude to high-latitude, as well as in tropical and equatorial areas.[10] Other atmospheric processes are also affected by urbanization, such as the dispersion of pollutants, fog formation, and

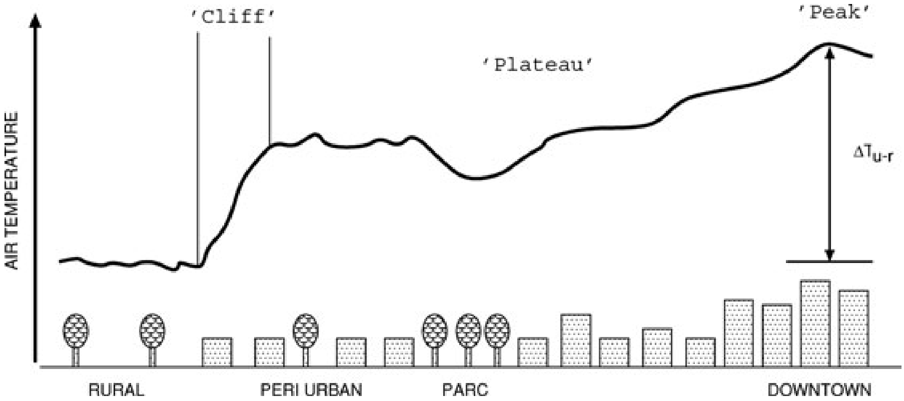

Figure 3. Typical air temperature characteristics in rural and dense urban areas. The spatial pattern of temperature is composed of the "cliff" at the rural–urban transition, the "plateau" in the suburban area, and the "peak" over the city center (adapted from Oke, 1987[8]).

dissipation. Since most economic activity and capital investment is concentrated in urban areas, research in this field is of high strategic value.

The time-varying characteristics of a UHI generally follows a daily cycle, increasing during the late afternoon or early evening, and reaching a maximum at night. Its intensity starts to decrease after dawn and generally reaches a minimum during the morning hours (see Fig. 3 for an example of a UHI in Toulouse, France, during winter). This temporal variability of the UHI has mainly been studied using pairs or groups of urban and rural or suburban weather stations (commonly airport weather stations). From analysis of the temporal evolution of an urban and a rural station (as in Fig. 3), it may be inferred that the UHI results from a differential cooling of the air at the two locations. The UHI is also affected by regional weather conditions. In the presence of strong winds or cloud cover, the UHI intensity is reduced, or the phenomenon may even disappear altogether. Seasonal cycles also affect the frequency of UHI occurrence. During rainy, cloudy, or windy seasons, a UHI may be less frequent or weaker, while the opposite is true for anticyclonic conditions.

At night, the UHI also follows a predictable spatial distribution. There is a sharp increase in temperature at the transition between rural and the urbanized zones. Towards the city center, there is a region of gradual temperature increase, with a maximum temperature being reached in areas of the most dense urbanization, characterized by high buildings and narrow streets (Fig. 4). Urban climatologists commonly use the ratio of building height to street width to quantify the density of urbanization.[11,12] The spatial distribution of the UHI has commonly been studied using instrumented cars traveling across a conurbation. This typical UHI pattern is clearly moderated by the structure of each city and the regional flow characteristics. For example, in a city with different cores of high urban density and for low wind speeds, the UHI can be multicellular.[13]

The nocturnal UHI generally extends a few hundred metres above the ground. In the case of a nocturnal UHI, a lower atmospheric layer (commonly 150 to 300 m high) is characterized by a linear reduction of the temperature[a] difference between the urban core and the

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[a] In Figures 3 and 5 the temperature variable used is in fact the "potential" temperature (θ), related to the true temperature (T) by: $\theta = T\,(p/100000)^{2/9}$, where p is the pressure (in Pascal). The potential temperature is equal to the true temperature near the surface. It is not, however, influenced by the ambient pressure decrease as a parcel of air rises. An air parcel rising adiabatically (without exchange of energy with its environment) would see its true temperature decrease (e.g., air is colder at the top of mountains) while its potential temperature stays the same.

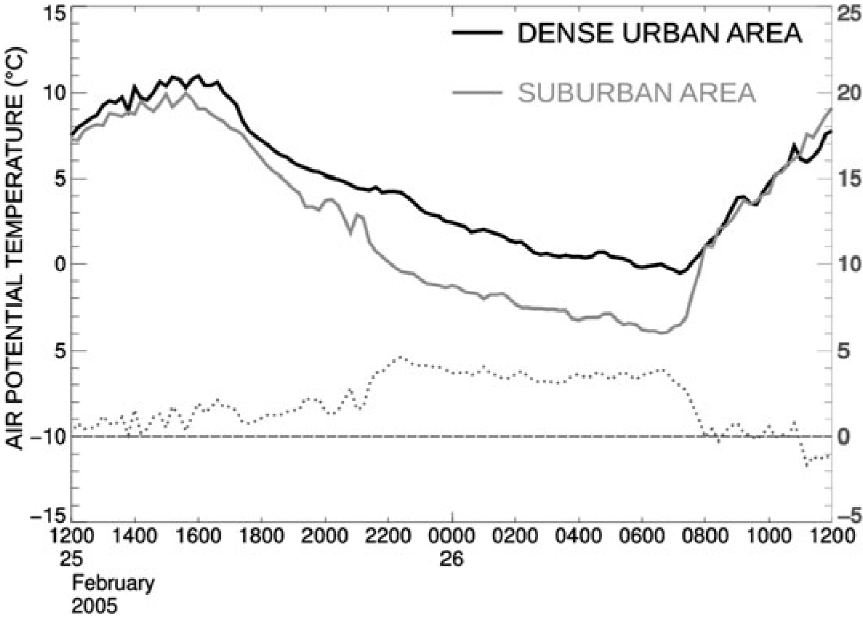

Figure 4. Temporal evolution of screen-level air temperature in an urban and an interurban area for a specific winter day in Toulouse (France). The temperature difference increases during the afternoon and reaches 5°C.

rural areas. In this case, the temperature difference disappears and a second atmospheric layer is observed, characterized by an opposite air temperature difference that favors the rural area. This atmospheric stratification is called the "crossover" (Fig. 5).

