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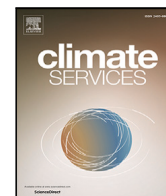
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How to disseminate the research results on climate change impacts in cities to guide adaptation public policies ? Application to the Paris region (France)

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ABSTRACT

The construction of efficient climate services relies on the interaction between decision-makers and scientists. Urban heat island is an issue that already preoccupies public authorities and is likely to be exacerbated by climate change, making assessment of its evolution crucial for effective urban policymaking and to size adaptation measures. This study analyzed interviews with 13 public stakeholders in the Paris area (France), highlighting their diverse needs for urban climate data. Their feedback on the high-resolution climate projections for the Paris region was assessed to provide recommendations to researchers for the effective dissemination of urban climate data. Public stakeholders in the Paris area need urban climate data for various purposes (awareness, diagnosis, decision support, and evaluation) and thus seek diverse types and formats of information. High-resolution climate projections may meet parts of these needs, but two key points require attention: (i) climate models appear to be difficult to apprehend by public stakeholders, thus an effort of pedagogy is necessary, (ii) climate projections often extend to 2100, but stakeholders primarily need short- to medium-term forecasts that align with public policy timelines. Indicators on extreme impacts and risks are a strong demand of public actors, especially in the health and energy sectors. Additionally, since recent urban climate resources remain largely unseen by public actors, we recommend enhancing its dissemination through local institutes recognized by policymakers, such as urban planning agencies. In summary, this case study provided valuable insights into the key mechanisms required for effectively disseminating climate research to promote climate change adaptation.

Practical information

This study investigates how climate information could be better communicated and used by public stakeholders for decision-making, particularly in the case of adapting cities to climate change. Cities are indeed places with significant societal, economic and environmental importance and could be particularly impacted by the effects of climate change across various different sectors. Furthermore, urban areas are already subject to a phenomenon known as the urban heat island (UHI): with nighttime urban temperatures being a few degrees higher than the surrounding countryside. The intensity of the UHI can vary according to different factors depending on the city itself, the geographical context, and weather conditions. The effect is particularly exacerbated during heatwaves (Li and Bou-Zeid, 2013) which can worsen the consequences

associated with these extreme events (health risks, energy overconsumption, infrastructure breakdowns, etc.). As heatwaves become more frequent and intense with climate change, the exposure of urban areas to strong heat is expected to increase. Public stakeholders in charge of regional and urban planning are already facing these growing challenges, and have to think about how to adapt their areas. To do so, they need science-based information that is both robust and appropriate.

In order to design and develop an urban climate service, scientific data must be disseminated as resources for stakeholders to help public action at the regional and local level. The aim of the study is to investigate what the needs of urban stakeholders in climate data are, how recent research results on the UHI phenomenon and its evolution with climate change could better meet the needs and expectations of public stakeholders, and be communicated effectively.

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To answer these questions, a case study was performed on the Paris region (France) by interviewing a panel of public stakeholders in charge of different thematics, from urban planning to energy consumption management, and also local climate plan. The analysis of the interviews enabled an inventory of current practices. It showed that, in the Paris region, urban or climate data are used 1) mainly in an attempt to raise awareness about climate change impacts both on local population and on elected representatives, 2) to establish a territorial diagnostic of local vulnerabilities to urban overheating, and 3) less often for decision-making, e.g. to choose between different urban planning or urban design scenarios, in which case climate data are needed at a very fine scale (building scale). Yet, climate change, albeit crucial to the future evolution of city living conditions, is usually not directly present in the data used by stakeholders. The case study showed that urban public actors have a need for climate information on a more regional and local scale than is currently available, and if possible tailored to their specific sectors (energy consumption, urban planning, etc.).

In a second stage, the results of the surveys were used to draw up practical recommendations on how to better communicate and disseminate climate projection results from research institutes to stakeholders. Firstly, the time periods covered by climate projections could be more in line with the temporality of public action. Indeed, stakeholders are in demand of short and medium-term prospective data that fits in with the public policy timetable and that can actually be used for decision-making. The next few decades are of particular interest for public actors, which highlights the need to foster and improve projections at the decadal scale. Then, data on the impacts of extreme climate conditions usually seem of better use to decision-makers than average values, both for raising awareness (a human being is more sensible to a more intense heatwave than to an average warming of 2 °C) and for supporting specific technical studies on the vulnerability of infrastructures to these extremes (e.g. can the electricity supply system meet higher demand during an extreme heatwave) and the sizing of adaptation solutions. A climate service must be able to respond to diverse needs and applications, intended for users with different levels of expertise. For effective dissemination and provision of climate data and information, two types of resources have been targeted: a) notes dedicated to public actors, with graphics that are clear and well explained, with key messages, so that they can be used directly by public actors without specific scientific skills; and b) reworkable and geo-referenced projection data that can be used by technical services or scientific teams to perform specific impact studies on a given sector. Finally, the study highlighted that it is essential for (urban) climate scientists and service providers to rely on local and regional urban planning agencies for the dissemination of new data and resources, which are clearly identified by stakeholders in the Paris area as key providers of urban climate data.

1. Introduction

Decision-making and action for risk prevention and adaptation to climate change should rely on current knowledge from scientific research. To promote the integration of climate information into development policies and enable the implementation of relevant adaptation measures, the Global Framework for Climate Services (GFCS) was established in 2009 (WCC3, 2009; Hewitt et al., 2012). Since then, many initiatives have been conducted in this direction, for climate services at different territorial scales (from global to regional), to meet as much as possible the needs of a wide range of users and sectors. The initial approach to developing this type of product and service was mainly based on a top-down approach (Jacobs and Street, 2020), where scientific data is produced by “experts” and supplied to potential users. More recent works show the importance of an iterative and interactive approach between data-providing scientists and data users in a context of operationalization and decision-making (Brasseur and Gallardo, 2016; Giordano et al., 2020). It is necessary to take into account users’

acculturation to climate data, their practices and their constraints in terms of resources, legislation or levels of governance (Carter, 2011; Cortekar et al., 2016). Responding appropriately to expectations also means going beyond raw scientific data and crossing expertise by considering local social, economic and environmental specificities (Swart et al., 2021). This is particularly true for urban environments, which are already facing major challenges due to the concentration of assets, socio-economic activities and population.

The specificities of urban areas linked to the strong artificialization and imperviousness of soils, to the complex morphology, and to the local emissions of heat and humidity, are deeply disrupting the local environmental conditions (Oke et al., 2017). The actors in charge of urban planning and urban design are for the most part already aware and concerned about these issues, which could become even more serious with climate change (IPCC, 2022). The urban heat island (UHI), that results in an urban overheating occurring predominantly at night, is certainly the local climate issue that has been most discussed and addressed in recent years in the orientation choices of urban planning policies. Worsened by global warming and increased heatwaves, the urban-scale climate conditions can lead to multiple sectoral impacts, e.g. on energy, thermal comfort, health, economic productivity, etc (Takakura et al., 2017; Vigiúé et al., 2020; Pascal et al., 2021a). Many urban climate research studies investigate strategies and action levers to reduce urban overheating, with spatial scales of action that vary from the very local street or urban space, to the neighborhood, or the entire city (Lemonsu et al., 2021). In this field of research, the link with stakeholders such as urban policymakers and urban planning professionals is already partially in place. Many research initiatives make an effort to transfer knowledge and make data available to assist in decision-making (Eliasson, 2000; Zhang and Yuan, 2023). Nevertheless, these are usually based on case studies, mainly covering large cities, and the generalization of these results to other cities and other environmental conditions is little discussed. In addition, although the studies in question are often performed by the “climate service” of a city, an explicit account of the effects of climate change on the UHI is overwhelmingly absent from these works.

At the same time, climate change studies are approaching increasingly finer scales, by the use of various statistical, dynamic or combined spatial downscaling techniques (Maurer et al., 2007; Hoffmann et al., 2018; Duchêne et al., 2022). The objective is to investigate regional and local phenomena and their evolution with climate change, and to conduct impact studies focused on specific issues and sectors. The description and treatment of urban areas in spatial downscaling approaches and in high-resolution regional climate modeling (Masson et al., 2020; Lucas-Picher et al., 2021) now offers the possibility to conduct more robust studies on the impacts of climate change in cities. In this context, the question arises as to how to effectively disseminate and communicate these new results to users and stakeholders in order to guide in the implementation of city-scale adaptation measures. There is a real challenge in designing climate services that are adapted to urban issues. They should be understandable, respond to the expectations and fit current practices of local actors. Nonetheless, they should provide relevant and scientifically sound information on expected vulnerabilities and impacts. There are two important issues to consider: providing reliable climate projections and impacts on time scales of interest to decision-makers (Brasseur and Gallardo, 2016), and communicating appropriately about the spread of climate model results and the associated uncertainties (Carter, 2011).

The research presented here examines both the role of climate communication strategies and use of climate information in decision-making. It is focused on the specific context of cities, where the challenges of adapting to climate change interact with the challenges of mitigating the effects of urban climate, especially the UHI already inherent in today’s cities. Using the Paris region (France) as a case study and selecting a panel of public stakeholders in charge of local planning policies, the study seeks to clarify their current practices in

integrating these issues, the existing climate data and climate services used, and the gaps and needs identified. Based on recent research work combining climate projections and dedicated modeling of urban climate to assess local multi-sectoral impacts of climate change on the Paris region, this study investigates how these new data could better meet the needs of stakeholders and be communicated effectively. To our knowledge, this is the first time a scientific tool capable of representing both future climate change and its local impacts on urban heat islands has been presented to a panel of local public stakeholders, to better analyze how these results can be better designed and communicated to improve its potential use. Section 2 describes the methodology used to select the public players and to draw up and analyze the semi-structured interviews, as well as the scientific material used as input. Section 3 presents the key findings of this analysis, from which some recommendations are drawn to improve the dissemination and use of current research results and prepare more generic future studies and support new climate services, in Section 4.

2. Material and methodology

The technical goal of this methodology is to identify the diverse viewpoints of stakeholders, rather than ensuring the representativeness of these viewpoints and of the actors sample. As a result, the method of semi-structured interviews, commonly used in social sciences to produce a qualitative analysis on a reduced number of interviews, is chosen. Indeed, it does not require a large size of actors sample, but rather a diverse range of participants.

In the following, we present how the panel of public stakeholders was selected (Section 2.1), how the interview grid was constructed (Section 2.2) based on some recent research results (Section 2.3) and how the interview material was finally analyzed (Section 2.4).

2.1. Identification of relevant public actors for the Paris region

The study is focused on Île-de-France, the most populous of the eighteen regions of France, centered on Paris, which gathers more than 12 millions inhabitants. A panel of public stakeholders was selected to cover a wide diversity of interlocutors of public action in the field of urban climate:

- urban development actors and urban planning agencies,
- local authorities in charge of planning documents (urban plans or climate plans) and operational projects,
- state services that support local authorities in their efforts.

Here, the decision was made to focus on institutional actors, which allowed for a clearer understanding of governance scales, areas of intervention, connections, and key stakeholders for information dissemination. While it would also have been valuable to include private stakeholders, that would have constituted a separate study.

