Modeling methods to assess urban fluxes and heat island mitigation measures from street to city scale

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Abstract

The urban microclimate is due to complex physical interactions with the contribution of water balance, thermo-radiative exchanges and airflows. In this paper, we present and discuss modeling of heat island effects and mitigation techniques in order to give consistent results considering different time and space scales, and different fluxes (heat, water and winds) from ground to urban canopy, including buildings. The models and numerical descriptions are presented in detail and illustrated on typical examples of heat island mitigation techniques. At the neighborhood scale, alternative rainwater management techniques are studied by considering their impact on both seasonal water table depth and surface-atmosphere heat fluxes. Assessing the building thermal performance interactions with the microclimate requires adapted models that have to be refined for a better description of building envelope and systems effects. Two examples at the street and the neighborhood scale, modifying the building radiative properties or using green envelopes, show how simulation brings out the potential benefits of these techniques for the heat island mitigation and building energy performance.

Keywords: urban heat island mitigation; urban modeling; building simulation; district scale; rainwater management

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1 INTRODUCTION

1.1 Context

The microclimate of the cities is characterized by the urban heat island (UHI) phenomenon, which results in higher temperatures in cities than in rural areas, especially at the end of the day. It is closely related to urban form, materials and anthropogenic loads dissipated into the urban fabric such as heat losses from buildings or air cooling systems. Building design and urban planning have to deal with various and complex physical phenomena that are often highlighted for their negative impacts. Urban sprawl consumes agricultural land and contributes to the air pollution along with increased transport needs, as well as more substantial hydrological risks through soil and aquatic environments. Urban densification results in increasing the proportion of impervious artificial surfaces and in changing the urban fabric morphology. Beyond building energy performance, thermal comfort (indoor and outdoor) and rainwater management issues, this raises health concerns, as in the case of the summer 2003 heat wave, which resulted in an estimated 70 000 additional deaths in Europe. Given that the Intergovernmental Panel on Climate Change announced in 2007 a global warming of 1.1 to 6.4°C by the end of this century, it is now

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essential to better understand and predict the impact of urbanization on UHI phenomenon and propose technical solutions for microclimate mitigation purposes. The assessment of such mitigation techniques can be achieved by means of numerical tools that are both robust and capable of simulating realistic urban settings. Simulation approaches are very useful indeed to assess planning assumptions, including the use of alternative techniques, as a simpler step than conducting real-scale experiments. According to the proposed techniques and the physical phenomena involved, the space scale of the models varies from the city scale, considering the UHI phenomenon, to the street and building scale, considering the materials and building uses in detail.

1.2 Physical basis

Urban microclimate results from radiative, heat and water exchanges between the deep soil, the urban surfaces and the atmosphere. The multiple interactions related to thermal, radiative, hydrological and aerodynamic processes, including the thermal behavior of the buildings, are sketched, see Figure 1.

The water balance (Figure 1a) reflects the exchange of water between the soil and buried networks, the surfaces and the atmosphere, during either wet or dry weather conditions. This balance takes into account the spatial characteristics of the surface (impermeability, presence of vegetation), soil hydrological properties (permeability) and the presence of underground networks capable of generating preferential drainage into the ground. The evapotranspiration fluxes between the surface and the atmosphere correspond to the latent heat flux included in the surface energy budget (SEB). The energy budget (Figure 1b) expresses the balance between net radiation, latent heat flux (originating from the water budget), sensible heat flux (surface convection) and conductive heat flux both in the soil and through the building envelope (storage). The advective and anthropogenic heat fluxes (not represented in Figure 1b) are also involved in the urban energy budget, included either in the surface balance (thus considering the city surface as thick surface) or in the energy balance written for the air representing the urban canopy. The conductive heat flux depends on indoor environmental systems and loads (i.e. heating, cooling and other building uses). The heat balance of the building includes the balance between heat fluxes through walls and roofs, solar benefits, internal loads (occupants, equipment, etc.) and fluxes related to ventilation and air infiltration through the building envelope (Figure 1c). Sensible heat flux at the wall surfaces depends on near-wall airflow and temperature. Ventilation rates and infiltration also depend on external airflow, which in turn determines the pressure coefficient on the walls.

The expression of both these balances highlights the fluxes and state variables used to interpret the interactions between physical phenomena, yet these interactions are often neglected or simplified, by focusing on a specific aspect that can be grouped into four model categories: hydrology, radiation, airflows and energy budget. According to all these models, the evolution towards adapting new urban planning assumptions and physical interaction representations are either directly integrated into existing models or else tied to specialized models.

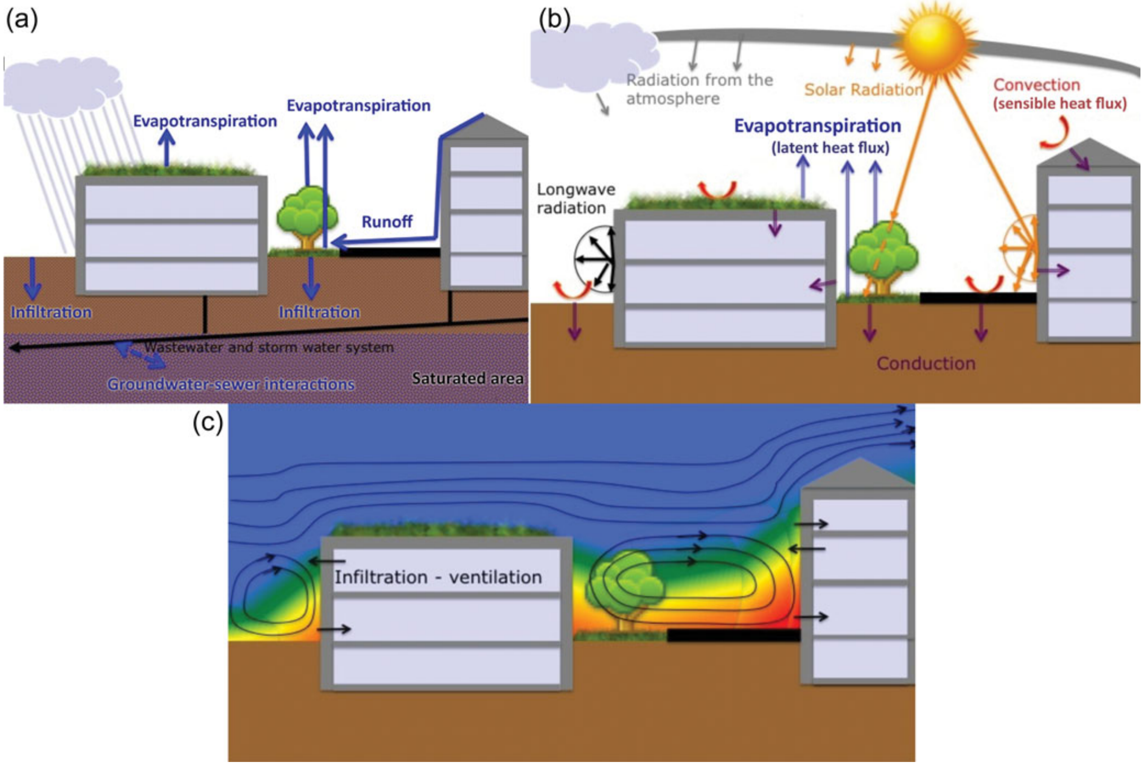

Figure 1. *Urban physical interactions contributing to (a) water balance, (b) thermo-radiative balance and (c) airflows.*