The processes that lead to the formation of a UHI have been established following urban field campaigns that focused on the exchanges of energy between the urban surface and the atmosphere[14–16]; the development of numerical models has been dedicated to the computation of these exchanges.[17–20] The formation of a UHI results in the modification of the Surface Energy Balance (SEB), which describes the energy exchanges between any "surface" (taking into account both the actual surface and all other obstacles: low-lying vegetation, trees, buildings, etc.) and the overlying atmosphere. Four common physical characteristics of urban areas modify the SEB and the micrometeorological processes that occur between a surface during the day and during the night compared to the same phenomena in rural areas. These are:

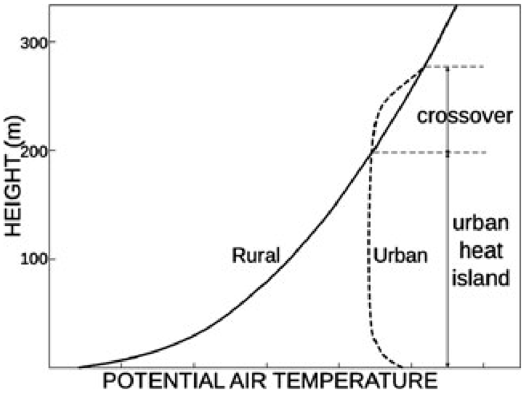

Figure 5. Nighttime air potential temperature profiles over a rural and an urban area. While the lower layers are dominated by the UHI effect, upper layers are not. This feature is called the "crossover."

[1] the scarcity of vegetation and the wide-scale use of impervious materials for buildings and pavements,
[2] the ability of building materials to store and release a large amount of heat within a few hours,
[3] the three-dimensional geometry of the urban surface (the "urban canyon" shape of streets),

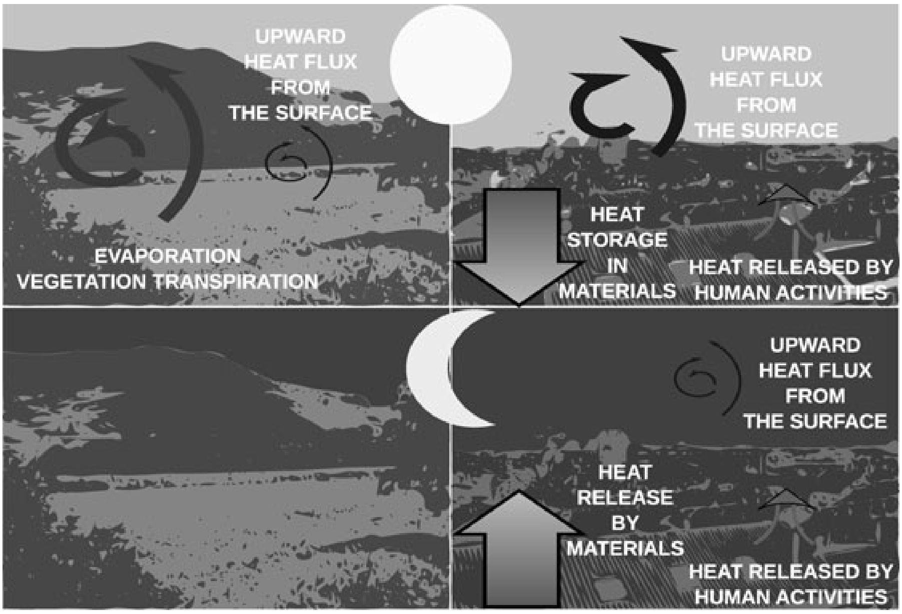

Figure 6. Sketch of Surface Energy Balance (SEB) over a rural area (left) and an urban land use (right) during the day (upper panels) and the night (lower panels). During the day, the rural SEB is dominated by evaporation of water from the surface while the urban SEB is dominated by the accumulation of heat in materials and air heating. During the night, while few exchanges occur over rural areas, the heat accumulated in material and released by human activities delays the air cooling.

[4] the release of heat by human activities (traffic, space heating, space cooling, industry).

During the day, most of the surplus energy coming from the positive net radiation (both in solar and infrared long waves) that heats the surface of vegetated areas (fields, forests, grasslands) is used up in the evaporation of the water contained in the soil, either directly at the surface or extracted by the roots and evaporated through the leaves of the plants (Fig. 6, upper left graph). However, when vegetation is scarce (characteristic [1] of the urban surface), this surplus energy is almost completely transformed into heat (materials and air heating). After this, characteristic [2] leads to an enhancement of the process of heat storage in the urban materials. As a consequence of these two properties, at the end of each period of daylight the urban materials have accumulated a higher quantity of solar energy than the equivalent vegetated rural area (Fig. 6, upper right graph). After dark, this large stock of energy is released to the overlying air and this delays or reduces the air cooling in the urban canyon (Fig. 6, lower right graph). Moreover, characteristic [3] further limits the cooling rate of the walls and the streets. Each (warm) wall and street in the urban canyon has a reduced exposure relative to a flat open surface (which is open to the sky and will cool more rapidly). Finally, characteristic [4] results in an additional source of heat in urban areas with a marked daily and seasonal cycle.

Observation of the UHI

The UHI was studied for the first time by Luke Howard [mostly known for the invention of the cloud classification (i.e., cumulus, stratus) already used today] in “The Climate of London (1820)”.[21] At that time, the population of London was approximately 1 million inhabitants, the largest city in the 19th century.