To avoid a potential bias of the study that would consist in staying too close to climate change experts, we were careful to select in the panel people with various backgrounds and expertises, dealing with broader or related issues to UHI, such as sustainability or urban planning and development.

We identified actors in structures covering the four main territorial scales of action against UHI: (1) national level through an incentive for local actors to take mitigation and adaptation measures, or through research funding (e.g. ADEME, see in next paragraph for definition); (2) regional level as an intermediate scale of support for municipalities in the Île-de-France region in terms of climate-sensitive urban planning and reducing energy consumption; (3) departmental or intercommunal level through a close and tailored support of municipalities, for ex. Plaine Commune, Saint-Quentin-en-Yvelines, chosen for having previously worked on urban climate adaptation; (4) communal level where actions can be initiated by the municipalities themselves, depending on in-house skills and financial resources.

Fig. 1 summarizes the public institutes that were selected for the interviews, according to the spatial scale of action or support and the status of these institutes. The ADEME (agency for the environment and energy management) is a central actor for ecological transition through support for innovation and research to application. The FNAU (national federation of urban planning agencies) leads the national network of urban planning agencies by promoting the exchange of expertise and collective projects. The DRIEAT (regional and interdepartmental directorate for the environment, planning and transport) is an organization that helps local authorities in the Paris region, for example, with regulatory aspects and territorial planning. Institut Paris Region is the urban planning agency commissioned by the Region, of which APUR (Parisian agency of city planning and renovation) is the Paris equivalent at the city level. The regional council is the deliberative assembly of the region, responsible for issues such as regional transport, secondary and higher education, regional planning, etc.

2.2. Construction of the interview grid

The interview grid was structured in two main parts to address the two objectives of the study. For both parts, the questionnaire was constructed based on several starting hypotheses, with the idea to investigate each of these through open questions. This approach allows for multiple sub-themes to be covered, while remaining open to any other comments than those previously anticipated.

Part 1 aimed to establish a diagnosis of the current use of urban climate data by public stakeholders and their possible needs. It was conducted without any visual of urban climate data, not to influence the interlocutor. The starting hypotheses were as follows:

- (1) Stakeholders have climate data needs for different areas of activities depending on their missions (e.g. development, planning, awareness of elected officials).
- (2) These data are mainly used for diagnosis but rarely for decision support, which requires more substantial work and resources (e.g. modeling and comparison of different urban planning scenarios).
- (3) The type of data used depends on the training and skills of people in charge of collecting and using/valuing them. An expertise in climate (or even in data processing) can facilitate the appropriation.
- (4) Climate data are preferentially chosen for their ease of use and understanding, confidence in their sources, but also by historical practice. There is potentially a lack of knowledge of the (new) data available, including those provided by Météo-France, the French institute for meteorology and climate.
- (5) To obtain tailored data to address local issues, the public actors can turn to local or national research centers (for example Météo-France climate services).
- (6) The need for local climate data on a target city may not yet be met, despite the data and devices at the disposal of public actors.

Part 2 aimed to get feedback on the new research outcomes to define recommendations and orientations. It was conducted with a presentation of schematic views of the climate model and its hypothesis, and a variety of samples presenting the new research results (with different types of content and presentation forms). This led the interlocutor to answer the questions of the interview grid. The starting hypotheses were as follows:

- (1) The actors do not have a clear view of all the information resulting from urban climate modeling, but can take a critical look at the choice of indicators and results formatting.
- (2) Both the geographical zoom level and the spatial resolution of the data are important factors in its use by public actors.
- (3) Stakeholders need tailored sectorial indicators that are not yet addressed by climate science (which usually deals with weather hazards without necessarily going as far as the impacts).
- (4) The representation of uncertainty is central in climate studies to investigate possible futures, but can confuse the messages for a non-expert audience.

The main questions that were asked to the interviewees are presented in a logical framework diagram, in [Appendix A, Fig. 10](#).

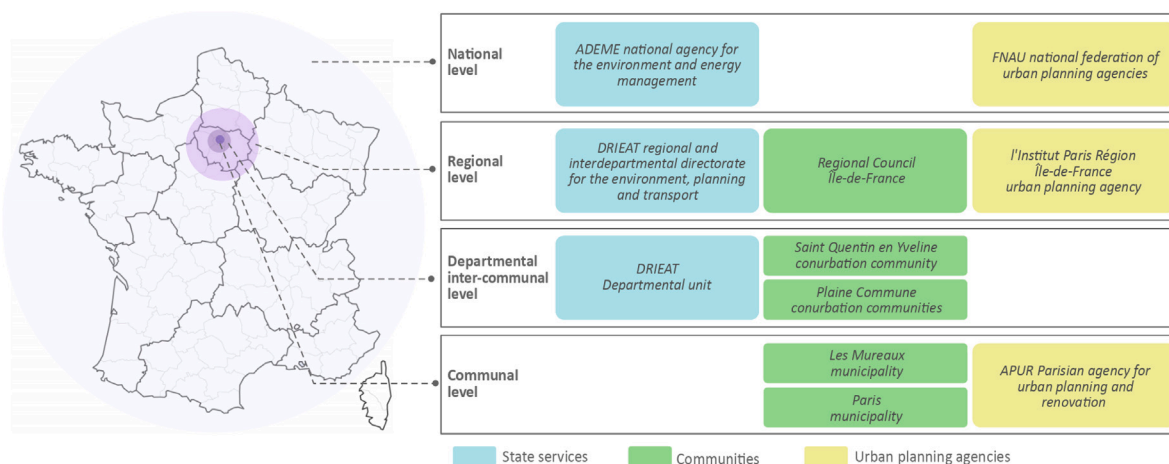


Fig. 1. Inventory of public institutes covered by the study through the people interviewed.

2.3. Research material as support to interviews

The research work that motivated and fed the reflection on the information dissemination to potential actors and users comes from the PhD thesis of Le Roy (2021). For the first time, multi-model and multi-scenario climate simulations with a high spatial resolution have been performed over the Paris (France) urban area in order to provide indicators of urban climate evolution and of urban-scale impacts of climate change. These climate simulations were based on an original and innovative methodology that took into account the evolution of the regional climate and its interactions with the local urban climate generated by the city itself (see Appendix B for the detailed methodology of the simulations). The study domain is covering the entire Île-de-France administrative region (that contains the Paris urban area). A 1 km resolution was used over the domain as illustrated in Fig. 2, showing the main land use patterns in Île-de-France. The climate simulations ran from 1970 to 2099 and consisted of 55 unique combinations of general circulation and regional climate models that projected both a scenario of moderate greenhouse gas emissions (RCP4.5, 14 simulations) and a scenario of high emissions (RCP8.5, 41 simulations). For each projection, the climate conditions in the urban areas were simulated with the dedicated Town Energy Balance urban model (TEB, (Masson, 2000; Lemonsu et al., 2012; Redon et al., 2017, 2020; Schoetter et al., 2017)). TEB can calculate, among other things, the street-level air temperature as well as the outdoor thermal comfort, and the energy consumption of buildings for air-conditioning and heating.

The raw data coming from these urban simulations were stored with a 1-hour time step over the time period 1970–2099, and at each grid mesh of the study domain. Nonetheless, a post-processing was applied to derive multi-sectoral indicators of local-scale climate change impacts (summarized in Table 1). These indicators can take the form of maps, time series, or integrative values (either spatially and/or temporally).

2.4. Methodology for analyzing interviews

A total of 13 interviews were conducted in French, each lasting approximately 1.5 h. For each of them, a written report of a few pages was made to summarize the discussion, according to the interview grid structure. The audio recordings of the interviews were useful for reporting and quoting accurately the respondents' answers, and were deleted afterward.

A cross-analysis of the 13 interview reports was conducted using a qualitative approach. This non-numeric exploratory approach is often used in sociology to understand social phenomena or the experiences of individuals, through the collection and analysis of nonnumerical data, such as polls, interview, observations, etc. Looking back at all reports in a transversal manner, we cross-referenced the answers point

by point. The aim was (1) to check whether the answers of the different stakeholders were consistent or not ; and (2) in case of discrepancy, to link them if possible with the difference between the actors' missions or the profiles of their structure (objectives, history, means of actions). The quotations that best illustrated the shared or different points of view for each question were selected. The stakeholders' quotations that are given in this paper are our own English translations from the French original verbatim.

The results of this qualitative analysis are presented in Sections 3.1 and 3.2. This analysis provided a broad view of the needs of stakeholders and the resources necessary to address them more effectively. On the basis of these results, several recommendations were drawn, intended for research teams on urban climate, in order to make the dissemination of the new climate results more efficient.

3. Results

3.1. Inventory of current practices of public actors

The first part of the survey made it possible to make an inventory and analyze the current practices of public actors, the data used and the identified needs, with regard to the issue of UHI or urban overheating.

3.1.1. Which applications involve urban climate data used by public actors ?

From the interviews, it appeared that urban climate data was used for four main applications: raise awareness, territorial diagnosis, decision support, and evaluation of implemented policies (Fig. 3). These four applications will be described in the following.

Climate data are used to raise awareness by local authorities and urban planning professionals on UHI and climate change. This can take the form of educational materials or recommendation guides, such as those produced and distributed by ADEME or APUR for example. The data can also be presented at times of discussion and consultation that accompany the urban planning process (at regional or intercommunal level, for example) to alert newly elected officials and technical staff.¹ Finally, climate data are used to raise awareness among a wider audience, to communicate on a city's actions, and to encourage public support.²

¹ As an example, the master plan for the Île-de-France region is seen as "an opportunity to get messages across, because there is a lot of collaborative work going on, with the territorial authorities of the Île-de-France." (Regional Council).

² "Having all this data, it allows us to launch training, awareness and communication programs on a large scale for all users in the Paris area." (City of Paris).

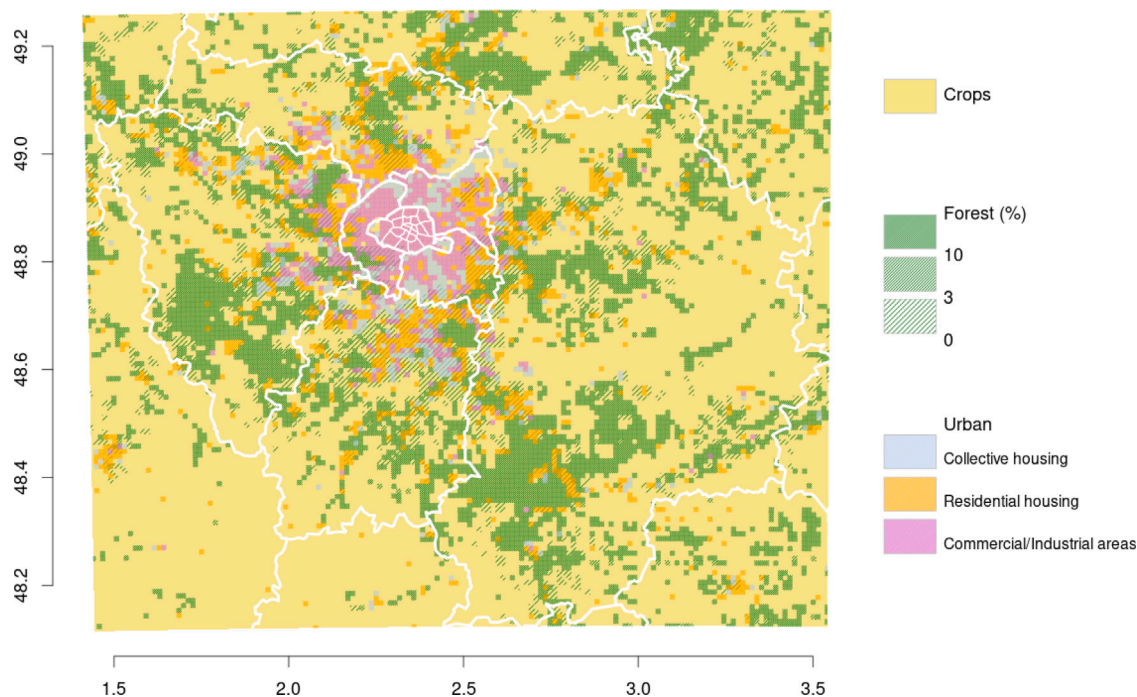


Fig. 2. Map showing the study area and the main land use patterns on the 1-km resolution modeling grid. The white lines represent the administrative boundaries of the counties (thicker lines) and of the districts of the city of Paris (thinner lines). More details in Appendix B.

