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Co-construction of climate services based on a weather stations network: Application in Toulouse agglomeration local authority

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A R T I C L E I N F O

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A B S T R A C T

This article provides insights into the development of climate services in Toulouse, France, based on an automated weather station network for microclimatic applications, such as urban heat island monitoring. Climate services are often thought of as a unique and complete entity that can be built by providers/sellers for users/buyers using different methods and degrees of involvement and participation. In this paper, the the local authority and its technical departments, helped by the national meteorological agency and researchers, were in charge of both providing and using the climate services. Each component, from network deployment to data production and their operational application, was directed by the local authority. Providers, users, products, and solutions were built from the ground up and developed over the last 5 years using the methodology of action research. This article discusses the possibility of understanding climate services by decomposing them into smaller components organized according to the disciplines, abilities, and challenges of each component to easily identify which actors in the local authority administrative organization can most effectively address them. Each component of the climate services based on a weather station network is discussed. This paper also describes how the governance and organization of climate services are built using action research. Co-construction processes with multiple actors encompassing multi-component projects, such as climate services, mobilize multiple disciplinary fields and require project management and organization. This article shows how the different components of the climate services in Toulouse have been integrated into different urban departments taking into consideration their competencies and their associated disciplinary fields with the goal of providing reproducible methods than can be applied elsewhere. The results indicate the real interest of urban departments in climate services. Some departments assumed responsibility for entire parts of the climate services. Their involvement reveals the complexity of truly integrating climate services as a transdisciplinary department into a public structure, in this case, the local authority. Managing the involvement and participation of all the stakeholders of the climate services implies organizing them using a governing body, even if they belong to the same organization or structure.

Introduction

Decades of work already exist concerning the concept of climate services (Vaughan and Dessai, 2014; Changnon et al., 1980). Throughout this period, the meaning of climate services has evolved from a focus on improving access to climate sciences and data to a concept of integrated services, that is, informed users and climate science-driven applications (Vaughan and Dessai, 2014; Lourenço et al., 2016; Bessembinder et al., 2019). In this sense, climate services are meant to establish a connection between two distinct universes: scientists, who are usually the providers of these services, and society, i.e., the users (McNie, 2012).

Because some connection issues remain between service providers and users (Lúcio and Grasso, 2016; Buontempo et al., 2014), multiple methodological frameworks, structures, guidelines, and scientific papers have been produced to help correctly establish the link between

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providers and users. We can cite as a flagship the World Meteorological Organization (WMO) and the global framework for climate services (GFCS) (Hewitt et al., 2012). As one of the many guidelines available, we can evoke the one designed for cities that we use as a reference point in this paper: Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services (World Meteorological Organization, 2018). Institutional non-climate-related stakeholders are also involved, such as the European Commission through its H2020 Research and Innovation Program, which published in 2015 a European roadmap for climate services. With more and more papers on climate services addressing the topic of connection issues, research concerning the interface linking users and providers has expanded considerably over the last seven years (Lugen, 2020). To describe these relationship between users and providers, terms such as participation, co-construction, and collaboration are used (Vincent et al., 2018).

However, even in these studies, the users are often considered to be an "external factor" instead of being a part of the process of building climate services (Stegmaier et al., 2020). The fact that the users often do not have a sufficient level of climate knowledge (concerning for example what types of data, technologies, products, and stakeholders exist) separate them from the development of the services themselves. This can lead to a paradox with respect to the wish to have user-driven climate services and justifies a market approach to develop the range of actors involved in the development of climate services (Cavelier et al., 2017).

In 2016, the local authority of Toulouse in the south of France decided to build its own climate services, starting with an automatized weather station network to monitor the urban heat island (UHI) effect. The local authority, taking advantage of the physical proximity of climate specialists (from the national meteorological agency and the university), built a partnership that allowed work on the following scientific question: "How can climate services, in their entirety, be integrated in a user-driven methodology through co-construction processes into a structure—here a local authority—to produce climate-related data for its own specific needs?"

This paper, after briefly presenting the local context of the study, proposes a methodology in which climate services are decomposed into components embracing the interdisciplinary fields inherent to their nature (Section 2). This deconstruction of climate services allows a selection of different stakeholders of the local authority for collaborations, building the governance of the climate services. This methodology of governance construction is presented in Section 3 and is here applied to the specific case of a weather station network but is reproducible with any other type of climate service.

Local context

Because of their capacity to concentrate populations, networks, and activities, urban areas have an increased vulnerability in the face of climatic events, whether ordinary or not. Cities then develop and organize their interventions around so-called adaptation and mitigation strategies. This is about both limiting the risks and reducing greenhouse gas emissions. To better calibrate these responses, it is necessary to control, assess, and calculate climate risks and vulnerabilities (Cortekar et al., 2016; Baklanov et al., 2018). Local authorities, administrations, and stakeholders of the urban fabric then try to respond to legislative frameworks and to local, national, and international political ordinances.

