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Sidonie Christophe[1], Jacques Gautier[1], Paul Chapron[1], Luke Riley[1,2], Valéry Masson[3]

1: LASTIG, Univ Gustave Eiffel, ENSG, IGN, F-94160 Saint-Mande, France
2: Université de Toulouse Jean Jaurès, ENSAT-INP Toulouse, France.
3: Centre National de Recherches Météorologiques, Météo France, Toulouse, France.

Abstract

This paper is about the relevance of proposing geovisualization methods to visually integrate, co-visualize and interact with urban and meteorological data into a 3D environment, in order to support the visual analysis of the urban climate. Meteorological experts and researchers already face meteorological data and climate models analysis issues, at larger scales into the city: yet even if they have existing practices and tools to address these issues, they could take benefit from the knowledge and the methods from the Geovisualization domain, to complement these analyses by a visuospatial reasoning approach.

In this paper, based on the knowledge of the expectations of the meteorological experts we are working with, we bring closer climate analysis into the city and visuospatial reasoning on both heterogeneous urban and air temperature data (1). We review the existing works regarding geovisualization of spatio-temporal phenomena and visualization of meteorological data (2). We then present the different approaches we fulfilled to provide a 3D geovisualization environment and graphic representations, visually integrating both meteorological and spatial data. One provides style and interaction capacities on those data, enabling the interactive 3D exploration of their spatial and value distributions, throughout the city. Another geovisualization-design experiment is presented as a co-visualization of meteorological data and morphological indicators on 2.5D maps (3). These complementary approaches are presented and discussed with the meteorological experts, based on their relevance to tackle climate analysis at a larger scale and on the refinements required to extend their exploration capacities (4).

Résumé

Cet article s'intéresse à la proposition de méthodes de géovisualisation pour intégrer visuellement, co-visualiser et interagir avec des données météo et des données topographiques urbaines, dans un environnement 3D, afin de pouvoir réaliser des tâches d'analyse visuelle. Les chercheurs et experts en météorologie sont confrontés à des problématiques d'analyse de données météorologiques simulées et de modèles de simulation, à des échelles fines en ville : même si des outils existent, ils pourraient également tirer parti des connaissances et méthodes de la géovisualisation, pour avoir une approche complémentaire en termes d'analyse visuelle, favorisant le raisonnement visuospatial.

Tout d'abord, à partir de la connaissance des attentes des experts météorologues avec qui nous travaillons, nous essayons de rapprocher les problématiques d'analyse du climat urbain et le raisonnement visuospatial, à partir des données hétérogènes à manipuler, que sont les données de température de l'air et des données urbaines (2). Nous faisons ensuite une revue des travaux existants sur la géovisualisation de phénomènes spatio-temporels et la visualisation de données météorologiques (3). Nous présentons les différentes approches que nous avons expérimentées, afin de fournir un environnement de géovisualisation 3D, intégrant visuellement les données météorologiques et spatiales. Une première proposition offre des capacités de stylisation et

d'interaction sur ces données, afin de faciliter une exploration interactive en 3D des distributions spatiales des données, dans la ville. Une deuxième proposition présente la co-visualisation de données météorologiques et d'indicateurs morphologiques dans des cartes 2.5D (4). Ces approches complémentaires sont décrites et discutées avec les experts météorologues, afin d'évaluer leur pertinence pour l'aide à l'analyse climatique, à des échelles fines en ville, et d'en extraire des améliorations pour étendre les capacités d'exploration (5).

Keywords:
urban climate, air temperature, urban heat island, geovisualization, 3D visualization, maps, urban morphology.

1. Introduction

Understanding urban climate dynamics requires the simulation of climate phenomena at various urban scales, using complex models (Lac et al., 2018). The Urban Heat Island (UHI) phenomenon, which causes higher temperature in cities is at stake and the object study of many researches for many years (Bouyer et al., 2011; Masson et al., 2014; Akbari et al., 2016; Equere et al., 2020), in order to properly support urban planning and public policies which could mitigate their impacts. Meteorological experts and researchers handle both simulated meteorological data and simulation models analysis issues, while evaluating the underlying uncertainties propagated by downscaling approaches from the national or regional climate models to urban scale climate models (Van de Vyver et al. 2019; Duchêne et al., 2020). The ERA4CS URCLIM project, implying various european meteorological institutions and IGN-France, geodata & map producer from France, aims at providing data, models and tools to move forward on the production of URban CLIMate services for urban planners and stakeholders in the city (Masson et al. 2020a). The consortium investigated how to create high resolution maps of urban parameters, to analyze the propagation of uncertainty through spatial scales, to evaluate multi-criteria impacts and various types of adaptation strategies and finally to design Urban Climate Services (UCS) with and for the stakeholders through visualization proposals (Masson et al., 2020b).

In this context, we tackle a particular issue regarding how geovisualization knowledge, methods and tools could be useful for meteorological experts to complement their climate analyses regarding space, by a visuospatial reasoning approach (Tversky, 2005). Geovisualization, as an interdisciplinary domain of the geographical information sciences, targets to visually integrate and analyze spatio-temporal data, based on the interaction of the users with these data and their attributes, in a geospatial context. Therefore, providing visualization methods to support the spatial contextualization and the visual analysis of simulated meteorological data helps meteorological experts, providers of climate simulation models and meteorological data to better understand the interactions and mutual influence of simulated meteorological data and urban data (Pinson and Masson, 2016; Le Roy et al., 2020). Diving deeper at a larger scale into the city implies to consider the spatial and geometric structure of these data, to be able to co-visualize them into the same graphical interface, augmented with interaction capacities to manipulate and explore them. In order to attempt this purpose, a co-design approach has been followed between geographic information and meteorological scientists to propose innovative 3D geovisualizations for climate analysis at larger scales.

In this paper, we review the existing related works regarding the use of visualization of meteorological data, for (spatial) analysis purposes, in order to properly delimit our scope of contributions. Then, based on the analysis of the expectations of the meteorological experts regarding visualization and the use they have of spatialized climate data, we specify design geovisualization guidelines to support the interactive exploration of the two following issues: first, both spatial distributions of simulated meteorological data and their interactions with the morphology of the city;

secondly, the co-visualization between air temperature and morphological indicators. We thus present two main contributions about the design of geovisualizations providing perspectives on the spatial interactions between meteorological and urban data at infra-city scales, based on the visual integration and manipulation of those heterogeneous data. Our first research work provides a 3D environment enabling the interactive spatial exploration of the air temperature spatial and value distributions and its relationships with urban morphology. This visual exploration is achieved by providing the user with some styling and interaction capacities. The second research work is an experimentation of the co-visualization of meteorological data and morphological indicators on 2.5D maps. These complementary approaches are finally presented and discussed with the meteorological experts, based on their relevance regarding the field.

2. Related works: the use of visualization for climate analysis

2.1 Geovisualization for expert visual analysis.

Geovisualization is the set of knowledge, methods and tools favoring the visualization and the visual analysis of geographic spaces and spatio-temporal phenomena, based on the user interaction with geographic or spatial data (MacEachren and Kraak, 2001; Dykes et al., 2005; Cöltekin et al., 2020; Christophe, 2020). Geovisualization as an interdisciplinary domain brings closer spatio-temporal data modeling, their graphic representation and rendering, interaction, perception and cognition. Interactive exploration of geospatio-temporal information enables knowledge inference on geographic spaces and spatio-temporal phenomena, while enhancing what is and could be meaningful for the users into the graphically represented geographic spaces and phenomena. Similarly to information visualization (Kerren et al., 2008; Yi et al. 2007) and data visualization (Friendly, 2008), but geospatial-oriented, geovisualization should facilitate both the exploration of the geospatial data and the first steps of visuospatial reasoning, including preserving the spatial structural relations of the world into graphic representations (Tversky, 2005; Lobben et al., 2019). Geovisualization addresses the complexity to visualize and interpret a spatio-temporal phenomenon interacting with the related geographic spaces, until the expected but difficult to achieve decision-making (Padilla et al., 2018).

A diversity of users expects to visualize complex spatio-temporal phenomena in order to see, explain, analyze and understand complex spatial dynamics and systems (Griffin and Fabrikant, 2012): investigating innovative modes to explore data and geographic spaces, virtually or in an augmented way experience, is at stake in our domain. Interaction tasks are supported by geovisualization environments, according to the expected or required level of interaction, as well as the final uses and users: communication of particular insights on a phenomenon to a large public, synthesis of complex information related to a phenomenon, raw data expert analysis, exploratory analysis approach (MacEachren, 1994; Roth, 2012). In parallel, more heterogeneous, imprecise and massive spatial and non-spatial data are available to be combined for visualization and in particular the visual analysis of complex geospatial phenomena for experts. Co-visualizing data, i.e. visualizing them together in a single visual display, may imply visual complexity and cluttering issues (Jégou and Deblonde, 2012) caused by their potential number but also their potential heterogeneity in source, scale, content, precision, dimension and temporality. Co-visualization offers opportunities to explore how data could be visually integrated while revisiting multiviews interfaces supporting the exploration of the different spatial, temporal, and semantic components of the data with the help of temporal diagrams, tabular representations, cartographic representations, 3D representations. This visual integration requires to figure out some graphical representation features to preserve legibility when combining heterogeneous, and sometimes numerous, data.

Existing scientific visualization libraries and softwares such as Paraview (Ahrens et al. 2005), ANSYS Discovery Live (Kristof & Papp, 2018) and VTKm (Moreland et al. 2016) propose different renderings of multi-dimensional data such as meteorological data, based on the representation of iso-volumes or 3D slices of 3D data. Such representations are interesting to explore in detail the values of temperature data at some specific locations (slice of 3D data), or the spatial distribution of specific temperature intervals (iso-volume). These tools are very efficient to represent the physics of a phenomenon efficiently, but they do not allow more in-depth spatial analysis of this phenomenon, since the other, non-meteorological, spatial data are not included, withdrawing some of the context of this very phenomenon. In addition, the issue of quality regarding scientific visualization, balanced with aesthetic issues is addressed for the visualization designers (Hanson, 2014).

Advances in modeling and simulation of geophysical spatio-temporal dynamics need more and more visualization support, for visuospatial analysis purposes (Perrin et al., 2020). Knowing that a phenomenon could be represented by raw, predicted, simulated or learned data, another complexity comes from acquisition sensors and input models, and their own imprecision to be (visually) propagated. In this paper, we target researchers and experts in meteorological data and climate simulation. Uncertainties of data (positional and semantic accuracy, logical consistency and completeness), models and phenomena remain difficult to convey and is still a major issue for geovisualization: visual variables have been explored and experimented (MacEachren et al., 2012; MacEachren, 2015; Bevis et al., 2017; Johannsen et al., 2018). But still, how could visualization effectively support perception and interpretation of climate data and phenomena?

2.2 Climate data visualization

Existing visualizations of climate and meteorological data regroup temporal diagrams, animated or not, aiming at communicating global trends on large time series, having a strong impact and strengthening the current message about global warming: for instance, the famous visualization of a climate spiral for 1850-2018 or an arctic sea ice evolution for 1979-2018 (Hawkins, 2018) and the famous updated warming stripes for any region of the world from 1850-2020 (Hawkins, 2021). Map design is also used worldwide to support the highlighting of the evolution of air temperature or rain values, as collections of juxtaposed maps, mainly at world or country scales: for instance various projections of the evolution of mean temperatures by season, compared to the period 1850-1900, related to several scenarios of global warming for France area (Haut Conseil pour le Climat, 2021, maps from G. Sutton); or animated maps representing the evolution of the distribution of spatial meteorological data over time (Mersmann et al., 2016). Spatio-temporal representations and animations are thus more and more used, in order to serve continuous animated visualizations of large time-series of spatial data. A lot of tools provide animations that are very useful to improve the global perception of a spatio-temporal phenomenon and its general patterns (NOAA, 2014). Nevertheless, even if animations are very useful to improve the global perception of these phenomena and related general patterns, it remains difficult to detect and analyze changes, at any scale, because interaction with data is missing. To solve this, such climate data visualizations integrate step by step interaction functionalities, allowing selecting specific time periods, spatial scales, and filtering the data to be represented (Granshaw, F.D., 2020; Hawking, 2021). Highly interactive environments also exist, proposing to visually explore different meteorological data through different interactive graphic representations, maps or temporal diagrams (NOAA's Climate Program Office, 2018; Windy, 2014). Some of these beautiful and impactful data visualizations are nevertheless not adapted to complex visual analysis of climate change or meteorological data analysis, regarding dynamic geographic spaces and other dynamic geophysical systems, even if some parameters may be used to compare, show and extract time periods and identify some effects.