Table 1

List and description of multi-sectoral impacts indicators derived from the climate simulation. UTCI, or Universal Thermal Comfort Index, is a measure used to evaluate the temperature as it is perceived by humans; it is detailed further in Appendix B.

Sector	Indicators (Units)
Urban climate	<ul style="list-style-type: none"> • Average air temperature over urban areas (°C) • Average air temperature over rural areas (°C) • Intensity of UHI computed as the difference between urban and rural temperatures (°C) • Spatial extent of UHI for a given threshold above rural temperature and expressed as a proportion of the city (%)
Thermal comfort	<ul style="list-style-type: none"> • Average number of hours per day spent above medium heat stress, i.e. for $UTCI \geq 26$ °C (hours per day) • Average number of hours per day spent below low cold stress, i.e. for $UTCI \leq 9$ °C (hours per day) • Average number of hours spent in different UTCI classes (hours per day)
Energy	<ul style="list-style-type: none"> • Average energy consumption due to heating (kWh) • Average energy consumption due to cooling (kWh)

Climate data are useful to assess the vulnerability of the territory, and thus meet the diagnostic obligation set by French urban planning documents at all levels (e.g. local urbanism plan at city scale, territorial coherence scheme at intercommunal level). The UHI estimation can be included in the diagnosis as a vulnerability factor for urbanized areas. City services need such tangible elements to mobilize their elected officials on the urban overheating issue.³ Spatial climate data on the target territory can also be used to identify the most impacted areas, and helps orientate and prioritize public measures accordingly.⁴ Some organizations even go beyond legal obligation, with initiatives to better understand how their territory is affected by UHI.

³ “to be able to tell them [their elected officials]: look, we’re not talking nonsense, there really is a problem of urban overheating in such and such a place. We can see it, it’s quantified, it’s that many degrees [...]. It allows us to cut short endless political debates.” (ADEME).

⁴ “It can be an opportunity to have zoning for problematic areas, where any development that would contribute to aggravate the UHI in these sectors, we could answer: watch out!” (Paris Region Institute).

Urban climate data can be used as a decision support in construction or renovation projects. The examples given by the interviewees are modeling specific constructions at the neighborhood scale or cities development scenarios, to compare them through their impact on temperature and thermal comfort. In addition, they can be valuable for labeling processes as those required for the construction of eco-neighborhood or high energy quality buildings (for considering UHI impacts).

At last, climate data may be used by public actors for the evaluation of implemented policies, that is a necessary step for public action. A good example is the schoolyard greening OASIS project (commissioned by the city of Paris, supported by the EU’s European Regional Development Fund) for which sensors were installed to measure local conditions before and after schoolyard greening and evaluate the cooling potential, especially during summer and heatwaves. The measurement-based evaluation of local impacts helps public authorities to quantify and demonstrate the effectiveness of implemented measures and justify their financial cost. It also enables the proposition of possible improvements.

By taking a step back on the interviews, the use of climate data for awareness raising emerges as the most frequent of the four identified

	Local measurements		Satellite imagery	LCZ GIS-mapping	Numerical modelling	
	Short-term	Long-term	Land surface temperature	Link LCZ-microclimate	Current state	Scenarios
Raise awareness	Green	Green	Green	Green	Green	Green
Territory diagnosis	Green	Green	Green	Green	Green	Green
Decision support for public action	Orange	Yellow	Orange	Yellow	Orange	Green
Public action evaluation	Orange	Green	Green	Orange	Orange	Orange

Fig. 3. Summary of the different types of urban climate data used by public actors and the objectives targeted by this use, with the following color code: green if used for this objective, red if not used, yellow if it can be used in certain cases. Local measurements can be conducted through a short-term campaign lasting a few days or weeks, such as during a heatwave or in the summer (referred to as “short-term” measurements). Alternatively, instruments can be installed for extended periods, collecting data over several years or decades. This allows for the creation of a longer time series and more comprehensive analysis (referred to as “long-term” measurements). Local Climate Zones (LCZ) is a method for mapping the territory according to the land cover and morphology of urban areas to group together neighborhoods whose thermal response is assumed to be similar. GIS (geographic information science) is a technology that enables the visualization and analysis of complex spatial data, and is often used in urban planning.

areas of application in Île-de-France public action. Conversely, the use of climate data for decision support is so far rather punctual (as mentioned by the FNAU). Another key point is that the timetable for the development of planning documents and public policies influences the receptivity and needs of public actors in terms of climate data. If the release of new data is not in line with these time constraints, the data is simply not used.

3.1.2. What types and formats of climate data are used by public actors ?

The climate data used by public actors (which are mainly temperatures or derived indicators) are mainly presented in the form of key figures and maps, depending on the purpose. The maps fit both with awareness-raising and territorial diagnosis. The key numbers allow rising awareness, but also to objectively and quantitatively evaluate the action. More marginally, mainly for climate projections, the data are presented as temporal evolution curves of meteorological parameters. The format and content are also adapted to the target audience. For example, the online dissemination of the climate plan of the Saint-Quentin intercommunality required a reworking of the data to make them understandable and effectively reach the general public.⁵

The results of the interviews show that four main types of urban climate data are used by stakeholders (Fig. 3) depending on the needs and objectives but also on the human and financial resources available. According to the interviews, the most meaningful and expected data for public actors is a direct measurement of the UHI on their territories by in-situ stations. Some French cities launched their own measurement campaign (ex. airborne thermal image of the Paris area acquired for a summer day) or deploy their own station network (ex. Toulouse, Grenoble, Nantes, Clermont-Ferrand, etc.). One-off campaigns characterizing the city at a given point in time, which provides diagnostic and awareness-raising elements, while permanent networks enable to monitor the evolution of physical variables over longer periods such as years or decades, which allows for the evaluation of local actions. These two time-scales for local measurement are referred to as “short-term” and “long-term” in Fig. 3. Nevertheless, these initiatives require expertise and funding, so that they are mainly implemented by large cities.

With no in situ measurements, medium-sized communities often turn to free satellite data. They are generally land surface temperature maps retrieved from infrared measurements. Depending on the satellite products and their spatial and temporal resolution, they can allow monitoring long-term evolution (from the 1990s) and ongoing changes, and possibly evaluate local projects. The resulting territorial diagnoses frequently lead to a confusion between surface temperature and air

temperature, which are, however, quite different information.⁶ Despite this risk of confusion, land surface temperature maps are widely used by many municipalities as a way to talk about the concepts of urban heating.⁷

The classification into Local Climate Zones (LCZ) is another approach used to compensate for the lack of urban-scale measurements. Proposed in 2012 (Stewart and Oke, 2012), this classification is based on knowledge of the urban climatology concepts. LCZ was constructed as a logical and universal classification of both urban and rural areas, based only on surface and urban properties, with the aim to differentiate locations in terms of their energy response to incoming radiation (thermal admittance, surface albedo) and thus in terms of local thermal response. The urban properties used for the classification are for example: building characteristics and construction material, street dimensions and geometry, vegetation and pervious surface fraction, but also human activities and heat production. Note that this classification in LCZ does not incorporate directly any weather or climate information, but highlights the different thermal responses of locations to a typical clear and calm evening. The typical effect on the 2 meters temperature that one can expect from different LCZ classes were assessed from urban measurements and numerical modeling, in the simple setting of a clear night (Stewart and Oke, 2012). Note that the effects on other meteorological variables (such as wind or humidity) were not assessed, as it was not the focus of the LCZ classification.

The main advantage of the LCZ classification is that it allows for a first-order assessment of overheating risk, using geographical data that urban planners typically have access to or can easily gather through field visits. For French urban planning agencies with Geographic Information Systems (GIS) skills, LCZ classification has therefore become a “classic method” (interview ADEME) for the analysis at scale of a few hundreds of meters to a few kilometers. For example, the Paris Region Institute developed an interactive map of the Île-de-France region that provides indicators reflecting the effects of urban overheating in relation to LCZ, urban parameters, and a land surface temperature map from the 2003 heatwave (<https://www.institutparisregion.fr/environnement/changement-climatique/chaleur-sur-la-ville/>). This LCZ approach offers a diagnosis for a fixed mapping of the city at a given time, yet it cannot be used for evaluation of implemented policies.

Finally, results of numerical modeling of the urban climate are also used by some public actors. They have the advantage of covering areas where measurements are sparse or non-existent, or even of

⁵ “When we made it available to the public for consultation, we got a lot of feedback from people who said: ‘We don’t understand it, there are too many figures, too many documents.’” (Saint Quentin en Yvelines).

⁶ “I have seen a lot of nonsense circulating about UHI data. With infrared measurements, people confuse UHI and energy loss of buildings...” (ADEME).

⁷ “Why do we still use this data? Well, simply because they are accessible and because they enable to talk about the subject, and being anchored in the territories. Otherwise, we would remain in concepts!” (FNAU).

simulating and evaluating prospective scenarios. Simulations from research projects such as MAPUCE (Masson et al., 2015) and P.ENDORA (Suher-Carthy et al., 2023; Gardes et al., 2020), [Projectpage](#)) are used for the cities of Paris and Toulouse. Yet, “many urban planning agencies do not have the chance to have access to modeling data made on their territories by Météo-France [...]” (interview FNAU). Modeling is more often provided by engineering firms, or more rarely by certain urban planning agencies. This is the case of the Paris agency APUR which is developing a simplified model to simulate the city-scale overheating for favorable weather conditions. However, the interviews revealed a reluctance to use data resulting from complex climate modeling, as they are generally considered as too complicated and mathematical.⁸ Simpler models that are better understood and mastered are preferred by non-technical people.⁹ The mistrust of non-scientist people can also stem from the perception that these models are based on too many assumptions and are subject to important uncertainties. The dissemination of climate modeling results to a non-expert audience is therefore much more delicate than for measurements, and requires progressive acculturation and guidance.