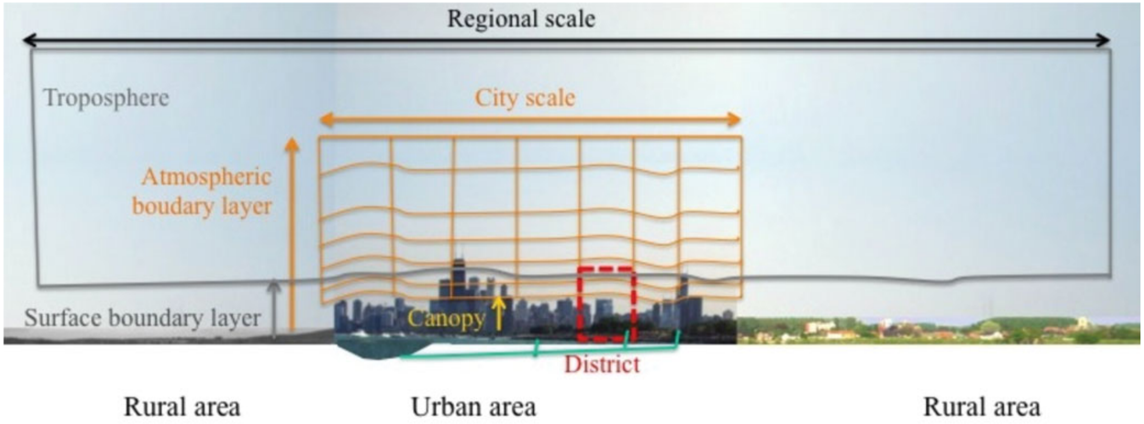

Figure 2. *Scales used in the field of urban microclimatology.*

1.3 Modeling approaches

Urban microclimate and hydrological behavior of urban surfaces and soils can be described at different scales (Figure 2) in order to satisfy different objectives.

To study the influence of cities on the atmosphere, with emphasis on the UHI phenomenon, the scientific community has developed models to reproduce the main energy and water exchanges between the urban surface and the atmosphere. In the past decade, there has been considerable progress in the 'urbanization' of atmospheric models [1–4]. However, examining urban amenities, the scale considered is that of the immediate environment, i.e. street, city square. These studies are usually performed with models requiring an explicit description of the urban scene (buildings and isolated trees) and that output the impacts of these elements on solar radiation, wind, temperature and humidity [5–9]. Two groups of urban climate models can thus be defined according to the modeled scales: those representing an urban fragment (i.e. extending from the street scale to a district), composed of different types of surfaces (i.e. buildings, soil and vegetation), in explicit terms (i.e. their geometry and relative positioning) and those representing a scale at which the surfaces cannot be explicitly described. It is worth noting that multi-scale approaches also exist. They were first developed to get more accuracy in modeling the pollutant dispersion in streets [10] but might be fitted to studying local microclimate. Then, a set of tools can be implemented to provide models designed at the scale of urban fragments with weather conditions from high-resolution models applied at a larger scale [11].

Hydrological models used in urban areas are usually focusing on the catchment scale, which varies between the district and the multi-district scales. Aiming at representing the hydrological response of a sewer pipe supplying with water an urban or sub urban river, urban hydrological models are based on a basic representation of the main land use features of the catchment, and especially man-made mineral surfaces for sewer design issues. Representing the runoff from impervious areas is indeed often considered as the dominant process of urban hydrology [12]. In the large-scale atmospheric models, the water exchanges between the deep soil, the surface and the atmosphere, required to estimate energy budget of the surface, are considered by means of simplified parameterization of hydrological processes in urban areas, such as in the SM2U [13] or TEB-ISBA model [2, 14]. However, Grimmond *et al.* [15, 16] have concluded that models accounting for these physical processes even in a crudely simplified way were more accurate in modeling sensible heat fluxes.

Moreover, in urban areas, the heat flux that contributes to the air warming contains a component related to human activity. A proportion of anthropogenic heat fluxes are indirectly represented when modeling the heat transfer by conduction in materials through buildings walls. Taking into account the anthropogenic fluxes resulting from the use of air conditioning systems and ventilation, which are closely correlated with weather conditions, should improve the modeling of both building energy performances and urban microclimate. Indeed, building operation contributes to UHI, especially in summer conditions when the cooling systems' loads increase, which consequently raises their contribution to the UHI simultaneously to their performance's cut. At micro-scale, building energy simulations are typically carried out over a 1-year period with an hourly time step and standard weather files generated from statistical processes covering several years of data [17] while microclimate simulations that calculate very local information tend to introduce a representation of weather types or climatic sequences over a few days. Combining these two kinds of models in order to estimate energy consumption, in considering both the local microclimate and the effect of the particular building on climate, requires special attention to each approach hypothesis. This is one of the main difficulties with coupled model implementation that lies in the differences between the spatial and temporal scales used to describe the inherent processes. At the urban scale, simplified thermal models for buildings (based on buildings typologies) have been introduced in some models [18–20] to address the climate–building interactions.

In this paper, we present some technical solutions and the necessary modeling tools to study and to include these techniques in decision processes. Each modeling approach presented in the following is adapted for its own studied scale, and the aim of this paper is to illustrate how it can be used for UHI mitigation in urban and building design; the bibliography references give more details on each model hypothesis. Models and technique studies from street to district scale are presented to highlight the design issues of UHI mitigation techniques (such as cool materials, green walls, etc.) and their impacts on building energy performance or thermal comfort. France's total energy consumption and the percentage attributed to the country's residential and commercial sectors have stabilized since 2006 around values of 162 and 71 Mtoe, respectively. These sectors account for 43% of all energy consumption and 23% of CO2 emissions. For the European building sector, the air conditioning of occupied spaces has been estimated at 57% of total energy demand and 33% of CO2 production. Such a reduction is much easier to achieve in new buildings than by replacing stock of older buildings, a program that should be planned over a several-year period. Reducing summer thermal stresses in an urban context may be partially and indirectly achieved by modifying the local climate through the use of mitigation techniques. These solutions present the advantage to be socially fair and healthy. They should be taken into account in the urban planning's decision process as well as in the building regulations and the development of methodologies taking into account the environmental, social and economic parameters. These issues are not easily integrated in neighborhood sustainability methods [21], such as HQE^{2}R in France, and need to be developed together with larger scale decision-support systems (DSS) for sustainable urban planning.

At this urban scale, the assessment of UHI mitigation requires larger-scale modeling of the physical processes presented here, which contribute to the urban metabolism components and the urban design. For example, the DSS developed in the European project BRIDGE [22] integrates the various physical fluxes (energy, water, pollutants . . .) in its inputs and outputs. However, we will focus here on mitigation techniques linked with rainwater management that favors infiltration of water in soils. Their influences on microclimate are presented using the results of both the urban hydrological model URBS-MO and the urban energy budget model SM2U, in order to illustrate the modification of the water and heat budgets due to these new urban planning tools.