Typical graphic semiology issues from map design, mainly about colors, but also about textures (Johanssen et al., 2018) remain for the visualization, the perception and the interpretation of meteorological data. 2D scalar meteorological data, such as temperature values, are represented in maps using color scales. In a lot of climate visualizations, data such as temperature values are represented through rainbow color scales using RGB (Red, Green, Blue) color palettes, even if the efficiency of these scales has already been criticized for cartography and visual analysis (Stauffer et al., 2015; Dasgupta et al., 2018), because of the fact that the rainbow color scales may show luminance gradients, which do not correspond to the represented data value gradients. Some propositions have been made to propose color scales respecting a continuous evolution of luminance through the use of sequential or diverging color palettes such HCL (Hue, Chroma, Luminance). Despite the user tests showing the better efficiency of such scales on the analysis of climate data (Stauffer et al., 2015; Schneider and Nocke, 2018), and the good user feedback on the efficiency of those scales, a lot of climate scientists still consider they are confident with rainbow color scales (Dasgupta et al., 2018). Usual and almost conventional color palettes for geo-physics phenomena are still in question regarding their relevance to support fine scientific analysis and sharing (Spekat and Kreienkamp, 2007; Thyng et al., 2016), and more generally, the semiological choices of the field.

2.3 Urban and meteorological data simulation & co-visualization at city scales.

In the existing visualizations of meteorological data, the visualization of the spatial component of the data is mainly limited to world and regional scales. The need for methods and tools allowing meteorological experts to tackle, at city scales and especially at infra-city scales, the outputs of different simulation models and the related input data is a major requirement. One of such infra-urban climatic phenomena of interest are the Urban Heat Islands (UHI).

The causes of urban heat islands are diverse (Oke, 2002; Akbari et al., 2001; Bouyer et al., 2011): mineralization of cities, lower albedo causing more solar energy absorption, building density, reduced air velocity caused by higher urban surface roughness (Masson et al., 2014; Plumejeaud-Perreau et al., 2015). A better understanding of the urban heat islands requires a more accurate knowledge of the urban morphology (Stewart and Oke, 2009; Plumejeaud- Perreau et al., 2015). A finer description of the urban space through the Local Climate Zone (LCZ) classification has been investigated, defining regions of uniform surface cover, structure, material, and human activity (Stewart and Oke, 2012; Rodler and Leduc, 2019), and extended by taking into account land use or socio-economic criteria (Plumejeaud-Perreau et al., 2015). Simulation models use this description of the urban space, as inputs to simulate temperature, wind, or humidity values. These simulations allow calculating the possible bounds of urban heat islands, but also providing a way to predict the effect of a possible urban planning policy on the evolution of the urban heat islands, providing help for the mitigation of their effects (Bouyer et al., 2011).

Visualizing meteorological data in their urban environment is a way to both validate simulation models and analyze the relationships between input indicators, simulation models outputs, and urban morphology, at the city scale but also until the building/street scale, since the resolution of models outputs are taken into account. Plane representations of aggregated land use or air temperature data are mainly displayed at city scales, due to the limit of the spatial resolution of those data. Those spatialized representations of 2D data are displayed as 2D maps, or as planes into a 3D environment, or projected as a texture of 3D objects into a 3D environment: for instance, the 2D air temperature represented as 2D maps or projected on a 3D urban model to support UHI analysis (Pinson et al., 2015; Pinson and Masson, 2016), the air quality data represented by the color of the ground in graphic representation of a city (Kurppa et al. 2020), the representation of the simulated temperature of buildings surface (Yaghoobian & Kleissl, 2012), or using colored 3D buildings to represent simulated air temperature near the ground surface (Bouyer, 2011). Other works explore ways to visualize 3D meteorological data: for instance, the representation of a 3D grid of air temperature data through the color of a 3D point cloud in a 3D visualization environment (Ruas et al., 2020). These propositions lead to the possibility for the experts' users to have various points of view on the spatial resolution of the represented information of temperature, heat waves or UHI. Playing with possible dimensions of 3D visualization environments allows using the visual variables of the 3D objects in order to represent 2D and 3D scalar data coming from meteorological and climate experts.

3. Our methodology: co-design with meteorologists experts on climate visualization

Our methodology is based on a co-design approach in geovisualization (Lloyd and Dykes, 2011) between meteorologists and geovisualization experts, all along the ERA4CS URCLIM project (Masson et al., 2020a). In this section, we describe first the expectations of the meteorologists experts on climate data analysis. Then we extract from those expectations what geovisualization could bring to solve them, and we specify some geovisualization guidelines rules to follow during our own process of designing geovisualization methods and tools. Finally we reformulate our approach of a co-visualization between heterogeneous data in a 3D environment.

3.1 Meteorologists experts' requirements on meteorological data analysis.

The identification of the users' requirements starts from the analysis of the existing expectations of the meteorologists experts on meteorological data analysis, upstream from the ERA4CS URCLIM project and at its very beginning. Originally, the very aim of the project was to fit the needs of urban planners and stakeholders, in order to support them in a decision making-process on issues related to urban climate. But it quickly appears that meteorological experts involved in the project need new methods and tools to analyze specific components of the urban climate, to handle the outputs of different simulation models at several scales, and to analyze these simulated meteorological data in relation to the data used as inputs of their simulation models. Since climate simulation models need input data related to land cover use, morphological indicators, etc., aggregated into the Local Climate Zone indicators, it means that the simulated meteorological data (output) depends on the model design but also on the initial quality of the input data (namely resolution, precision, and semantic information).

Regarding spatial climate analysis. The meteorological experts involved in this work are urban climatologists from Centre National de Recherches météorologiques, Météo France, one of them being co-author of this paper. The experts are specialists in interactions between the city and the lower atmosphere, and the processes at play in the atmosphere. We distinguish the following needs from the meteorological experts at the beginning of the project. The list of what meteorological experts need to analyze is obviously not exhaustive here, only an extraction of the main issues in the ERA4CS URCLIM project, that converge to spatial analyses issues.

- They need to validate the input data and the initial configuration of the simulation models, in order to get them to cover homogeneously and continuously the area of Europe, but also at each important and shared scale level. This main issue of spatial scales avoids having homogeneous approaches for analysis in Europe (even while sharing standard models) and being able to easily integrate meteorological data from one country to another.
- They need spatial insights and analysis to confront their input data, meteorological data and climate models. They do not solely need to spatialize meteorological data, on the top of a background map (spatialization of thematic data), or to plot a curve or a trend on the top of a

cross-section of the city, which is interesting to initiate spatial reasoning, but also find useful to locate the data and identify global patterns.

- They need to address the issue of how climate and spatial objects, shapes, structures and morphology, that are themselves dynamic, actually interact together in space and in time. This needs to have ways to address what is spatial, what is climate, independently and together, on the same support.
- They need to be able to cross spatial scales, while following upscaling and downscaling issues of the climate simulation models. Through the related works, we can see that there are categories of visualizations for each scale level according to some climate issues to tackle. The need of downscaling models and the analysis of the interaction between urban and meteorological data is also a stake here, including the (propagation of) underlying uncertainties while downscaling.

Considering that climate simulation models could become more precise, allowing to simulate meteorological data at very large scale, meaning at the scale of the urban blocks, or even the streets, the meteorological experts need new methods and new tools to analyze the urban morphology and the meteorological data at larger scales than the city scale. At the moment, it is possible to easily detect global patterns and trends at small scales (meaning worldwide level), but the issue now is how to identify and detect patterns, trends, even artifacts and outliers at larger scales, below the city level.

Regarding visualizations. What is particularly relevant, surprising and interesting at the same time is the positioning regarding visualization aspects at the beginning of the project. During the preliminary steps of the project, visualization was at the center of it and all meteorologist partners were saying they needed visualization. It took time to understand which type of visualization we were discussing. We only discuss visualization here for meteorological experts and not for other stakeholders. Actually, visualization concerns mostly work outputs and communication purposes (so, how to make a map with a list of values, i.e. values spatialization and simple map making), and they have tools for that matter already, but possibly need help to refine them: GIS map outputs, diagrams and graphs, and the sets of indicator maps (morphological, LCZ, land cover use, etc.) finally constituting a lot of sufficient and efficient visualizations by now. At the other extreme of the spectrum regarding ‘what could bring visualization?’, a very little part of the researchers were very aware of scientific visualization tools and were not really looking for other proposals, because according to them, these tools totally reach their goals in terms of (physical) analysis of meteorological data, climate phenomena and final scientific visualizations of simulation results.

Regarding visual spatial analysis. During these preliminary discussions, a part of our methodology consisted in proposing regularly some insights and examples coming from our research, to start thinking together about how to provide smart visualizations for their needs regarding meteorological data analysis, and not only output and communication purposes, but in a spatial/climate approach. It appears that the main challenge was about providing innovative methods and tools for geovisualization to bring closer simulated meteorological data at larger scales and what we know about urban morphology, and not solely through the creation of indicators, or through the use of a set of maps. It was then clear here that in order to navigate into the data presented in all those maps, we will have to find strategies to explore them with another perspective. Based on the fact that an existing part of the project was considering the elaboration and the accessibility of those maps, we decided to go forward on innovative visualization for meteorological experts, fitting their expectations on spatial climate analysis at larger scales. Our proposal at the time was to be able to explore, together and in the same interface, heterogeneous data (meteorological and urban), similar in one aspect: they are both tri-dimensional and would benefit from a 3D environment to be displayable, manageable and explorable.

All along the project, we focused on that contribution, explicitly and regularly discussed with some meteorological experts, in order to elaborate a specific use case with Météo France researchers, based on the sharing of existing visualizations and step by step first visualization proposal. As we know from previous works, some expectations are also difficult to apprehend, because more implicit, and the design of a geovisualization tool should support the explicitation and the emergence of those needs regarding climate analysis.

3.2 Use case for innovative visualization to support urban meteorological data analysis.

We need to integrate the explicit users' requirements and expectations regarding visualization, in order to formalize what we could propose as innovative geovisualization methods and tools to support urban meteorological data analysis. In a geospatial perspective, the needs regarding spatial analysis of meteorological data could be addressed in a way that is complementary to what is being done elsewhere: visual reasoning on spatio-temporal phenomena on Earth. In order to go from users' requirements to suitable geovisualization tools, we need first to specify the use case.

The use case. Our use case targets meteorological experts who want to visualize complex 2D or 3D meteorological data obtained from simulation models, while having access to individual values or ranges of values, horizontally or vertically in space, in their urban context (shapes of the buildings, the urban blocks, main streets, city morphology). They also need to better understand urban climate phenomena and their relationships with the urban morphology. They also would need to be able to reach some thematic information on morphological indicators that are already used as input of the simulation and to have the possibility to see them, visually related to both simulated meteorological data and urban data.

Possible expected users' tasks regarding visualization and usability. As soon as the use case is clarified, some expectations come more easily regarding the visualization capacities.