3.1.3. Which needs have the public actors expressed ?

The public actors interviewed expressed the need for a more detailed territorial diagnosis in order to target and prioritize the areas where intervention is needed.¹⁰ They underline the scarcity of local measurements for monitoring the temperature in the cities and UHI. In particular, it was deplored by several respondents that the only station in Paris of the Météo-France weather network is located in a large urban park (Montsouris), that does not allow for an accurate measurement of the UHI. On the other hand, some public actors would like finer UHI modeling to get closer to the local scale, but with imprecise and disparate requests regarding the spatial resolution (from the municipality to the neighborhood level).^{11,12}

Concerning the use of urban development scenario studies as a support for decision-making, the expectations of public actors are for the production of more operational scenarios than what can be achieved by some prospective scientific studies (i.e. less generic and more localized), better in line with public action and implementation constraints.¹³

The link between UHI and climate change can rarely be made explicitly because the available data do not allow it. Public actors are increasingly demanding urban climate data that integrate trends in climate projections, and take place in an adaptation perspective. This dimension becomes a prerequisite for the calls for research projects funded by ADEME. Nevertheless, in the absence of such data, the public actors now complement their territorial diagnoses on UHI with a discussion on the expected increase in the occurrence of weather situations (especially, heatwaves) that exacerbate the UHI and associated impacts.¹⁴

⁸ “When you present data from modeling to elected officials, there are some who are very perplexed, and who say to us, but how can you be sure that this will go this way?” (Saint-Quentin-en-Yvelines).

⁹ “We don’t necessarily like very complicated models. For people in urban planning, we prefer them to be able to grasp the ins and outs [...] We are wary of black box phenomena”.

¹⁰ “Having climate projections [...] that are very localized would be very interesting, I think. It would allow us to prioritize our actions even more, to really know where to start first.” (City of Paris).

¹¹ “10 km would be really good already.” (ADEME).

¹² “What we are really interested in is having a downscaling with a fine mesh, let’s say, almost to the district level.” (City of Paris).

¹³ “When you talked about doubling the green spaces in Paris, well, that’s interesting, let’s admit it. But it’s not operational enough: we don’t have a project that is either double or not double the green surface!” (Les Mureaux).

¹⁴ “Now we have a systematic discussion about climate change in our diagnoses: the heat phenomena that we encounter today, tomorrow are likely to be multiplied, to concern new territories.” (FNAU).

3.1.4. Who do public actors turn to for urban climate data ?

The results from interviews show that there is a very wide disparity in terms of in-house technical and scientific skills and human and financial resources between structures.¹⁵ The city of Paris is a driving force in city-scale impacts studies of climate change. It has a dedicated department on these issues, which can itself contribute to the UHI diagnosis and the implementation of local actions. On the contrary, the absence of a geomatics department for many organizations is a significant barrier for efficient access and processing of urban climate raw data, and adapt it to the specific needs of the actors concerned. Therefore, although some planning agencies have the capacity to produce data or process existing data, many structures turn to consultancy firms. This may involve data from measurement campaigns, or climate modeling on different scales, or modeling on a very local scale for a particular project.

The time constraints may dictate the choice of entrusting an analysis to a private study agency rather than a research team.¹⁶ Research projects (typically 3–4 years long) do not necessarily respond to the dynamics of public action, which is notably punctuated by local and regional elections. Nevertheless, the cost of consulting firms is a limiting factor and encourages the local authorities or State services to turn instead to institutional partners. Some structures are identified as resources for providing or producing UHI data: the State technical agency CEREMA (Center for studies and expertise on risks, the environment, mobility and planning) with a recognized expertise on urban thermal issues, the ADEME for energy issues, the AIRPARIF regional air quality monitoring association, or the Teddif network (Territories, environment and development in Île-de-France). The State services can play a role in redirecting communities to these expert resources.

For public actors, Météo-France is the reference for reliable meteorological and climatic data and products.¹⁷ Still, except for public actors who have been involved in research projects, Météo-France is not identified as a resource on UHI-related issues, especially regarding its practical translation for development and planning actions. According to the Paris Region Institute, which has collaborated a lot with the research center of Météo-France and CNRS (National center for scientific research), the project reports are not efficiently publicized to the urban planning community. Although reports and main results are accessible on Météo-France website and published in the scientific literature, the results and data from those projects are not clearly identified as available and retrievable by most public actors.

Instead, the interlocutors considered as the real reference on UHI issues in the Paris region are the urban planning agencies (Fig. 4). Both Paris Region Institute and APUR (for the regional and Paris urban level, respectively) are very well identified by the local authorities, particularly for their expertise on the link between UHI and public planning policies.¹⁸ The local authorities rely on the technical notes and publications relayed by the Paris Region Institute, which are highly appreciated because they are truly adapted to operational needs.

¹⁵ “I’ve seen some [communities] take ownership of datasets, have a geographic information system engineer who deals a little with climate data. There are really very different levels of involvement, and very different needs depending on the territories.” (ADEME).

¹⁶ “consultancies generally work faster [...]. For example, the study with Ramboll took only about four to six months.” (City of Paris).

¹⁷ “Obviously when you also have a study stamped from Météo-France, it is always reassuring for everyone. It’s Météo-France, so it’s reliable.” (City of Paris).

¹⁸ “It is true that we work more particularly with Arc [Energy Climate Regional Agency] or the Paris Region Institute when we want data like that, that are so specialized. So they are quite the experts. This is part of the missions delegated to them by the Region.” (Regional Council).

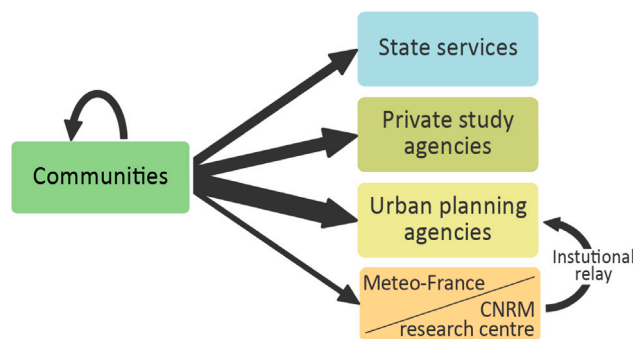


Fig. 4. Schematic view of the actors toward which communities would generally turn to, if they want some urban climate data. The larger the arrow, the stronger the link.

3.2. Feedback of stakeholders to new research outcomes

The second part of the survey made it possible to collect the reactions of the same actors interviewed to the presentation of new data resulting from research work on the urban climate and its expected evolution with climate change. The objective here is to clarify to what extent this data, its method of calculation, its representation and format can meet the needs of the actors. For this part of the survey, we presented to the actors some visuals based on research results to illustrate the different aspects discussed.

3.2.1. About the setup of the simulations

Before considering the results, the interviewees were asked about some important configuration elements for the simulation, i.e., the geographic area covered, the spatial resolution chosen, the main assumptions of the model. They first reacted on the description of the study area. The use of a fixed land cover mapping for the region that is based on the current state (as shown previously in Fig. 2), with no change in urbanization during the climate simulation, is unanimously seen as an important limitation.¹⁹ The actors would have appreciated taking into account the old land use for the simulation of the past period, and a projection of the land use in the future combined with some generic assumptions of urbanization, thermal renovation of buildings, increasing installation of air conditioning equipment, etc. The comparison of different evolution scenarios (e.g. land use planning, energy renovation plan, urban greening) would also have been very interesting for the public actors.²⁰

Despite this, stakeholders were very keen on the results presented, provided that the assumptions made were highlighted. The 1-km horizontal resolution of the simulation was generally highly appreciated and considered as an important step in raising awareness about UHI and climate change in the Paris region.^{21,22} Nevertheless, some actors, mainly those with a background in urban planning, would like to go to an even finer resolution (typically, at street level).²³ They therefore

¹⁹ “The city extent of 1970 is not one of today! The year 1990 can only be used if you have access to the urbanization of that time, otherwise it is strongly recommended to run the model only on recent years.” (APUR).

²⁰ “If you make several scenarios, it would be very interesting. There are big debates about nature in the city, these are electoral and political issues.” (DRIEAT - Energy Climate).

²¹ “I think that what you are presenting, this downscaling [to 1 km], is really capable of moving the lines.” (DRIEAT - Energy Climate).

²² “1 km is already something very interesting, especially for a planning exercise.” (FNAU).

²³ “You should in fact give a degree of precision that makes it possible to deal with the district, [otherwise] the project leaders, the elected representatives, they will find it difficult to use what we bring them.” (DRIEAT - departmental unit).

insist on the importance of completing the results at 1 km by local modeling or by measurements.

As for the potential need to aggregate the data from the 1-km grid to an administrative unit, the stakeholders were unanimous that it was better to keep the native resolution to preserve the maximum precision.²⁴ Any further change of scale or aggregation of the data may be relevant depending on the needs and applications, but at a later stage and preferably by the users themselves (Section 4). For example, aggregated numbers on a municipality’s territory could be of use by local geomatics services to compare more quantitatively different territories, using the raw simulation results.

The presentation of a given result at different levels of zooms appeared very useful to local actors (Fig. 5). They are primarily interested in the issues specific to their own territory.²⁵ But that way, they can also compare the impacts and urban effects in their municipality (or department) with those of neighboring municipalities.

3.2.2. About the hypothesis and temporal characteristics of the climate projections

In a second stage, the question of the choice of emission scenarios and climate projections, as well as the temporality of these projections and their analysis, was addressed. Stakeholders did not express a strong preference for one of the greenhouse gas emission scenarios, and seem satisfied with the scientific results often based on the RCP8.5 scenario with the highest emission levels and the strongest warming signal, as far as the definitions are explained. However, this extreme scenario may be difficult to back up by the State services given its incompatibility with the carbon neutrality objectives by 2050.²⁶ As a result, they could be more comfortable with medium (RCP4.5) to low (RCP2.6) emission scenarios. Stakeholders agreed that showing different possible futures raises awareness of the importance of mitigation actions and of a scalable and flexible adaptation.²⁷ Nonetheless, they preferred the results to be limited to a few scenarios (three at maximum) for the sake of clarity.²⁸ In their opinion, it is not necessarily useful to systematically overlay the results of several emission scenarios. They suggested illustrating the main message based on a single selected scenario, then showing how this can be amplified or reduced with other emission scenarios on a few chosen examples.

The climate simulations that led to the results presented in the survey covered the period 1970–2099. As most climate analyses based on a statistical approach of trends, the results were presented as averages of three 30-years periods, i.e. historical (1976–2005), near future (2020–2049), and far future (2070–2099) as illustrated on Fig. 6. The survey revealed that this presentation of the results in the form of a 30-year time-slice was very difficult to grasp for stakeholders, because it is such a long period compared to the timescale of most public actions.²⁹ There is a gap between the information expected by the actors on the one hand, and the scientific results and analysis methods on the other. Due to the inter-annual climate variability, it is not statistically

²⁴ “Temperature does not stop at the municipal boundary! If we take the average at the commune level, we risk having a wrong interpretation afterward, within the same territory, the results are heterogeneous. No, I don’t see the point of aggregation.” (FNAU).

²⁵ “the map zoomed in on Paris, that’s absolutely certain, because that’s our territory, and that’s where we’re competent.” (City of Paris).