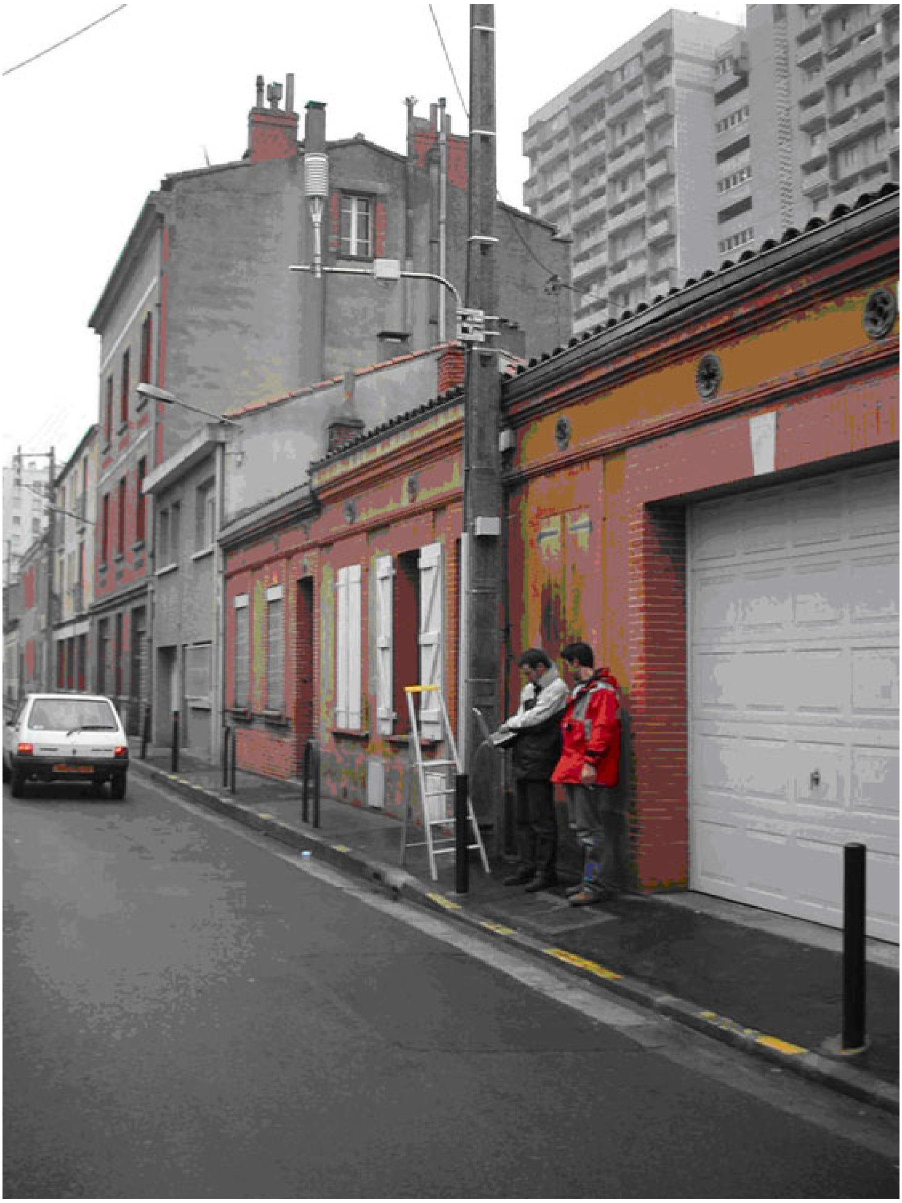

Figure 7. During the CAPITOUL campaign: the temperature and relative humidity instrumentation set up on an electricity pylon.

Howard studied 9-year temperature records from two meteorological stations, one in the city center and one in the outskirts of the English city, and found positive UHI by night (the city was 3.70 degrees hotter) and negative UHI by day (the city was 0.34 degrees cooler). He attributed this to the extensive use of fuel in the city (e.g., instantaneous heat releases by anthropogenic activities) and not to the built structure of the city itself. Historical as well as meteorological works would be necessary to determine the cause of this first observed UHI.

Additional studies of the UHI continued to use this methodology, i.e, the comparison of air temperatures measured simultaneously inside and outside the city[22] (this method has the

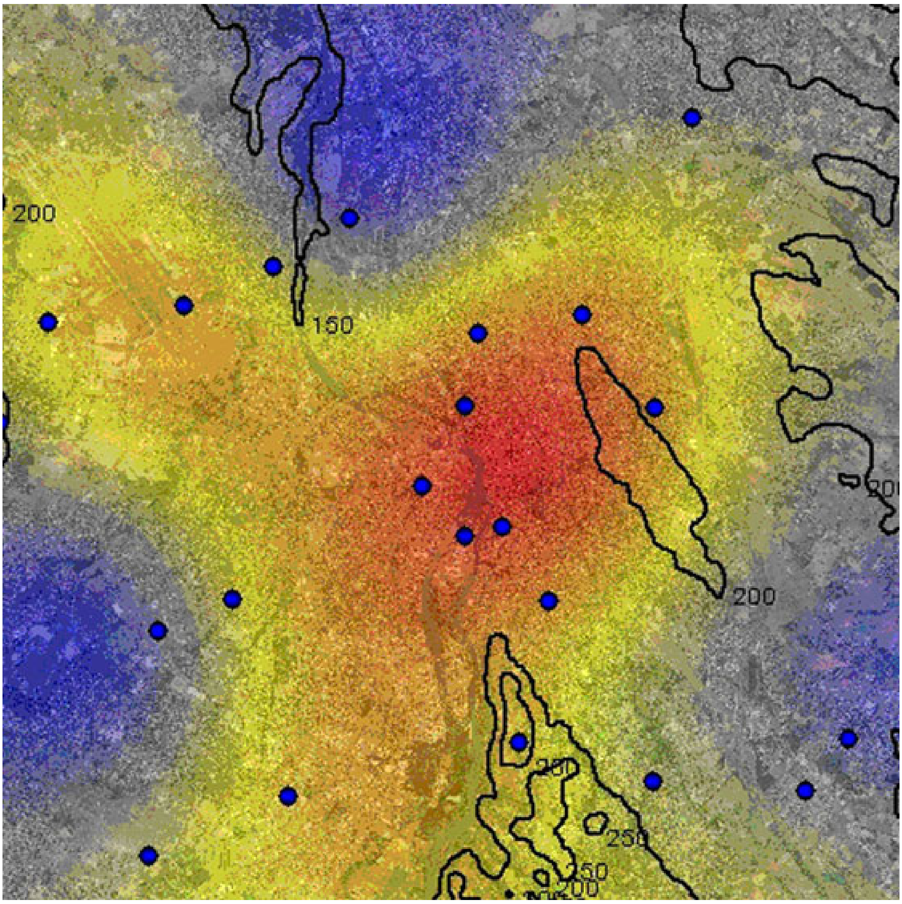

Figure 8. CAPITOUL campaign: Toulouse Urban Heat Island (UHI) (2 m above ground level observed potential temperature July 4, 2004, 22UTC; blue, 17°C; red, 21°C). Meteorological stations are displayed as blue dots (black lines are topography every 50 m).

advantage of available long-term records) or using instrumented cars (allowing good spatial distribution analysis but poor temporal representation). The earlier studies focused on the intensity of maximum heat island as a function of city morphology (see a review, Ref. 23). The diurnal evolution of the UHI is now well confirmed as well as its dependency on wind (the more wind, the less UHI). The UHI also tends to be larger in winter than in summer, but this may vary from one city to another depending on specific factors in the environment of the city (as the presence of mountains or sea coast). More recent works (reviewed in Ref. 24) tend to observe and analyze both the spatial and temporal variability of the UHI. For example, the study of the spatio–temporal variability of the near surface (2 m above ground level) UHI was an objective of a recent experimental campaign in Toulouse (France)[25] (Figs. 7 and 8). The seasonal distribution of the daily maximum UHI in Toulouse is displayed in Figure 9. For this medium-size European city (approximately 1 million inhabitants), the maximum UHI is indeed observed in winter (up to 8 degrees) and is smaller in spring (no more than 6 degrees). However, winter is also, by far, the season that has the largest number of days without any UHI (twice more than in spring and four times more than in summer). This can clearly be explained by the more windy and cloudy weather conditions during winter. Overall for