- Providing a visualization of meteorological data in a more simple way than in the initial output format: meaning that we have to get the data, to find the relevant geometric structure to project the data on, and to have extensible capacities of style and interaction thereafter. We have to consider the dimensionality of the data to make the more suitable proposition there. We also have to tackle the issues regarding the heterogeneous resolution of the represented data, and the issues regarding the different levels of uncertainty.
- Providing the possibility to spatially explore the data (through zoom in/zoom out/pan tools) and the value distribution (through tools to reach the values and to display them somehow).
- Providing clues and methods to identify inconsistencies in the simulation results, that could be improved thereafter, in order to validate the simulation models.
- Providing the visualization of the city and its morphology, in the same interface as the meteorological data.
- Possibly providing a visualization of additional climate parameters (wind, rain, etc.) and input indicators or maps of the simulation models.

3.3 Design rules for a 3D co-visualization of urban meteorological data at larger scales.

Those design rules should drive the way we will tackle graphic representation and visual interfaces, in order to effectively support a set of tasks of the meteorological experts, enabling spatial visual reasoning on data. This implies to translate the previous user's requirements into geovisualization design rules.

- Visual integration of heterogeneous tri-dimensional data: meaning that the 3D meteorological data has to be visually integrated with 2D/3D topographic data, in the same visual environment.
- Enabling style capacities to support data graphic representation and scene appearance, better data perception and exploration: meaning using abstract stylization for any data, and simplified representation of urban data to better perceive shapes, volumes and depth. Another issue to consider is the visual and semiologic overload: ways have to be found to simplify graphic representation (disappearing/opacity edition).
- Enabling interaction capacities to support subtler data exploration and analysis: style will offer some exploration capacities, but providing additional tools, into the scene or besides, or elaborated tools which could be diagrams, graphs synchronized with the 3D scene in order to select and filter some properties and values of the data (common feature of multiviews in (geo)visualization).
- Managing visual complexity: in order to lower visual complexity, semiological choices and interaction capacities have to be controllable by the users.
- 3D environment handling: we have to consider how to manage the scene and the related functionalities: to explore into the scene continuously and smoothly (3D engine capacities) and to browse the data, value distributions, semantics, etc. (additional tools in another view).
- Managing spatial scales and resolutions: Meteorological data and urban data have different resolution levels and it is not possible to mix/provide them, for any scale, from the sidewalks to the building's roofs level: some clues have to be given to the users to avoid misinterpretation while downscaling.

These design rules come from the initial analysis of the users' requirements and the related use case, and have been refined overtime with the help of regular discussions with meteorological experts, based on the demonstration of elementary prototypes or elementary functionalities, to be tested and validated by them.

4. 3D Co-visualizations of urban and air temperature data

In this section, we present our contributions of the design of 3D co-visualizations of simulated air temperature and urban data, at larger scales, in order to fulfill the different users' tasks (3.2). We propose:

- to enable a visual exploration of spatial and value distributions of simulated air temperature data through interactive graphic representations;
- to enable in the same interface an analysis of their relations with, on the one hand, the urban morphology in the three dimensions of space, on the other hand several urban morphological indicators. To reach this objective, the proposed 3D co-visualizations are developed in regard to the design rules (3.3).

The visualizations are WebGL applications, implemented using the ThreeJS Javascript library. The 3D visualization has been implemented as an independent web application, using WebGL and ThreeJS for the construction of the 3D scene, and JQuery for handling the interaction (4.1, 4.2). The 2.5D visualization has been created using the QGIS plugin QGIS2ThreeJS, allowing the export of the content of a 2D visualization created in QGIS in a WebGL 3D visualization (4.3).

4.1 3D visual exploration of air temperature and building data at urban block and city scales.

We provide a way to perform a visual analysis of the 3D distribution of temperature values at city and urban block scales, and its relationships with the urban forms. We propose to visualize both 3D simulated air temperature data with a 3D urban model inside an interactive 3D visualization environment. The visualization methods and tools supporting this proposition have been presented in prior works (Gautier et al., 2020a, b).

4.1.1 Geometric representations of simulated air temperature and urban data.

The air temperature datasets are simulated using the TEB (Masson, 2000) and Meso-NH (Lac et al., 2018) simulation models of Meteo-France: these data can be represented as a 3D irregular grid of points, each point being related to one simulated value. We represent this grid as a grid of polyedric cells, the punctual location "O" of each simulated temperature value being at the center a corresponding cell (Figure 1, left). We consider that the air temperature bears a unique value inside the same cell. This grid has a horizontal resolution of around 650 meters near the ground, and a vertical resolution from 1 meter near the ground and around 20 meters near the building roofs (Figure 1, center). The topographic dataset describes the building blocks of the city, with their corresponding areas, altitude and height, and comes from the BD-TOPO of the IGN (Figure 1, right).

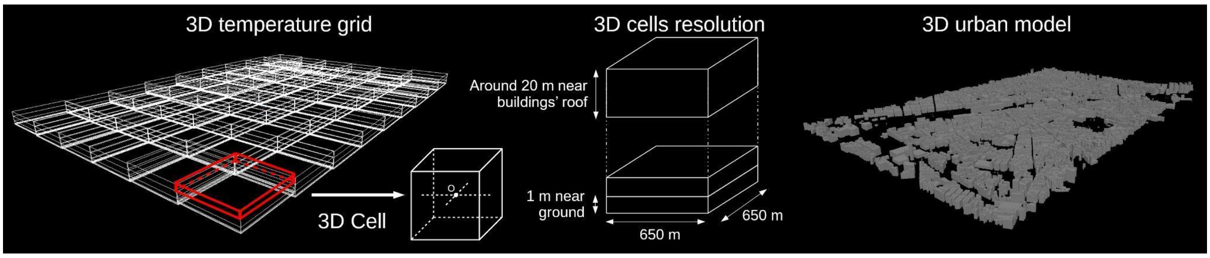

Figure 1: Input data of the 3D geovisualization: 3D grid of simulated air temperature data (left and center); and 3D urban model (right).

A way to visualize the temperature distribution in space is to use a color scale representing the entire temperature extent in the represented area. In order to visualize the temperature in its 3 spatial dimensions, one solution could be the representation of 3D iso-volumes, representing 3D areas reaching a temperature above a defined threshold, but such a solution would imply to superimposed different 3D iso-volumes in order to visualize the spatial distribution of different temperature values at the same time, which could bring occlusion issues. Therefore, the representation of the 3D distribution of temperature values could imply to project the corresponding color scale on geometric structures covering the entire vertical and horizontal extent of the temperature data. The creation of such geometric structures is addressed in regard to the potential occlusion issues, by letting the user be able to observe both temperature values projected on these geometric structures, and the buildings' shape. We propose several geometric structures as proxies, covering the 3D spatial extent corresponding to the temperature grid's cells. Each of these proxies is designed to fulfill a specific role in the visual analysis of the temperature data: to better see the horizontal distribution, the vertical distribution and the interactions with urban shapes and volumes. We designed three geometric structures (Figure 2):

- Horizontal planes, each plane corresponding to one height level above the ground (in our case, one vertical level of the 3D grid of temperature), forming piles of horizontal planes, to better co-visualize the horizontal distributions of temperature values at different altitude levels.
- 3D point clouds, filling the entire 3D space covered by the temperature grid's 3D cells: to better address the potential problem of occlusion caused by the use of horizontal planes, which could let temperature values or buildings be hidden by the horizontal planes, and help the users observe different levels of temperature through the voids of the point cloud.
- Road-based vertical planes, extruded from the city's road network, to better co-visualize the vertical distribution of temperature, at several locations in the map, which will take place in urban canyons between the city's buildings.

The temperature values are represented by a color scale projected on these geometric structures, providing a way to represent the distribution of these values in the 3 dimensions of space. To allow the identification of temperature gradients, and to improve the distinction between high and low values of temperature, we use color scales respecting the guidelines enounced by Stauffer et al. (2015) about the representation of gradients of values by corresponding gradients of color luminance, i.e. a blue-red diverging color scale (Figure 2).

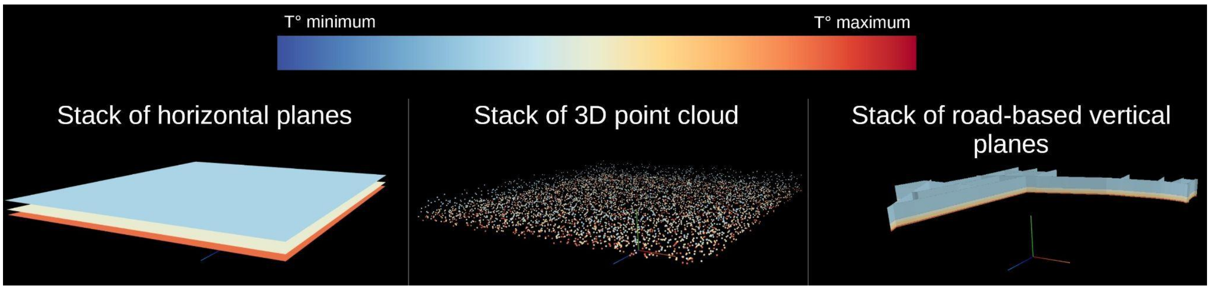

Figure 2: The different geometric structures: horizontal planes, 3D point cloud, road-based vertical planes, with the same color scale.

We represent each building as a polyedric feature, with a flat bottom and summit, providing a co-visualization of the 3D urban model and the previous different geometric structures (Figure 3).

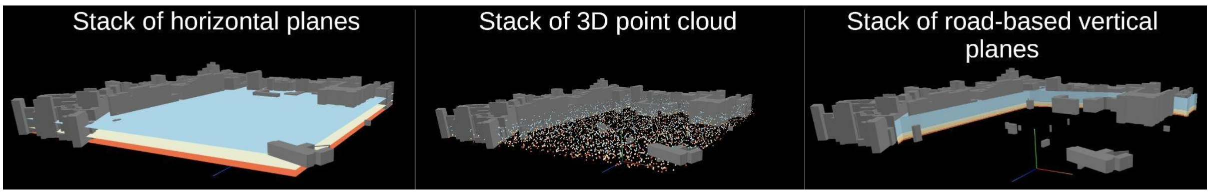

Figure 3: Co-visualization of the 3D urban model and the different geometric structures.

4.1.2 Style capacities for simulated air temperature and urban data.

Style parameters can be modified in order to improve the observation of both data, aiming at reducing either visual cluttering or occlusion issues, while highlighting or softening some objects, in the 3D scene.

First, in order to avoid occlusions of data or buildings, the transparency of the horizontal and vertical planes supporting the representation of temperatures can be modified (Figure 4). Second, the color scale is set by default as a blue-red diverging one, but can be modified: the choice of a sequential red color scale instead of a blue-red diverging scale could be much suitable if the represented temperatures are all above a high value, in order to not mislead the user by representing high temperature values with a blue color; a rainbow color scale, with which meteorological experts can be familiar, can be selected also.