In France, there is no legal obligation for a local authority to engage in any type of climate monitoring. The only obligation for a climate plan exists in laws related to the Grenelle de l'Environnement (the August 3, 2009, "Grenelle 1" law and the July 12, 2000, "Grenelle II" law). Climate plans are divided into two components focusing on mitigation and adaptation to climate change. Air quality and energy consumption management are also taken into consideration. Climate change mitigation concerns efforts to control greenhouse gas (GHG) emissions into the atmosphere. This first section of these documents includes particularly well-established regulation tools such as GHG assessments (compulsory for communities with more than 20,000 inhabitants), even though several calculation methods exist. The second part, which is still ill-defined, focuses on the notion of adaptation to climate change.

To provide the adaptation part of the climate plan with a strong tool, in the same way as the GHG assessment, the local authority of Toulouse, within its department in charge of the Climate Plan and supported by its elected representative, wanted to establish urban climate services. The needs expressed concerning these services related in particular to internally produced data adapted and used in conjunction with other documents (e.g., the master plan and building permits). The desired climate services first need to characterize and map areas of lower temperatures and urban overheating. Second, these services need to provide indicators to monitor the impacts of urbanization on the local climate. Finally, they need to thematically and locally complement the climatological profile regularly provided by the national meteorological agency (Météo-France).

Accordingly, the local authority and climate researchers from Météo-France and the University of Toulouse, both based in Toulouse, built a partnership. The aim was to introduce the expertise necessary to develop a weather station network producing near real-time data for the local authority and the entire data treatment chain. This means that all the components of the climate services should, ultimately, be implemented in the structure of the local authority.

Methodology: Decomposition of components to identify the necessary competences in the departments of the local authority

Climate services are often treated as a "black box," or as a single object; however, such services are complex and contain many interdisciplinary retroactive processes. Climate services based on weather stations, for example, imply knowledge necessary to choose measurement sites, choose telecommunications technologies, or to provide user-friendly data visualization. For a local authority, which works with a structure organized into departments related to competences, climate services need to be decomposed into multiple parts related to those competences. Then, each part can be redistributed to the different relevant departments of the local authority (Fig. 1). This constitutes the first part of the methodology described in this paper. We used the component organization for climate services provided by the WMO World Meteorological Organization (2018c), Grimmond et al. (2020) and separated the components related to each disciplinary field into stakes, norms, and standards. We use this methodology for our case study (an observation-based service) to demonstrate how it can be operationally applied.

Then, once every component (and associated required competence) of the service is identified, we work with the local authority departments to discuss how they will oversee each identified component. This leads to the governance, which will discussed in detail in the second part of the paper (Section 3), with the territory of the agglomeration of Toulouse, France, as an example. The departments are hierarchical and organized depending their participation levels and their involvement in their dedicated component . The paper general methodology is described in Fig. 1.

Decomposing theoretical climate services into several operational parts

Climate services are often associated with a clear frontier between users and providers, between buyers and sellers, between demand and supply, and between science, society, and policy (Harjanne, 2017). In the case of this paper, these frontiers are less distinct. The main user and main provider are the same entity, the Department of Environment and Energy of the Toulouse Metropole, in charge of the climate plan. Therefore, the following climate services were envisaged as a sum of components linked to specific competences instead of as an entire product.