2 URBAN MICROCLIMATE MITIGATION FROM THE CITY TO THE DISTRICT SCALE

2.1 Modeling the interactions between the soil, the urban surface and the atmosphere

2.1.1 *SEB models*

As stated in the section Introduction, the key of urban microclimate modeling is the representation of the interactions between the surface and the atmosphere through energy exchanges that condition the thermodynamic behavior of the urban atmosphere. This is the main purpose of urban SEB models that determine the heat and humidity fluxes at scales ranging from a hundred meters to several kilometers. At these scales, the various elements of the urban canopy cannot be represented explicitly. A study of climate at urban or neighborhood scales thus requires representing the urban environment characteristics that affect wind, temperature and air humidity. These characteristics include the urban morphology, the presence of impervious surfaces, the proportion of built and natural surfaces, and the physical properties of both the surfaces (albedo, emissivity) and materials (conductivity and thermal capacity). The main issue is to acquire urban data and transform them into useful model parameters. The fundamental morphometric parameters (and the derived morphological parameters) as well as the surface covering modes can be easily computed from the detailed urban databases such as those provided by the Land Registry [23] or by National Institutes of Geography [3]. The data about the surface radiative properties are more difficult to estimate due to the heterogeneity of the urban fabric and of the three-dimensionality of the urban canopy. New methodologies are developed in order to extract this information from satellite data [24]. Finally, the information about the envelope of the building is generally not available and has to be estimated, on average, from the knowledge of the practices at build time.

Whether empirical [25] or physically based, all SEB models are based on one common principle: the net radiation resulting from surface radiation budget is split into sensible heat flux, latent heat flux and stored heat flux, this later representing the heat transfer by conduction in materials and soil (Figure 1).

In the simplest physically based models (i.e. so-called bulk models), the sensible and latent heat fluxes are modeled at the interface between the urban canopy (as a whole) and the atmosphere above. The canopy is represented by its mean aerodynamic (roughness length), radiative and thermal properties. These fluxes depend on the temperature or humidity differences between the atmosphere and the surfaces as well as on an aerodynamic resistance, which may be a function of wind and atmospheric stability in the surface layer. With these simple models, such as the SM2U model [26] used in this paper to illustrate the influence of alternative techniques on microclimate, it is possible to distinguish the various surfaces (natural surfaces, vegetation, roads, roofs and canyon), which contribute in different ways to heat and humidity transfers at canopy–atmosphere interface.

More elaborated models consider just one canopy layer [14, 27] characterized by a simplified urban fabric (streets canyon, whether oriented or not, in which roofs, streets, and walls are distinguished); they model the interaction between these surfaces and the air in the street and above the roof by a system of aerodynamic resistances that prove more complex than the 'bulk' methodology, even though they are based on the same principle. In this case, the wind in the middle of the canyon is determined by empirical equations and the temperature in the canyon is derived from the balance between heat fluxes at the surface and those at the top of the canyon. Finally multi-layer canopy models exist where fluxes are calculated at different heights within the canopy; these calculations require knowing the vertical wind and temperature profiles. Whenever these models are directly implemented into an atmospheric model [1, 4], the climatic variables (and turbulence) are computed by solving fluid dynamics and thermodynamics equations, which have been modified within the canopy to take into account the averaged effect of buildings on wind and turbulence, plus the source/sink of heat and humidity at different levels.

All the SEB models can be used offline (i.e. without coupling with atmospheric models): the atmospheric forcing is then imposed by the radiation and meteorological data recorded above the canopy. For multi-layer models, the wind, temperature and humidity in the canopy are obtained by solving the simplified atmospheric surface layer equations [19, 20, 28, 29].

Choices have been made to take into account the physical processes involved in the SEB, regardless of the method chosen for computing sensible and latent heat fluxes. Some modelers have chosen to neglect the latent heat flux resulting from vegetation evapotranspiration, in considering only the characteristics of heavily built environments. In contrast, the effects of vegetation such as shading and radiation absorption can be directly integrated into the urban fabric representation [30]. In intermediate approaches, the latent heat flux from natural surfaces and vegetation contributes to total flux by virtue of its density, although vegetation does not directly interact with other surfaces. Heat storage, which may be significant in urban areas due to the characteristics of materials and the urban morphology, is sometimes calculated as the residual of energy budget, or else empirically estimated as a fraction of net radiation [25] based on the surface characteristics or computed using the formula for heat conduction through the various layers of materials. Moreover, in densely built areas, the solar radiation is trapped due to the reflections occurring between the different street surfaces and the radiative cooling at night is reduced. The sky view factor for the different surfaces of the street gives an indication about the intensity of the radiative exchanges between the surfaces and the atmosphere (compared with flat horizontal surface), so that it is currently used in urban SEB models for estimating the characteristics of the radiation. In models suited to the neighborhood scale, the sky view factors are computed for representative floor and walls based on morphometric parameters such as the mean building separation (or the street width) and the mean building height. In the SM2U model, for example, the radiative trapping in the streets is parameterized through the computation of an effective emissivity and an effective albedo, which also depends on the solar angle [26].

No real correspondence can be identified between the various modeled processes and the type of models (bulk vs. canopy) described earlier. For the specific reason of establishing modeling guidelines, an international research effort has recently been made to conduct a comparison of these models. The purpose therein was to ‘classify’ the most successful approaches for representing exchanges between the urban canopy and the atmosphere, in addition to the physical processes that must not be neglected as part of physical modeling [15, 16]. One of the conclusions of this study is that a representation of the effects of vegetation and natural surfaces, even when present in a small proportion, improves the model results. At the same time, it appears that the latent heat flux is the less well-modeled component of the energy balance. This outcome may be due to poor knowledge of the soil water content or to the use of rural vegetation models. While two potential urban climate regulations call for the widespread use of vegetation and new rainwater management practices, efforts must be coordinated with hydrologists in order to better represent, in climate models, interactions between the surface and the underground.

2.1.2 *Urban hydrological models*

Traditional hydrological modeling approaches often focus on representing hydraulic flows, aiming at either simulating storm events potentially generating urban floods or sizing sewer systems (sewer pipes and retention ponds). These approaches have evolved over the past 10 years in favor of models including a more detailed representation of the water cycle [31, 32]. Various modeling approaches have been developed in order to further refine a detailed representation of the water cycle in urban areas, as characterized by strong material heterogeneity (e.g. mineral surfaces, vegetation), also resulting in heterogeneous water flows.

Hydrological models adapted to urban areas usually introduce a rough parameterization of the evapotranspiration flux and separate the evaporation flux due to the soil surface from the transpiration flux due to vegetation. The actual evaporation flux is estimated as a fraction of the potential evapotranspiration (PET), in proportion to water storage in the soil surface reservoir [23, 31]. This parameterization is carried out without taking into consideration the potential effect of mineral surfaces warming on the evaporation flux. The transpiration flux of pervious areas is estimated based on knowledge of soil moisture and PET, in accordance with the parameterizations derived by modeling work performed on rural hydrology [31, 33]. These ‘hydrological’ parameterizations avoid any use of data and microclimatic parameters (temperature, humidity, wind profiles, etc.).

‘Water-energy’ approaches associate the simulation of energy and water balances with a better representation of water flow to the surface. As part of a simplified approach, Xiao *et al.* [34] presented a hydrological model in which the PET was estimated from a modification to the Penman equation, through the use of the following data: net radiation, air temperature, wind speed at a distance of 2 m and saturation vapor pressure. The actual evapotranspiration can then be deduced from PET by following the same method as in the models described earlier. This Xiao model is used in particular to test the impact of Best Management Strategies applied at the neighborhood scale and may help developers compare their efficiency with respect to water balance changes.

In more elaborate approaches, water and energy balances are simulated through a coupling, like in the Water and Energy transfer Process model [35] and the NICE-URBAN model [32]. This innovative approach towards coupled modeling allows simulating the impact of mitigation strategies so as to evaluate their performance in terms of water and energy balances. For example, it shows that the use of porous materials, capable of storing water (permeable pavement and/or asphalt), instead of more conventional materials (asphalt or concrete) can reduce not only the surface temperature but also air temperature above the surface by a few degrees compared with the conventional materials. This type of analysis would not be possible with the hydrological modeling approaches reviewed earlier.

