Geoclimatic modeling: tools, limits and outlooks

Modélisation géoclimatique : outils, limites et perspectives

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ABSTRACT. Today, urban climate diagnostic tools can be useful to local authorities and cities: they provide input for urban planning and development project design at different spatial scales, in a context of mitigating both global climate change and local climate heat peaks. In the following paper, we identify and list diagnostic tools, and mainly focus on geoclimatic ones. The latter have the particularity of requiring geomatics and geographic data to provide useful outputs for diagnosing overheating in cities. A classification of these tools is presented, based on four criteria. The first criteria is based on how the urban fabric is considered by each of the tools: simplified or detailed. The second criteria is the type of output produced by the software: it contains physical quantities or qualitative information (e.g. shadow or sunlit). The third criteria is relative to the choice of the problem-solving approach: physical vs statistical? The last criteria is what type of physics the software tool addresses (air temperature, wind, radiation, etc.). Finally, tools are sorted according to this classification and their relation to geomatics further described. It emerges that each tool has been developed for a particular need and from a specific point of view. This point of view will also help to explain the strengths, weaknesses and simplifications of each tool. Lastly, it highlights areas where software development, or even model development, require the attention of the GIS sciences.

RÉSUMÉ. Les outils de diagnostic du climat urbain peuvent être utiles aux autorités locales et aux villes : ils fournissent des informations pour la planification urbaine et la conception de projets de développement à différentes échelles spatiales, dans un contexte d'atténuation du changement climatique mondial et d'adaptation aux pics de chaleur localement. Dans le document suivant, nous identifions et répertorions les outils de diagnostic, en nous concentrant principalement sur les outils géoclimatiques. Ces derniers ont la particularité de nécessiter des données géomatiques et géographiques pour fournir des résultats utiles au diagnostic de la surchauffe dans les villes. Une classification de ces outils est présentée, basée sur quatre critères. Le premier critère est basé sur la manière dont le tissu urbain est pris en compte par chacun des outils : simplifié ou détaillé. Le deuxième critère est le type de résultat produit par le logiciel : il contient des quantités physiques ou des informations qualitatives (par exemple, ombre ou soleil). Le troisième critère est relatif au choix de l'approche de résolution du problème : physique ou statistique ? Le dernier critère concerne le type de physique abordé par l'outil logiciel (température de l'air, vent, rayonnement, etc.). Enfin, les outils sont triés selon cette classification et leur relation avec la géomatique est décrite plus en détail. Il apparaît que chaque outil a été développé pour un besoin particulier et d'un point de vue spécifique. Ce point de vue permettra également d'expliquer les forces, les faiblesses et les simplifications de chaque outil. Enfin, il met en évidence les domaines dans lesquels le développement de logiciels, ou même de modèles, requiert l'attention des sciences des SIG.

KEYWORDS. Urban overheating, GIS, geomatics, software, climate, geoclimatic.
MOTS-CLÉS. Surchauffe urbaine, SIG, géomatique, logiciel, climat, géoclimatique.

1. Introduction

In addition to global warming, there is a significant temperature difference between dense urban areas and rural areas. This specific response of built environments, known as the urban heat island effect, was described as early as the 19th century and can lead to discomfort, increased morbidity and even mortality during heatwaves. These observations have prompted a broader examination of how urban environments impact outdoor thermal comfort. When focusing solely on meteorological factors, outdoor thermal comfort is determined by a combination of air temperature and humidity, wind speed and radiation at a given location (Coccolo et al. 2016).

The urban morphology of the city, the man-made materials and the human activity exacerbate the impacts of climate change. This is why the issues of urban overheating and thermal comfort are becoming increasingly important in urban climate adaptation strategies. Although climate change is a significant concern that affects various fields relevant to urban planning (such as water scarcity, food production and transportation, public health, etc.), it must be addressed as one more issue to deal with. Consequently, there is a need for tools that can easily generate maps illustrating the effect of urbanization on various factors including thermal comfort related health, transportation, access to food, and levels of noise or air pollution. GIS software are appropriate tools since they offer the possibility to easily manipulate, analyze and represent spatial data dedicated to any application field.

Different models can be used to assess urban overheating based on the geographical, morphological, surface and anthropogenic characteristics of the urban environment. They have been developed to simulate the physical phenomena involved in urban climate at both neighborhood and city scales. There are mainly two types of tools used to investigate the effect of the city on the climate variables: the ones that solve energy and mass balance equations (called “physical-based” models / tools in the following) and the ones that use observation and geomatics to draw general rules (called “spatial-based” models / tools in the following).

Many authors have focused on solving physical energy balance equations. Various simulation tools coexist (e.g. *Solene-Microclimat*, *ENVI-met*, *SUSHI*, *Traboule*, *TEB*). Each tool, shaped by its unique history, possesses distinct characteristics and assumptions. The approximations used to define mathematical models, the level of detail of the physical phenomena represented and the input data can vary significantly from one tool to another. To compare them, many articles propose classifications of these tools (Frayssinet et al. 2018; Sola et al. 2020; Swan and Ugursal 2009; Lauzet et al. 2019). Most of these classifications are based on spatial or temporal simulation scales. For instance, in urban climatology, we frequently present the following spatial scales: ‘building/street’, ‘neighborhood/district’, ‘city’, which are representative of the objects under study. Additionally, physically-based tools are often categorized according to their temporal resolution and the simulation period (Fig. 1).

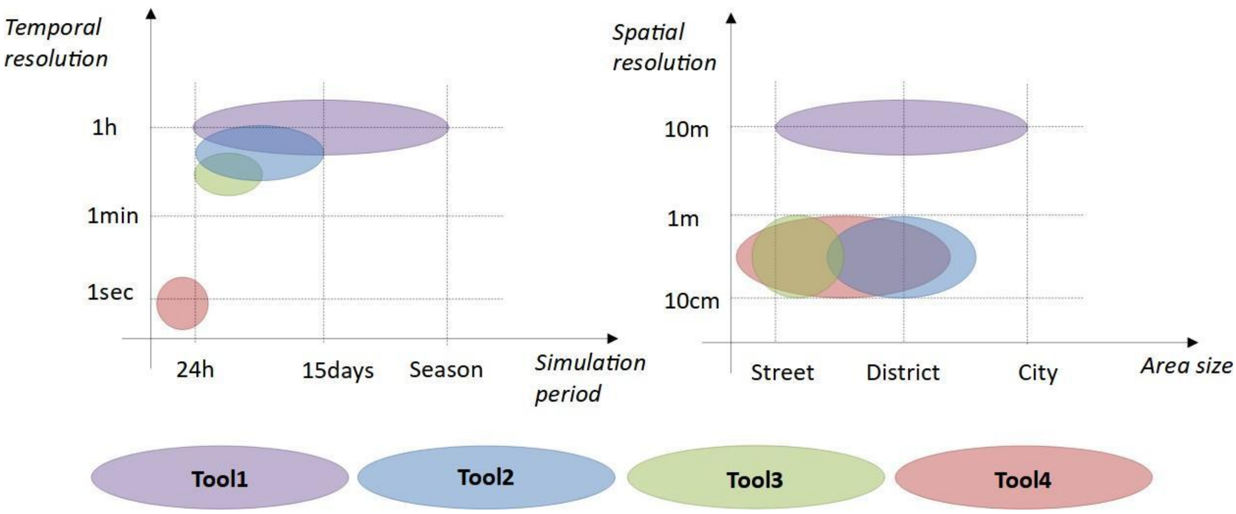


Figure 1. *Two ways of organizing physics-based tools as a function of time and space resolution.*

Some of the physical-based models are called “parametric models” in the sense that they are applied to a large area (larger than a city), thus not all geographical objects (such as buildings)can be modeled explicitly: the main properties of an area have to be summarized by parameters having a well-known climate impact (such as mean building height or building density). The other physical-based models can be run without any spatial preprocessing. This is the case for all models that explicitly solve equations for all surfaces (Rodler et al. 2021): *Solene-Microclimate*, *ENVI-met*, *EnvibatE*, *SUSHI*, *Traboule*, etc.