²⁶ “We need to be in line with what the SNBC [Stratégie Nationale Bas Carbone] and the government say about our climate targets.” (DRIEAT - Departmental unit).

²⁷ “If you show two scenarios, you show a range of possible, credible futures.” (DRIEAT - Energy Climate).

²⁸ “We could present a few scenarios, but not too many, because if you present more of them, people are lost. Two, three, but not more!” (Saint-Quentin-en-Yvelines).

²⁹ “When you say 2020–2049, I find it hard to see what it means. Can’t we work on time horizons that are a little more precise?” (City of Paris).

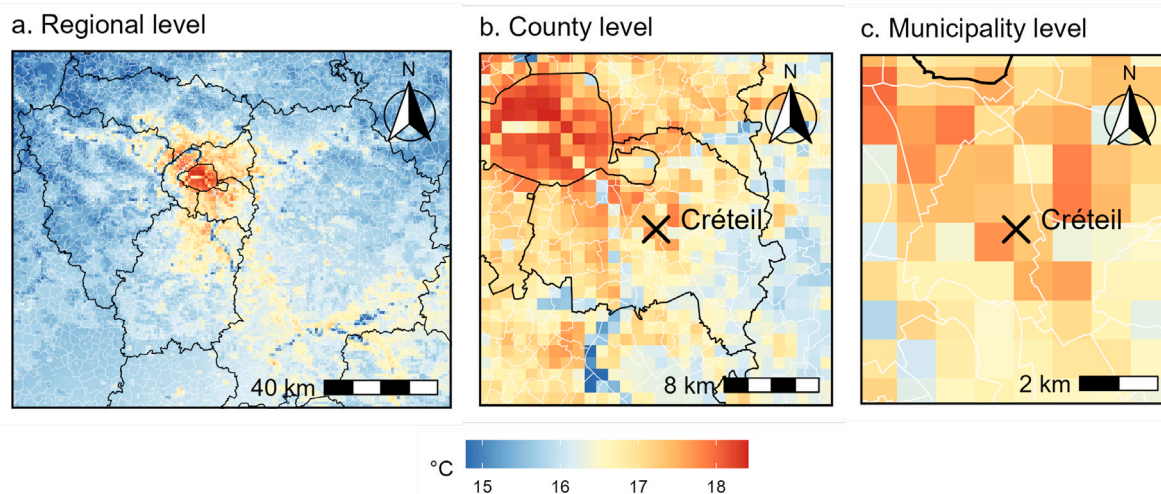


Fig. 5. Visual presented during the interviews, showing the same 1 km resolution simulation data at three zoom levels. Average nighttime temperature for the hottest summer simulated by one model over the historical period 1976–2005.

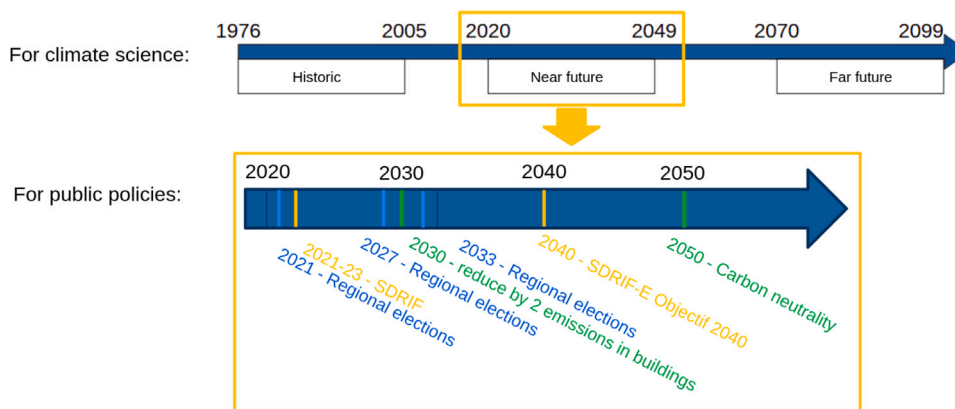


Fig. 6. Illustration of the different time scales at scales for Climate sciences compared to public policies, with regular elections, urban plans (such as the SDRIF -Schéma directeur Île-de-France-, carbon emission reduction objectives, etc.

robust to reduce significantly the length of the periods over which climate trends and impacts are calculated. Therefore, to speak of “time horizons” instead of “periods” by referring to the central year of the 30-years time-slice (e.g. “2020-2049” becomes “horizon 2035”) is a simple communication element that allows to take up the usual codes in public policy.

Climate projections to the end of the 21st century did not emerge as deadlines that interested and challenged most of the public actors.³⁰ The temporality that was relevant for them had to be linked to the rhythm of public action and elections³¹ and planning documents (for ex. 20 years for the SCOT, a local urban planning document). Therefore, from the perspective of adaptation decision-making by elected public actors, it appeared to be more effective and relevant to present them with short and medium-term projections (until 2040, even 2050) rather than long-term. Nevertheless, the projection data up to 2100 should remain available for technical services and for actors of long-term energy prospective or urban planning.

³⁰ “2080, it’s a long way off. The further away the targets are, the less concerned the people.” (Regional Council).

³¹ “Town representatives are in place for 6 years: they want to do things now, that have an impact now.” (Saint-Quentin-en-Yvelines).

As for the temporal integration of a result, the interlocutors generally advised against the use of averages, when aiming at raising awareness: the concept of mean seems not easy to grasp.³² Instead, the interviewees recommended highlighting the results on extremes, which can impact people, health and activity sectors a lot: for example heatwaves or extreme temperatures.³³

Last but not least, the presentation of models uncertainties to elected officials or the general public appeared to be counterproductive, based on the survey feed-backs. These uncertainties based on statistical notions made the information more cumbersome and complex, which could confuse the core of the message for a non-technical public.³⁴ On an evolution curve, a colored band around the average value could be enough to remind people of the dispersion of the models without

³² “In my experience, when you communicate with the general public or policymakers, people do not understand what an average is.” (APUR).

³³ “There are times when the thresholds of acceptability are crossed. [...] If we say that there will be 32 days in the summer when our infrastructure will be at the breaking point, when the rails will bend because it will be too hot [...] this can really mark people.” (DRIEAT - Energy Climate).

³⁴ “I think you need to have the clearest message possible. The min and max will confuse a more complete reading of the graph.” (DRIEAT - Departmental unit).

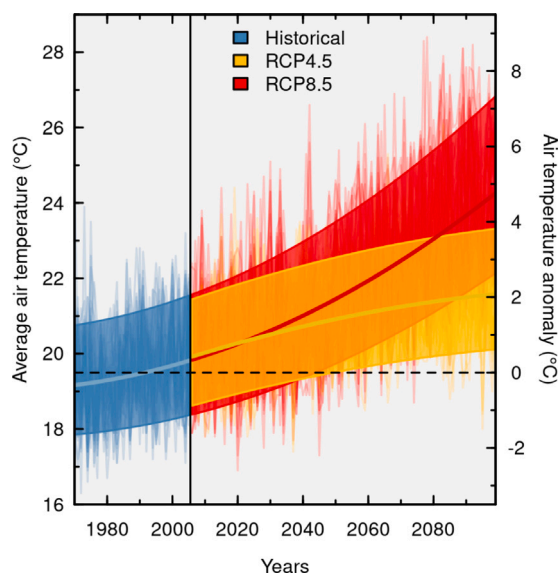


Fig. 7. Temporal evolution of the average summer urban air temperature over Paris. The background lines represent the variability associated with the multiple models used and their natural variability. Two scenarios are represented: RCP4.5 in orange and RCP8.5 in red. The smooth lines and envelope represent the multi-model mean and the 90% uncertainty range smoothed by polynomial regression. The dashed horizontal line indicates the temperature anomaly relative to the 1976–2005 mean.

making the graph too heavy (Fig. 7). Still, for technical services, uncertainty assessment would be necessary to define robust adaptation strategies.³⁵

3.2.3. About the choice of indicators

Respondents were asked about the relevance and interest of the different indicators that have been selected in the research work to assess the local impacts of climate change on the Paris region (see Table 1). First, the surface air temperature was presented and discussed, and by extension the associated UHI (Fig. 8). The surveys showed that these data over the region was already of great interest to the actors. The surface air temperature and UHI maps were considered to be relevant tools for awareness and diagnosis. All respondents found these maps to be very meaningful and useful for diagnosing and viewing the geographic sectors affected by UHI hazard, even in areas that may not be perceived as problematic in peri-urban municipalities. Some respondents felt that confusion or misunderstandings are still possible, depending on the vocabulary used. Stakeholders and municipality services usually work with their own definition, for example a local-scale evaluation of UHI on their own territory and for a specific weather situation, as opposed to the evaluation that was proposed here for the whole region and for a summer average. Besides, for energy and transports operators, the surface air temperature appeared to be of great interest to estimate the risk of rupture of specific infrastructures.³⁶

Two other meteorological indices related to temperature emerged as particularly relevant for some stakeholders because they are frequently used in their territorial studies: heatwave days and tropical nights. According to the French warning system, a heatwave is defined as a

³⁵ “The mustache box [showing the standard deviation around the mean for a given value, as presented during the interview] is of no use to the elected representatives I think, but for the technical services of the climate plans it is worth having this report in detail.” (ADEME).

³⁶ “If you say, it will reach 50 °C around the regional trains catenaries, or if the tar melts too fast in some areas, that will be of great interest for them.” (DRIEAT - Energy Climate).

period of at least three consecutive days when the daily mean temperature does not fall below a threshold prescribed for each county by the national health agency (Pascal et al., 2021b). The tropical nights corresponds to days when the minimum temperature does not fall below 20 °C (ETCCDI: <https://etccdi.pacificclimate.org/indices.shtml>, (Karl et al., 1999; Zhang et al., 2011)).

Indicators relating to thermal comfort (or heat stress) were presented in a second step. They are similar to the notion of perceived temperature depending on environmental conditions (i.e. combination of temperature, humidity, wind, and radiation). This concept is still emerging in France and needs a minimum of guidance, but it was very well received by the respondents because it addresses the individual’s scale.³⁷ The feedback from the surveys indicated that comparing spatial data (map) and temporal data (evolution over a day) helped to understand the exposure of individuals according to their mobility and the time of day. In addition, integrated over the day, they provided daily exposure maps under heat stress conditions which was very informative for urban planning. Respondents emphasized the complementarity of these results to the nighttime temperature maps, with the influence of urban form and compactness on wind and sunlight sometimes leading to counter-intuitive results on urban comfort. Nevertheless, there was a strong demand to give even more informative data concerning the impact of thermal discomfort on health, if possible in a quantitative way.³⁸

The last indicators concerned energy. The evolution of energy consumption for air-conditioning and heating has undoubtedly emerged as a prospective data much awaited by municipalities and operators to prepare for the energy transition.^{39,40} An important point of vocabulary was underlined by some respondents: it would be more appropriate to speak of cooling demand rather than air conditioning demand. The message thus referred to a more systemic reflection on the renovation of buildings to ensure summer comfort, rather than an incentive for the systematic development of air conditioning systems. The respondents reminded that two levels of information could be useful, i.e. (1) the evolution in annual energy consumption to support municipalities in their planning and (2) the evolution of peak power to address the electricity supply issues of grid operators. For energy, the question of the unit and the appropriation of these quantities is crucial to communicating to a non-technical audience. An analogy with concrete quantities would help for a better understanding of the consumption volumes (expressed in kWh m⁻² yr⁻¹) for instance by referring to an equivalent number of nuclear reactors, or a number of wind turbines or a surface area of solar panels.