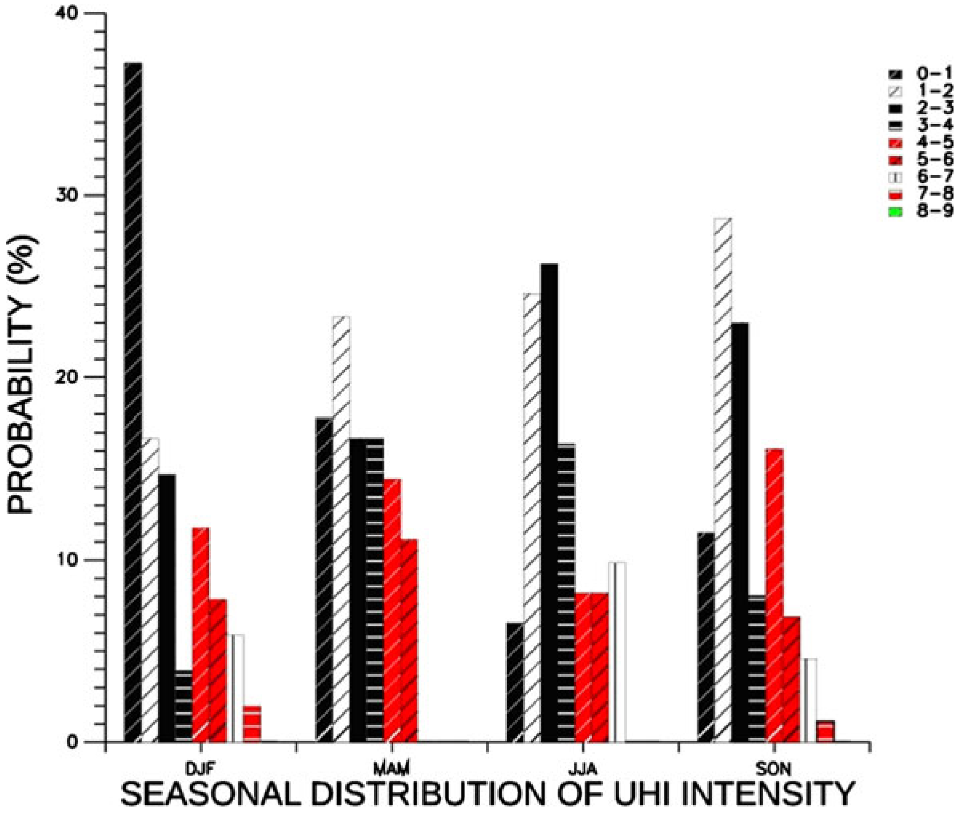

Figure 9. Climatology of the seasonal distribution of the daily maximum UHI observed in Toulouse during the CAPITOUL field campaign (winter: December, January, February; spring: March, April, May; summer: June, July, August; autumn: September, October, November). The scale indicates the range in Kelvin of the maximum intensity of the UHI for each day.

this city, a medium UHI effect (3 degrees or more) occurs more frequently during the warm seasons than cold ones, but the stronger UHI occurs in winter anticyclonic conditions when both large anthropogenic heat flux (from domestic heating) and insulation (leading to high heat storage) occur simultaneously.

Finally, new satellites with sufficient high-spatial and temporal resolutions allow the use of satellite images to measure the UHI. However, as outlined by Refs. 26 and 27, the link between the observation of the satellite (a *surface* temperature that is itself a mixing of temperatures of vegetation, roof, building wall, and road temperatures) and the *air* temperature of the UHI is not straightforward and is still an open field of research. The use of modeling tools to perform the transition between surface temperature and air UHI may be a good strategy.[28]

Urban Plumes and Breeze Caused by Turbulence in the Canopy

All urban areas have key impacts at the scale of a conurbation (from 1 to 100 km for megalopolises) which result mainly from variations in land use at this scale (i.e., from dense urbanized land to less developed land outside the urban area, either countryside or sea). As explained in the previous section, the SEB of urban areas usually induces a greater heating of the air leading to the UHI phenomenon. This heating can propagate in the lower atmosphere, also called the *Urban Boundary Layer* (UBL) in this case (see Fig. 10A, typically up to 1 km in height), and then toward areas downwind of the city. This is the “urban plume.”[8] For high wind speeds or in rainy conditions, the impact of the city on lower atmosphere dynamics is negligible

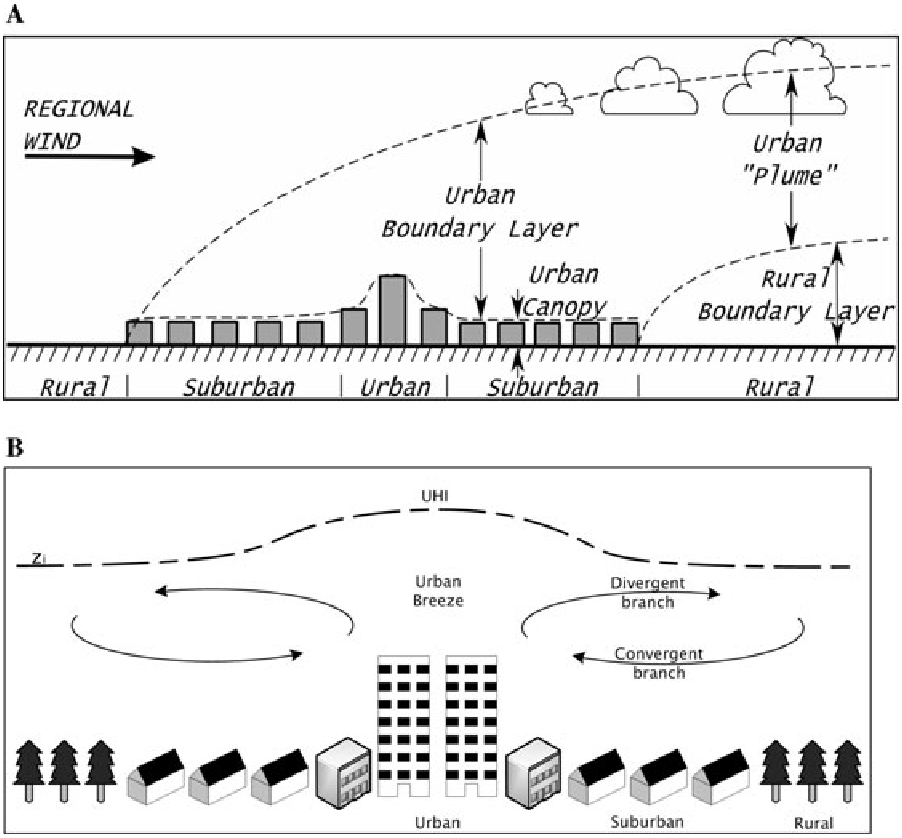

Figure 10. Schematic representation of **(A)** the urban boundary layer (UBL) in the case of the urban plume. **(B)** Schematic representation of the urban-breeze circulation in a hinterland city.