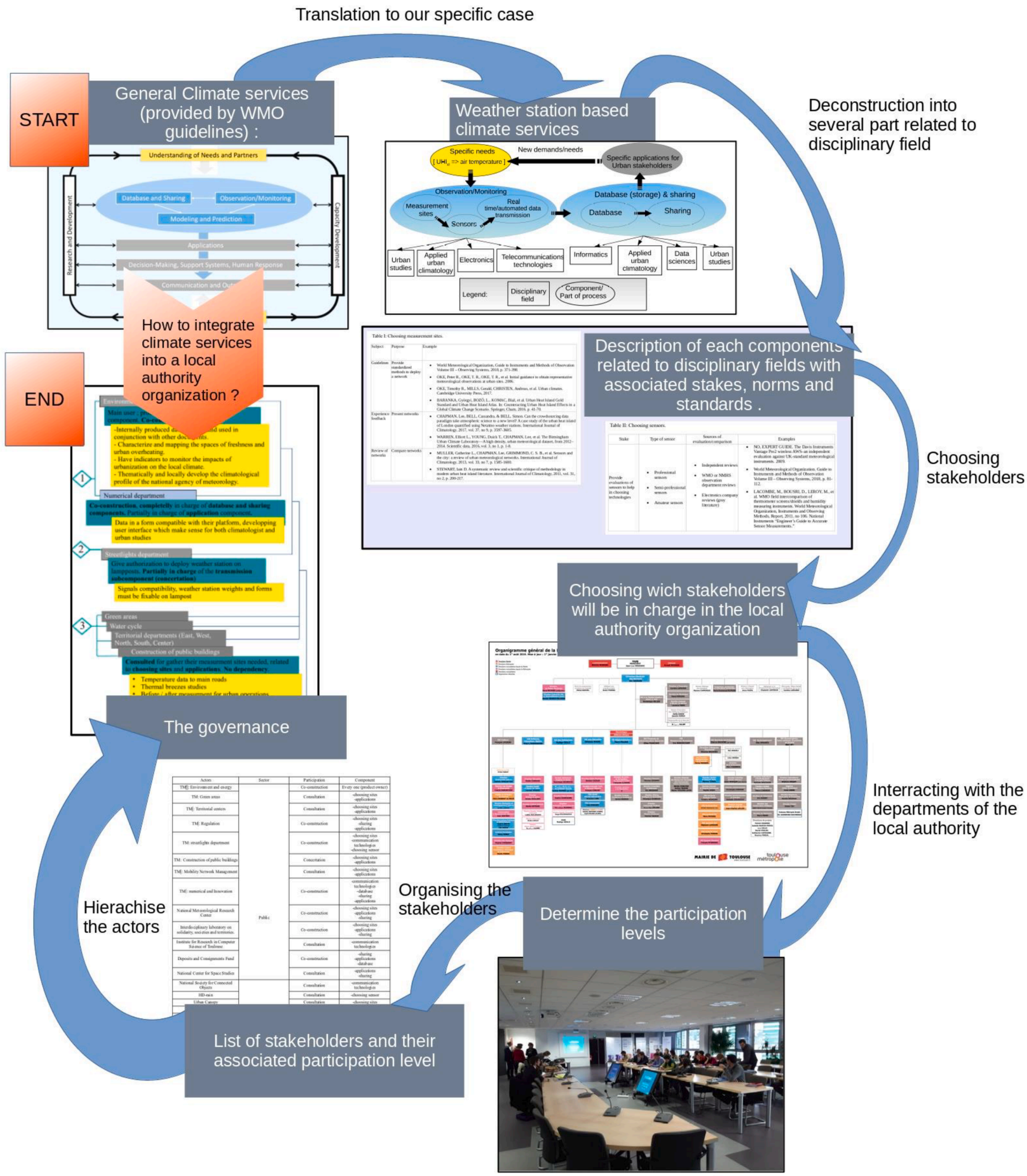

Fig. 1. Methodology to translate general climate services into multiple components to integrate them as hierarchical and organized climate services into the organization chart of a local authority.

Translating general urban climate service components into weather station-based urban climate service components

The first step was to decompose the climate service into a sum of multiple smaller components using the WMO structure for climate services. Once this step was complete, we translated the component to our specific case, that is, a climate service based on an observation network, to identify the competences that were needed to implement an operational climate service. Accordingly, we used state-of-the-art methods in each of the disciplinary fields involved in each component. On the form, it is linked to an organized state of the art, but with respect to the content, it is more a guideline to enable urban actors or other to approach each component according to their issues, objectives, and standards.

We started using the WMO integrated urban service (IUS) general components, which are organized via a retroactive process (Fig. 1). This dictates a relationship between the users (and their needs) and the providers.

Ten key points define the structure of an IUS, and these points are organized into four interdependent components.

- The first core component consists of data production with three subcomponents acting in interaction with each other:

  -Database and Sharing;
  -Observation/Monitoring; and
  -Modeling and Prediction.

- The next three components show the effective use of the data by the users:

  -Applications;
  -Decision Making, Support System, and Human Response; and
  -Communication and Outreach.

- The following two components are framing:

  -Research and Development; and
  -Capacity Development.

- The remaining components materialize the retroactive process, that is, the component "Evaluation, Assessment, and Impacts" returns to the starting component "Understanding of Needs and Partners."

As shown in Fig. 2, IUS development requires interactions between the users and the providers (sometimes called the "suppliers") as a co-construction process. This is shown by the bidirectional arrows in the structure. This follows recommendations to strengthen the link existing in climate services between scientists and non-scientists (Hewitt et al., 2012; Baklanov et al., 2018). This is a key point as many studies rank the collaboration aspect, including co-construction, as being the main criterion to successfully create and perpetuate an IUS (McNie, 2012; Christel et al., 2018; Grimmond et al., 2020). The goal is to avoid the usual process of production delivery from sciences to society commonly described as a "loading dock" or linear model (Cash et al., 2006; McNie, 2012).