The spatial-based models contain a non-negligible part of their algorithm which are based on geomatics methods which have long been used and documented in the GIS software. These models can still have a physical-based component.

There are very few review articles dedicated to list urban climate tools based on geomatics or integrated in a GIS. Jänicke et al. (2021) have listed user-friendly tools dedicated to urban climate, but their list also contains CAD tools, while a large number of geomatics-based tools are missing. ,. This paper lists tools that are dedicated to study urban climate and that include geomatics algorithms. A classification is proposed, gathering a given set of tools that use geomatics for a similar purpose. This work serves two objectives:

– It highlights what can be the perspectives for the geomatics to serve the urban climate issues. This can mainly be interesting for research purposes.

– It can help potential users such as urban planners to quickly identify which tools can be needed to meet their given need.

The main contribution of this manuscript is not to produce an exhaustive list of tools, but rather to propose a classification. Note that we solely focus on tools either directly integrated within a GIS or which are based on algorithms resting on geomatics. Tools that have been documented on web-sites or scientific literature but which are not available for download have been excluded from this work.

The manuscript consists of two sections. First, the method to classify geomatics tools is introduced. Second, tools are sorted and presented according to the classification. The paper ends with a discussion and a conclusion.

2. Method used to classify geoclimatic tools

A quick review of software tools dedicated to analyze urban microclimate within the context of geographic information science and technology reveals four simple criteria for distinguishing between them (Fig. 2).

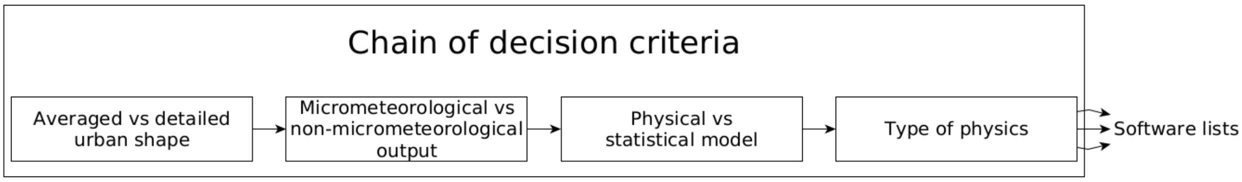


Figure 2. *The four criteria we have used to build our decision tree*

The first criterion “averaged vs detailed urban shape” relates to the handling of the urban fabric itself. Is the latter simplified as an average or, conversely, described in detail? In the first scenario (averaged), the unit of analysis (resolution - cf. (Leconte et al. 2025)) contains one or several geographical objects (e.g. building, trees) and for each resulting item from this process, a set of parameters describing the corresponding urban layout is generated (e.g. mean building height or building fraction). On the other hand (detailed), each individual geographical object is directly considered as it is by the simulation tool.

The second criterion used to differentiate the tools is the type of output produced by the software: micrometeorological versus non-micrometeorological. Micrometeorological data are often quantitative data such as a scalar field (e.g. surface temperature or air temperature), a vector field (e.g. wind speed), or any other data that could be described as “Micrometeorological”. The non-micrometeorological data can cover quantitative and qualitative data types; quantitative when it characterizes well defined characteristics (such as sky view factor) or qualitative such as a local climate zone or shadow polygons.

The third criterion for differentiation relates to the choice of problem-solving approach (physical vs statistical model). In a hypothetico-deductive model, is it simply a matter of applying and solving a physics equation? Or should we proceed inductively, deducing the model from observations, using a statistical approach?

The fourth criterion relates to the type of physics that the software tool addresses: create a radiation balance, identify airflow zones, generate a temperature field, estimate energy consumption, or assess thermal comfort in buildings?

From a user perspective, looking for a tool to answer a specific need:

– the first criterion can be seen as the scale of his / her problem: averaged urban features being often used at city (or more) scale while considering explicitly all urban features is often possible only at neighborhood scale.

– the second criterion is related to the familiarity of the user with the urban climate thematic: non-micrometeorological information is often qualitative information that are voluntarily easier to interpret while the micrometeorological data needs a certain expertise of the field.

– The third criterion can be interpreted as a potential of applicability of a tool outside the scope / the location it has been created: physical models are often more robust in this kind of situation.

– The fourth criterion depends on the user output need: a tool only dedicated to wind speed calculation will not be useful for a user looking for solar radiation.

Fig. 3 is a classification that summarizes all the software tools presented in this article.

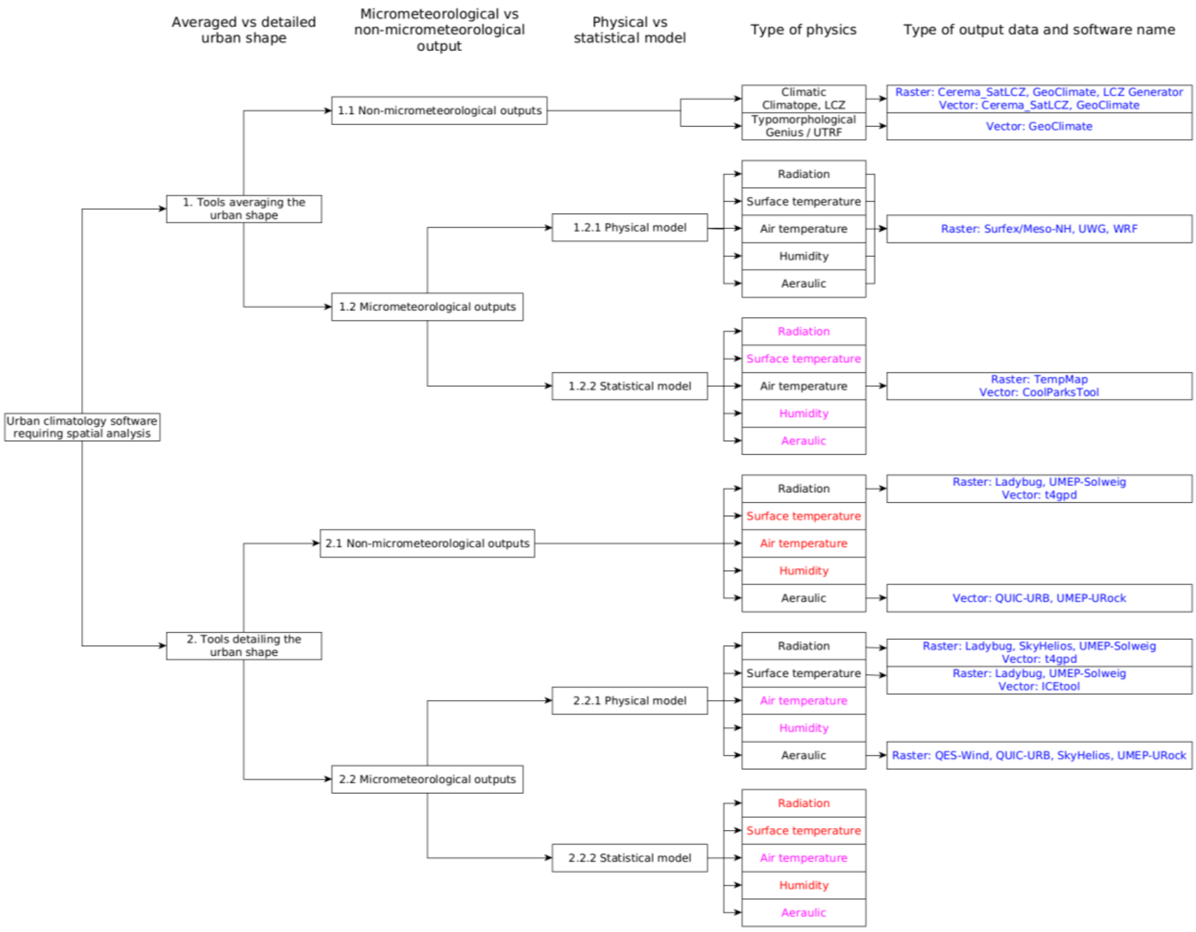


Figure 3. *Classification of the software tools presented in this article. Red entries in "type of physics" means that to our knowledge there is neither a software implementation nor even a set of scripts that might have been used by academics (at least not openly shared with the community). Magenta entries are academic models that can be available as a set of scripts but have no software implementation*

3. Classification implementation

This section presents the reviewed tools according to the classification proposed in Fig. 3.