This evolution in hydrological simulation tools may be related to changes in soil models that simulate the energy balance in adopting a simplified consideration of hydrological processes in urban areas, such as in the SM2U [13] or TEB-ISBA model [2, 14]. An evaluation of alternative urban planning options for improving the amenities of city dwellers (e.g. more vegetation, infiltration and reuse of rainwater, use of permeable or reflective materials) requires this kind of integrated approach. Efforts made regarding more targeted studies on the hydrology of urban areas need to be pursued.

2.2 Energy and water approaches for mitigation strategies assessment

2.2.1 *Alternative techniques for rainwater management*

The evolution of urban hydrological modeling described earlier is in agreement with the recent evolution of rainwater management strategies dedicated to the urban context. These strategies promote rainwater infiltration, local storage and evapotranspiration, through the use of techniques that are called ‘Best management strategies’ (BMPs) in urban planning, including landscaped ditches, green roofs, porous materials and the creation of water zones or basins. These types of techniques are currently applied in low impact development neighborhoods, called ‘ecoquartiers’ in France. These techniques were initially implemented in order to reduce the volume of rainfall runoff at the outlet but are effective at retaining pollutants too [36, 37]. Some other impacts of these strategies should be further investigated. Infiltrating more water in the soil should modify the soil moisture distribution and can cause rising groundwater tables in urban areas [38]. The possible perturbation of urban climate is another focus: the impact of specific alternative techniques such as green roofs on UHI effect reduction has been studied by several authors [39, 40]. These strategies could contribute to the urban environment cooling, but some further studies are necessary in order to evaluate the overall impact of rainwater management strategies. This is illustrated thereafter on a case study.

2.2.2 *Assessment of mitigation strategies*

Methodology The impact of the alternative techniques for rainwater management is studied by modeling the water and energy budgets with two models. The physically based hydrological model URBS-MO, for Urban Runoff Branching Structure Model [23], can reproduce both the spatial and temporal variability of the hydrological processes in an urban catchment, including the runoff contribution of each land use (house, natural soil and street), the evapotranspiration and the soil moisture. The urban SEB model SM2U (see Section 2.1.1) forced by meteorological forcing such as solar radiation, wind, air temperature and humidity determines the fluxes between the canopy and the atmosphere. These fluxes depend on the average land use fraction in the neighborhood: artificial (impervious) surfaces, buildings and natural (pervious) surfaces. Vegetation can partially cover natural (and artificial) surfaces, intercepting water during rainy periods and favoring evapotranspiration processes during warm days. The soil water budget takes into account the evapotranspiration, the water infiltration from natural surfaces and the diffusion between the natural surfaces and two soil layers (a root zone and a deep soil layer). A part of the runoff rainwater from roofs and roads is collected in the network while the other part is collected by natural surfaces, contributing to the increase of the soil water content. All these features allow us to assess the influence of various hypothesis of urban planning on urban microclimate. When used offline, i.e. without retroaction on the climatology variables, the analysis is based on the diurnal evolution of sensible, latent and storage heat fluxes. Note that the SM2U model was previously validated for densely built urban area [26] and for residential suburban district [13].

The case study concerns an urban catchment area located within the Nantes metropolitan growth center (western France) called Bottiere-Chenaie. This is a 40 ha ‘ecoquartier’ (neighborhood sustainability program) under construction in the catchment area (Figure 3—left) with a rainwater management strategy (2008–2013). BMPs implemented in this neighborhood include green roofs, vegetated ditches (Figure 3—right) and retention basins. The runoff rainwater is mainly collected by vegetated ditches, which favor the infiltration within the soil.

Two development scenarios have been simulated for this case study: the actual ‘ecoquartier’ (i.e. ecodistrict) scenario, which consists in modeling the 40 ha neighborhood with the rainwater BMPs, and the potential ‘traditional’ scenario, which consists in modeling this neighborhood without BMPs, i.e. with traditional buried sewer pipes collecting runoff rainwater and with basic sloping or flat roofs. The vegetated fraction is 46% in the traditional scenario whereas it is 62% in the ecoquartier scenario, the difference being mainly due to the replacement of part of the street surface by vegetated ditches and to planting vegetation on the bare soil (Table 1).

The hydrological modeling of both scenarios has been implemented with URBS-MO by using the following input data: rainfall intensity observed in the Gohards catchment [23], Penman PET (PET) collected from the meteorological station located 10 km from the catchment outlet. Morphological features of the neighborhood, including natural and impervious fractions, were estimated based on the urban databanks available for the Nantes metropolitan area. The water budget parameter set used for the evaluation of URBS-MO in the Gohards catchment [23] has been transposed to the ecoquartier simulation, due to the proximity of both catchments. URBS-MO makes it possible to simulate BMPs due to basic modifications of the unit modeling scheme [41].

Figure 3. *Project map of the urban planning of ecoquartier Bottiere-Chenaie in Nantes (left); vegetated ditch receiving runoff rainwater coming from streets and houses (right).*

Table 1. *Description of the neighborhoods in the three configurations analyzed with the SM2U model results.*

	Traditional dense (%)	Traditional (%)	Eco-quartier (%)
Artificial surfaces	30.0	20.0	15.0
Built surfaces	45.0	22.5	22.5
Bare soil	4.0	11.5	0.5
Vegetated surfaces	21.0	46.0	62.0
Runoff rainwater collected in network	100.0	100.0	20.0

The relevance of the model URBS-MO has been evaluated using long and continuous series of atmospheric forcing on a close catchment [23]; in this study, this model was used in order to assess the hydrological processes sensitivity to the development scenarios.

The techniques favoring the rainwater infiltration in the soil might have an influence on the microclimate. In order to assess their impact, we used the SM2U model under the same assumptions for surfaces fractions as in the hydrological study. A third configuration more densely urbanized is also studied to serve as reference. The morphological features are presented in Table 1. The simulations were performed using meteorological data collected at the permanent observatory site of the IRSTV [42] located close to the ecoquartier Bottiere-Chenaie (Figure 3). In order to analyze periods when natural surfaces and vegetation might have an important role in the energy budget, we chose a 5-month period extending from April to September 2008.

Results The hydrological impact of the ecoquartier compared with the traditional development has been estimated through a two-year continuous simulation with URBS-MO from August 2003 to August 2005. Both the runoff reduction and the water table modification have been analyzed. The peak flow reduction is in average 8% for the ecoquartier scenario compared with the traditional one, which is a well-known and expected effect of such rainwater management strategies. The hydrological model simulates both the soil moisture and the water table in any point of interest; here, we represented the water table in the middle of the ecoquartier (Figure 4). Initially located 1.5 m below the soil surface, the water table depth shows a seasonal evolution, increasing in winter and decreasing in summer. Infiltrating water in the soil modifies tremendously the shape of the water table evolution and shows high differences in winter, where the main rainwater is produced. Both the water table level and the soil moisture are also modified in the summer to a lesser extent.