and only the emission of pollutants and their chemical transformation downwind of the city are important (see the next section). When the winds are moderate, as for anticyclonic conditions, the urban plume can transport the heat from the city center to the surrounding area. If the mean wind speed is low, then an "urban breeze" can develop (Fig. 10B). The urban breeze is a closed circulation associated with the UHI and is characterized by a strong updraft motion at the city center, by horizontal convergent flow above the heated surface, and by divergent flow in the upper layers. This urban breeze has been observed by aircraft over St. Louis, Missouri,[29] and recently over Toulouse, France.[30] A slow downdraft remote from the city closes the circulation. Such phenomena can be important because the divergence in the upper layers may modify the transport of pollutants. It should be noted, however, that for coastal cities, conditions that favor urban breezes also favor sea breezes, the latter being much stronger (e.g., Refs. 31–33). Fresh marine air that is transported by the sea breeze over the city is heated and transported inland as an urban plume. In mountainous areas, the interactions between cities and mountain flows (upslope and downslope flows) have been less well studied. Depending on the size of the city and the meteorological conditions (especially during long-lasting winter anticyclones), a city can develop its own microclimate, usually associated with high pollution. In summer, however, stronger mountain breezes limit the climatological influence of the city.

Finally, at smaller scales, a large heterogeneity may be observed. For example, street orientation, compared with mean wind direction, influences the channeling of air. Sunlit and shadowed roads (or pathways) experience very different temperatures. In this respect, the role of parks should be highlighted. The presence of green parks in dense city centers lowers the air temperature by a few degrees, not just in the park but also in denser areas up to typically 100 m around the park. In this way, the systematic inclusion of parks by urban planners could be a more reasonable alternative to any systematic increase in the use of air conditioning (this has been shown to increase the air temperature in a city as a whole by 1°C[34]). A detailed description (at least statistically) of atmospheric perturbations, especially for wind conditions, in streets below roof level and just above it is not important for understanding the urban microclimate at the scale of a city. This description is, nevertheless, crucial for understanding the dispersion of pollutants from road traffic and for estimating the pollution at the pedestrian level, including the fast chemical reactions that take place in the air (see next section) and the associated venting of these pollutants above the roof level into the urban plume. Several experimental campaigns have focused on statistical descriptions of the motion and temperature fluctuation of air at the street level (e.g., BUBBLE in the city of Basel, Switzerland[35]). These together with chemical measurements at the city scale allow a better understanding of the links between the small-scale thermodynamics of atmospheric flows and the related pollution.

Precipitation Induced by UHI and Cloud Condensation Nuclei

Over the last three decades, numerous field studies have shown that rainfall patterns in and downwind of urban areas have been modified (see the comprehensive review in Ref. 36). The most consistent finding has been an increase in the frequency of cloud cover and lightning, with associated enhanced precipitation. During the 1970s, the Metropolitan Meteorological Experiment investigated a possible increase in convective activity in the surroundings of St. Louis, Missouri (see Ref. 37), and confirmed that deep and moist convection was increased up to about 40 km downwind of the city. Since this study, other research has confirmed a similar increase in convective activity in other cities, such as Atlanta (Georgia)[38] and Mexico City.[39] Recently, the use of lightning detection networks[40] to analyze lightning flash data and satellites to derive both cloud frequency and rainfall rates (e.g., Ref. 41) have revealed significant increases in cloud-to-ground lightning, low-level cloud frequency, and rainfall rates in and within 30–60 km downwind of large cities.

There are three possible causes of urban-induced convective phenomena: (1) changes in circulation that are induced by the UHI, (2) an increase in urban surface roughness, and (3) an increase in the concentration of condensation nuclei (CCN; e.g., particles to which water can be adsorbed to form cloud droplets) from urban air pollution. The suggested influence of the UHI is a downwind updraft cell. This is consistent with the analysis of surface meteorological data that show a convergence zone induced by the UHI that favors the development of convective thunderstorms (e.g., Ref. 38). The effect of the increased urban surface roughness is a result of convergence induced on the upwind side of urban areas.

Over badly polluted cities, a large quantity of aerosols (small liquid or solid particles) may be emitted to the atmosphere. These can have physically the same effect as GHGs via a direct feedback mechanism that is caused by a change in radiation properties.[42] Their presence absorbs or reflects the solar radiation, limiting the amount of sunlight received at the surface, sometimes by more than 10% (e.g., over Mexico City[16]). However, aerosols also actively influence processes of cloud formation (indirect feedback mechanisms). Larger quantities of aerosol particles usually mean a larger quantity of CCN. The effect of CCN could be different for rain than for ice precipitation. Therefore, on the one hand urban and industrial air pollution can suppress rain and snow by increasing the concentration of CCN, which causes nucleation of many small cloud droplets that coalesce inefficiently into raindrops.[43] On the other hand, the reduced cloud droplet size results in a clear delay in the onset of precipitation, which could allow more intense updrafts and consequently more intense ice precipitation, hail, and lightning.[44]

Modeling studies have shown that the UHI exerts the greatest influence on deep moist convection,[45] initiating an updraft cell downwind of itself under favorable conditions.[46] The role of the increased urban surface roughness seems to be of lesser importance because although it induces convergence of the air flows in upwind urban areas, modeling studies have shown that it is too small to initiate moist convection. There are more uncertainties relating to the contribution of urban aerosols. Modeling studies[47] have suggested that variations in aerosol levels may not be the major reason for urban modifications to rainfall and instead the destabilization of the boundary layer by the UHI is the most important factor.

Recent work by Han and Baik[48] could yield a better understanding of the dynamics associated with this UHI from a theoretical point of view. In this work (i) a linear, theoretical, analytical solution for the perturbation of vertical velocity in a three-dimensional, time-dependent, hydrostatic, nonrotating, inviscid, Boussinesq airflow system is obtained and (ii) a nonlinear numerical model is used that includes extensive dry and moist simulations using a numerical model with advanced physical parameterizations. The analytical solution revealed a characteristic internal gravity wave field, including low-level upward motion downwind of the heating center, which could be the cause of the increase in precipitation that is observed downwind of urban areas. The nonlinear modeling showed that the maximum updraft in three-dimensional dry simulations propagates downwind and then becomes quasistationary. When using moist simulations, the downwind upward motion induced by a UHI can initiate moist convection and result in downwind precipitation.