Co-construction needs to be distinguished from collaboration. Co-construction is an interdependent relationship (Panet-raymond and Bourque, 1991) and here is understood to be a social process of the construction and sharing of long-term relationship goals (Lévesque, 2001). Co-construction is balanced by multiple points including legitimacy (between stakeholders involved), interests (financials, pedagogical, etc.), and mutualizing (Audoux and Gillet, 2011). It is strongly related to the IUS component "Understanding of Needs and Partners." Today a lot of literature is dedicated to the co-construction of climate services, from theoretical concepts to application cases, as shown later in Sections 2.2.5 and 2.2.6.

The multiplicity of partners in a co-construction process implies interdisciplinary and transdisciplinary work and some project management (Webber, 2019). In this paper, interdisciplinary refers to the integration of disciplines in terms of, for example, methods, models, and data, while transdisciplinary refers to cooperation across scientific and mostly non-scientific stakeholder communities.

For an IUS based on observations, every component must be discussed when co-construction begins. Because the observation component is the core component of this type of IUS, from which the production of data will result, this process could start with building the following three components:

- Observation/Monitoring, which can be divided into three subcomponents: choosing measurement sites, sensor types, and telecommunication types;
- Database and Sharing, which are already divided and refer to how the data are organized and available; and
- Applications, which embody the effective use of the data.

The transdisciplinary and interdisciplinary aspects of co-construction can be observed when each component is connected to several disciplinary fields. For example, the two components Observation/Monitoring and Database and Sharing are composed of six main distinct disciplinary fields. The organization of the co-construction process applied to these components, and their associated disciplinary fields, is shown in Fig. 3.

Figure 3 describes a retroactive process. Once the

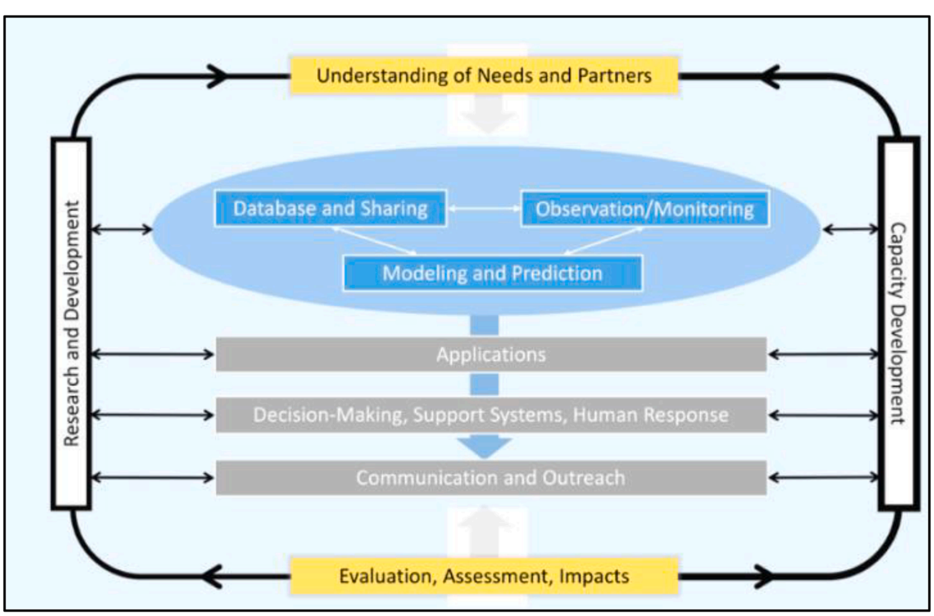

Fig. 2. Schematic of the components of an integrated urban service system (Grimmond et al., 2020).