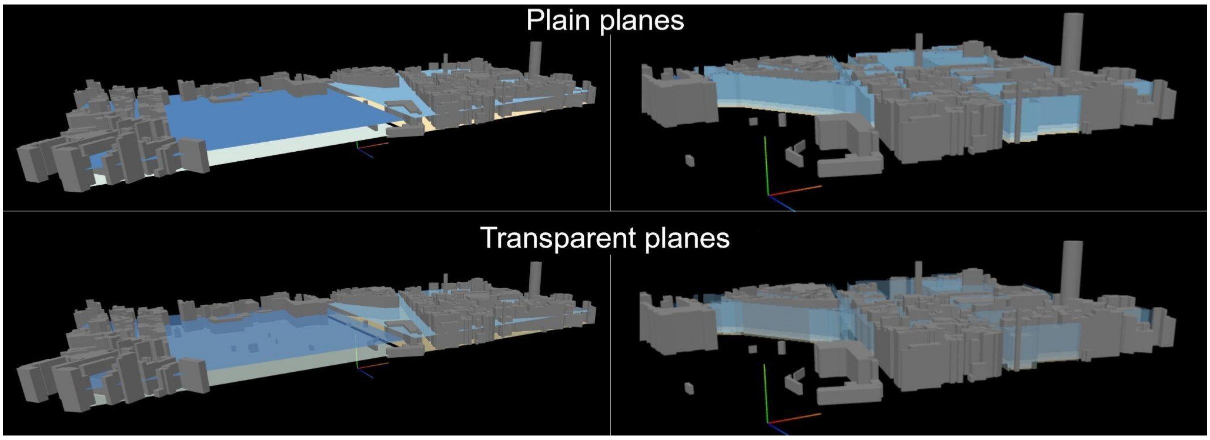

Figure 4: Modification of the transparency of the air temperature representation, using horizontal and vertical planes proxy geometries.

The density (low/high) and the size (small/big) of the points are parameters of the style of the 3D point cloud geometric structure (Figure 5).

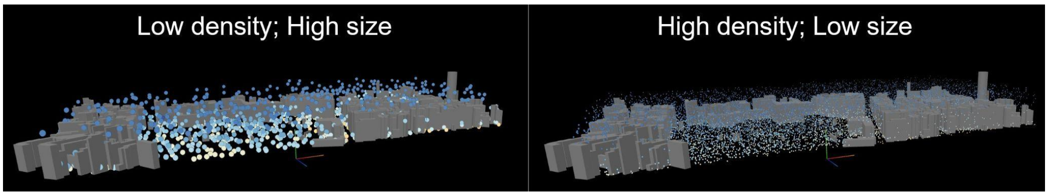

Figure 5: Modification of the points' size and density of the air temperature representation, using 3D point cloud proxy geometry.

The disposition of the points can also be modified (Figure 6), the user being able to switch from a 3D cloud of randomly positioned points, to a 3D cloud of regularly positioned points in order to improve the visualization of different levels of data through the gaps of the clouds. It is also possible to use, instead of a 3D cloud, a series of 2D planar clouds representing the horizontal distribution of temperature at several levels of height above the ground. The urban model also has style properties setting its transparency (plain or transparent façades), or being represented by its footprint (Figure 7).

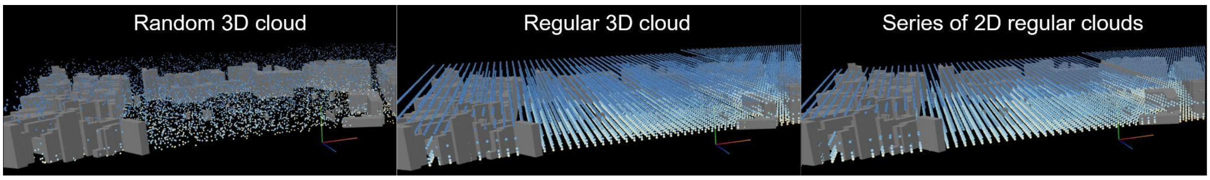

Figure 6: Various points' distributions for the air temperature representation, 3D point cloud proxy geometry.

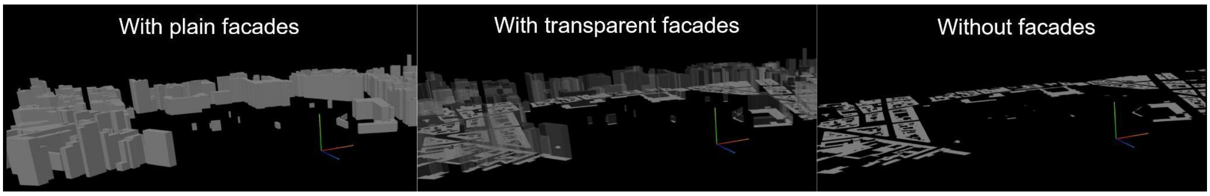

Figure 7: Modification of the style of the 3D urban model representation.

4.1.3 Visual analysis of 3D air temperature spatial distribution

The visual analysis of the spatial distribution of simulated temperature values and its relationship with urban morphology relies on one hand on the graphic representation of both simulated temperature values and building model in their 3 dimensions, and on the other hand on the possibilities for the user to interact with the graphic representation by dynamically changing the style of the representation through different graphic parameters.

Regarding the navigation in the 3D scene. The visual analysis process relies also on the possibilities of navigation inside the 3D scene, allowing the user to explore the temperature and urban data to identify possible relationships. Through navigation tools (pan and zoom) and the possibility to change the camera orientation, it is possible to explore the temperature data at different scales, and from different points of view. The possibility to switch between the different geometric proxies used to represent the temperature values can also support the user's exploration, by letting him choose the adequate geometric structures to represent the temperature data from its visualization scale and point of view. Using these different interactions, the user can perform an exploration of the temperature data, ranging from the analysis of the overall distribution of temperature to the analysis of the temperature distribution in a specific area (Figure 8). For instance, the user can start an overview of the 2D distribution of the temperature with a visualization of the entire scene from the top using the horizontal plane's proxy, then perform a visualization of the 3D distribution of temperature by using the vertical planes proxy and a oblique bird's eye view, and finally look for specific details in the temperature distribution by zooming on a street and using a combination of horizontal planes to represent the temperature near the ground, and 3D point clouds to represent the temperature between the ground and the buildings' roofs. All graphic parameters can be dynamically modified during the navigation, in order to improve the user's observation, for instance by modifying the buildings' transparence to address occlusion issues, or by modifying the size and the density of point clouds: sparse clouds of big points can be used to distinguish the temperature values in areas located far from the user's point of view; dense clouds of small points can be used to represent the 3D distribution of temperature in areas close to the user's point of view without hiding buildings.

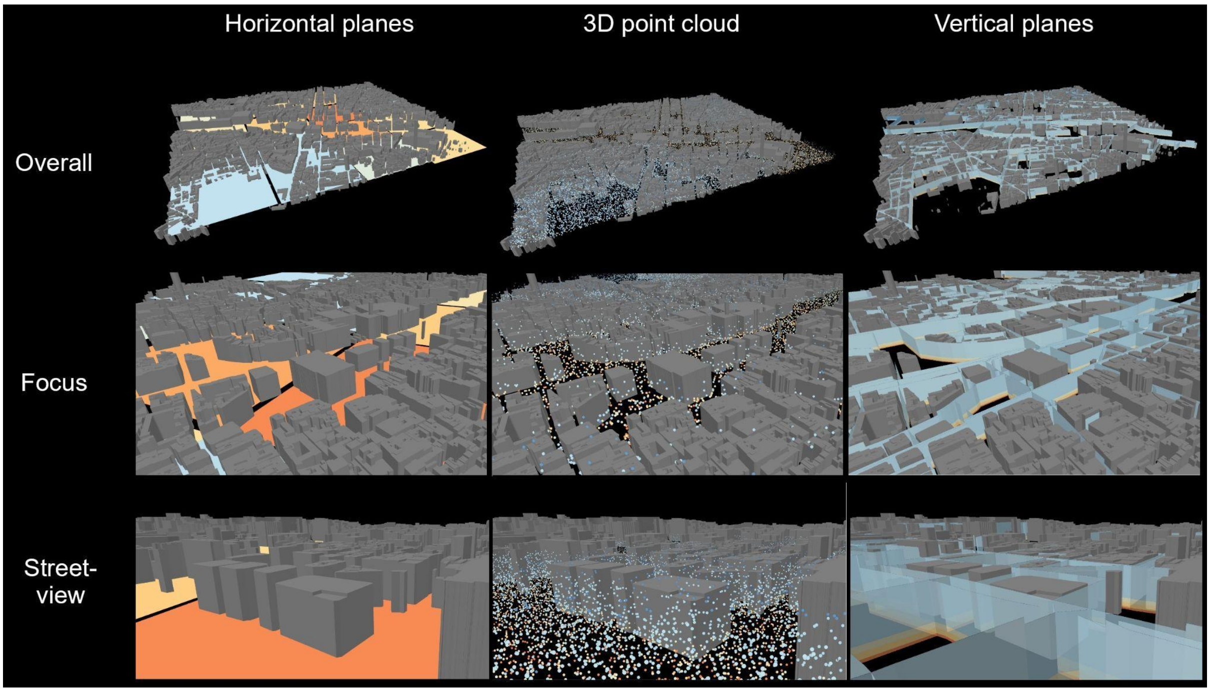

Figure 8: Navigation into the 3D scene. Representations of air temperature data from different points of view (overview, focus, street-view), using the three different geometric structures.

Regarding finer exploration and analysis of the temperature distribution. Different styles and interaction possibilities are proposed to improve the observation of local gaps and spatial gradients in the spatial distributions of air temperature. Figure 9 presents the dynamic histogram (in green) of the complete distribution of temperature values (here from 24.2°C to 27.3°C), represented in the visualization by the default color scale. The amplitude of this color scale may be editable, while modifying its boundaries (blue on the very left at 23.6°C and red on the very right at 27.3°C), resampling how (green) temperature values may be actually represented in the visualization: if the user reduces this amplitude, this will induce a re-spreading of the color scale for the same set of temperature values. The color classes values remain the same, but their borders are modified, changing thus the color affected to a temperature value. The temperature values below the value represented by the blue axis (< 23.6°C), and above the value represented by the red axis (> 27.3°C), are represented respectively by the first (dark blue) and last color (dark red) of the color scale (Figure 9).

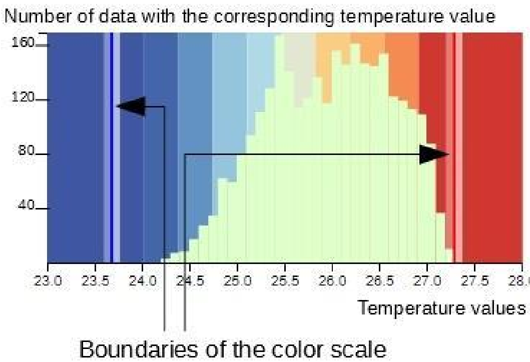

Figure 9: Interactive histogram representing the global temperature value distribution (in green), and the related color scale.

Through this interaction, the user can highlight specific intervals of temperature, in order to improve the identification of gaps or gradients in the temperature distribution. In Figure 10, the temperature values range from 26.8°C to 27.5°C, and are represented on the left by a color scale covering a temperature interval which varies between 24.8°C and 27.7°C. By moving the blue axis, the user can reduce the temperature interval represented by the color scale from 24.8°C to 27.7°C on the left, to an interval from 26.6°C to 27.7°C on the right. After this modification, the temperature intervals represented by each color are redefined, and the parts of the histogram covered by each color are modified as well. The temperature values, represented by the green bars in the histogram, being all located in parts of the histogram covered by medium and dark red color on the left, are then located in parts of the histogram covered by medium and light blue color, and light and medium red color. The horizontal planes representing the corresponding temperature values, originally presenting all medium and dark red color (on the left), presents after this modification colors going from medium blue to medium red. The user can then identify the small differences in the distribution of temperature by highlighting the differences between the values originally represented by medium red horizontal planes (on the left) and now represented by light and medium blue horizontal planes (on the right) either by looking at the histogram or the horizontal planes (Figure 10).