Air Pollution

About 70% of the European population lives within city boundaries, and a major part of anthropogenic air pollution sources originate in conurbations. These pollutants not only have local effects (on human health, building materials, ecosystems) but may also cause impacts all the way up to the regional (acidification, eutrophication) and, as mentioned in the introduction, global scales (atmospheric composition, climate changes; see Fig. 1). At the local scale, atmospheric pollution from urban features is related to the urban emission of harmful pollutants (gases and aerosols, mostly from transport, energy production, and other types of industry) that have effects on the environment that are harmful to health as well as radioactive contamination from the release of radionuclides. This problem occurs mostly at urban and regional scales. The European Environment Agency has estimated that over 40 million people living in 115 major urban areas in Europe are exposed to pollutant levels that exceed the reference levels stated by the World Health Organization.

Many European urban areas have seen a general improvement in air quality in recent decades. Cleaner fuels and improved technologies for private heating, the introduction of catalytic devices in cars, and a general reduction in heavy industrial activity has led to a decrease in urban air concentrations of primary pollutants (SO_2, NO_X, total suspended particles) in many EU cities. Nevertheless, the quality of urban air is still considered a problem, particularly during short-term episodes that occur under adverse meteorological conditions (e.g., low winds, stable stratification, urban breeze; for example, in London in 1995 NO_2 concentration exceeded 400 parts per billion). This is a major concern for the protection of human health in the urban environment and has led to the introduction of EU Air Quality Directives to mitigate against

Figure 11. Main causal links between megacities, air quality, and climate.

the adverse effects on health of air pollution for European citizens. The new EU air quality standards, to be implemented by 2010, focus even more than before on the prevention of pollution events and on effective forecasting. Moreover, a reliable urban-scale forecast of air flows and meteorological fields is of primary importance for urban emergency management systems in the case of accidental toxic releases, fires, or even chemical, radioactive, or biological substance releases by terrorists, the potential risk of which has emerged during recent months.

As previously mentioned, urban emissions of pollutants, especially aerosols, are leading to climate forcing, mostly at a local and regional (but possibly global) scale. It is necessary to highlight that the effects of aerosols and other chemical species on meteorological parameters have many different pathways (e.g., direct, indirect, semidirect effects) and must be prioritized in integrated modeling systems. Chemical species influencing weather and atmospheric processes over urban areas include GHGs, which warm near-surface air and aerosols, such as sea salt, dust, and primary and secondary particles of anthropogenic and natural origin. Some aerosol particle components (black carbon, iron, aluminum, polycyclic and nitrated aromatic compounds) warm the air by absorbing solar and thermal-infrared radiation, while others (water, sulfate, nitrate, and most organic compounds) cool the air by backscattering incident short-wave radiation to space. In 2007, Baklanov *et al.*[49] demonstrated that the indirect effects of urban aerosols modulate dispersion by affecting atmospheric stability (the difference in deposition fields is up to 7%), besides which its effects on the UBL thickness could be of the same order of magnitude as the effects of the UHI ($\Delta h \approx 100$–200 m for the nocturnal boundary layer).

In Figure 11, we present a schematic description of the ways in which air quality and climate interact in a large city. Some of the links shown in the figure have already been considered in previous studies and are reasonably well understood. Nevertheless, there is a clear need for a more complete quantitative picture of these interactions. Understanding and quantifying these missing links is the focus of the new European project MEGAPOLI.

Modeling the Urban Influence of Cities on the Atmosphere

Urban Heat Island—Surface Energy Balance

Effective urban SEB modeling has been a research goal of the international community for some time in order to better represent UHI in atmospheric models or in numerical weather prediction (NWP) systems.[50] With the increase in numerical computing resources in past years, the typical spatial scale of NWP has decreased.

Nowadays, this scale is of a few kilometers and, in the model grid, some cells are completely urbanized. When the cells of the model were large, the fraction occupied by the cities was negligible and the representation of the urban SEB was not necessary. This means that operational NWP models were able to forecast the rural weather only (typically wind, temperature, and humidity in the countryside). Of course, the final meteorological forecast was also done for urbanized areas, but this was performed by an adaptation of these numerical rural forecasts by a human forecaster or by statistical relationships. Now, thanks to both the appearance of the urban surface models and the higher horizontal resolution of the atmospheric models (with some grid cells entirely covered by urban areas), the new generation of NWP models will have the ability to accurately forecast the urban microclimate, as for example, the UHI.

Three general approaches have been developed for urban SEB modeling: (i) the development of models statistically fitted to observations, (ii) the modification of existing models originally designed for modeling vegetated areas, and (iii) the development of new models dedicated to urban areas and based on a more realistic conceptualization of the urban surface.

The first approach is mainly based on the exploitation of observations of the SEB that are collected during field campaigns conducted in urban areas. The models obtained from this approach use statistical relations derived from the observations. The main asset of these models is their simplicity. They need very few inputs (type of surface, incoming solar radiation) and their computation is very efficient. Their main weakness is that they are only valid in the range of conditions observed in the field. One of the most complete and accurate of the models derived using this approach is the NARP-OHM-LUMPS.[18,51,52]

The second approach takes advantage of the long experience and background developed from soil–vegetation–atmosphere-transfer (SVAT) models. Some parameters from these models have been adapted to take into account the specific effects of urban surfaces on the exchanges of momentum; of water via evaporation at the surface; and of heat via conduction, radiation, and convection. Among the main parameters to be modified are the increase of surface drag from the presence of numerous large obstacles, the reduction of water available at the surface, the increase of heat storage in the surface materials, the trapping of radiation inside the canyon shape of the streets, and the additional releases of heat by human activities. Rapid advances have recently been made using this approach in atmospheric modeling and the coupling of these models to SVAT models.[53–55]

The aim of the third approach is more holistic. Models in this category are based on a more accurate conceptualization of the urban surface, for example by specifying canyon shape structures as considered in the Town Energy Balance (TEB) by Masson,[19] the "building blocks" approach considered by Kanda *et al.*,[56] and the "buildings of different height" approach considered by Martilli *et al.*[20] As a consequence, these models are based on more general and realistic physical equations for the different processes and require more computational resources for each model run. However, these kinds of models yield new perspectives for studying the interaction between urban areas and their environment. For example, the TEB model, which computes the demand of energy for space heating and considers the wide range of complex factors relating to the exchange of heat between urban areas and the atmosphere, is an interesting tool for estimating the evolution of energy demand as a function of climate change. Using these models, the impacts of urban planning policies could also be evaluated in advance. Over the next few years, efforts made in the development of these models will be directed towards improving the descriptions of the interactions between dry urban areas and vegetated areas and between the inside and the outside of buildings.