3.1. *Tools averaging the urban shape*

Tools with non-micrometeorological outputs are presented hereafter.

3.1.1. *Tools with non-micrometeorological outputs*

Climatic: climatope, local climate zones

There are mainly two popular conceptual frameworks for urban climatic classification and evaluation: the climatopes of the Urban Climatic Map (UCMap) system (Ng and Ren 2015) and local climate zones (LCZs) (Stewart and Oke 2009; 2012). Both classifications are used as a cartographic representation of climatic information and translating climatic evaluation results into planning language (more detail in (Leconte et al. 2025)).

Regarding the local climate zone classification, different tools using specific input data and methods co-exist. Based on a raster approach, we can cite the *Geoclimate* chain, the LCZ generator and *Cerema_SatLCZ* tool. *GeoClimate* is vector-based and *LczGenerator* raster-based whereas *Cerema_SatLCZ* tool can be both. Table 2 summarizes the main features of each generator.

Tool Name	Methods’ implementations of LCZ	"Spatial indicators needed by the method"
LczGenerator	Supervised classification method based on a random forest algorithm. Some of the zones of the study area have to be assigned to a given LCZ by the user. The training is based on this (ground) truth and the corresponding pixels of satellite images. Then the trained RF model is applied to the rest of the study area using solely the satellite image.	The LCZ type of a sample of the area of interest should be set before running the supervised training.
GeoClimate	Stewart and Oke have defined for each LCZ a range of values taken by seven UCP (Urban Canopy Parameters). In a seven-dimensional space, each class can then be represented by a hypercube. In GeoClimate, the seven indicators are calculated for each unit (thus a unit is a point in the seven	Sky view factor, aspect ratio, building fraction, impervious fraction, pervious fraction, geometric average building height, effective terrain roughness length, vegetation fraction, high vegetation to all vegetation fraction, water
	dimensional space). For most of the urban LCZ types, the LCZ assigned to a given unit is then the one of the closest hypercube in the seven- dimensional space. For all other urban LCZ types and the land use ones, a decision tree based on the value taken by a set of UCP is used.	fraction, fraction of heavy industry buildings, fraction of commercial buildings, fraction of residential buildings, average number of building level (area weighted).
Cerema_SatLCZ	Two methods are distinguished: The reference method, more complex, is based on a decision tree that, as GeoClimate, faithfully reproduces the LCZ thresholds. The “international” SatLCZ method is more easily applicable anywhere and quicker to implement. It is based on a tree allowing ~~it~~ to work with “full satellite” indicators, some of which are derived from the initial LCZ indicators.	Mainly: Sky view factor, Aspect ratio, mean height of buildings, rugosity class, building ratio, impervious surface ratio, pervious surface ratio. If provided, few other information can be considered: thermal effusivity, albedo, anthropogenic fluxes.

Table 2. *implementations of the local climate zone classification and required indicators.*

Typomorphological: GENIUS/ UTRF

We have listed a third classification with a slightly different approach than the previous ones. This method named GENIUS (GENerator of Interactive Urban blockS) is based on building geometries, envelope materials and surroundings ground covering (Tornay et al. 2017). Its aim is to integrate building scale data into urban microclimate and energy consumption modeling. This morpho-typo classification was obtained thanks to a combination between interviews of urban planners to characterize a typology of urban forms in the whole French territory. Each building can be attributed to a given archetype, depending mainly on its size and the type of building block it belongs to (see Table 3). To our knowledge, only the *GeoClimate* tool (Bocher et al. 2021) can automatically attribute a GENIUS/UTRF type to a given building, based on more than 70 indicators, but more indicators can be processed (Bocher et al. 2018). This classification, although it is not necessarily intended for climate purpose, is currently used in some climate research. Nagel et al. (2023) have used the concept of openness / closeness of an urban block to study the impact of the building morphology on the wind: to subdivide some of the LCZ built types into open blocks and close blocks (blocks that have a courtyard). The building type is also used by a building database (called DANUBE), along with information such as building age and location, to infer the thermal envelope of any French building.

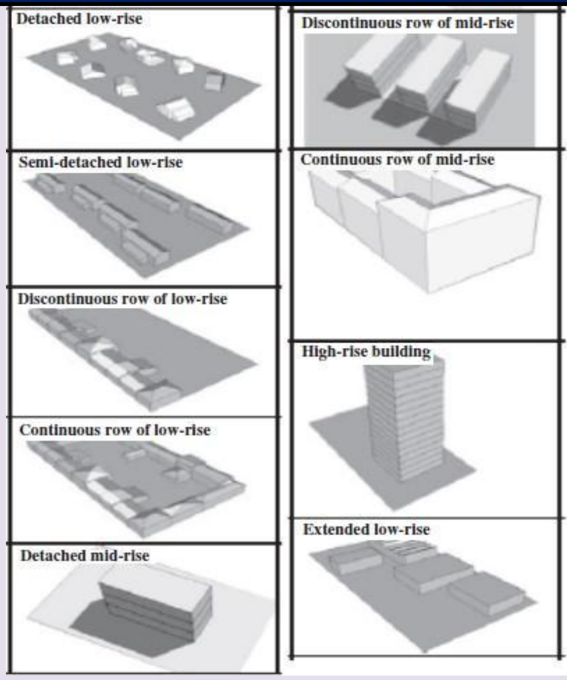
Tool Name	Indicators	Classes
GENIUS	Net building density, building height, contiguity, building compactness, building footprint coverage ratio, road width, road density, net building density, building height, contiguity, building compactness, road width, road density, vegetation density.	

Table 3. *GENIUS classification and required indicators (Figure adapted from Tornay et al. (2017)).*

3.1.2. *Tools with micrometeorological outputs*

3.1.2.1. Physical models

Most of the tools of physical models are made of several “submodels” (for example a building energy model) that can be activated or not. Each submodel requires additional input parameters, for example floor area fraction of each building type and building use to set building material composition and energy uses over time (Table 4). We have not detailed what parameter is needed for each submodel but rather give a non-exhaustive list of the parameters that can be useful for each tool. All these tools usually deliver as output one or more physical variables as a raster file (matrix of values having geolocation as metadata) that can have many types of extension (netCDF, grib, asc, etc.).

Model	Initial application	input
WRF (Chen et	Study meteorological and	Most of the indicators are related to building morphology (building fraction, distribution of building height, etc.). The
al. 2011)	climate processes at regional, meso or local scale	Local Climate Zones (LCZ) can also be used as input (alone or combined to other indicators).
SURFEX -Meso-N H (Masson et al. 2013)	Study meteorological and climate processes at regional, meso or local scale	The Town Energy Balance (TEB) is the urban model part of the SURFEX model. It is made of several submodels that require very diverse information (several building morphology indicators, fraction of roads covered by trees, fraction of grass, building type and building use, classification such as LCZ, etc.) (see (Jacquinod et al., 2025))
UWG (Bueno et al. 2013)	Simulate the canyon air temperature for a given neighborhood in order to perform more accurate building energy simulations.	Urban configuration described by several parameters such as building density and height or vegetation cover

Table 4. *Application and indicators needed for WRF, SURFEX-Meso-NH and UWG.*

Depending on the application, spatial data can be processed differently. For modeling a large area, a grid having a resolution of one to several hundred meters can be used to average information such as building fraction (Fig. 4 b). For modeling a given area, the indicators can be calculated at one to several meters resolution using a moving average with a circle window of one to several hundred meters diameter (Fig. 4c - cf. (Hamdi et al. 2023)).