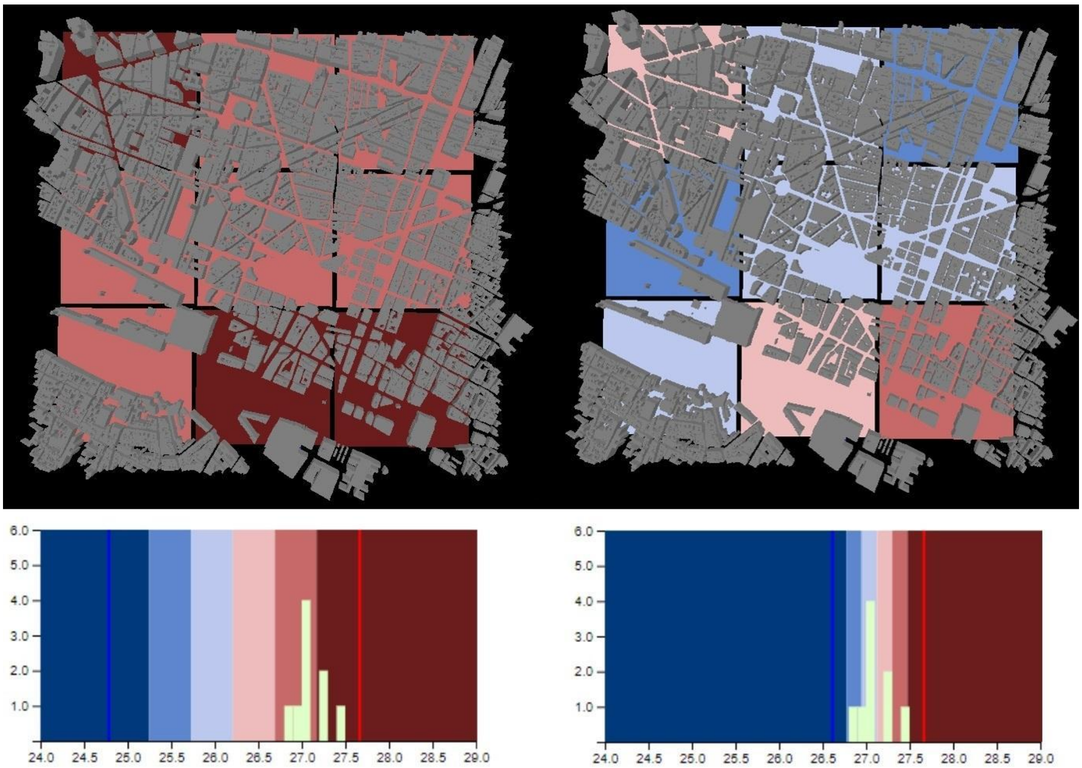

Figure 10: Comparison of two different representations of the 2D distribution of temperature values, by modifying the temperature intervals in the color scale.

The user can use the same interaction to highlight small differences in the 3D distribution of temperature (Figure 11). Through the highlighting of these temperature gaps, the user can identify vertical and horizontal gradients of temperature. For instance, before an adjustment of the color scale, the user can identify a vertical decrease of temperature from the ground to the buildings' roof level, and slightly higher temperature at this level in the right corner of the scene (Figure 11, left). The adjustment of the color scale highlights this vertical decrease of temperature and reveals another decrease of temperature from the foreground to the background of the scene, while still highlighting the presence of higher temperature in the right corner of the scene (Figure 11, right).

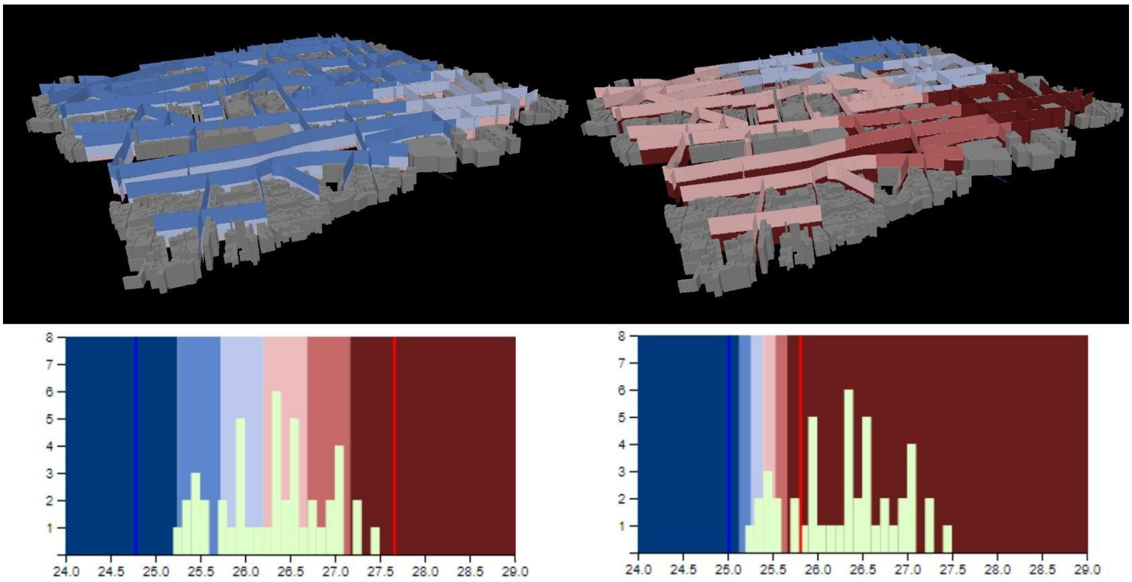

Figure 11: Comparison of two different representations of the 3D distribution of temperature values, by modifying in the histogram the temperature intervals represented by the color scale.

Other interactions are explored to provide ways to identify spatial gaps and gradients in temperature values distribution. The size and density of the point cloud can be used to represent the temperature value, for instance to represent high temperature values using a dense cloud of big points, and low temperature values using a sparse cloud of little points. We explore the use of filtering and animation to successively display different parts of the point cloud along an axis (Figure 12). This approach can be used to display an animated slice of point cloud, moving into the city along a horizontal or a vertical axis, in order to successively visualize the temperature values at different places in the city or at different altitudes, and to reduce the visual cluttering due to a high number of points.

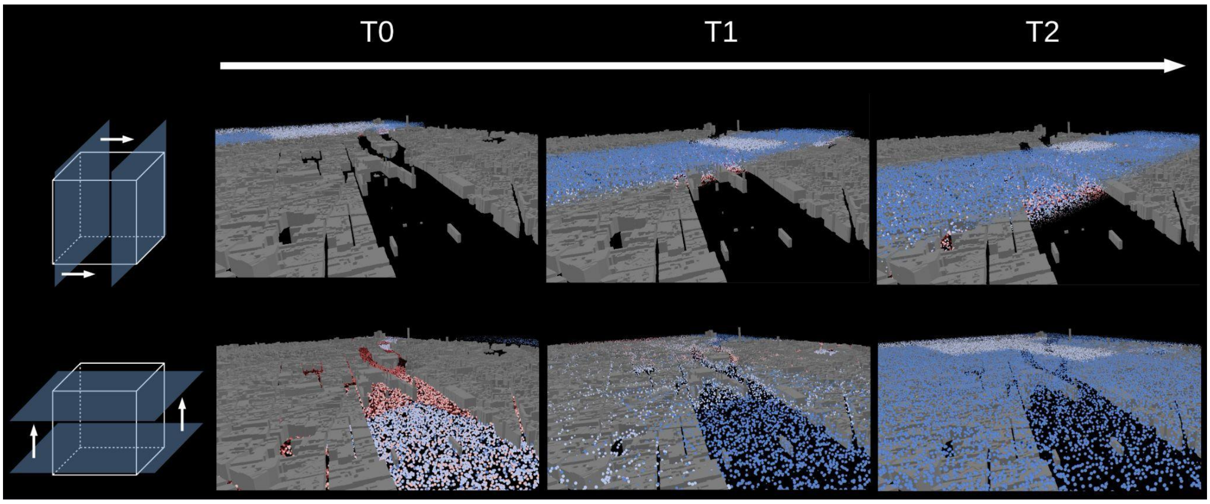

Figure 12: Use of filtering and animation to create vertical/horizontal slices of point cloud, moving along the city, representing the vertical/horizontal distribution of temperature values at several locations/altitude levels.

We also explore the use of animation to successively display parts of the point cloud corresponding to different intervals of temperature, in order to identify temperature gradients by observing the position of the successive displayed points. Instead of successively visualizing the value distribution of temperature at different spatial locations or heights above the ground like in Figure 12, we successively visualize the spatial distribution of different temperature values. Figure 13 shows that using this technique, we can successively display the hottest temperatures represented in dark red located in the background, near the ground (Figure 13, left), then the cooler temperature represented in light red located above them (Figure 13, center), and finally the coolest temperature values represented in blue located in the foreground, near the buildings' roof (Figure 13, right). The user could then interpret these different locations to identify two gradients of temperature, one vertical from the ground to the buildings' roof level, and one horizontal, from the background to the foreground.

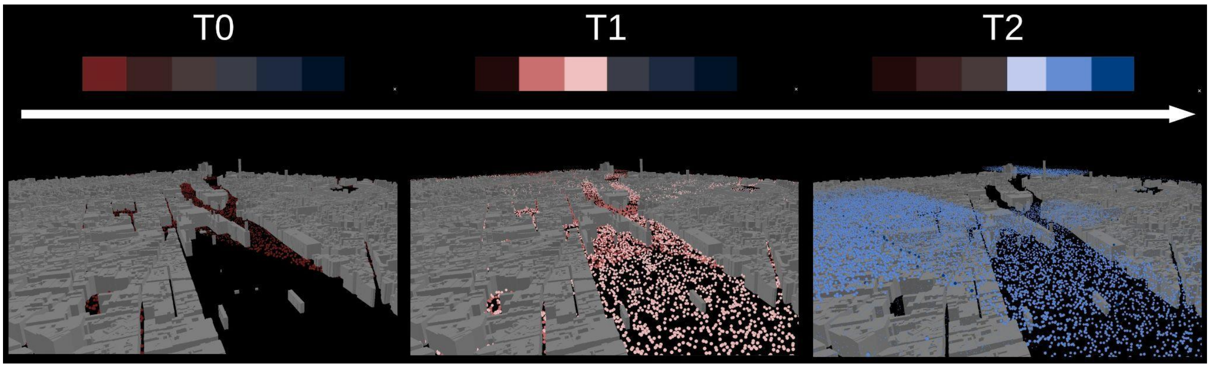

Figure 13: Use of filtering and animation to successively display the position of different temperature intervals, in order to identify spatial gradients in the distribution of temperature values.

This dynamic 3D visualization offers the possibility to explore the distribution of simulated meteorological data and urban forms along the three dimensions of space, and therefore to analyze their possible relationships. The representation has yet to make the user keep in mind the heterogeneity of these data, and the potential gap of resolutions between them.

4.2 Exploratory 3D co-visualizations of air temperature and building-projected 2D morphological indicators.

Another of our objectives is to provide a co-visualization allowing establishing relationships between the simulated temperature values, and some relevant morphological indicators. Co-visualizing these data offers a way to better highlight the relationships between urban climate and urban morphology, but also a way for meteorological experts to validate or improve their simulation models, by allowing them to identify possible inconsistencies between morphological indicators used as input data and the output of their models. We propose to visually integrate one indicator in the previously presented 3D visualization environment (4.1), with the help of another distinguishable color scale represented on the 3D urban model. This indicator can be chosen by the user through the interface: vegetation ratio for the influence of green areas on the presence of islands of freshness, density of population for its influence on higher temperature, etc. These indicators are mostly represented through a 2D division of space. Applying an indicator on a 3D scene consists of projecting those values to the buildings into the same elementary area of the 2D spatial division: the buildings are thus represented by the color of this area. According to the resolution of the morphological indicator (mainly urban block-scaled), this building-projection is homogeneous for an urban block where each building will be represented by the same color. This helps to quickly identify typical areas, volumes and shapes, informed with an indicator. As this adding of information could increase the cluttering of the 3D scene, the style of the buildings could be refined, in order to manage occlusions and cluttering effects (4.1.2): plain 3D buildings, transparent 3D buildings, or just their 2D footprints on the ground, all keeping their color codes.