Urbanization of Atmospheric Models

As presented above, the key element that drives the urban microclimate is the urban SEB. The meteorology and climate are modeled by solving the atmospheric fluid mechanics equations (with several degrees of complexity and approximations). The lower boundary condition is determined by the topography and the exchanges between the surface and the atmosphere. Different kinds of models are used, depending on the scale of the processes under investigation.

- Urban- or regional-scale climate models, research-based meteorological models, NWP models, atmospheric pollution models.

The output from these models is an urban microclimate representation at the city scale (spatial resolution of around 100 m for the most detailed models), including the UHI effect. Consequently, only an idealized "averaged" representation of the urban canopy needs to be represented, but this input is crucial for simulating the SEB correctly. Thanks to recent increases in computational power, even NWP models now have a spatial resolution in the order of 2 km. With such a high resolution, the urban microclimate can be represented for most large cities (more than half a million inhabitants). Therefore, the coupling of an urban SEB scheme with an atmospheric model is mandatory. An extensive review of the methods used to achieve this coupling is presented in Refs. 49 and 57, and, as a summary, one of two main options is generally followed. First, for some specific air pollution studies (at the city scale), the statistics of the flow in the "averaged" canopy can be important, especially if the release of pollutants takes place at street level (see the next section). The atmospheric model will therefore represent the atmosphere at this level. This implies a relatively complex coupling of the urban canopy with the atmospheric model up to the top of the canopy. A recent overview of this can be found in Ref. 58. Second, for most studies of the urban microclimate, only the impact of the heat flux that originates from the surface, together with any slowing of the flow by the obstacles, is needed. In this case, the atmospheric model only goes down as far as roof level. In this way several phenomena have been simulated successfully, such as the UHI and urban breeze,[59,60] exacerbation of storms by cities,[45,36] interactions between the urban plume and the sea breeze,[32,33] nocturnal pollution,[61] and the impact of air conditioning in a high urbanized city.[34] Detailed description of the vertical profile of air down to the street level while retaining a simple coupling in atmospheric models has been done recently.[62,63] In future, this will allow a more detailed treatment of pollution studies (with a more accurate estimation at pedestrian level), as well as a better representation of the exchanges of energy between the buildings and the atmosphere. The latter opens the way for research on the impact of climate change and the evaluation of urban planning policy on the urban microclimate, especially in relation to issues of public health (e.g., in order to mitigate against the consequences of heat waves in cities).

- Small (building)-scale dispersion models.

For dispersion studies at very fine scales (e.g., to simulate the impact of chemical releases by terrorists) where flows along individual roads and around buildings are of interest, another kind of simulation tool is generally used. The total domain of interest is restricted in space (generally only a few blocks) and time (up to 1 h). In this case, only the flow dynamics are usually represented, not taking into account thermal effects or the heating of the air by surfaces. Therefore, classical (e.g., computational fluid dynamics [CFD]) type flow dynamics models are used, the influence of the surface being reduced to the precise shape of the individual buildings.

Pollution Issues

Urban air pollution (UAP) and atmospheric chemical transport (ACT) models have different requirements in terms of the way in which they represent urbanization (e.g., different importance of low-atmosphere structure details) depending on (i) the scale of the models (e.g., regional, city, local, micro) and (ii) the functional type of the model, e.g.:

- forecasting or assessment models,
- atmospheric pollution models for environmental and air quality applications (mostly for city scale),
- emergency preparedness models (mostly for city scale or micro-scale),
- integrated ACT and aerosol models for climate forcing,
- urban-scale research ACT models.

Incorporation of the urban effects into urban- and regional-scale models of atmospheric pollution should be carried out, first via improvements in the accuracy of meteorological parameters (velocity, temperature, turbulence, humidity, cloud water, precipitation) over urban areas. This requires a kind of "urbanization" of meteorological and NWP models that are used as drivers for urban air quality models or special urban met-preprocessors to improve nonurbanized NWP input data. However, in comparison with NWP models (as mentioned in the previous section), the urbanization of UAP models has specific requirements, e.g., better resolution of the UBL vertical structure; by themselves, the correct surface fluxes over the urban canopy are insufficient for UAP runs. Furthermore, for urban air pollution, from traffic emissions and for the modeling of preparedness for emergencies, there is a much greater need for vertical profiles of the main meteorological parameters and the turbulence characteristics within the urban canopy. Other important characteristics for pollutant turbulent mixing in UAP modeling include the mixing height, which has a strong specificity and inhomogeneity over urban areas because of the internal boundary layers, and blending heights from different urban roughness neighborhoods.[64]

For the modeling of preparedness for emergencies at local scale (e.g., biological, chemical, or nuclear accidental releases or terrorist acts) the statistical description of building structure is suitable only for distances longer than three or four buildings from the release, whereas for the first two to four buildings from the source, more precise obstacle-specific approaches are needed.

Other specific effects of urban features on air pollution in urban areas, which cannot be realized via the urbanization of NWP models, include:

- deposition of pollutants on specific urban surfaces, e.g., on vertical walls, from different building materials and structure, vegetation, etc.
- specific chemical transformations, including increasing the residence times of chemical species (e.g., inside street canyons), the heterogeneity of solar radiation (e.g., street canyon shadows) for photochemical reactions, and specific aerosol dynamics in street canyons (e.g., from the resuspension processes).
- very nonhomogeneous emission of pollutants at the subgrid scale, especially from traffic emissions, which need to be simulated on detailed urban road structures by taking into account the distribution of transport flows, etc.
- the indoor–outdoor interaction of pollutants (not only via heat fluxes), which requires a more comprehensive description and modeling of emissions.

The effects of air pollution on health are the final and most important aim of UAP modeling. It is therefore important to combine the UAP with population exposure modeling, which includes high-resolution databases of urban morphology and population distribution and activity.[65]

As was mentioned in Section A, urban pollution and climate are controlled by different scale interactions within the