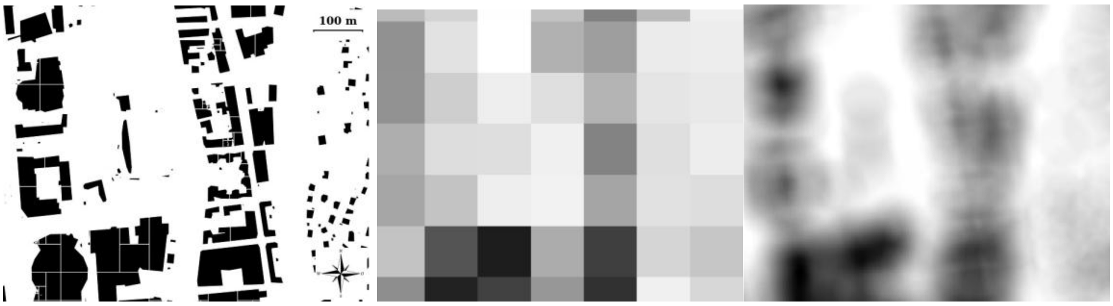


Figure 4. *Building (a) footprint, (b) building fraction over a 100 m grid resolution, (c) building fraction average over a 100 m buffer circle diameter - value every 1 m.*

3.1.2.2. Statistical model

Air temperature

While many models have been proposed to explain the spatial variation of the air temperature from geographical features (Unger 2004), only few have been converted into an easily accessible GIS tool. This is the case of *TempMap* (Touati, Gardes, and Hidalgo 2020). The tool can be used to interpolate air temperature measured at given locations to a whole territory based on city density, terrain elevation and distance to the station through multiple linear regression plus kriging to interpolate the residuals (Fig.

5). The city density is defined as the sum of road fraction, building fraction and facade density. These three parameters are not calculated by the plugin: the user can either provide the MApUCE data (Bocher et al. 2018) for the study area or directly a raster of the city density. The city density indicators and also the other input information used by the model (terrain elevation, distance to station and air temperature) are attributed to each cell of a 100 m wide square grid. The code comes as a QGIS plug-in but it is not directly available within the official QGIS repository. It has to be downloaded via a GitHub repository and imported in QGIS as a zip file plugin. Note that it is currently valid only for QGIS 2.14 and 2.18 (Python 2) but a new version is under development.

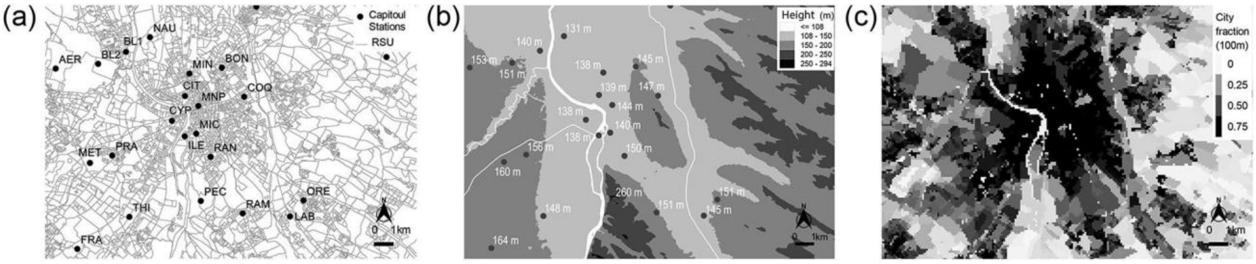


Figure 5. *Examples of input data. (a) Reference Spatial Units[6] such as defined in the MApUCE project. (b) Digital Elevation Model. (c) City Fraction raster built from MApUCE data. Source: Touati, Gardes, and Hidalgo (2020).*

CoolParksTool[7] is a tool that uses aggregated spatial information at a given scale to derive air temperature at a finer scale. Contrarily to *TempMap*, it focuses on a very specific application: investigating the effect of the park composition on its cooling potential and the effect of the morphology of the built environment around the park to facilitate the transport of cool air far outside of the park (Rodler et al. 2020). To this purpose, two metamodels have been built:

– the first is used to estimate the park cooling according to park size and fraction of land type (bare soil, grass and asphalt) and the type of tree canopy (no tree, isolated tree, forest and dense forest)

– the second is used to estimate the distance of cooling outside the park according to indicators describing the urban morphology (building mean height, average number of streets, etc.)

CoolParksTool calculates the effect of a park along corridors defined according to the wind direction (Fig. 12a). For eight wind directions, the fraction of each land type and tree canopy as well as the building morphology indicators are calculated. They are the input of simplified models that are used to then spatialize the air temperature around the park (Fig. 12b).

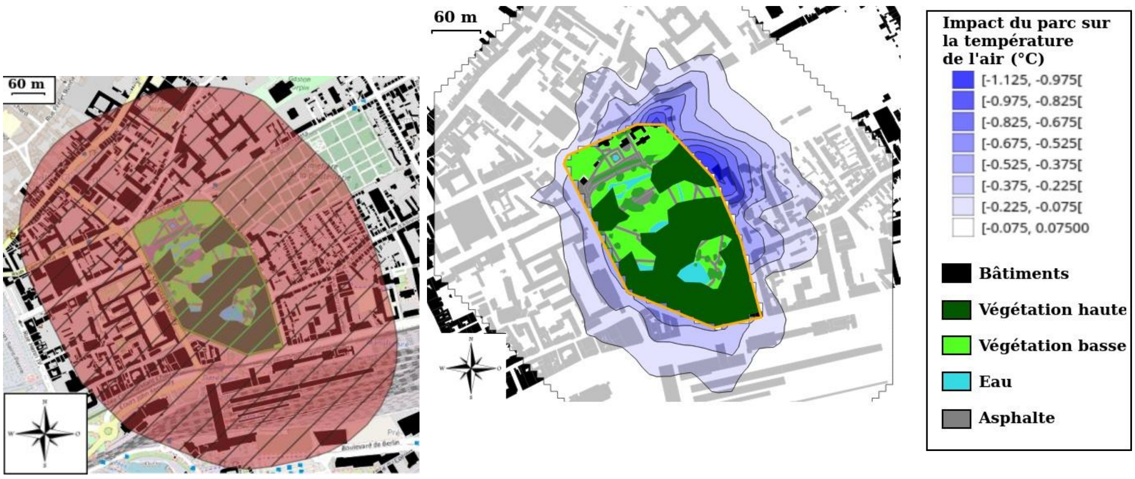


Fig 6. *Illustration of the CoolParksTool tool: (a) definition of corridors for indicator calculation - here for a 45° from North clockwise wind direction - and (b) resulting air temperature and building energy impact (the bluer the more intense the impact).*

Note that *CoolParksTool* is also designed to evaluate the impact of the cool air generated by the park on the energy and thermal comfort of the buildings located nearby the park depending on their type. To this purpose, a third model is used to evaluate the thermal comfort stress or the cooling energy need reduction according to the park cooling at this distance and building characteristics (thermal properties, orientation, fraction of shared walls, aspect ratio of the surrounding streets).

3.2. Tools detailing the urban shape

The aim of this section is to identify and describe a sub-set of tools used to analyze the urban climate. The tools in this subset all share the same requirement: they use an explicit description of urban geometric shapes when calculating climate variables.

3.2.1. *Tools with non-micrometeorological outputs*

Radiation

In the words of Mardaljevic and Janes (2013), "Planners and architects have long appreciated, at least qualitatively, that the perception of the urban environment is directly related to the prevailing daylight conditions, or as it is often called, the 'urban solar microclimate' (USM)". The unique connection between the urban environment and solar resources likely explains why, after designing analog devices like solar abacuses and heliodons, the community involved in urban planning or design has focused on developing tools that go beyond modeling thermo-radiative aspects and energy balances. The objective here is to investigate the connections between the solar resource and the built environment, and to convert architectural concepts like solar envelopes (Knowles, 1974 cited in Knowles (2003)) into a software tool, such as *SustArc* (Capeluto and Shaviv 1997) or *SolCAD* (Juyal, Kensek, and Knowles 2003). In other words, it entails translating intangible information, like the shadow cast by a building on the ground, into a geometric object that can be defined and manipulated. This is an example of what has been developed using a heliodon projection mechanism in a software tool like *SOLENE* (Groleau 2000).