Input data. For our experimentation, the Local Climate Zone (LCZ) indicator is used (Steward and Oke, 2012). We use the LCZ classification which has been calculated among the outputs of the Mapuce project (Bocher et al., 2018), for a spatial resolution slightly larger than the building block. We also chose to keep the color scale of (Bocher et al., 2018) for the representation of LCZ classes.

The three ways to graphically represent the indicator on buildings/blocks is presented in Figure 14 (first line), as well as the co-visualization with 3D air temperature in their three ways of graphic representation (horizontal planes, point clouds, and vertical planes). This matrix of graphic representations of indicators and buildings/blocks, based on their style capacities (color, opacity, displaying of buildings' facades) show the potential for the users to manage their own data, and adapt their data exploration with these tools, while this exploration can be increased or refined thanks to those tools.

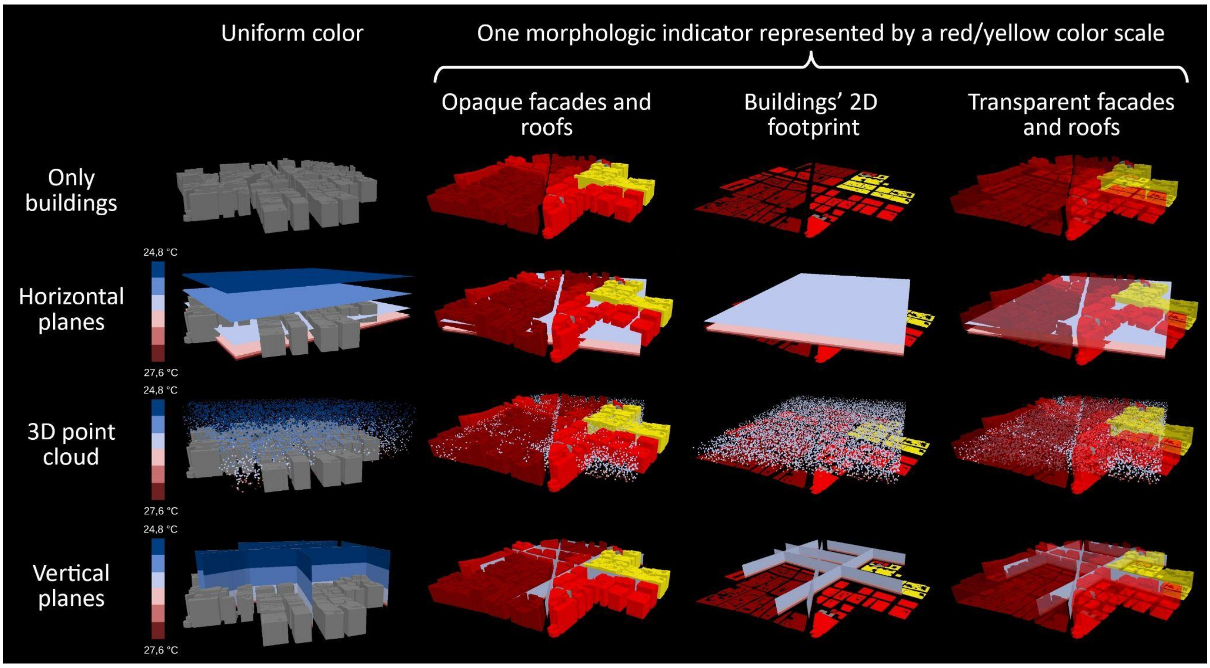

Figure 14: Co-visualization of three possible representations of simulated air temperature data (horizontal planes, 3D point cloud, vertical planes), and the representation of the values of one morphological indicator on buildings (by color, with plain or transparent facades, or with its 2D footprint).

The user can use the graphic representation of the temperature through the geometric proxies, and the different interaction and navigation tools, to visually explore the 3D scene to observe patterns reflecting a potential relationship between the temperature and the represented morphological indicator. As an example, the users can observe the co-presence of low air temperature, represented by cold colors projected on vertical planes, near an area with a high vegetation ratio represented by dark colors of a green color scale projected on buildings. As another example, the user can observe the co-presence of high air temperature represented by warm colors projected on vertical planes, near an area with a high population density ratio represented by a dark color of a gray color scale projected on buildings. As a final example, a user could observe the differences in the intensity of air cooling with the height above the ground, above areas presenting different values for these morphological indicators. Finally, this representation allows the user to validate the climate simulation model, by comparing the simulated meteorological data with the morphological indicators used as input, in order to identify possible inconsistencies.

Most importantly, the difference of resolution between the represented objects (buildings) and the represented indicator (block) has to remain clear, legible and interpretable for the users: the level of indicator aggregation has to be easily interpretable, including its related uncertainty. The differences of resolution between represented indicators (block) and simulated or recorded air temperature values (650 meters on a horizontal axis/1 meter to around 30 meters on a vertical axis for TEB simulated air temperature data) has also to remain clear and interpretable.

4.3 Exploratory 2.5D co-visualizations of 2D air temperature and morphological indicators.

We propose exploratory 2.5D (carto)graphic representations, allowing to co-visualize 2D temperature values with a combination of 2D morphological indicators, in order to allow the user to identify possible correlations between them. Considering that the urban heat island phenomena can be influenced by several factors, we want to provide a visualization allowing a user to identify the effect of a combination of several indicators on the temperature. We explore the possibility to use 2.5D (carto)graphic representations, in order to co-visualize 2D air temperature data, simulated for a height of 0.5 meters above the ground (and corresponding to the first height level of the 3D air temperature data represented in our first visualizations), with two morphological indicators: the principle of the 2.5D graphic representation is to use the horizontal axes of 3D graphic representations to represent the geographic space, and the vertical axis to represent a thematic attribute: this implies to extrude the 2D polygonal features into 3D polyedric volumes, and to use the height of the extruded feature to represent the value of one of the feature's attributes. It is not real 3D, because the third dimension is based on the extrusion in height of a value, and not from a real geometric and volumic representation of objects in 3D. This said, the final visualizations are seen in 3D.

4.3.1. The design of a set of indicators

We performed a spatial analysis of several morphological indicators highlighted in Rodler and Leduc (2019), most of them provided in the results of the Mapuce project (Bocher et al., 2018), in order to identify which indicators would be the most relevant to explore the link between morphological properties of the urban fabric and its climate. A given indicator may be relevant either because of its spatial correlation with ground temperature, or because it exhibits contrasted spatial configuration, such as clusters of high or low values, discontinuities or any salient feature (e.g. frontiers) of the urban landscape susceptible to be of interest for a micro-climate perspective. This spatial analysis consists of Moran's Local I (Anselin, 1995) calculation and a Geographically Weighted Regression (GWR). Moran's Local I was chosen to identify locally homogeneous or heterogeneous clusters of spatial entities, hoping to delineate "hot spots", or even cold spots, in the spatial repartition of the indicator values. GWR was also selected to improve the quality of a classical linear regression between morphological indicators and temperature, by taking its neighboring values and their distances into account.

Each indicator is provided through a spatial division of the city of Paris, into "Reference Surface Units" (RSU), representing areas slightly larger than a building block (Bocher et al., 2018). From the output of our spatial analysis, we decided to set aside the ratio of pervious and impervious surfaces and chose to focus on the following indicators, presenting salient patterns in their spatial distribution and/or a sufficient correlation with urban temperature:

- the “Building Surface Fraction” (BSF), defined as the ratio of RSU built area and RSU total area;
- the “Height of Roughness Elements” (HRE), which corresponds to the RSU BSF value, weighted by the mean height of its buildings.

HRE and BSF performed quite equally regarding Local Moran’s I and GWR, which is not surprising regarding the similarity of their construction. Figure 15 shows the raw values, respectively of BSF and HRE: as examples, on RSU corresponding to urban parks and woods, the BSF and HRE show both low values, on cells corresponding to the city center of Paris (characterized by dense high buildings), the BSF and HRE show both high values, and on cells corresponding to La Defense district (characterized by very high administrative buildings with large spaces between them), the BSF presents medium values while the HRE present high values.

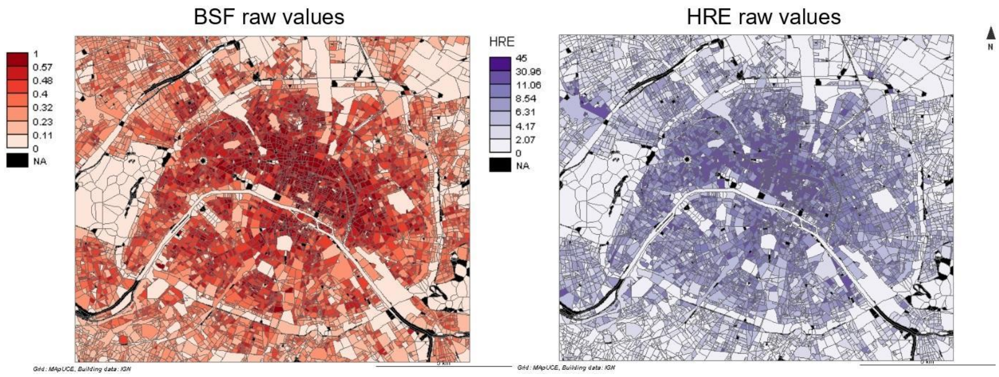

Figure 15: Raw values of BSF and HRE (Riley, 2020).

4.3.2 Exploration of 3D co-visualizations of 2.5D temperature and indicators.

Our first proposition is to use a graphic representation of the geographical space based on the spatial division by RSU. The different steps to build the visualization are the followings:

1. We use a 3D representation where the height of one extruded RSU represents the value of one indicator, for instance the BSF in Figure 16, where the height of extruded RSU is based on the following rescaling equation $H = ((BSF - BSFmin) * (BSFmax - BSFmin)) * C$ aiming at exaggerating the extrusion and better distinguishing the BSF values distribution, with H representing the height of extruded RSU, BSF the BSF value of the RSU, $BSFmin$ and $BSFmax$ the minimum and maximum value for the BSF indicator for the entire area of study, and C a constant.

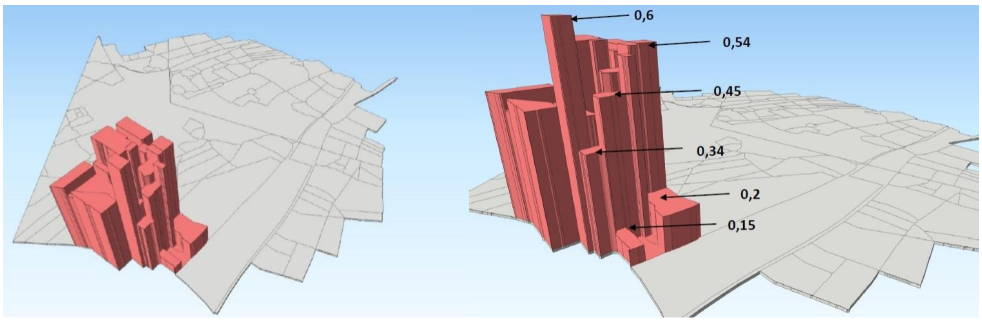

Figure 16: Representation of the values of one morphological indicator (BSF) through the height of extruded RSU (Riley, 2020).

2. The second step consists in using a sequential green color scale projected on these extruded features to represent the value of another indicator, for instance in Figure 17, the HRE, represented into 5 classes.