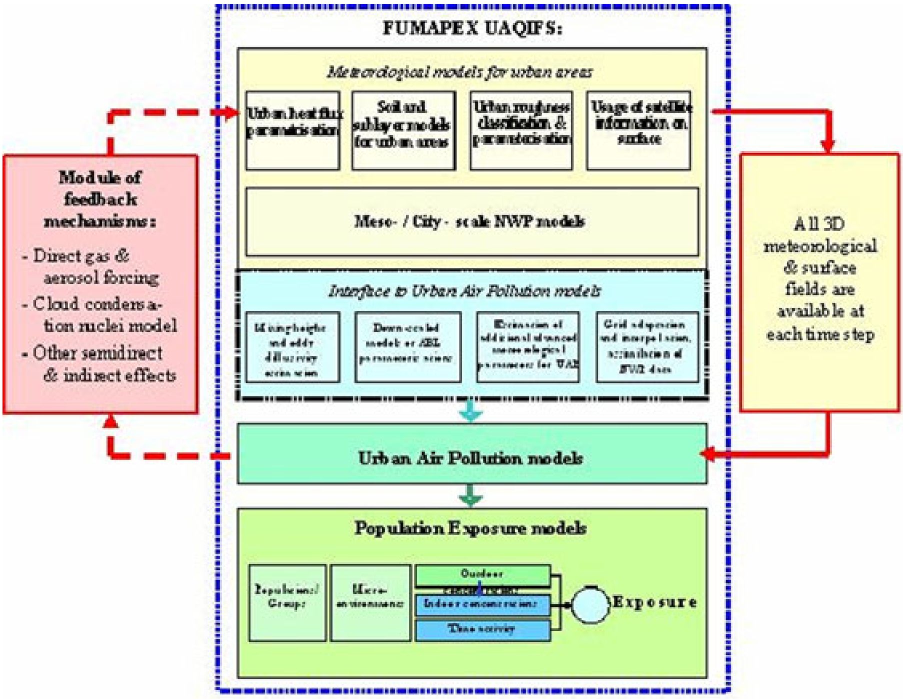

Figure 12. The online integrated system: Extended FUMAPEX scheme of the improved meteorological forecasts (numerical weather prediction) in urban areas, interfaces, and online integration with urban air pollution and population exposure models for urban air quality information and forecasting systems.

urban environment, air quality, and processes of climate change. Atmospheric processes at the micrometeorological scale depend not only on local features but also on larger scale processes, e.g., those of the mesometeorological (a few tens to hundreds of km) or even regional scales. Urban emissions also have an impact on air quality and climate not only locally but also regionally and perhaps globally. Therefore, the new generation of ACT models uses a nesting technique for the downscaling and upscaling of the models.[66–68]

One of the important requirements of air quality modeling is to develop more integrated modeling systems that can be used to interpret the impacts on the regional and global climate of aerosols and gas-phase compounds that are emitted from urban sources. Anthropogenic pollutants and, in particular, urban aerosol emissions are highly nonhomogeneous. The formation and transformation processes of aerosols with respect to the concentration of particles and precursors and their gas-phase chemistry are highly nonlinear. As a consequence, the scale at which the emissions, formation, and transformation processes are resolved in models has a significant influence on the resulting concentrations of the aerosols and gas-phase compounds.

Upscale cascade simulations can be performed using a combination of models resolving from urban to regional and global scales. Urban-scale modeling is primarily intended to evaluate the source term and the role of local processes in the transformation of aerosol emissions. The mesoscale model can define intense sources, such as those found in megacities, and investigate the evolution of large urban plumes (see e.g., Ref. 61). These plumes are subgrid phenomena in the regional–global models with the highest resolution (between 10 km and 100 km grid sizes) in the areas of particular interest. Therefore, urban-scale models can be applied to derive these subgrid parameterizations for the regional–global model. In order to understand the impact on the regional and global processes of aerosols and gas-phase compounds that are emitted from local and urban sources, three scales of the integrated atmosphere–chemistry–aerosol and general circulation models must be considered: local, regional, and global.

Conversely, it is also important to build a chain of urban models of different scales with nesting and downscaling of high-resolution models into larger scale lower resolution models. Usually, the micro-scale (street canyon) models are obstacle resolved and consider detailed geometry of the buildings and urban canopy, whereas the upscaled city-scale or mesoscale models consider parameterizations of urban effects or statistical descriptions of the geometry of the urban buildings. One example of such model downscaling and integration for urban meteorology, air pollution and population exposure modeling, which is based on the FUMAPEX methodology,[57,69] is demonstrated in Figure 12. This method can include downscaling from regional (or global) meteorological models to urban-scale mesometeorological models with statistically parameterized building effects and further downscaling to micro-scale obstacle-resolved CFD-type models.

In a general sense, the scale interaction can play an important role in both directions, i.e., not only from a larger scale to a smaller micro-scale but also from the urban micro-scale to the larger scale processes (e.g., the atmospheric transport of harmful pollutants initially released and dispersed in a street canyon; and urban climate and wind climatology). Therefore, two main types of nesting technique for the model downscaling can be chosen: (i) one-way nesting, when effects of the local city scale on the larger scale are not considered, and (ii) two-way nesting, when the scale effects in both directions (from the mesoscale on the city scale and from the city scale on the mesoscale) are considered in the same model.

Conclusions

This paper reviewed some of the ways in which cities influence atmospheric thermodynamics and airborne pollutant transport. Air quality is an important issue in the urban environment, and major cities have, for several decades, funded agencies to observe and forecast local air pollution. These agencies have two main roles. The first is to monitor and manage urban sources of the emission of pollutants hazardous to human health, such as gases and aerosols, mostly from urban transport, energy production, and other types of industry as well as possible chemical, biological, and nuclear releases from accidents or terrorist acts. This problem occurs mostly at an urban and regional scale. Their second role is related to the emission of GHGs and aerosols, which leads to climate forcing, at the city, regional, and possibly even global scale. In order to forecast atmospheric pollution in urban areas, models of the quality of urban air must address urban features, the chemistry of specific urban emissions, turbulence and wind flows within the urban canopy, aerosol feedback on urban climate, as well as other factors. One of the main requirements of air quality modeling is to further develop integrated modeling systems that can be used to understand the impacts on the regional and global climate of aerosols and gas-phase compounds that are emitted from urban sources.

Cities also influence the local meteorology, leading to what can be called the urban microclimate. Apart from air quality, the UHI is the best-known urban climate feature. The UHI mechanisms of generation are (i) heat storage in materials (by day) and/or heat release from materials (by night), and (ii) heat directly released by human activities (domestic heating, air conditioning, industries, traffic, among others). The first mechanism is more from changes in land use, while the second is from more immediate anthropogenic activities. State-of-the-art urban surface schemes now take into account these particular activities by modeling the complex radiative and energetic exchanges in an idealized three-dimensional geometry of the surface (often one or several "street canyons") and any anthropogenic heat releases.

Modification of the energetic exchanges between the urban surface and the atmosphere (compared to what occurs in the countryside) allows urban-specific atmospheric circulations at the scale of an individual conurbation. The presence of a city, under favorable weather conditions, modifies the low-atmosphere dynamics favoring the formation of thunderstorms, urban plumes, and urban-breeze circulations. All these local modifications of the climate from cities influence urban citizens' comfort and health as well as energy demands and economic consequences. As cities will continue to evolve, and most probably grow, in the future, these influences will become more drastic and add to those from climate change. In adaptation strategies, the development and urban planning of sustainable cities should take these considerations into account.

Conflicts of Interest

The authors declare no conflicts of interest.

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