With the rise of computer hardware and software, these concepts, initially implemented in the context of CAAD tools, have now found their way into geographic information science and technology. (Morello, Eugenio and Ratti, Carlo 2009) have developed a solar envelope instance in a raster context. In a vector GIS framework, it is possible to identify corridors that ensure shadow continuity over time (even over several consecutive hours if necessary) and space by overlaying polygonal shapes of shadow patterns. In this case, the goal is to identify multiple overlapping zones, not only in terms of cartographic depiction but also in terms of generating geometric entities. This delineation can be implemented using standard geomatics processes such as polygonization of shadow contours and overlay mechanisms to count the number of shadow polygons covering each polygonized element. The results shown in Fig. 6 were produced using GIS processing of this kind, implemented in the context of the t4gpd[8] software tool (Leduc, Stavropulos-Laffaille, and Requena-Ruiz 2022).

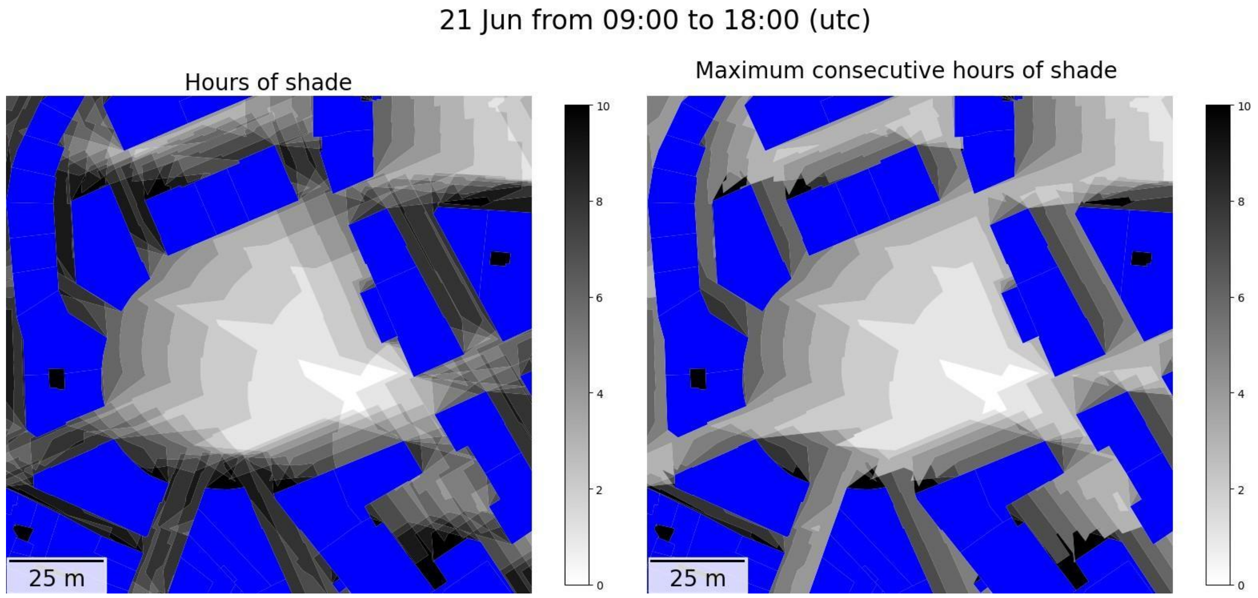


Figure 7. *On a specific date, the ground shadow of each building forms a polygon as determined by axonometric projection. By repeating the operation at each time step within the same day, we generate a set of shading polygons. By applying geometric Boolean operations to this collection of polygons, we can create a solar database that is useful for urban design purposes.*

Aeraulic

The method used by *UMEP-URock* (Bernard, Lindberg, and Oswald 2023), *QES-Wind* (Margairaz et al. 2022), *QUIC-URB* (Brown et al. 2009) and SkyHelios (Fröhlich and Matzarakis 2018) is based on the Röckle approach (Röckle 1990), where the wind is first initialized in some regions around buildings having a well-known wind behavior. Except *UMEP-URock* that is a QGIS plug-in, all these softwares are standalones[13]. They all need information about building footprint and height and *QES-Wind* and *QUIC-URB* can also take Digital Elevation Models (DEM) to account for variation of terrain elevation. When *UMEP-URock* is run, you get as output a wind field but also the zones that have been used to initialize the wind field. Fig. 7 shows an illustration of some of these zones and their corresponding representation in QGIS (note that the same kind of figure can be performed using *QUIC-URB*). Several types of zones are identified around each building. Their shape and size as well as the wind speed and direction inside them is set according to empirical observation deriving mainly from wind tunnel observations.

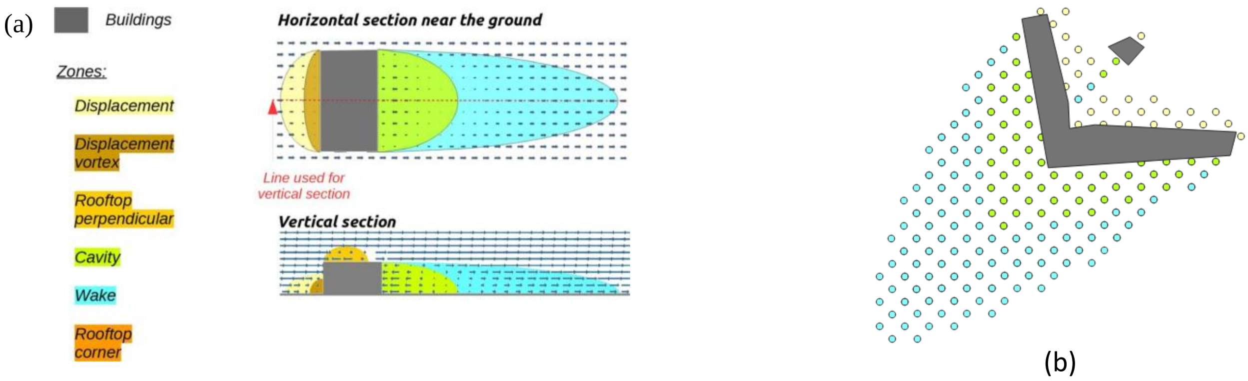


Figure 8. *Some of the Röckle zones used in the UMEP-URock model (a) Zone definition (Source: Bernard, Lindberg, and Oswald (2023)) and (b) zone representation in QGIS.*

3.2.2. *Tools with micrometeorological outputs*

3.2.2.1. Physical model

Radiation

Some physical models provide a detailed description of the radiative environment by processing geographical data. In particular, this involves studying the mean radiant temperature (equivalent temperature globalizing the radiative contribution of thermal comfort), which is a central parameter for describing local variations in comfort (Thorsson et al. 2014).

Particular attention is paid on calculating the proportion of visible sky (SVF, i.e. unmasked by buildings or vegetation). Depending of the tools, it can be calculated in different ways:

– using a ray-tracing algorithm based on a vector layer, as in Ladybug (Roudsari and Pak 2013) or *t4gpd* (Cui et al. 2023).

– by analyzing a fisheye photo. *SkyHelios* (Fig. 8) by Matzarakis and Matuschek (2011), combines images derived from a digital elevation model (DEM) and a vector layer representing obstacles, generates such images and uses this technique.

– by a spatial method of repeated translations of a digital surface model (DSM) layer along the direction of each sky pixel, as is the case with *UMEP-SOLWEIG* (Lindberg and Grimmond 2011).