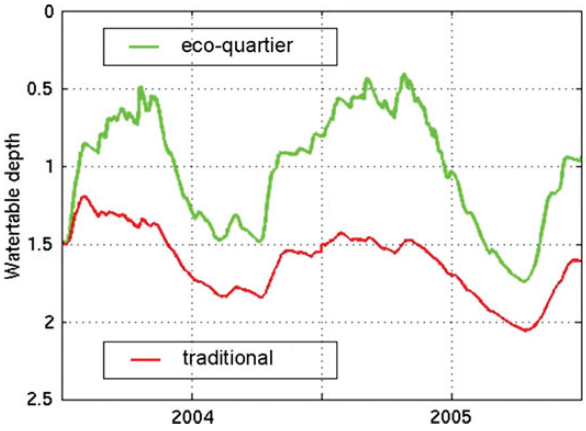

Figure 4. *Comparison of water table depth in the traditional and 'ecoquartier' scenarios.*

The results from SM2U simulation show that the soil moisture in the eco-quartier configuration (ECO) presents larger variations than in the other scenarios (Figure 5). For significant periods of rain, the soil moisture in the ECO simulation increases fast because 80% of the runoff rainwater infiltrates through natural surfaces. It reaches values ∼2.5% higher than in the traditional configuration (TRAD) and 3.8% higher than in the dense traditional district (TRAD-dense). However, the soil moisture in the ECO scenario also decreases faster than in the other scenarios during warm (and dry) periods, and the values obtained are slightly lower than those of the TRAD scenario. This behavior is due to the evapotranspiration by the vegetation that represents a larger fraction of the surface in the ECO than in the TRAD (or TRAD-dense) scenario (Table 1). In the TRAD-dense simulation and during this quite dry period, the soil moisture stabilizes around a value ($0.25\ m^3/m^3$) up to 8% higher than in the ECO simulation. This behavior results from the large fraction of impervious surfaces, which limits the water exchanges between the soil and the atmosphere.

As suggested in the previous analysis, the surface covering types (including vegetation fraction) and the strategies for decreasing the runoff have an influence on the canopy energy budget. An increase of the evapotranspiration (equivalent to the latent heat flux, LE) due to the change of artificial surfaces by natural surfaces should result in a reduction of the sensible heat flux (Hs) and/or of the storage heat flux (G) in the soil (and in artificial materials). The sensible heat flux is very important for the air temperature diurnal variation, since during the daytime it is responsible for the air warming induced by the heat exchanges between the surfaces and the atmosphere. The sensible and latent heat fluxes are presented on Figure 6 for the three scenarios during two sunny days corresponding to a dry period. As expected, the latent heat flux is weak in the highly urbanized district (TRAD-dense). The higher values are observed during daytime for the district ECO, and the maximum reached around 12:30 in the TRAD scenario is $60\ W/m^2$ weaker than in the ECO. Despite the large deviations in the latent heat fluxes, the maxima of sensible heat fluxes in configurations TRAD and ECO only differ $\sim 12\ W/m^2$. This is the result of the heat storage in the soil that contributes to balance the energy budget. The heat released from the soil and materials during the night leads to a positive sensible heat flux, which is the weakest in the ECO scenario. It is interesting to notice that the fluxes simulated in the ECO scenario are close to those of a rural area where the sensible heat flux is generally weaker than the latent heat flux.

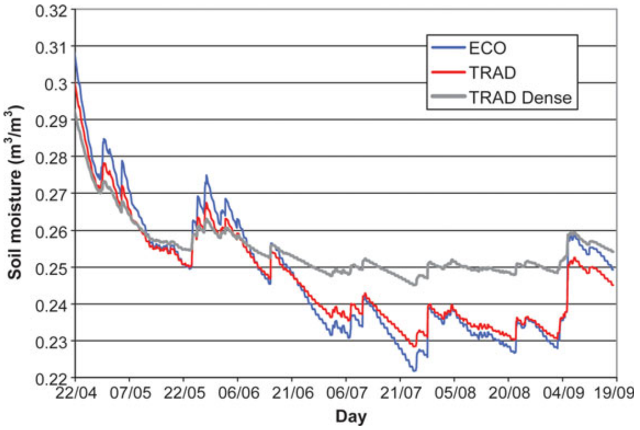

Figure 5. *Comparison of the soil moisture computed by SM2U for the 3 scenarios: TRAD, Trad-dense and ECO.*

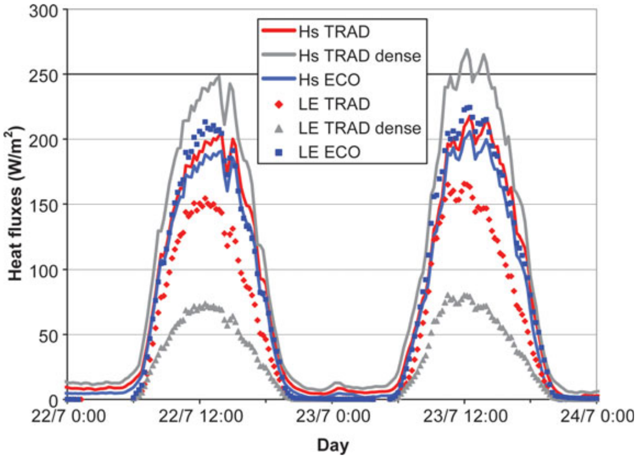

Figure 6. *Comparison of the sensible and latent heat fluxes computed by SM2U for the 3 scenarios: TRAD, Trad-dense and ECO.*

From this sensitivity study, it is clear that rainwater management techniques consisting in replacing impervious by pervious surfaces or increasing the vegetation fraction might have a positive impact on the regulation of the summer urban microclimate. However, in order to quantitatively highlight their influence under more severe conditions, other meteorological scenarios (including those of other climates and the predictions of climate change) should be considered as well as other urban morphology and material properties.

3 THE THERMAL ENVIRONMENT AND ENERGY DEMAND CONSIDERING HEAT ISLANDS EFFECTS AT BUILDING SCALE

3.1 Energy performance and local effects of UHI

3.1.1 *Assessing microclimate around buildings*

Focusing on providing an accurate assessment of heat and mass flows for a limited domain, simplified and semi-empirical approaches are often needed to complete the mass and energy balance equations within built-up areas, soil, vegetation and urban canopy layer.

A first group of models is specialized in radiative and solar energy computation, which is one major contribution to the UHI. Complex urban forms can be computed with tools like DART [43], SOLENE [44, 45] and SOLWEIG [46]. The thermal comfort can be assessed from the mean radiant temperature, which is a representative indicator of thermal comfort conditions in the external environment. Thus, the SOLWEIG model overcomes the heat balance of walls with a few approximations: according to this model, surface temperatures are evaluated from both air temperature and sun exposure over time. Therefore, this model mainly focuses on a radiation computation completed by parameterizations for the other phenomena.