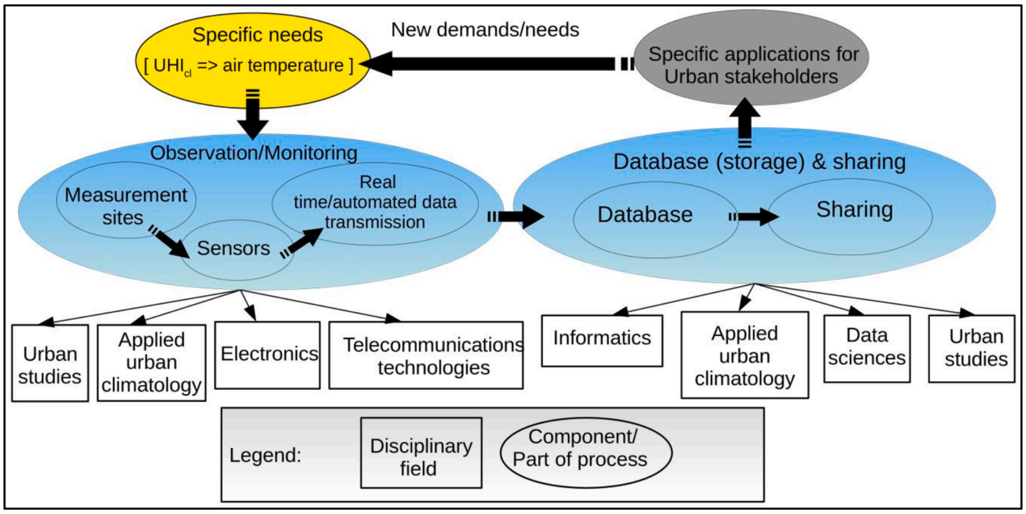

Fig. 3. Components and disciplinary fields of climate services built for UHI monitoring using a weather station network.

observational needs are determined, a succession of steps must be taken.

- The quantity and position of the measurement sites are discussed in the Observation/Monitoring component. The type of sensors and the technologies for transmitting the data are also determined. These three subcomponents are linked together. For example, for a given budget, it needs to be determined if the focus will be on the number of sensors or on their quality.
- In the Database and Sharing component, questions focus on how to store the data and how to make them available and understandable to specific users. Applications are based on the form of data delivery. The boundary between this component and the Observation/Monitoring component is permeable. For example, the frequency of sampling is determined in the "real-time/automated data transmission" subcomponent but will be limited by the storage capacity and its organization.
- Applications result in new demands or needs as users manipulate the applications and ask for improvements or novel functions. The providers can also propose technologies or new and improved observation systems. This component is not related to only one main disciplinary field specifically, we discuss it through the prism of the interdisciplinarity as it question multiple aspects of climate services.

To facilitate and conceptualize this co-construction process of an IUS based on weather stations, Tables 1–6 present several references that clearly express the different components of Fig. 3. These references include guidelines, experience feedback, reviews, and standards. Some references come from organizations such as the WMO for climatology. All of these references help build an IUS because they indicate the specificities that each user and provider need for each component.

Six components of urban climate services based on a weather station network

Choosing measurement sites

Choosing where to locate meteorological stations is an important step in mobilizing urban studies and applied urban climatology. The urban heat island (UHI) effect is a well-known phenomenon, particularly the canopy layer (UHIcl) type. The canopy layer corresponds to the external air that extends from the surface (e.g., a road, garden, or car park) to the building top. UHIcl is evaluated according to the difference between the temperature of the air in the city and the corresponding height in the near-surface layer in the countryside (Stewart, 2011a). This is the most important and commonly studied type of heat island (Stewart, 2011b) because it describes the characteristics of the air where people live.

To observe this microclimatological effect, stationary or mobile thermometers, preferably in radiation shields, are used. In a stationary approach, each probe is usually placed at representative sites in urban and rural local climate zones (Stewart and Oke, 2009; 2012). A sensor can also be mounted on a vehicle, which would constitute a mobile approach to studying small-scale spatial variations in the temperature.

Moreover, a weather station network can be deployed in various forms or shapes (Robinson, 2010; Muller et al., 2013), as described below.

- A systematic network has a point for every square of a grid. Such a network could be interesting for a city with large identical urban areas but is not relevant if there is high variability in the urban forms.
- A radial-type network corresponds to a star shape with samples along transects of each branch of the star. Such a network is useful to determine the temperature gradient of a city starting from the downtown area and extending to peripherical areas.
- A random network, or a semi-random network with random samples, can occur when amateur weather stations are used because there is no one authority in charge of the overall placement of the network. This type of network can also occur when the sites are imposed. Some considerations are less constraining, such as using only traffic light poles. Everything depends on the density of the potential authorized sites and the number of sites that can be equipped. For example, if there are 10 stations and there are only 10 schools, the network is fully random (from a meteorological point of view), while if there are 5 stations for 10 schools, then the network is semi-random. The boundary between semi-random-type and gradient/transect-type networks can be very blurred.
- In political networks, administrative boundaries impact the sample positions.
- Gradient/transect-type networks have gradient samples at different densities or along lines. Such networks can look random; however, every location corresponds to a specific choice. The transect method can represent the thermal amplitude between a city center and its surroundings following different axes and thematics (Fast et al.,

Table 1
Choosing measurement sites.