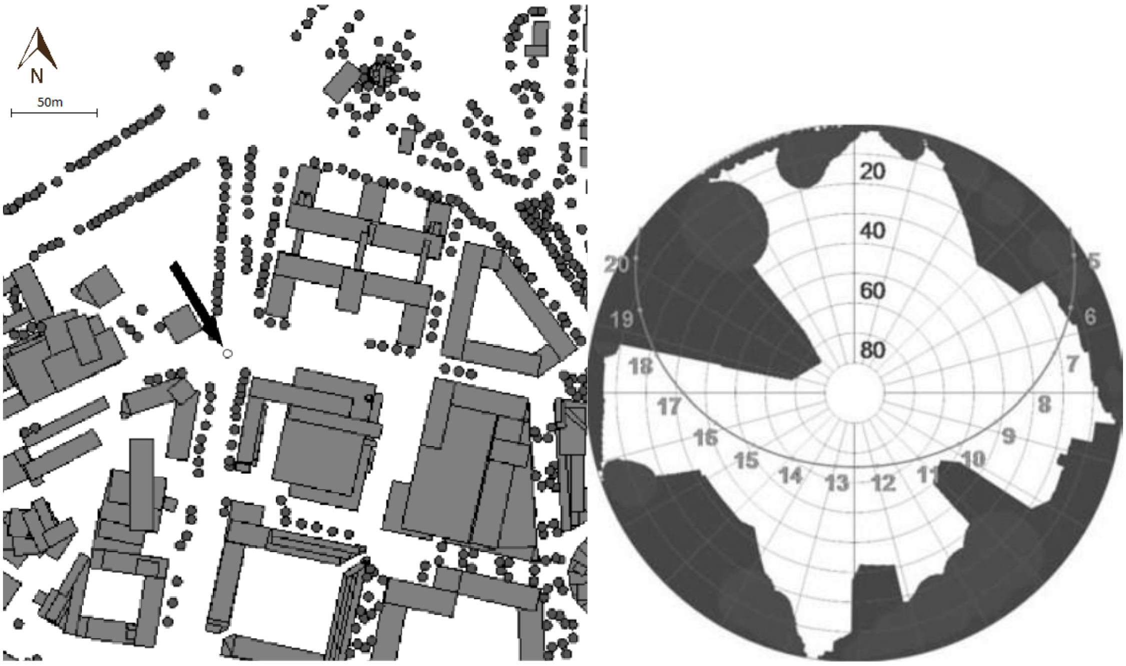


Figure 9. *Construction of a fish eye photo (right) from building and vegetation vector layers (left) on SkyHelios (source Matzarakis and Matuschek (2011)) in the University of Freiburg (48°N 7.51°E) - sunpath calculated on the 18th of july*

A radiative balance (more or less simplified) can then be established, based on the SVF, considering short-wave radiation coming from the sun and long-wave radiation coming mainly from the contribution of the various surrounding surfaces as a function of their temperature. The latter is possible by studying the co-visibility of surfaces (by ray casting for *Ladybug* and *t4gpd*) or by estimation (based on a derivation of the SVF for *Skyhelios*, or on a fictitious environment based on the average height of surrounding buildings for *UMEP-Solweig*).

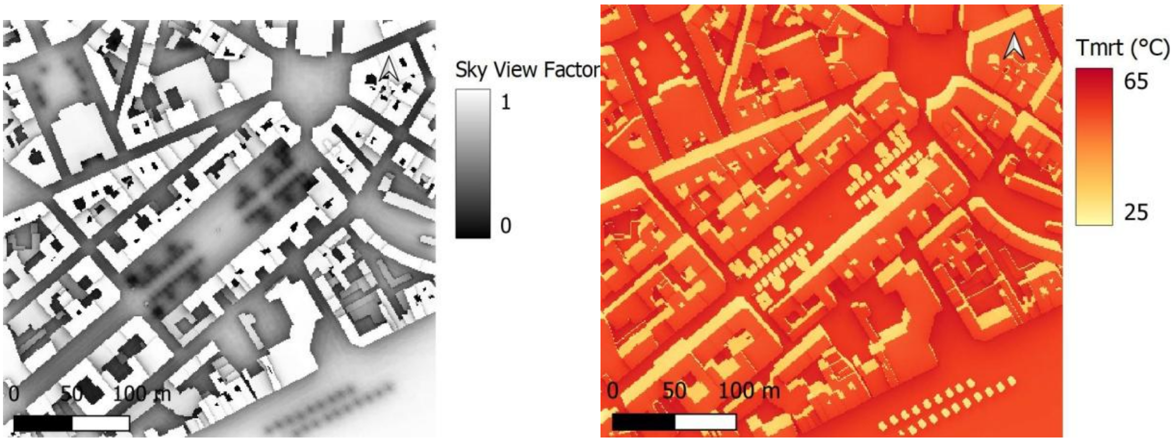


Figure 10. *Example of a UMEP-SOLWEIG simulation in Nantes, SVF on the left and mean radiant temperature on the right*

Surface temperature

Considered as an output or an intermediate parameter towards comfort indicators, surface temperature is studied by several tools.

A tool like *Ladybug* (Roudsari and Pak 2013) establishes the surface energy balance for the entire environment via the *EnergyPlus* model. The radiative part of this balance is based on a radius throw calculation of the co-visibility between different surfaces.

ICEtool (Fig. 11) uses the same algorithm as SOLWEIG to calculate shading (and SVF), using the method as described in (Leduc et al., 2025). From this method, *SOLWEIG* calculates the temperature of horizontal surfaces based on an empirical law that depends on the evolution of the sun/shade state of the pixel and the type of surface (Lindberg, Onomura, and Grimmond 2016). While *ICEtool* also doesn't consider the radiative contribution of the built environment either, it calculates surface temperature by solving a surface energy balance.

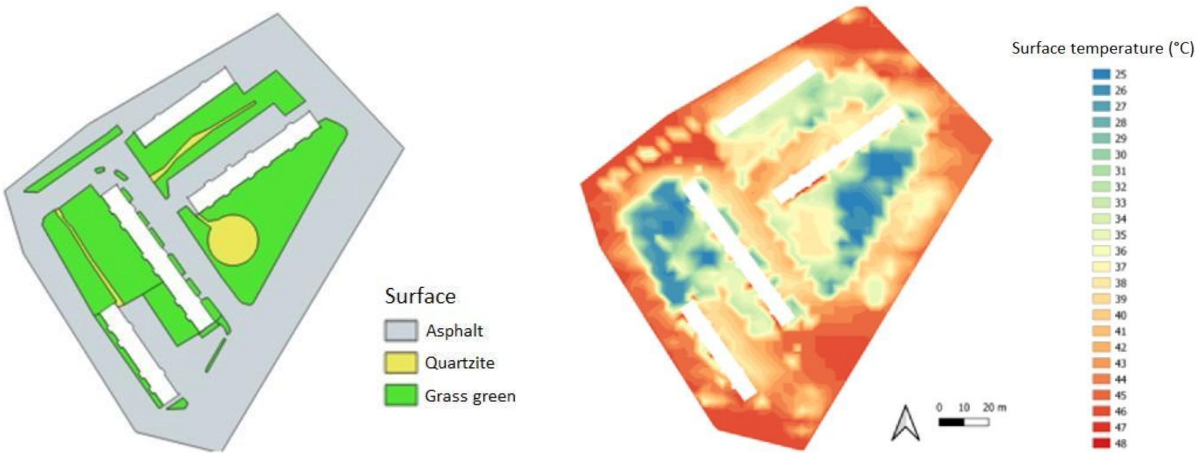


Figure 11. *Example of an ICEtool simulation, surface temperature on the right (Source: software documentation).*

Aeraulic

Many models have been developed to calculate the wind speed at neighborhood or point scale or to classify urban fabric for the ability of their morphology to affect the wind (cf. (Leduc et al. 2025)). However, at our knowledge, only a few of these models are available as tools. The most common way to deal with wind issues for urban areas remains physical based models such as *WRF* or *MesoNH* at city scale or *Code-Saturne*, *OpenFoam* or *ENVI-MET* at neighborhood scale.

Semi-empirical based models have also been quite widely developed these last few years. These models, all based on the Röckle approach presented in (Leduc et al. 2025), are a mix between geomatics and numerical methods to solve differential equations. The vertical wind profile of the study area is set according to the roughness height and displacement length, both deriving from geometric mean obstacle height, building fraction and buildings frontal area. The spatial variation of the 3D wind speed within the study area is then calculated in two steps:

1. initialization: different types of 3D zones are created around buildings. The size of each zone and the law to set the 3D wind speed inside comes from empirical relations derived from wind tunnel observations. All these relations are based on distance (distance between buildings or between a given point of the zone and building) and orientation (orientation of a given building facade from the wind direction) calculations

2. wind speed balance: the wind flow is then balanced minimizing the modification of the wind field initialized in the previous step (See resulting wind field and wind speed Fig. 11).

Four tools have been identified as using this method: *QUIC-URB*, *QES-Wind*, *SkyHelios* and

UMEP-URock. Although the four of them rely on geomatics, only *UMEP-URock* is directly available in a well-known GIS software (QGIS). Note that only *QES-Wind* and *UMEP-URock* are free and open source softwares.