Another group of models can be distinguished as mainly based on solving heat, mass and momentum conservation equations within a gridded air volume. ENVI-met [47], SOLENE-microclimat [48, 49] and 'coupled simulation' [50, 51] would be categorized in this group; they are used to calculate radiative fluxes, surface temperatures, wind velocities, air humidity and temperature in a complex urban geometry, and even with the presence of vegetation. For the purpose of these models, vegetation is considered as a porous medium to wind and semi-transparent to solar radiation. The evapotranspiration and photosynthesis processes are expressed via the mass and heat balances. These three models have similar applications but reveal in their implementation two distinct approaches:

- ENVI-met and 'coupled simulation' were developed as comprehensive models, which require model integration for all phenomena. This approach has required the development of simplified sub-models. E.g. ENVI-met 4.0 now integrates heat storage in the walls [47]. In 'coupled simulation', model development is limited in its potential range of geometric complexity, by only considering an orthogonal grid, which remains unsuitable for most urban fragments found in European cities.
- The step of coupling specific models was developed in SOLENE-microclimat. An evaluation of outdoor comfort conditions was computed by Robitu [9], Figure 7 from [48], through a strong coupling between SOLENE (for radiative and thermal transfers in walls and floors) and FLUENT (for airflows). Airflow modifications due to natural convection effects were taken into account. This strong coupling is computationally extremely intensive but could be conducted for the amenity issues studied herein, which require sufficiently short simulation periods. Subsequently, in seeking to evaluate building energy consumption in urban context, Bouyer [6] reduced computing time to run simulations for an extended period of several days, as required for building simulations. The model was simplified by taking into account just the heat and mass transport as well as diffusion inside the airflow. Further simplifications were studied by Malys *et al.* [49] who compared different coupling methods. It was demonstrated that during winter, the coupling procedures have a weak but non-negligible impact on the energy consumption assessment, especially for non-insulated buildings, due to the relative effect of convective and long-wave heat fluxes. For the insulated building, the effect of the local modification of outdoor air temperature is clearly negligible. So, it seems acceptable to avoid thermal coupling with the aerodynamic model to represent the effects of the neighborhood, if the long-wave radiation exchanges are properly taken into account. Thermal coupling appears more relevant in the summer due to the impact of solar irradiance in the modification of local air temperatures. Malys *et al.* [49] propose the use of an intermediate coupling method using a homogeneous control zone, whose temperature is assessed with this process instead of CFD calculation.

To satisfy the need for evaluating alternative techniques in urban development, these models evolve so as to incorporate different types of urban elements such as:

- The presence of vegetation and its impacts associated with its type [51–53], its location [52, 54, 55] and its management (i.e. intensive vs. extensive);
- Alternative systems for rainwater management at the parcel scale (roof storage, infiltration wells and rainwater drip) or at the district scale (retention ponds and landscape ditches);
- The specific construction materials for treating UHI (selective coatings) such as 'cool paints' on the roofs [56] or the facades [57], or active energy systems such as solar panels;
- Urban form (layout, density, etc.), on which a specific design procedure can be implemented with specific comfort or energy consumption objectives [58, 59].

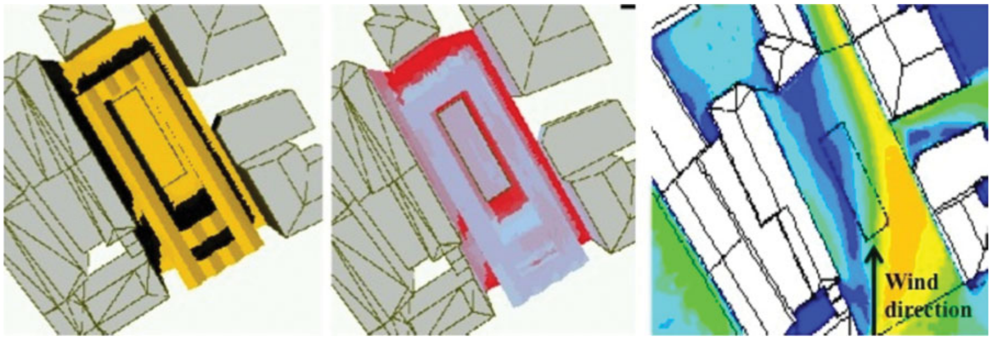

Figure 7. *Examples of results obtained by coupling SOLENE-microclimat and FLUENT (solar flux, surface temperature and air velocity in an urban square with trees).*

3.1.2 *Modeling local UHI phenomena with the interactions of buildings and local phenomena*

Taking into account the building interactions with local microclimate is needed for a proper assessment of both building energy consumption in dense urban areas, and contributions of buildings to the microclimate itself. Indeed, as outlined Figure 8, the anthropogenic heat from building operations, such as air conditioning systems, contributes to the UHI locally and globally, with reduced performances [60].

The anthropogenic contribution to urban microclimate obviously also stems from various other parameters [61] like motor traffic, industry and human metabolism (accounting for less than 1%). In contrast to the contribution from indoor building environments, these parameters, which pertain to population behavior and city characteristics, can be derived from databases or other model results in addition to serving as inputs simulation models.

So, considering the main heat transfers at the built-environment interface, the models need to assess the following:

- Heat exchanges by convection (depending on the near-wall air velocity and the local variations of outside temperature);
- Solar irradiation (direct, diffuse and reflected);
- Long-wave radiation exchanges with the sky and surrounding surfaces and
- Heat fluxes due to ventilation and infiltration.

Methods Physical models that address both the building and urban environment are rare. An initial approach consists of evaluating the direct impacts of the environment (e.g. masks) on the buildings; a second approach would then evaluate the interactions between a building and its environment.

This initial approach is introduced in SUNtool and CitySim [62, 63], which take into account the luminous and solar masking effects of the urban environment in calculating the energy consumption of buildings; this is also the option chosen by the building thermal research team at Sevilla University as part of the European project 'Greencode', which was responsible for the development of the street canyon model 'GreenCanyon' for estimating the influence of the urban environment on the thermal behavior of buildings [64].

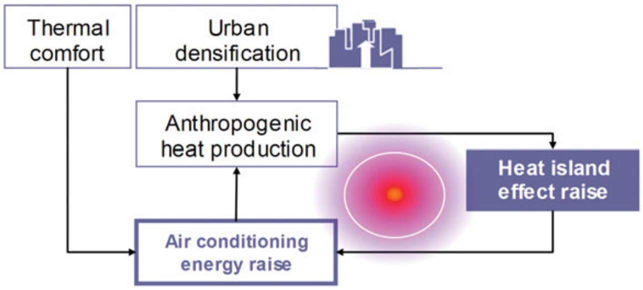

Figure 8. *Anthropogenic heat contribution to UHI in urban confined spaces and at larger scales.*

The second approach requires resolving scale compatibility. It is in fact difficult to accurately represent the urban environment as well as the buildings and their uses. The interactions' study thus requires either a reduction in the urban area studied, focusing on a building in a street canyon [65], or a simplified thermal model of the building [6]. In both cases, based on current developments, only one building is under the heat balance.

This complete coupling of building and environment, however, offers the advantage of allowing an evaluation of the environment impact on the thermal behavior of the building, along with the building's impacts on the urban microclimate itself [50, 66]. This consideration should provide a better thermal loads' estimation related to the human control of indoor spaces [61]. In narrow street canyon configurations, detailed modeling of heat and mass transfer between buildings and the street shows the possible interactions due to low air change rates, radiation interchange and anthropogenic heat. The development of a zonal model of a street canyon [66] including the air conditioner heat due to condensers positioned on facades (see Figure 9) has allowed assessing both the impact of this design on building energy demand and the confined street thermal environment.

Results on the street canyon case Temperature variations within this street canyon (23 m high, 7 m wide and 200 m long located in Athens, Greece, 37′ 58°N, 23′47°E, with a South West and a North East oriented facades) were computed with this model for a one-month period of August [66] considering air conditioned buildings (indoor temperature T_{int} maintained at 25°C). Taking into account the air conditioning systems, the mean air temperature peaks of the street are amplified during heat waves, see Figure 10.

3.2 Modeling the building behavior at the street or district scale to study new mitigation techniques

Heat from absorbed solar radiation is one of the main UHI parameters, and the urban buildings' envelope modifications are often proposed as a mitigation technique. A comprehensive review of reflective and green roofs technologies and their efficiency to fight UHI has been given by Santamouris [67]. Indeed, the absorbed heat can be reduced with high albedo and high thermal emissivity surfaces, known as cool roofs or facades. Otherwise, water evaporation systems can be used to reduce temperature due to this solar radiation, which is another way to modify building surfaces with water ponds roofs or green roofs and facades. Building simulation uses models for the direct effect of these techniques on the building itself. The advantage to use a coupled simulation of the building energy performance and the local microclimate from the street to the district scale is highlighted here.