Subject	Purpose	Example
Guidelines	Provide standardized methods to deploy a network	• World Meteorological Organization (2018a). World Meteorological Organization, Guide to Instruments and Methods of Observation Volume III – Observing Systems, 2018, p.371–398 • Oke et al., 2006. Oke, T.R., et al. Initial guidance to obtain representative meteorological observations at urban sites. 2006 • Oke et al. (2017). Oke, T.R., Mills, G., Christen, A., et al. Urban climates. Cambridge University Press, 2017 • Baranka et al. (2016). Baranka, G., BOZÓ, L., KOMAC, B., et al. Urban Heat Island Gold Standard and Urban Heat Island Atlas. In : Counteracting Urban Heat Island Effects in a Global Climate Change Scenario. Springer,Cham,2016. p.41–7070.
Experience feedback	Present networks	• Chapman, L., Bell, C., & Bell, S. (2017). Can the crowdsourcing data paradigm take atmospheric science to a new level? A case study of the urban heat island of London quantified using Netatmo weather stations. *International Journal of Climatology*, *37*(9), 3597–3605. • Warren et al. (2016). Warren, E.L., Young, D.t., Chapman, L., et al. The Birmingham Urban Climate Laboratory—A high density, urban meteorological dataset, from 2012 to 2014. Scientific data, 2016, vol. 3, no 1, p. 1–8.
Review of networks	Compare networks	• Muller et al. (2013a). Muller, C.L., Chapman, L., Grimmond, C.S.B., et al. Sensors and the city: a review of urban meteorological networks. International Journal of Climatology, 2013, vol. 33, no 7, p. 1585–1600. • Stewart, I.D., A systematic review and scientific critique of methodology in modern urban heat island literature. International Journal of Climatology, 2011, vol. 31, no 2, p. 200–217.

2005). Such a network can follow a river or follow a succession of increasingly dense industrial or residential areas.

In any case, well-chosen measurement sites will determine the sample quality of the network in terms of the representativity of their immediate environment.

Table 1 shows different types of bibliographic references concerning these subjects. The standards are described as guidelines. These documents explain how to interpret urban areas from a climatological point of view using a systemic approach. The WMO is one of the main providers of this type of document.

Experience feedback allows a network to be evaluated, to compare its characteristics with standards via a point of view anchored in its environment (e.g., geography or policy) with the relevant specificities (e.g., economics or density).

The third type of reference consists of reviews, which allow networks to be compared to each other. A user can then quickly see the varieties and complexities of networks and look for a network corresponding to stakes relevant to that user.

Table 2
Choosing sensors.

Stake	Type of sensor	Sources of evaluation/ comparison	Examples
Provide evaluations of sensors to help in choosing technologies	• Professional sensors • Semi-professional sensors • Amateur sensors	• Independent reviews • WMO or NMHS observation department reviews • Electronics company reviews (grey literature)	• No, expert guide, 2009. No, expert guide. The Davis Instruments Vantage Pro2 wireless AWS–an independent evaluation against UK-standard meteorological instruments. 2009 • World Meteorological Organization (2018b). World Meteorological Organization, Guide to Instruments and Methods of Observation Volume III – Observing Systems, 2018, p.81–112 • Lacombe et al. (2011). Lacombe, M., Bousri, d., Leroy, m., et al. WMO field intercomparison of thermometer screens/shields and humidity measuring instruments. World Meteorological Organization, Instruments and Observing Methods, Report, 2011, no 106 • National Instruments, 2009. National Instruments "Engineer's Guide to Accurate Sensor Measurements." (white paper)

Urban studies are not presented here directly. However, they play a role in obtaining other readings in a territory. The type of population, future real estate operations, and urban renewal are some examples of points for urban stakeholders to consider when choosing measurement sites appropriate to the evolution of the urban area studied.

Choosing sensors

The choice of sensor depends on the physical variables observed; this is relevant to the disciplinary field of electronics. Most weather station networks used for UHIcl studies are only able to measure the temperature or the temperature and moisture data. In France, the city of Dijon has installed more than 50 temperature and moisture probes since 2014 as a part of the MUSTARDijon research project (Richard et al., 2018; 2019; De lapparent et al.). Few of these probes include a complete range of sensors including rain, temperature, moisture, pressure, wind speed and direction, and solar radiation. In France, excepting the present study, only the University of Rennes possesses a complete network of approximately 30 weather stations at the intra-urban scale (Foissard, 2015).

Measuring more than just the temperature allows a network to be used for deeper analyses of the relationships between the UHI and other meteorological effects and enables other applications in addition to UHIcl studies (Chapman et al., 2015). The quality of the sensors

Table 3
Choosing telecommunications technologies.