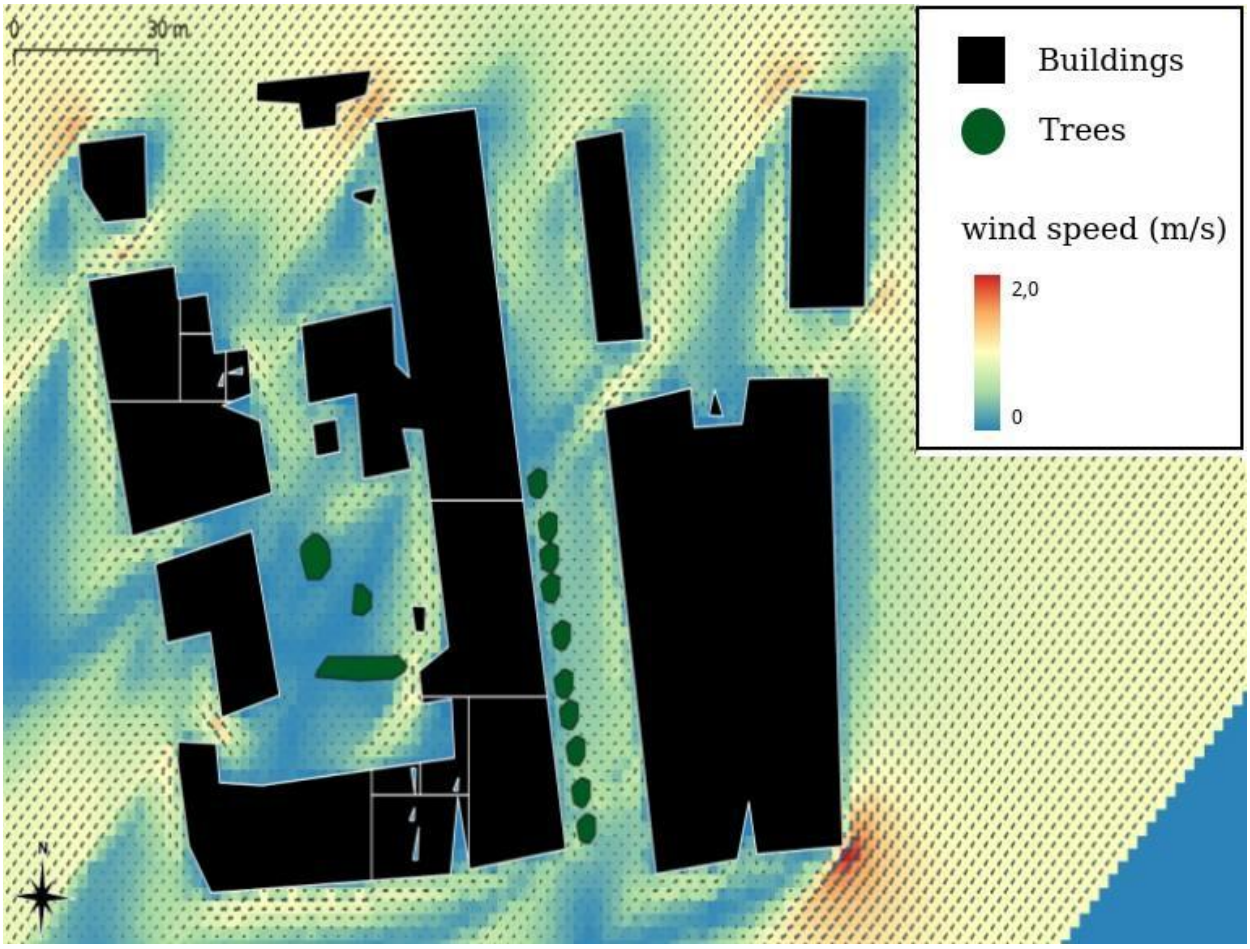


Figure 12. *Example of URock simulation result for a Gothenburg neighborhood with wind speed coming from North-East and 10 m wind speed being 2 m/s.*

4. Conclusion

Micrometeorological parameters are mainly calculated using physical models through numerical simulations. However, radiation and wind are directly connected to the position, the size and the organization of buildings and vegetation. The analysis of the form is then often used to derive wind or radiative fields through GIS modeling (cf. (Leduc et al. 2025)). The other micrometeorological variables, within the urban canopy, are the results of energy and mass balances at the surface, which are themselves dependent from radiant fluxes and wind speed values but also from the ground cover type. Thus, the form and the ground cover types can greatly affect the spatial variations of all meteorological parameters at local and micro scale. Except for the humidity which is much less studied (Kastendeuch, Najjar, and Philipps 2019), many geography based models have been developed within the last decades to make profit from these relations: Unger (2004) for the air temperature, Merville et al. (2023) for the mean radiant temperature, Xu, Gao, and Zhang (2023) for the urban airflow, etc. In this paper, the objective was to classify the tools dedicated to producing local climate information. The segmentation of the classification was performed based on the following aspects. The tool:

- needs raw spatial information or average spatial information,
- produces a physical field of values or simply polygons with qualitative attributes,
- is physical or only spatial based,
- type of physics it is dedicated to.

Only tools either directly integrated within a GIS or at least which are based on algorithms resting on geomatics are discussed. Even though there is a great diversity of models dedicated to the modeling of some meteorological variables using geomatics, not all of them have been implemented into software. This observation has been illustrated in Fig. 3, showing for each model type (scale and physical or statistical based) and micrometeorological variables if it is has been extensively investigated through modeling and has led to software development (blue leaves), if the field has been mainly limited to modeling (orange leaves) or if even modeling has been rarely performed (red leaves).

5. Discussion

With the advent of open science and the consensus around the need to guarantee some form of reproducibility of published work, we might expect that models developed by researchers can be more often implemented into software. At the same time, with the increasing number of platforms dedicated to sharing code, ideas and identifying bugs, we can expect an increase of the algorithm's robustness. We can also expect that new methods can be more easily and quickly tested within a given community. Indeed, model improvements can come from collaborations between physical and GIS sciences. This is the case for some of the tools described in this article:

- A new version of the physical model *SURFEX-MesoNH* has been proposed recently (Schoetter et al. 2020), considering the drag effect of buildings at different levels of the atmosphere. This new model needs new input data that has been processed by the *GeoClimate* software. The *W2W* Python package has been developed to convert a LCZ map into the needed *WRF* spatial inputs (Demuzere et al. 2022). These are two recent examples of how the results of spatial calculation can lead to better model physical processes, thus highlighting the need for more collaborations between GIS and meteorology researchers.

- Some of the existing Röckle zones (zones where the wind is known to have a certain behavior) proposed by the *QUIC-URB* community and implemented within the *URock* model have shown limitations when compared with some wind tunnel data (Bernard, Lindberg, and Oswald 2023). This improvement need has been clearly addressed to communities of researchers interested in analyzing the relations between wind patterns and urban form.

This emergence of new software in the geomatics context is inseparable from the publication of new datasets, more specifically linked to the climate (for example, the Open Source publication of hourly data from MétéoFrance stations since 1 January 2024). This opening up of geomatics to the new field of application of Climate Studies represents a major step forward in the adaptation of cities to climate change. It enables the geographic information departments of our urban metropolises to grasp new concepts, and to manipulate and update new geographic entities, without having to overhaul their software and work habits. This broadening of the skills of city technical departments is good news, because it paves the way for the indispensable regulatory evolution that will interweave urban form and its microclimatic consequences.

Note that climate modeling is directly connected to atmospheric pollution or building energy and comfort. These fields are also strongly connected to the analysis of geography and urban morphology. Some tools making profits from these relations exist but they were not included nor described in the scope of this study. It might be interesting to focus on these fields in the future.