3.2.1 *The effect of cool coatings for roofs and facades*

At the building scale, cool coatings are more and more developed for cooling energy performance or indoor thermal

Figure 9. *Zonal mesh (left) of an urban canyon considering air conditioned buildings (constant indoor temperature* T_{int}*) and outside air temperature and street canyon location in Athens (right).*

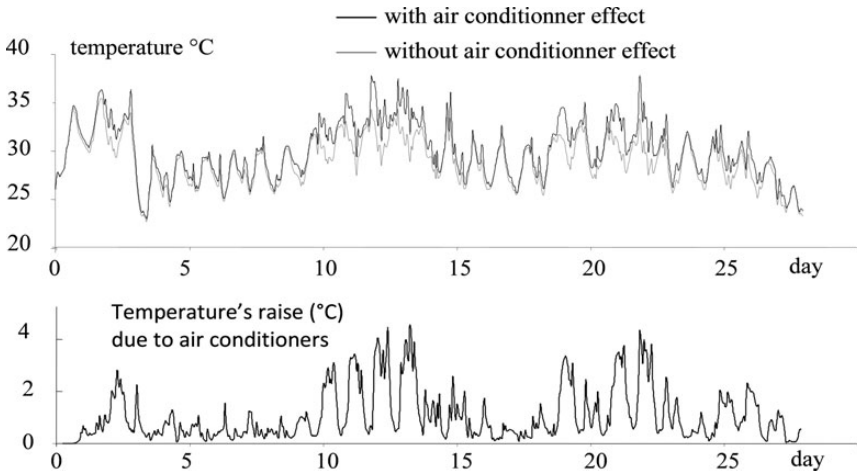

Figure 10. *Mean temperature evolution within the street and difference due to the implementation of air conditioners' units.*

comfort in summer, especially for roofs (see US Cool Roof Rating Council or EU Cool Roof Council [68]). As shown in Figure 11, the surface temperature's drop between a reflective roof and a reference roof with an asphalt membrane in the summer conditions can exceed 20°C. For the three membrane samples (see Table 2, [69]), the roof surface temperatures were monitored simultaneously in La Rochelle (France) during 3 months (from June to August).

While the measured temperatures' peaks of the reference roof are strongly reduced by high albedo for both cool roof and metal roof, the night cooling is not efficient for the metal roof due to its low thermal emissivity. So for the metal roof, it appears that more than 50% of measured temperatures are a few degrees higher than the reference sample. For the cool roof membrane with high thermal emissivity similar to the reference roof, 50% of measured surface temperatures are almost identical due to this night cooling phenomenon. This cool roof technique is an efficient alternative to mitigate the heat transfer to the building and to the environment, i.e. the UHI contribution in urban context.

Modeling methodology for building interactions The direct contribution of the cool roof technique on the building for summer conditions can be assessed precisely enough through transient building simulation codes. A building simulation was validated through experimental results in Poitiers (France) for a non-cooled dwelling that was refurbished with a cool coating [70]. This model computation demonstrates the direct contribution on the indoor operative temperature, taking into account the local climate conditions. Taking into account realistic use and thermal behavior of the building throughout a complete season, these detailed building models are necessary to assess the indoor thermal comfort or cooling loads. Yet, they lack of realistic local climatic data in urban context due to the density and UHI. Moreover, building refurbishments modify locally and globally the UHI as reported by Santamouris [67] through many study results on the impact of cool roofs on the peaks of ambient temperature in urban context.

Locally, the surface temperatures modify the building cooling loads, especially in confined spaces such as street canyons. The effects of facade cool coatings in these streets have been investigated here with the same case study presented Figure 9, same model and climatic conditions (Athens, Greece). The pavements were considered to have a constant albedo ($\rho = 0.40$). The refurbishment of the dark facades ($\rho = 0.20$) with white coatings ($\rho = 0.83$) cut the peaks of absorbed solar radiations as represented for one day in Figure 12.

Results The solar radiations' interchange strongly increases, and thus the absorbed flux during the morning due to radiative interchange, which is accentuated in the lowest parts of the facade (Figure 12). Then, the exposure time to solar irradiance is increased by interchange effects with less absorbed energy during the day, which would be valuable for better daylight within the street (and the flats) and the mitigation effect on facades temperatures, the street air temperatures and building energy demand. From the coupled simulation results (see Figure 9), for the 21th of July, the maximum surface temperatures of the dark facade varies from 38.5°C (bottom) to 52.5°C (top). The white coating affects these facade temperatures that vary from 34.1 (bottom) to 38.7°C (top). The reduction of daily solar radiation absorbed by the facades has a direct impact on street air temperatures, with a maximum decrease of 5.6°C during the studied period [7]. This calculation of coupled effects of cooled building together with the street microclimate can help to have a better assessment of the building energy performance in an urban context taking into account correctly the radiation trapping and the thermal confinement of dense urban areas.

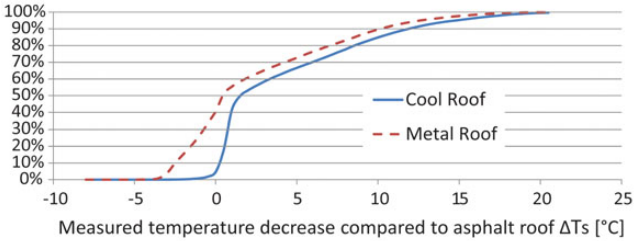

Figure 11. *Cumulative frequencies of surface temperature decrease $T_{reference} - T_{sample}$ for 2 samples (cool roof and metal roof) compared with a reference asphalt roof, for a 3-month period from June to August.*

Table 2. *Radiative characteristics of roof membrane samples.*

Sample	Asphalt membrane	Metal roof	Cool roof membrane (reference)
Thermal emissivity ε	0.84	0.06	0.86
Albedo ρ	0.22	0.82	0.73

3.2.2 *The study of green coatings*

In a first approach, using SOLENE-microclimat, Bouyer *et al.* [71] have studied the impact of trees and natural soil, compared with mineral environment (Figure 13; [71]), on buildings' energy demand. The case study is a modern office building in Lyon (France). For a typical winter week, they found a difference of less than 1%, the heating loads being slightly higher in the 'green' case, because of the residual shading of trees. For the summer week, sensible cooling loads are reduced by 10% in the green case while latent loads are increased by 12%; but due to their relative order of magnitude, the total cooling loads are reduced by 9%. It has to be noted that the variations in the results due to the different assumptions in modeling (shades, long-wave radiations, convection . . .) are higher than those attributed to the kind of surface examined. So, this emphasizes that before comparing the effects of different surrounding surfaces, it is important to make sure that the model represents correctly the exchanges with the surrounding.