Subject	Purpose	Example
The Internet of Things (IoT) or cyberstructure (including smart cities)	Analyze and compare the characteristics of IoT objects	• Minerva et al. (2015). Minerva, R., Biru, A., et Rotondi, D. Towards a definition of the Internet of Things (IoT). IEEE Internet Initiative, 2015, vol. 1, no 1, p. 1–86 • European Telecommunications Standards Institute works (BESEN, Stanley M. The European telecommunications standards institute: A preliminary analysis. Telecommunications policy, 1990, vol. 14, no 6, p. 521–530.)
Standards and communications systems	Compare technologies and standards	• Morin (2018). Morin, E.. Interopérabilité de protocole de communication adaptatifs basse-consommation pour des réseaux de capteurs. 2018. Thèse de doctorat. // Morin Elodie, Interoperability of communication protocole for low consumption sensors networks. IoT Standards landscape and future evolutions (European Telecommunications Standards Institute 2016, technical report) • Liu et al.. Liu, J., Zhang, B., et Lv, B.. An intelligent framework of Automatic Weather Station • Murty et al. (2008). Murty, R. N., Mainland, G., Rose, I., et al. Citysense: An urban-scale wireless sensor network and testbed. In : 2008 IEEE conference on technologies for homeland security. IEEE, 2008. p. 583–588

Table 4
Organizing databases.

Type	Purpose	Examples
Database standards and guidelines (**methods**)	Help in homogenizing and organizing data and associated metadata	• The SMM-CD Working Group, 2019: The guidance booklet on the WMO-Wide Stewardship Maturity Matrix for Climate Data. Document ID:WMO-SMM-CD-0002.Version: v03r00 20190131. • Guidance for creating WMO Core Profile Metadata in version 1.3, 2015. • Secretariat (2001). Secretariat, W. M. O. I-Purpose and Scope of WIGOS Metadata. • Guide to the WMO Information System, 2017. • Muller et al. (2013b). Muller, C.L., Chapman, l., Grimmond, c.s.b., et al. Toward a standardized metadata protocol for urban meteorological networks. Bulletin of the American Meteorological Society, 2013, vol. 94, no 8, p. 1161–1185.
Database software comparisons (**tools**)	Help in choosing the best software suites to process data and metadata	• Li and Manoharan (2013). Li, Y., et Manoharan, S. A performance comparison of SQL and NoSQL databases. In : 2013 IEEE Pacific Rim Conference on Communications, Computers and Signal Processing (PACRIM). IEEE, 2013. p. 15–19 • Jatana et al. (2012). Jatana, N., Puri, S., Ahuja, M., Kathuria, I., & Gosain, D. (2012). A survey and comparison of relational and non-relational database. *International Journal of Engineering Research & Technology*, *1*(6), 1–5.

themselves vary from amateur to professional. For example, participative science and crowdsourcing data sometimes use amateur weather stations such as Netatmo (Napoly et al., 2018). The quality of such data can fluctuate and demand a less dense and more accurate network for validation (Meier et al., 2017), but the amount of data is often sufficient (Chapman et al., 2017).

Each sensor has its own technical characteristics. There are many criteria to take into consideration, including the accuracy and lifetime of a sensor. Moreover, it must be determined if the technical solution will be made using a subcontractor or a pre-existing ready-to-use product. The costs can vary drastically, and partners must communicate to adjust the products to their specific needs. The cited references can be used to compare and analyze different technical solutions with respect to their qualities and limitations (Table 2).

Choosing telecommunications technologies

A weather station network is related to telecommunications technologies via two aspects.

- The first aspect is its characteristics as an Internet of Things (IoT) structured object. Telecommunications technologies mobilize new concepts and categorize different components of a network. This aspect involves certain questions. Are the terminals of the network able to receive information? Are the gateways able to communicate with each other?
- The second aspect concerns the telecommunications system used to transmit the data. This is strongly related to the electronics and informatics. Data transmission can be performed using a manual or an automatic routine. Depending on the definition of the network used, a manual transmission type is usually referred to as a "collection sensor." This means that, until someone comes to collect the data, the data are stored using a datalogger. This is the method used by the MUSTARDijon project and the HiSAN network in Taiwan (Chen et al., 2018). Some networks, conversely, can provide real-time data with automatic weather stations, such as the network in Szeged, Hungary (Skarbit et al., 2017) . Additional questions include if the network is wireless, if it has a long range, and if it has sufficient energy if connected to a solar panel.

For both aspects, standards, including ISO, exist and must be respected. These standards may change from one country to another. For example, Europe is regulated by the European Telecommunications Standards Institute.

Organizing databases

Organizing a database requires focusing on both the methods and the tools and is related to informatics.

Table 5
Delivering data.