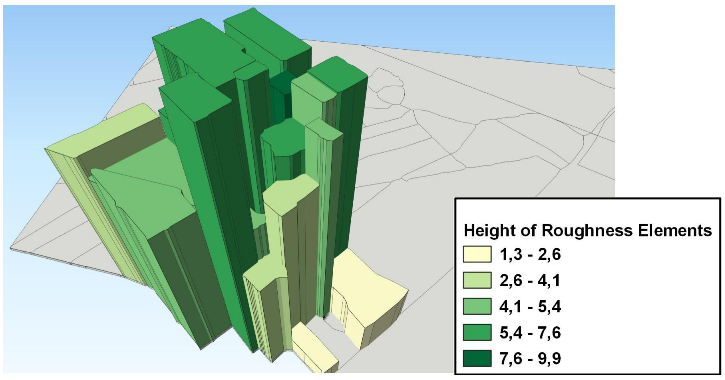

Figure 17: Representation of the values of two morphological indicators (BSF, HRE) through the heights of extruded RSU (BSF), and a related green color scale (Riley, 2020).

3. The third step consists in graphically representing the temperature through the use of 3D isolines: we classify the temperature values into 7 classes and calculate the corresponding 2D isolines (Figure 18). To perform this classification, we calculate the air temperature near the ground surface for each RSU, from the simulated air temperature data corresponding to the first level of the TEB simulation model (0.5 meters above ground surface).

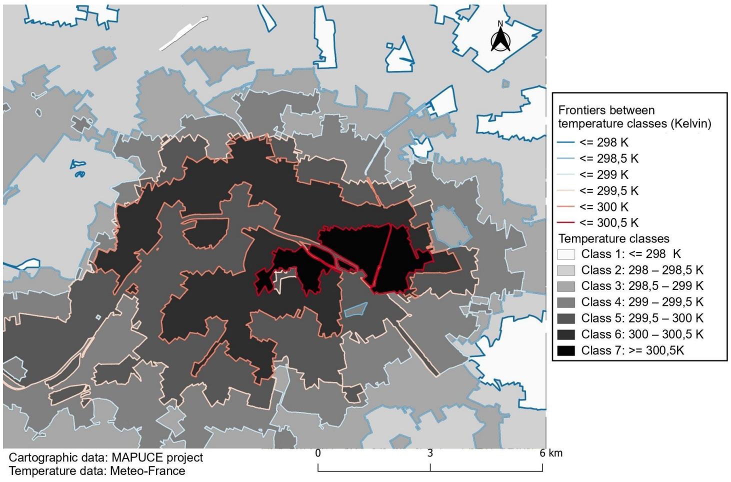

Figure 18: Definition of the different temperature classes and the corresponding isolines (Riley, 2020).

4. The final step consists in extruding the calculated 2D isolines, in order to obtain 3D isolines taking the shapes of a series of vertical "walls". On a horizontal plane, these isolines separate the RSUs corresponding to the different temperature classes. On a vertical plane, these isolines are placed above each extruded RSU, according to its height level.

Figure 19 presents the resulting visualization: on the left a 2D co-visualization of simulated air temperature data, represented by isolines, with one morphological indicator (HRE) represented by a sequential green color scale applied on RSU; on the right a 2.5D co-visualization of simulated air temperature data, represented by 3D isolines, with a morphological indicator (BSF) represented by the height of extruded RSU, and another morphological indicator (HRE) represented by a sequential green color scale projected on extruded RSU. This 2.5D visualization is interactive, allowing the user to navigate in the 3D scene using zooming and panning tools. Through this navigation, the user can explore the data in order to analyze relationships between the temperature and the two indicators, through the identification of patterns such as a correlation between a high density of buildings represented by high-sized extruded RSU, a high HRE value elements represented by RSU bearing a dark green color, and high temperature value represented by red 3D isolines.

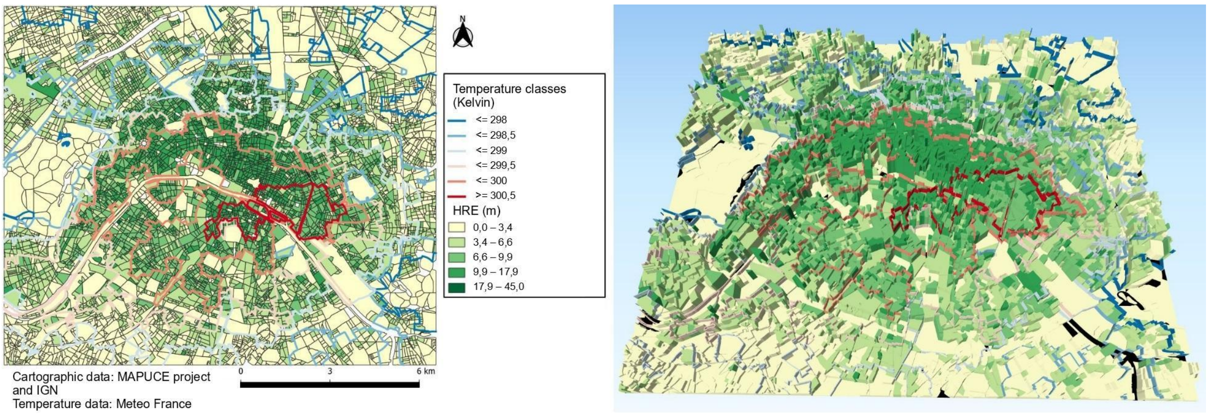

Figure 19: 2D co-visualization of simulated air temperature data with one morphological indicator (HRE)(Left). 2.5D co-visualization of simulated air temperature data (3D isolines), with the indicators BSF and HRE (Right) (Riley, 2020).

Refinement of our proposition. We sample the geographical space into 2D hexagonal cells of equal area, for which we recalculate the values of the two morphological indicators and of the simulated air temperature, from the values stored by the RSUs. We use a 3D representation where the height of extruded hexagonal cells represents the value of one indicator (here the BSF), and a sequential green color scale projected on these extruded cells represents the value of another indicator (here the HRE). The temperature values are represented by a diverging blue-red color scale, projected on 3D isolines, following the horizontal frontiers and the vertical level of the hexagonal extruded cells. On a horizontal plane, the isolines separate the different cells, and on a vertical plane, they are placed above each extruded cell. Figure 20 presents the resulting visualization, in 2D to the left, and in 2.5D to the right.

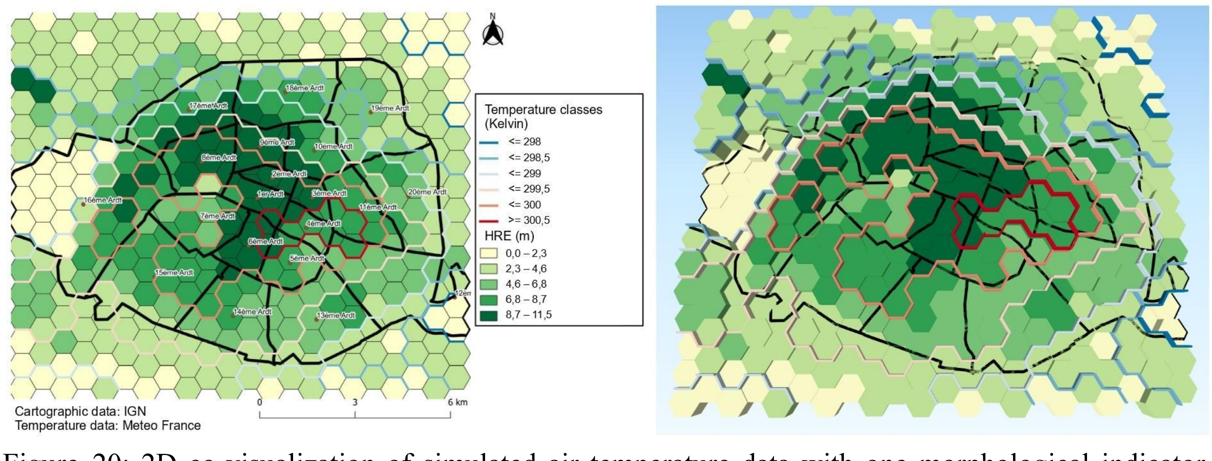

Figure 20: 2D co-visualization of simulated air temperature data with one morphological indicator

(HRE)(Left); 2.5D co-visualization of simulated air temperature data (3D isolines), with the indicators BSF and HRE (Right); using a hexagonal spatial grid with a resolution of 650 meters (Riley, 2020).

We propose different visualizations corresponding to different spatial granularities for the hexagonal cells' division of space. For each of these visualizations, we recalculate the values for the indicators and the temperature values using the values stored in the RSU. Figure 21 presents the resulting visualization with a finer resolution, in 2D to the left, and in 2.5D to the right.

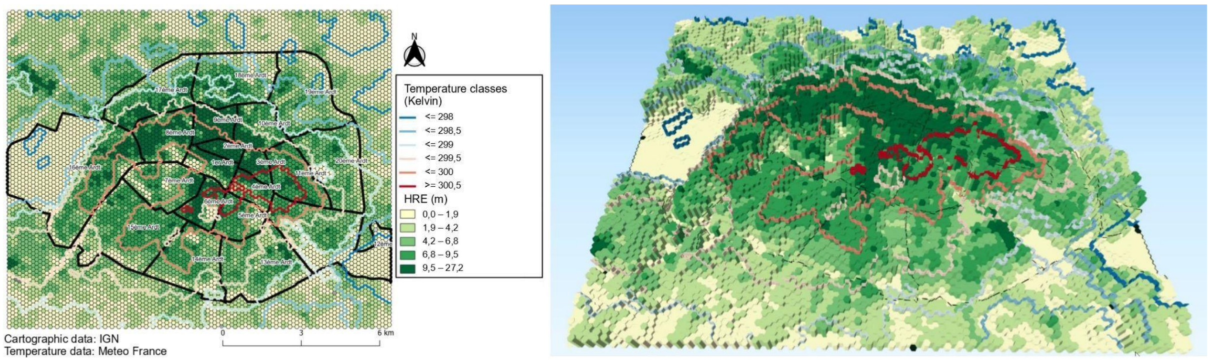

Figure 21: 2D co-visualization of simulated air temperature data with one morphological indicator (HRE), using a hexagonal spatial grid with a resolution of 20 meters (Left); 2.5D co-visualization of simulated air temperature data (3D isolines), with the indicators BSF and HRE (Right); using a hexagonal spatial grid with a resolution of 20 meters (Riley, 2020).

This visualization proposes the same interaction possibilities, allowing the user to navigate in the 3D scene using zooming and panning tools. Figure 22 shows an example of a free exploration of the data through the navigation tools. For instance, the user can be able to spot islands of freshness (Figure 22-a) in areas where low-height cells bearing a yellow color witness the presence of low constructed areas, for instance, near the Gardens of Luxembourg in Paris (Figure 22-c). The user is able to spot by a succession of zooms and pans (Figure 22. a, then b, c, and finally d) the presence of the hottest temperature near the city center of Paris (Figure 22-c-d), and the fact that these hot temperatures are correlated with the presence of a high ratio of buildings surface, but not with the highest values for the height of roughness elements. These observations can then lead to the visualization of other indicators in place of the height of roughness elements, such as the density of population.