The indicators mentioned above were all welcomed with interest but also led to an expression of needs from the actors in relation to their fields of intervention. Stakeholders expressed a strong demand to cross-reference climate data with sectorial data to assess new types of impacts (e.g. the effect of high temperatures on urban infrastructure and transport networks). Not surprisingly, the impact on health emerged as a central issue. Even if thermal comfort is already a very relevant information, the transition to the evaluation and understanding of the vulnerability of the inhabitants is at the heart of the concerns. Putting sociodemographic data or data on sensitive equipment into perspective with climate data could support action for risk prevention.

³⁷ “[Universal Thermal Comfort Index is interesting] because it’s on a human scale, and not just on the physical scale of Météo-France [laughs]: it’s not just a thermometer.” (Plaine Commune).

³⁸ “What does it mean to spend 3 h in thermal stress? Personally, I don’t know if there is a clear difference between 2 h and 6 h. One needs to give a framework, a context that is established.” (Plaine Commune).

³⁹ “All these elements of the evolution of the demand for air-conditioning in a changing climate, in the urban and periurban areas, these are very, very precious elements to situate the extent of the challenges today!” (Paris Region Institute).

⁴⁰ “This will be of great interest to Énédis [a French electricity distributor] and RTE [the French electricity grid operator], who will have to make sure that they can supply the necessary electricity.” (DRIEAT - Energy Climate).

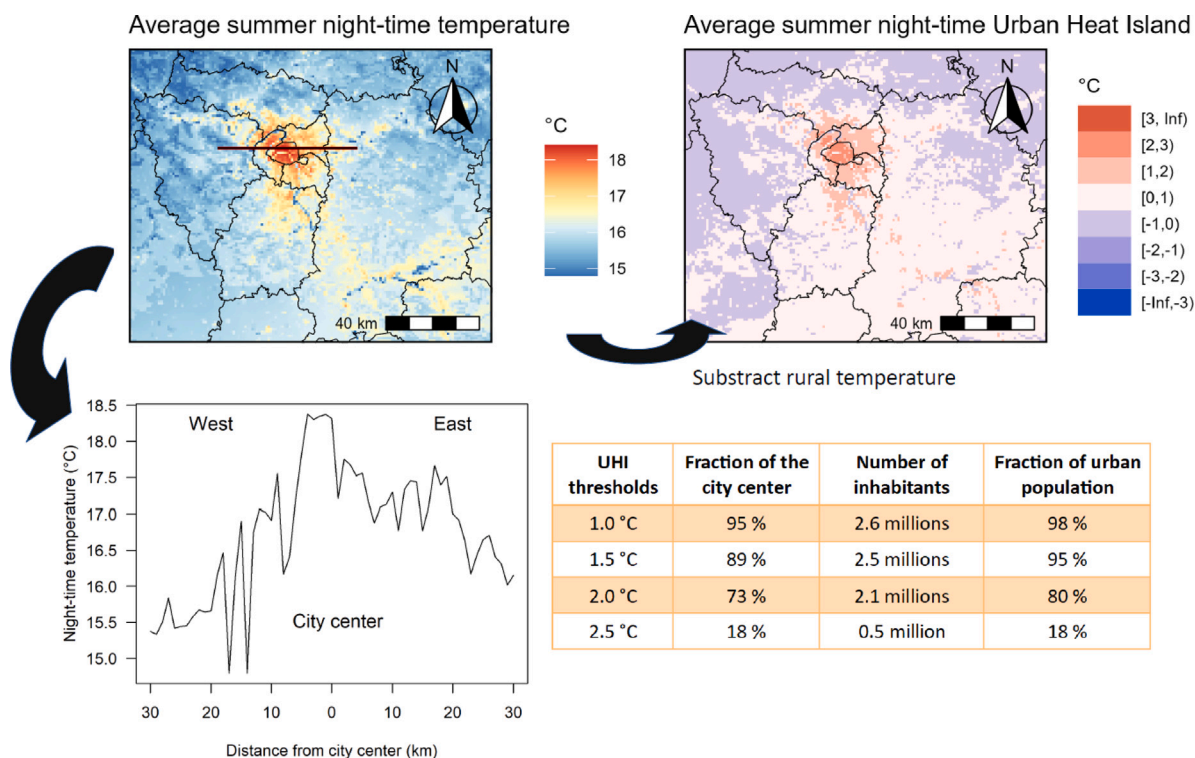


Fig. 8. Visual presented during the interviews, showing different ways of representing the impacts of nighttime Urban Heat Islands. Average nighttime temperature for the hottest summer simulated by one model over the historical period. Top left: the temperature at 2 meter from the ground, with a continuous color-scale; top right: the same temperature field to which its regional mean has been subtracted, giving the Urban Heat Island field, with a discrete color-scale. Bottom left: a transect of the temperature field through Paris city center, from West to East; bottom right: table with the number of people in the Paris area affected by given levels of UHI.

3.2.4. About the visualization and data accessibility

In a last stage, the respondents also commented on the proposed visual media and formats for presenting indicator information. The first important result is that the cartographic medium is clearly the easiest to access and the most meaningful for the actors (but also for the general public).⁴¹ This is in line with current practices in the urban planning sector, where this type of medium is widely used. The scientific curve - such as a temperature transect across the region - is much less common and more complex for a non-expert audience.

To facilitate reading and interpretation, but also to reinforce the message, the maps (or other graphic media) should be supplemented by reading elements in the form of combined map data, key messages, diagnosis, etc. For example, superimposing land use and occupation information on UHI maps (location of parks and urban centers by colored or hatched areas) raises awareness of the link between soil sealing and urban overheating. Technical services could rely on these media to support the preservation of natural areas. Another example, the data on the population affected by different UHI levels (Table in Fig. 8) is a key figure highly appreciated by respondents⁴² because it reinforces in a concrete way the information provided by the map. Even if the respondents would like these figures to be refined especially by accounting for sociodemographic variability, they considered the figures to already provide crucial information on a first level of impact, and could feed into more detailed studies carried out directly by the municipalities.

⁴¹ “This section curve chart speaks much less than the map. You would have to be used to reading graphs. Besides, this form of graph is not often used. I think that the average person who does planning will find it difficult to understand.” (DRIEAT - Planification).

⁴² “That’s the first thing people ask us: but how many people does your thing impact?” (Paris Region Institute).

For map plotting, the survey outputs highlighted that the choice of color scales and temperature ranges (with continuous or discrete values) was important in reading the map and the resulting perception. Although the zoning effect associated with discrete thresholds can help identify high-stakes areas, it can also be counterproductive for taking action in areas where mitigation goals may seem unattainable. This point emerged from the respondents’ feedback on the UHI maps, for which a discrete scale may be suitable for a regional overview, while a continuous scale is preferred when the maps are zoomed in on smaller areas.

Finally, concerning the way to show the evolution of indicators over time, three approaches were presented at the interviews: maps at different time frames, tables of key figures, and curves of temporal evolution. Again for stakeholders, the comparison of maps for the current state and the expected future stood out as the most meaningful medium, as map visualization is widely used in planning so that elected officials are familiar with it.⁴³ A key figure extracted from curves or maps could also be sufficient to convey a message, to raise awareness among all types of actors.^{44,45} In contrast, the respondents recommended avoiding the graph as time evolution curve (perceived as too mathematical) when addressing elected officials or the general public.⁴⁶ The presentation of time series to a non-specialist audience requires a real work of formatting. The reader must be guided through the graph to make it more accessible, for instance with storytelling.

⁴³ “The map is what speaks, and it is what makes it possible to illustrate to elected representatives.” (DRIEAT - Departmental unit).

⁴⁴ “Some key figures that elected members could feed back into their speeches.” (FNAU).

⁴⁵ “It’s more like key figures that we give to show the need for action [...], it’s meant to reinforce the message.” (Plaine Commune).

⁴⁶ “I really think that there is not a great culture of mathematical graphs in urban planning and the population in general.” (DRIEAT - Energy Climate).

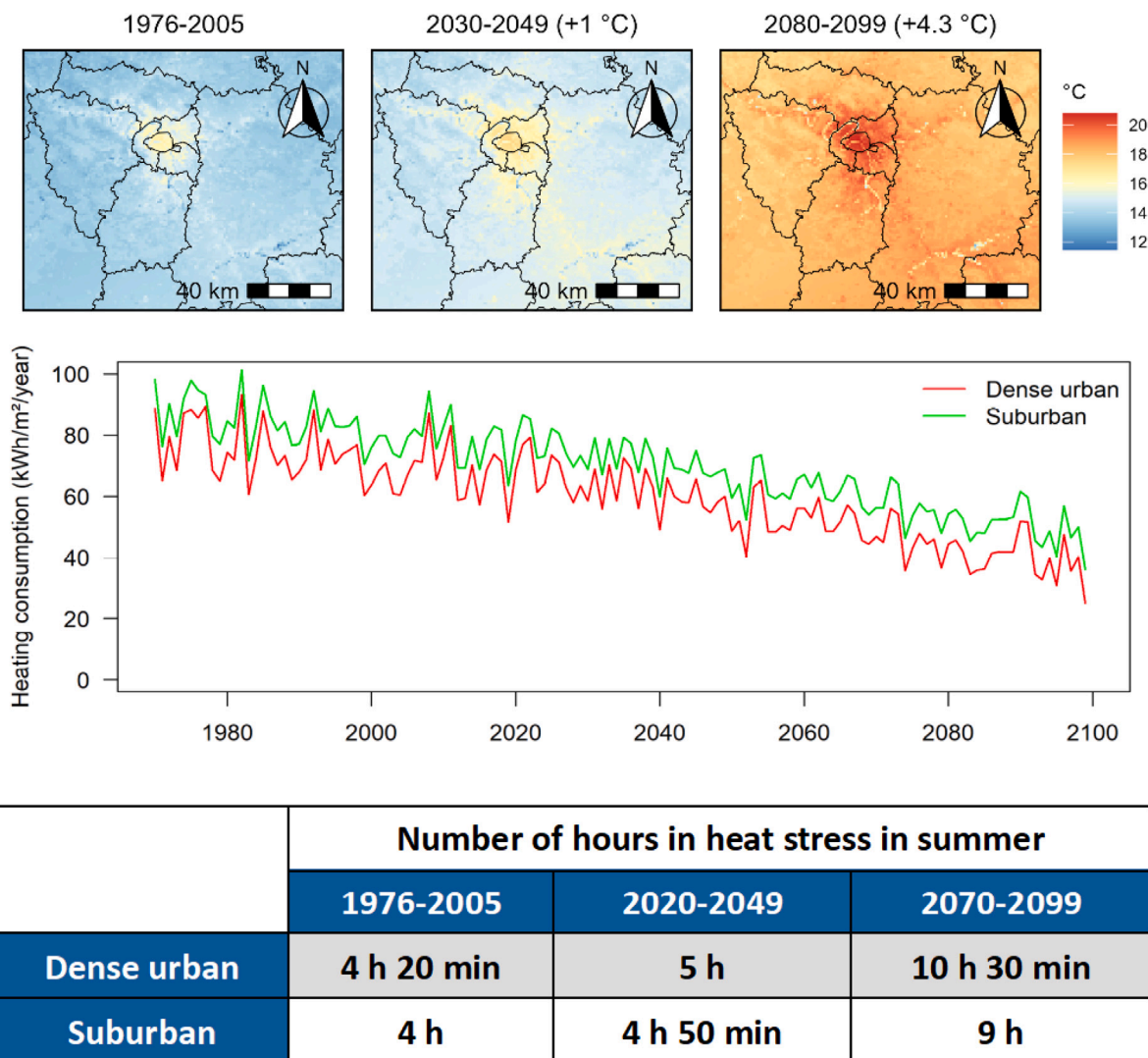


Fig. 9. Visual presented during the interviews, showing different ways of representing the future evolution of a given variable. By row: average summer nighttime temperature, yearly energy consumption due to heating, average number of hours in heat stress per summer day.