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Appendix 1: Description of each tool presented in the manuscript

Tool name (and access link)	Scope	Method	Minimum spatial inputs	Outputs
LczGenerator (https://lcz-generator.rub.de/)	Classify the territory according to the Local Climate Zone referential.	Random forest algorithm based on satellite images and a training data (LCZ type for a sample of the study area) provided by the user	The user should submit a sample of the study territory with its corresponding LCZ type (this sample is then used to extrapolate the entire study area).	The LCZ type for each pixel (100 m resolution) of the study area
GeoClimate - LCZ (https://github.com/orbisgis/geoclimate/wiki/LCZ-classification)	Classify the territory according to the Local Climate Zone referential.	The study area is split into elementary spatial units. For each unit, urban canopy parameters defined by the LCZ referential are calculated. The LCZ type attribution is then performed based on the value of these indicators compared to the value range defined in the LCZ referential	Two types of datasets can be used: the OpenStreetMap data or the French topographical dataset BDTopo. If the OpenStreetMap data is used, it is automatically downloaded by the software. If the BDTopo is used, the user has to first download the data and provide it as input.	The LCZ type of each unit of the study area (can be topographical based units or cells of a rectangular grid)

Tool name (and access link)	Scope	Method	Minimum spatial inputs	Outputs
Cerema_SatLCZ (https://www.spaceclimateobservatory.org/fr/satlcz)	Classify the territory according to the Local Climate Zone referential.	The study area is split into elementary spatial units. For each unit, urban canopy parameters defined by the LCZ referential are calculated. The LCZ type attribution is then performed based on the value of these indicators compared to the value range defined in the LCZ referential	Two types of inputs can be provided: the more accurate method needs vector data (buildings, roads, etc.) and satellite images while the less accurate method only needs satellite images.	The LCZ type of each unit of the study area (it can be roads or areas such as urban blocks)
Geoclimate - UTRF (https://github.com/orbisgis/geoclimate/wiki/UTRF-classification)	Classify the buildings according to the GENIUS referential.	Random forest algorithm based on urban canopy indicators and a training data (genius type attributed to buildings located in several French urban areas)	Two types of datasets can be used: the OpenStreetMap data or the French topographical dataset BDTopo. If the OpenStreetMap data is used, it is automatically downloaded by the software. If the BDTopo is used, the user has to first download the data and provide it as input.	Buildings with their corresponding GENIUS type or topographical units with its more frequent GENIUS building type
WRF (https://www.mmm.ucar.edu/models/wrf)	Mesoscale atmospheric model which can be used for numerical simulation of urban climate	Physical based model solving both surface and atmospheric processes equations	Most of the indicators are related to building morphology (building fraction, distribution of building height, etc.). The Local Climate Zones (LCZ) can also be used as input (alone or combined to other indicators).	Spatial and temporal variation of numerous meteorological variables

Tool name (and access link)	Scope	Method	Minimum spatial inputs	Outputs
SURFEX/MesoNH (https://www.umr-cnrm.fr/surfex/ and http://mesonh.aero.obs-mip.fr/mesonh57)	Combination of the SURFEX surface model with the MesoNH atmospheric model which can be used for numerical simulation of urban climate	Physical based models solving both surface and atmospheric processes equations	The Town Energy Balance (TEB) is the urban model part of the SURFEX model. It is made of several submodels that require very diverse information (several building morphology indicators, fraction of roads covered by trees, fraction of grass, building type and building use, classification such as LCZ, etc.) (see (Jacquinod et al. 2025))	Spatial and temporal variation of numerous meteorological variables
UWG (https://urbanmicroclimate.scripts.mit.edu/uwg.php)	Urban climate model to numerically simulates the effect of urbanization on canopy-level air temperature and humidity.	Physical based model solving surface processes equations	Urban configuration described by several parameters such as building density and height or vegetation cover	Temporal variation of urban canopy air temperature, air humidity and wind speed

Tool name (and access link)	Scope	Method	Minimum spatial inputs	Outputs
CoolParksTool (https://github.com/j3r3m1/coolparkstool)	Tool dedicated to the evaluation of urban parks impacts on local outdoor air temperature and building energy consumption	Empirical models are used to estimate: the cooling generated by a park the impact of the urban morphology on cool air transport Models are based on predictors describing urban parks and urban morphology	Four spatial layers are needed: park boundary park land cover type park canopy type building footprint and height	Spatial and temporal variation the air temperature around a park and spatial variation of the building thermal comfort and energy use during summer time
TempMap (https://github.com/ntouati/TempMap)	Estimation of the UHI spatial variation	Interpolate air temperature measured at given locations to a whole territory based on city density, terrain elevation and distance to the station through multiple linear regression plus kriging to interpolate the residuals	Two types of inputs: Air temperature and location of air temperature sensors located within the study area City density (sum of road fraction, building fraction and facade density) and terrain elevation	Spatial variation of the air temperature
Ladybug (https://grasshopperdocs.com/addons/ladybug.html)	Radiative model coupled with a surface balance model to evaluate the thermal comfort in urban areas	The model is based on a ray-tracing algorithm	Building and tree geometries in a format that can be imported into the Grasshopper software.	Irradiance fields, ground shading polygons

Tool name (and access link)	Scope	Method	Minimum spatial inputs	Outputs
UMEP-Solweig (https://umep-docs.readthedocs.io/en/latest/processor/Outdoor%20Thermal%20Comfort%20SOLWEIG.html)	Solweig is a model dedicated to the calculation of radiative processes in urban areas.	The method is based on a spatial method of repeated translations of a digital surface model (DSM) layer along the direction of each sky pixel	Topographic data provided as raster, including building footprints, height attributes and tree alignments, as well as digital terrain model, among others.	Raster of shadow, mean radiant temperature, radiative fluxes.
t4gpd (https://t4gpd-docs.readthedocs.io/)	Shadow-casting and radiative model	The model is based on a ray-tracing algorithm	Topographic data, including building footprints, height attributes, and tree alignments, among others.	Scalar irradiance, irradiation fields, and ground shading polygons.
QUIC-URB (https://www.lanl.gov/projects/quic/)	QUIC-URB is dedicated to the simulation of aeraulic processes. It also includes the calculation of building facade pressure coefficients and of the dispersion of airborne contaminants	The wind model is based on the Röckle approach: first, the wind field is set according to empirical laws; second the wind flow is balanced minimizing the modification of the original wind field.	Building and vegetation footprint and height, digital elevation model.	3D wind speed and wind direction, location of Röckle zones
UMEP-URock (https://umep-docs.readthedocs.io/en/latest/processor/Wind%20model%20URock.html)	URock is a model dedicated to the calculation of wind fields in urban areas.	The wind model is based on the Röckle approach: first, the wind field is set according to empirical laws; second the wind flow is balanced minimizing the modification of the original wind field.	Building and vegetation footprint and height	3D wind speed and wind direction, location of Röckle zones

Tool name (and access link)	Scope	Method	Minimum spatial inputs	Outputs
SkyHelios (https://www.urbancli-mate.net/skyhelios/)	The combination of a radiative model and a wind model dedicated to thermal comfort applica-tions in urban areas.	The radiative model is based on the analysis of a fisheye photo. The wind model is based on the Röckle approach: first, the wind field is set according to empirical laws; second the wind flow is balanced minimizing the modifi-cation of the original wind field.	SkyHelios supports many different spatial input file formats that also may be combined (mostly formats supported by the geospatial data abstraction library/openGIS simple features reference implementation GDAL/OGR).	Mean radiant temperature, global ra-diation, wind speed and ind di-rection, Sky View Factor, sun-shine duration, shadow and bi-oclimatic indices (PT, UTCI, PET)
ICEtool (https://github.com/Art-Ev/ICEtool)	Estimate ground temperature in ur-ban areas	Based on the UMEP-Solweig model, it applies a ground energy balance.	Topographic data provided as ras-ter, including building footprints, height attributes and tree align-ments, as well as digital terrain model, among others.	Surface temperature
QES-Wind (https://qes-doc-umenta-tion.readthedocs.io/en/lat-est/QES-Winds.html)	QES-Wind is dedi-cated to the simula-tion of aeraulic pro-cesses. It includes the calculation of the dispersion of airborne contami-nants.	The wind model is based on the Röckle approach: first, the wind field is set according to empirical laws; second the wind flow is balanced minimizing the modifi-cation of the original wind field.	Building and vegetation footprint and height, digital elevation model.	3D wind speed and wind di-rection