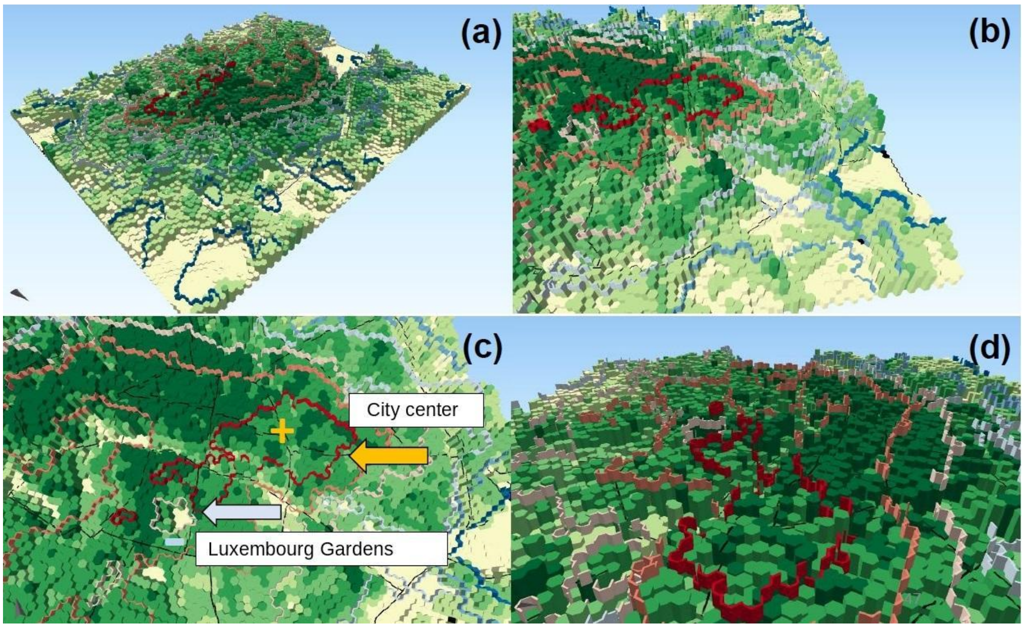

Figure 22: Visual analysis of the relationships between simulated air temperature at 0.5 meters from the ground, the indicators BSF and HRE, using the navigation tools of the 3D scene (Riley, 2020).

5. Users' feedback and discussion

5.1 Evaluation of the 3D co-visualization of air temperature and urban data

The 3D visualization was presented to and discussed with several meteorological scientists implicated in the ERA4CS URCLIM project. These discussions already gave us feedback to work forward on the visualization of urban temperatures. These feedbacks confirm their interests of co-visualizing both simulated meteorological data with a 3D urban model at a city block level: on the one hand, to validate their simulated data by comparing them with urban data used as input data of their simulation model; on the other hand, to enhance the understanding of these simulated data, and analyze spatial relationships between these data and urban data. These discussions were held on the temperature and buildings (geometric and graphic) representations, and the capacities of these representations to support the interpretation of air temperature data spatial distributions.

The first feedback is related to the different proposed geometric structures used to represent the simulated temperature values (4.1.1). The horizontal planes were appreciated for the analysis of 2D temperature values at specific levels above the ground, despite the potential issues of occlusion when using plain colors and issues of colors when using transparency. The use of 3D point clouds appeared controversial for the analysis of 3D distribution of air temperature, because of the observed difficulty to identify a spatial order in the data points distribution. The identification of different levels of values was possible as they could identify one high temperature value among different low temperature values, by observing a dark red point among other blue points. But, they had a lot of difficulties to evaluate the position of the different points in relation to the others, and therefore to interpret the position of low and high temperature values in space. Among the different possibilities for the 3D point cloud style, they privileged the use of regularly placed 3D point clouds, in order to improve the perception of different data levels. The use of vertical road-based planes was much appreciated and appears to have the preference of the scientists to perform an analysis of the 3D distribution of temperature, and not only for the analysis of the vertical 2D distribution of temperature. They especially appreciated the possibility to visualize simultaneously how the temperature evolves with the altitude at several places. The most appreciated use was the possibility to identify above which height above the ground a horizontal homogeneity was observed.

The other feedback was related to the co-visualization of temperature data with urban data. The representation of these temperature data with a controllable 3D urban model were very appreciated to support the recognition of the city, particularly the identification of specific features such as rivers or wooded areas, which could be correlated with lower temperature values, or, large avenues which could be related to modifications into the temperature distributions. Finally, the possibility to add new information related to a morphological indicator in the same 3D scene, through the color of the buildings (4.2), appeared to be an interesting way to support the analysis of relationships between the simulated temperature values and the morphological indicators, especially those which were input data in the simulation models, providing a new way to validate the simulation models, but also to address the relevance to add other significant existing indicators (socio-demographic ones) and to build new ones (freshness, energetic comfort, heat losses) for such visual analysis.

The interaction possibilities were also discussed. The possibility to explore the distribution of specific ranges of temperature, through the modification of the color scale with the histogram device, was much appreciated (4.1.3): this tool is fully innovative for them and supports a finer exploration of the temperature data. This also allows a relevant questioning about the colors choices' benefits and pitfalls for temperature representation, in order to highlight the type and the range of the value distributions as well as to identify particular thresholds or peaks in temperature distributions.

The meteorological scientists appreciated the possibility to manipulate different ways to represent the temperature data, in order to support the data exploration with different points of view. The possibility to navigate into the 3D scene at several scales and with different points of views received really positive feedback (4.1.3), and the possibilities to dynamically change the graphic parameters appeared to be really important for them (4.1.2). The possibility given by the animation of 3D point clouds, for successively displaying the 2D distribution of temperature at several locations/heights above the ground, or for identifying temperature gradients (4.1.3), appeared not as efficient to analyze the temperature distribution, as the continuous representations offered by vertical or horizontal planes.

5.2 Users' evaluation of the 3D maps of morphological indicators and air temperature at the city scale

Evaluation of Figure 19. This first visualization appears difficult to interpret, partly because of the irregular division of the space due to the diversity in RSU's area values. Furthermore, the extrusion of a variety of RSU areas will produce equally variable volumes. As noticed in the meteorologist feedback, the heterogeneity in RSU shapes and sizes adds supplementary complexity to the 3D scene. The disparity in RSU's area can lead to a misinterpretation of the visualization, bigger extruded RSU, represented with a bigger volume, being much more attractive for the user eye. A huge perceived volume may be misleadingly interpreted as a high value or a salient built area, and conversely, narrow RSU with high BSF values may not be distinguishable in the middle of medium height extrusions, at least unless a proper angle of visualization is chosen. Another fallout of the RSU partition of the zone is that 3D isolines contours are necessarily jagged and noisy, as they are shaped by the road network since RSU are based on building blocks, leading to an unnecessary granularity. Generally speaking, the choice of mapping two different variables on extrusions heights and extrusions colors may be hazardous, especially if these variables are not correlated. In this case, HRE and BSF are sufficiently well correlated to not impair the interpretation of the height-color combination.

Evaluation of Figure 20. In this proposition, each cell has been made comparable one to another, which makes it easier to read zones and immediate neighborhoods of a particular point of interest. The inevitable smoothing of this uniformisation process requires superimposing Paris' arrondissements' borders (in black) and labels to provide users with points of reference. Temperature isolines are more readable in the 2.5D scene. The representation of BSF values with hexagons' extruded height in the 2.5 scene allows the user to quickly locate and distinguish areas of low (Invalides neighborhood, Bois de Boulogne city park, in West-Paris) or high construction (city-center of Paris). The representation of both BSF with height and HRE with color also allows distinguishing skyscrapers areas from other built areas, such as the south-east of the 13rd arrondissement (south-west Paris). In this case, temperature, BSF and HRE values are not redundant: the hottest zone, surrounded by solid red isolines, does not stand in the middle of the highest BSF values (high extruded hexagons) and HRE values (dark green) zone. Finally, isolines delineate "iso-temperature frontiers", that can be easily compared to the borders of "iso-HRE" zones since the shades of green are sufficiently distinct. We believe that this visual comparison is a good way to assess the explanatory power of the selected indicator, here HRE.

Evaluation of Figure 21. With a finer granularity, the comparison of isolines of temperature and iso-HRE zones borders is more difficult, as the complexity of zones and isolines increases. On the other hand, the global structure of the zone is more obviously depicted: the Seine's rivers and Paris' ring road are now clearly visible. Furthermore, local heat or freshness islands can be more easily observable, as well as their characteristics regarding BSF and HRE, allowing to analyze the influence of the presence of low constructed areas (in this case, the urban park of the Gardens of Luxembourg, in South-Paris) on the local temperature.

Evaluation of Figure 22. The interactive WebGL application allows the user to rotate and zoom the view in order to obtain a more convenient point of view, which is especially useful for focusing on a particular zone with successive zooms or pans (Figure 22-b; c; d). These interactions allow the user to go from an analysis of global patterns in the overall distribution of temperature and morphological indicators (Figure 22-a) to an analysis of specific areas allowing him to identify local gaps and gradients in the temperature and morphological indicators distributions (Figure 22-c; d). By doing so, the user can easily be lost without the help of fixed labels and/or landmarks.

These first feedbacks on our co-visualization propositions are very promising at several levels. First, they validate the efficiency of the co-design approach we had during the project, to provide something innovative and useful for a visual analysis of simulated air temperature. Secondly, we designed several ways to represent same information, the simulated air temperature, regarding their possible geometry and style: this is very useful to have an extensible proposal, in order to provide meteorological and climate scientists interaction modalities based on geometry and style, but also to add other new properties in the future. Thirdly, we succeed in providing a 3D framework visually integrating heterogeneous data, at various scales into the city, from the global city scale to street or building scale: this permits to prepare the short-term evolution of our proposal, while integrating finer simulation to the models' outputs, allowing the user to cross-navigate between all urban scales.

6. Conclusion

This paper presents methods and tools to visualize simulated air temperature at large urban scales (building and block scales), and to support the visual analysis of their distributions in the three dimensions of space into an urban environment, and the visual analysis of their spatial relationships with one or two morphological indicators. Various leads of visualization designs were investigated, in order to co-explore with meteorological experts, what could be relevant for meteorological data analysis and thereafter climate analysis. Our methodology of a co-design approach is satisfactory regarding our own purposes and those we shared and tackled with the meteorological experts, until those propositions of co-visualizations increasing the interaction and the points of view on the data: they were effectively discussed and validated by the meteorological researchers, and some became a support for open discussions between meteorological researchers about the represented data and what they could actually infer here as new considerations on the observed and analyzed geospatial phenomenon. Through our different propositions, being able to change perspectives on the data is really appreciated by the meteorological experts, and validates our assumptions for geovisualization purposes.

Our proposal of using geometric structures to represent simulated air temperature were also thought to be extensible to other properties or dimensions of the output data of air temperature simulation models. They could then be applied to the representation of other simulated meteorological data (e.g. atmospheric pressure). Furthermore, our propositions for the co-visualization of simulated air temperature data with morphological indicators, through the color of the 3D urban model or 2.5D maps, can be used to analyze the relationships between different meteorological data and different morphological indicators, according to the user's choices.

The main lead to follow now is to allow a better interpretation and understanding of the temporal dimension of the urban climate by allowing a visualization of the temporal component of simulated meteorological data. We plan to work on several sets of data-simulation at different times, and so to enhance our 3D geovisualization prototypes with new functionalities to observe and analyze the data in time. The exploration of the temporal dimension offers to add a new point of view on the simulated data, while regarding possibly long-time series as well as daily evolutions.

As we developed open prototypes, we would like to add new data, to better support urban climate analysis at larger scales, by considering other meteorological data, such as wind (Belgacem et al. 2018) or rain, other urban data (material energy, thermal losses, finer morphological indicators on buildings, etc.), socio-economic indicators for instance extracted from LCZ maps (Sepena et al. 2021), and other properties or indicators regarding how people perceive geographical spaces and related aspects about climate (IHU, freshness zones, real temperature vs. perceived temperature, etc.). This goal would imply to work further on how to visually integrate more (potentially massive) heterogeneous data, balancing between various types and levels of abstractions (conceptual, geometric and graphic), in visualization environments allowing diverse interactions with data, even augmented and immersive point of view on the phenomenon (Christophe, 2020).

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