Lastly, the respondents were asked about how they would like to access this kind of data. The first mode of diffusion should be ready-to-use information at the Île-de-France regional level, in the form of a synthetic summary, that would be of use for most type of actors. This summary should present the project results in broad terms; it should explain where the simulation data comes from (model principle, hypothesis and inherent limits) and give general results, such as the spatial structure of UHI and its projected evolution in the future.⁴⁷ It should also highlight the kind of output that could be provided from these simulations, with an example for each variable. The respondents highlighted that for such a document to be used by technical agencies or public actors, it had to be very clear and self-explanatory. Any impact map (e.g., a UHI map with localized maxima in certain areas) that may highlight areas that are more vulnerable than others should therefore be accompanied by explanatory information.⁴⁸ In this way,

⁴⁷ “For technicians like me, it allows us to understand how it was set up. It shouldn’t be 70 pages long because we won’t have the time. I read the quick notes that the Paris Region Institute makes, which are between 6 and 10 pages long.” (Saint-Quentin-en-Yvelines).

⁴⁸ “If there are maps, we need explanations. To enable us to use them, to present them, and to answer the questions we will be asked.” (Saint-Quentin-en-Yvelines).

the technical staff of a municipality can truly take ownership of these results and explain them themselves to their elected officials.

The second mode of diffusion should be raw data, that anyone can work on. Indeed, the interviews revealed that some of the stakeholders needed to perform their own tailored analysis at a smaller scale, or to cross-reference with sociodemographic or technical data.⁴⁹ Thus, a selection of interesting simulation outputs should be made available freely online. It would make sense to incorporate this into already existing platforms like DRIAS (<https://www.drias-climat.fr/>) from Météo-France, especially as it is becoming well-known by French public services. It is noteworthy to highlight that the respondents were not necessarily familiar with the format usually used for climate data (NetCDF files), therefore data should also be provided in a georeferenced format more common in the field of urban planning (e.g., Shapefiles, ASCII or geodatabase). Finally, once the data is available online, it appears imperative to publicize its existence and availability on a regular basis.

⁴⁹ “Planning agencies will want reusable data, where they can adapt the mode of representation, cross-reference with other data, etc.” (FNAU).

4. Recommendations and conclusions

These analyses gave a better understanding of the current practices of Île-de-France stakeholders in terms of their use of climate information for public policies in territorial development and urban planning, of their potential needs and expectations, and of who are the actors considered as reference for the UHI issue. This work made it possible to formulate a set of recommendations with a view to disseminating and promoting the current research results more effectively, and to provide guidelines for future studies.

With regard to the general dissemination strategy, several levels of information and data are expected. The results must be disseminated first as a level of information that is accessible and usable directly by all local authorities. The major issue is that every stakeholder can appropriate and use the data without the need for specific technical expertise, such as an internal geomatics department or a consulting firm, which not all municipalities have at their disposal. A second level of provision, with reworkable and geo-referenced data, is also expected by some of the stakeholders to carry out processing and analyzes based on their own expertise. Lastly, some of the scientific data produced can be shared in open access to other scientific communities of users (in particular by engineering firms) for feeding into new impact studies on finer spatial scales that address more diversified sectoral impacts.

To succeed in this transfer of data and knowledge, it is necessary to reinforce the visibility of the work already done, which is currently very insufficient because it is too restricted to the academic research community. With this aim, researchers must rely on key local interlocutors as relays between the field of research and the field of operationalization. Urban planning agencies can play this strategic role: they have both a very good understanding of scientific results, perfect knowledge of territorial policies, and a very well-established network of stakeholders and users. A generalization of this dissemination process to other cities in France will therefore require to systematically identify the entities that are located in these territories and active on climate and urban-overheating issues, in order to work with them. These could be the urban planning agencies in priority, some decentralized State services, but also local and regional climate and energy associations.

Several ways to improve the presentation of results were identified. Numerical modeling tools and their results are complex, therefore it is essential to clearly explain the configuration and the main concepts and assumptions of the simulations with the implications on the results (for example, the choice of a fixed land use and urbanization map must be justified). Besides, to effectively raise awareness on vulnerabilities, it seems more relevant to communicate on extreme conditions (e.g. during heatwaves) which often results in increased risks for population, urban systems and networks, rather than presenting annual average values that are usually not appropriately understood.

The stakeholder feedback highlighted that surface air temperature is considered to be a relevant tool for awareness and diagnosis of UHI and its evolution with climate change. In this way, a shortcut is too often made between surface temperature and UHI. To avoid confusion and in the absence of increased skills among stakeholders, we strongly suggest not to use surface temperature from satellite data to deal with UHI, as it does not represent the temperature felt by citizens, and does not compare with either modeled or measured surface air temperature. The selected panel of climate and impacts indicators is already very relevant and informative according to our results and does not necessary need to be completed. Still, suggestions have been made to guide the calculation of indicators based on the stakeholders' needs, particularly for energy where municipalities are interested in annual consumption at the scale of their territory, when energy suppliers are rather interested in peaks of consumption in the region during extreme events. Respondents regularly express new perspectives and areas of interest on risk and impact assessment. The current tools and results do not meet all these expectations, but could serve as a basis for further studies by experts in the concerned fields.

To sum up, it is crucial to work for a good comprehension and accessibility of the data, to reinforce its diffusion through local operational actors, and to adapt the format to the different needs.

A final important point concerns climate projections. The time frames chosen for the presentation of climate change and impacts should be reviewed. Stakeholders are in demand of short- and medium-term prospective data that are in coherence with the temporality of political action and public policies, and could be a relevant support in decision-making for adaptation. The next few decades are of particular interest for public actors, which highlights the need to foster and improve projections at the decadal scale. Yet, if such results are given, the uncertainties linked to natural variability must be properly highlighted. Regarding terminology, it could be more meaningful and understandable to speak of a "time horizon" (using a central year, e.g. "horizon 2035") rather than the corresponding 30-years climate period over which the analyses were performed (2020–2049). Finally, the feedback from respondents highlights the difficulty to deal with complex uncertainty representation (whether related to the dispersion of multi-model climate projections or to the different emission scenarios). When the aim is to raise awareness, we recommend simplifying the representations of uncertainties (showing for example the multi-model mean and a single scenario or level of warming). However, scientists should explain the importance of uncertainty in climate projections and convince stakeholders of the need to take it into account for the appropriate planning and sizing of adaptation levers. How to deal with uncertainties and communicate this information to decision makers is still an open question.

CRediT authorship contribution statement

Julie André: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Benjamin Le Roy:** Writing – review & editing, Writing – original draft, Visualization, Data curation. **Aude Lemonsu:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Morgane Colombert:** Writing – review & editing, Methodology, Investigation, Funding acquisition. **Valéry Masson:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Logical framework diagram for the interviews

The logical framework diagrams shown in [Fig. 10](#) and [Fig. 11](#) highlight the chronology and the logical links between the questions that we asked during the interviews.

Appendix B. Climate simulations and impact indicators

The research work that motivated and fed the reflection on the information dissemination to potential actors and users comes from the PhD thesis of [Le Roy \(2021\)](#). An original methodology has been developed to study the impacts of climate change in cities, taking into account the evolution of the regional climate and its interactions with the local urban climate generated by the city itself. This methodology was applied to the Paris region to produce a set of multi-sectoral indicators (described below) reflecting the evolution of the impacts of climate change at city-scale during the 21st century and according to two greenhouse gas emission scenarios. This required three major steps: (1) to configure an urban climate model, as well as associated descriptive databases, for the Paris region ; (2) to spatially downscale climate projections provided by regional climate models to run the urban model with atmospheric conditions tailored to city-scale ; (3) to

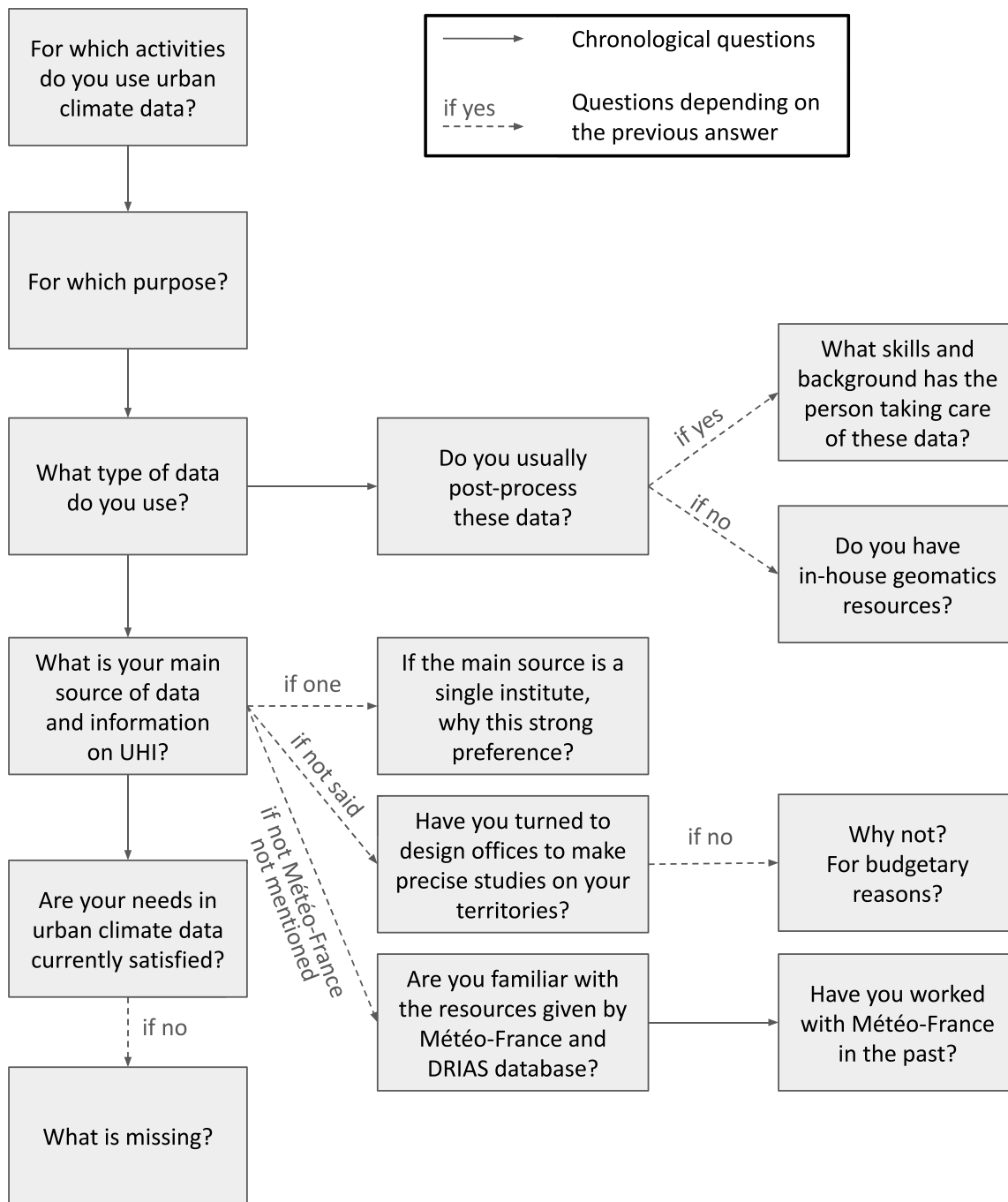


Fig. 10. Logical framework diagram of the interview grid, Part 1: What are your current usage and need of urban climate data?.

define and calculate indicators to quantify some relevant impacts on urban climate, thermal comfort and energy consumption.