To assess the direct and indirect impacts of vegetation on buildings' energy consumption, Malys [72] has added green roofs and green walls into this model. The green wall model has been

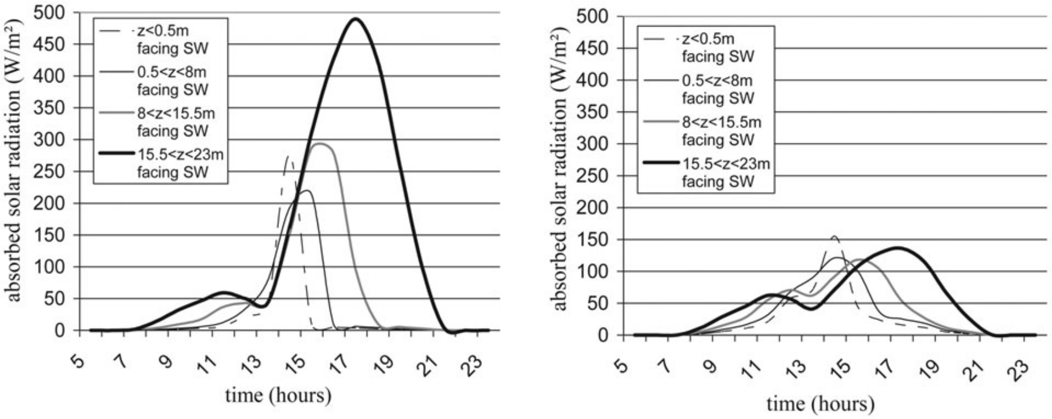

Figure 12. *Absorbed solar radiation for the SW-exposed facade of a street canyon (21 July) with dark (a) and white facades (b).*

calibrated using the data acquired by LEEA laboratory; Figure 14 from [72] (HEPIA, Reto Camponovo et Peter Gallinelli).

The results of this developed model have been first calibrated using local data (wall, ground air temperatures). The effects of three kinds of green coatings are then compared: walls, roofs, soil. The results are obtained for a central building, surrounded with other similar buildings (Figure 15 from [49]) and taking into account the distribution of the building windows. Two configurations are tested: insulated and non-insulated. For the summer period, the results show that green walls cool efficiently the surroundings, mainly by the way of long-wave radiation. Indeed, in dense cities, a building surrounded by other buildings coated with green walls releases more energy by long-wave radiation due to the lower temperatures of the surrounding walls. The same phenomenon also influences comfort in the outdoor spaces. In this study, green roofs have less impact on buildings energy consumption because their effects are limited to the upper level of the buildings.

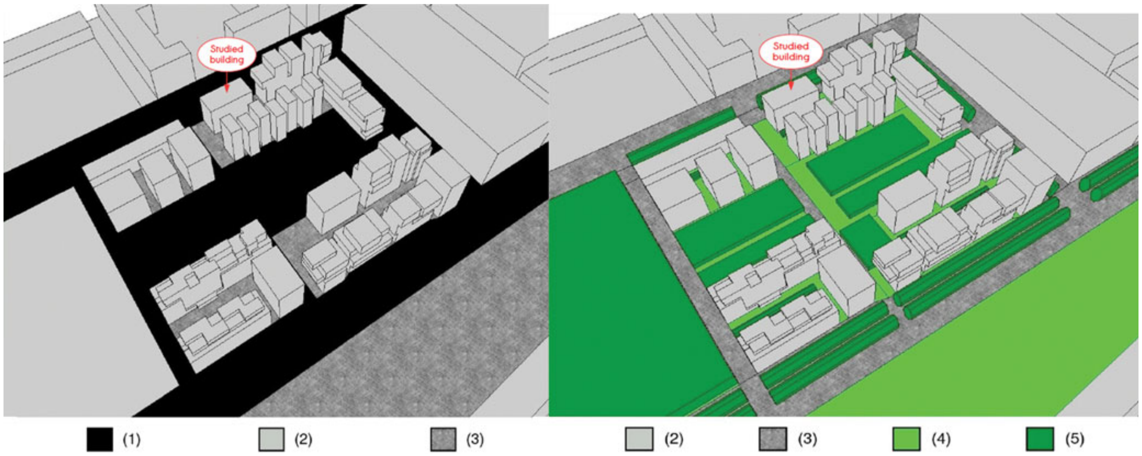

Figure 13. *Vegetated and mineral scenario (1) black asphalt; (2) concrete; (3) sandstone paving; (4) turf; (5) tree crowns.*

Figure 14. *Green walls used for model calibration, LEEA laboratory, HEPIA.*

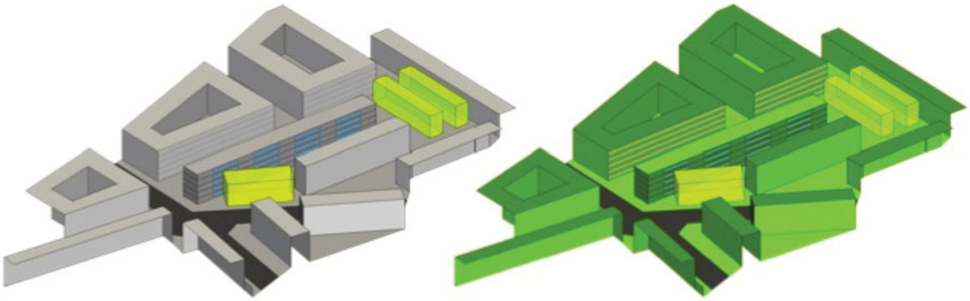

Figure 15. *Studied district and location of green coatings (dark grey).*

4 CONCLUSIONS

We reviewed various urban microclimate models at different scales and their capabilities in coupled approaches. These modeling techniques become more and more comprehensive with a more detailed description of urban areas. Once the urban scales properly detailed, a compromise must be found considering the modeling accuracy, the computing capabilities, the data availability and the effort required to enhance these models. This consistency relative to the objectives remains the basis of any modeling methodology as it was illustrated for the different case studies here. It can be expected, with the increasing computing powers, that the coordination between simulation tools and urban databases will provide the necessary documentation to represent the urban microclimate characteristics in greater details. This breakthrough would certainly be very valuable in terms of understanding and knowledge of the underlying phenomena, in addition to highlight the various impacts of urban parameters (type of buildings, land use, anthropogenic processes, . . .) on microclimate and UHI mitigation.

We have shown the importance of these modeling techniques to study the impact of urban fabric on the temperatures, humidity and heat fluxes at different scales, and finally the UHI. The global effectiveness of these solutions requires further developments and stronger coupling methods to assess the footprint of a district to the other microclimates throughout heat and mass transfers between streets and the complex thermal behavior of buildings. By developing these approaches, we would be able to evaluate in a more realistic and accurate way the energy performance at larger urban scales and the UHI effects locally in correlation with urban planning.

As highlighted through the studies and the results presented in this paper about the impacts of UHI mitigation techniques, the developed models require a complex integration of various specialized modeling approaches for each phenomenon like multi-reflections, evapotranspiration, hydrological fluxes, etc. The close relationships between these phenomena make it difficult to assert general results. Indeed, in the last case study, it was found that green facades were more efficient than green roofs for building energy demand, but the results could have been different for other built configurations of urban morphologies. Similarly, the results presented at the neighborhood scale on the impact on microclimate of water management techniques are very sensitive to the vegetation type and to the ability of plants to generate evapotranspiration.

It is thus necessary to compare these numerical experiments to measurement campaigns or long-term observation periods of the processes involved in urban microclimate [73–75] or on climate models at the urban fragment scale such as an urban street canyon [76]. However, for real urban fragments, which consist of a variety of surfaces (built or natural), the validation process first requires the knowledge of a wide range of data on buildings' operation and physical properties of urban surfaces (building envelopes and soil). Beyond the implementation of experimental methods for collecting the necessary data for model assessment, it appears that the main obstacle to progress lies into possessing a detailed knowledge of the input data. This lies on strong collaboration between several research domains including remote sensing, geographical databases, etc.

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