Urban climate model

Here, the future evolution of Paris urban climate is simulated using the modeling platform SURFEX (*Surface Externalisée*; Masson et al. (2013)) that describes and processes the surface with a regular square-mesh 2D grid. SURFEX combines three main land surface models devoted, respectively, to rivers and inland waters (FLake; (Salgado and Le Moigne, 2010)), natural soils and vegetation covers (Interaction

Sol-Biosphere-Atmosphere (ISBA); (Noilhan and Planton, 1989)), and urban areas (Town Energy Balance (TEB); (Masson, 2000)).

TEB is a state-of-the-art urban canopy model for meteorological modeling applications, covering horizontal resolutions from few hundred meters to several kilometers. This is a parametrization that does not explicitly resolve each building but applies the average urban canyon assumption (Nunez and Oke, 1977) at the model mesh scale. This simple shaped canyon is defined by average parameters for geometry, land use and surface distribution, material properties, etc. This set of parameters is mapped according to the model grid to reflect to some extent the heterogeneity of the urban landscape. TEB incorporates urban vegetation in interaction with the built environment (Lemonsu

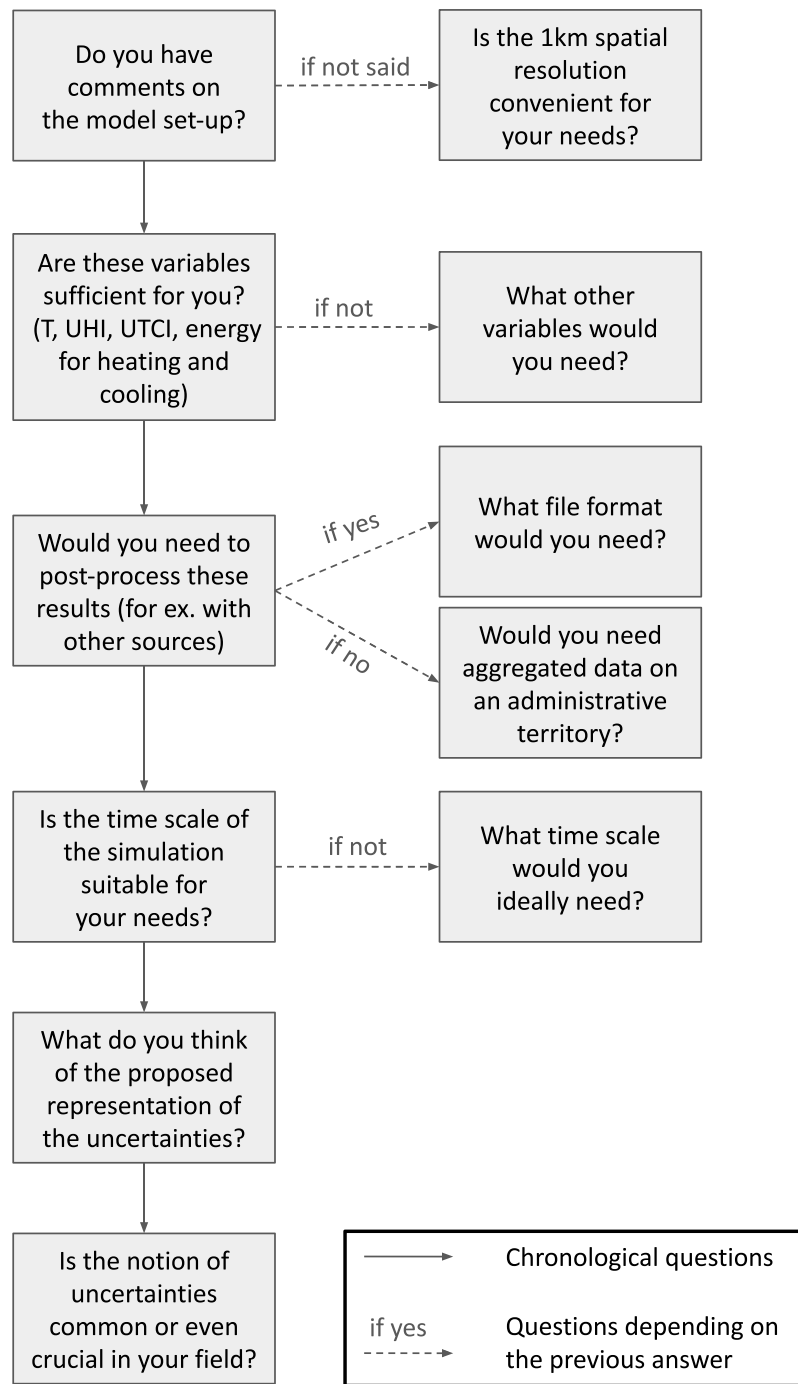


Fig. 11. Logical framework diagram of the interview grid, Part 2: Feedbacks about current results on future urban climate?.

et al., 2012), by separating the ground vegetation and the tree-foliage layer (Redon et al., 2017, 2020). TEB also includes a building energy module (BEM; Bueno et al. (2012)) that resolves internal balance of buildings in interaction with outdoor climate conditions.

Data and hypotheses for simulation

The simulation domain is a 157 km × 128 km rectangle covering the entire Île-de-France region with square meshes of 1 km sides. The descriptive characteristics of the study area that the land surface models need to run are derived from several databases. The land cover mapping of natural areas (crops, forests, grasslands, etc.) around the Paris

urban area, is provided by the ECOCLIMAP-I database (Champeaux et al., 2005), derived from the CORINE Land Cover European inventory (Bossard et al., 2000) (and dating from the 1990s. For urban areas, the more recent and accurate data produced during the MApUCE project are used. They improve among other things the representation of land use, urban morphology (Bocher et al., 2018), materials of buildings and their physical properties (Tornay et al., 2017), and building usage typologies (residential, tertiary, commercial and industrial). This data was combined with a more accurate description of urban vegetation, distinguishing between ground-based and tree-vegetation strata, provided by the region urban planning agency.

This description of the region and the urban area is prescribed as fixed data, i.e. it remains unchanged for the complete study time period.

Local climate conditions over the 21st century

To simulate the evolution of the urban climate with climate change, the surface modeling platform was fed by atmospheric conditions provided by regional climate projections, first adapted to local and urban scales. This so-called statistical-dynamical downscaling methodology is described in details by [Le Roy et al. \(2021, 2024\)](#). It corrects the regional atmospheric fields to incorporate the city's air temperature footprint on the local atmosphere, which is not explicitly taken into account by the regional climate models ([Daniel et al., 2019](#); [Langendijk et al., 2019](#))).

A set of 55 climate projections has been processed from the EURO-CORDEX database ([Jacob et al., 2014, 2020](#)), using different pairs of general circulation and regional climate models, allowing the spread of climate models to be considered. The data cover the domain of interest with a horizontal resolution of 1 km, and the time period 1970–2099 continuously. They include 14 projections with the moderate emission scenario RCP4.5 and 41 projections with the high emission scenario RCP8.5. Before running the urban climate simulations, the regional climate projections used to drive the urban climate model were bias adjusted. This correction was carried out for the air temperature, as some of the impact indicators calculated can be very sensitive to thresholds being crossed (e.g. the activation of heating or air conditioning in buildings). A conservative adjustment of the average monthly temperature was chosen in order to maintain the representation of local climatic conditions simulated by the regional climate models. (see [Le Roy et al. \(2024\)](#) for more details).

Impact indicators and main results

The use of the SURFEX platform including the TEB dedicated urban model makes it possible to compute meteorological variables and to derive more specific multi-sectoral indicators (summarized in [Table 1](#)) that are of interest for public stakeholders or decision makers. One of the main questions regarding the impact of climate change on the urban climate is related to the expected evolution of the UHI phenomenon. Prior studies have found conflicting results and are quite uncertain because of different methodologies ([Doblas-Reyes et al., 2021](#)). The use of SURFEX and TEB makes it possible to analyze this evolution by comparing the urban and rural temperatures throughout the century. [Le Roy et al. \(2020\)](#) have proposed two indicators of the UHI, one focusing on its intensity and the other one on its extent (i.e. the area of the city where the temperature is a certain number of degrees higher than in the rural area).

To be able to quantify the outdoor thermal comfort of inhabitants inside the city beyond simply using the air temperature, a simplified version of [Fiala et al. \(2012\)](#)'s Universal Thermal Comfort Index (UTCI) has been implemented in TEB ([Kwok et al., 2019](#); [Redon et al., 2020](#)). The UTCI model computes a perceived temperature based on the thermal exchanges between an individual and the outdoor atmospheric conditions. It relies on the individual's physical characteristics, its clothing, and level of activity, as well as the temperature, humidity, radiation and wind conditions in the street. The UTCI scale (in νC) is divided into 10 classes of thermal stress ([Bröde et al., 2012](#)) ranging from "Extreme Cold Stress" (UTCI < -40 νC) to "Extreme Heat Stress" (UTCI > +46 νC).

In TEB, the UTCI is computed at every dynamical step of the model for every urban grid point, which allows knowing how much time per hour was spent in each class. The results can then be aggregated in time: average number of hours per day spent in some stress class, or in space: average conditions per type of building or land cover ([Fig. 9](#)).

The last indicator that was studied is the energy consumption of buildings due to heating and cooling. It is simulated thanks to the BEM module. The amount of energy consumed depends on the air temperature outside the building as well as a setpoint temperature inside the building. Depending on the type of buildings and their usage, different setpoint temperatures and hours of occupancy are defined. Other behaviors are also taken into account, such as ventilation by opening the windows or the use of shading.

Data availability

Data will be made available on request.

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