Type	Purpose	Example
Delivery feedback	Feedback on the development and evaluation of the delivered tools	• Christel, I., Hemment, D., Bojovic, D., et al. Introducing design in the development of effective climate services. Climate Services, 2018, vol. 9, p. 111–121. • Ren et al. (2011). Ren, C., Ng, E.Y., et Katzschner, L. Urban climatic map studies: a review. International journal of climatology, 2011, vol. 31, no 15, p. 2213–2233 • Soreide, N.N., Sun, C.L., Kilonsky, B.J., et al. A climate data portal. In : MTS/IEEE Oceans 2001. An Ocean Odyssey. Conference Proceedings (IEEE Cat. No. 01CH37295). IEEE, 2001. p. 2315–2317 • Taylor et al. (2015). Taylor, A.L., Dessai, S., et De Druin, W.B. Communicating uncertainty in seasonal and interannual climate forecasts in Europe. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 2015, vol. 373, no 2055, p. 20,140,454 • Deandreis et al. (2013). Deandreis, C., Lemond, j., Dandin, p., et al. Recent progress towards climate services in France. Pollution Atmospherique, 2013, p. 120–128 • Dandin. Dandin, P., Corre, l., et l'hôte, d.. Drias, une stratégie de service pour l'adaptation. Villes et climat, p. 15 • Jourdain et al. (2015). Jourdain, S., Roucaute, e., Dandin, p., et al. Le sauvetage de données climatologiques anciennes à Météo-France: De la conservation des documents à la mise à disposition des données. La Météorologie, 2015

- The methods concern how the data content are organized with respect to their type. Satellite data and observational data require specific metadata and can require some amount of storage management. For example, guidelines and standards provided by the WMO enable data to be homogenized and shared in a common format used in climate sciences.
- The tools depend on the software architecture of the desired data platform, and there are several studies that provide comparisons of various technologies. Criteria that should be examined include the virtual space storage efficiency, Internet portal utilization or speed of information transmission, and access.

Delivering data

The delivery of data consists of both aesthetics and substance. Where climate data are concerned, some aspects of the results need to be refined. The reliability, accuracy, political sensitivity, and limits of the data are all criteria that need to be taken into consideration. Experience feedback is a way to address these issues. However, there is a lack of comparative reviews concerning the delivery of climate data in climate services.

An interesting point here is the appearance of the "design" disciplinary field. The delivery of climate services to users is often associated with a visualization interface, and there are studies available concerning this specific aspect. This aspect can also serve as a point for exchange and co-construction and can refer to design study methodologies (Sedlmair et al., 2012). Data visualization in climate services is still a field of active research. This may be due to the relative novelty of the exercise. One point to remember is that the variation range of the data visualization and the data delivery characteristics correspond to the variation range of the users. In other words, the more the user's needs and applications vary, the more the data will be shaped in different forms.

Table 6
Climate services transdisciplinarity.

Type	Purpose	Example
Guidelines	Provide guidelines for development (e.g., co-construction and components)	• . Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services, 2019 WMO Guideline series. • Daniels et al., 2019. Daniels, E., bharwani, S., Butterfield, R.. The Tandem framework: a holistic approach to co-designing climate services. Sei Discussion Brief. Stockholm Environment Institute, 2019
Climate services as science services	Provide the conceptualization, goals, and stakes of climate services	• McNie, E. C. (2012). Delivering climate services: Organizational strategies and approaches for producing useful climate-science information. *Weather, Climate, and Society*, *5*(1), 14–26. • Brasseur and Gallardo (2016). Brasseur, G. P., Gallardo, L. (2016). Climate services: Lessons learned and future prospects. *Earth's Future*, *4*(3), 79–89. • Bessembinder, J., Terrado, M., Hewitt, C., Garrett, N., Kotova, L., Buonocore, M., Groenland, R. (2019). Need for a common typology of climate services. *Climate Services*, *16*, 100135.
Experience feedback	Present integrated climate services via different aspects	• Chapman, L., Muller, C.L., Young, D.T., et al. The Birmingham urban climate laboratory: an open meteorological test bed and challenges of the smart city. Bulletin of the American Meteorological Society, 2015, vol. 96, no 9, p. 1545–1560. • Christel, I., Hemment, D., Bojovic, D., et al. Introducing design in the development of effective climate services. Climate Services, 2018, vol. 9, p. 111–121. • Kotova et al., 2017. Kotova, L., Terrado, M., Krzic, A., Djurdjevic, V., Garrett, N., Stratchan, J., Bessembinder, J. Lessons and practice of co-developing climate services with users, European climate observations, monitoring and services initiative, 2017 • McNie, E. C. (2012). Delivering climate services: Organizational strategies and approaches for producing useful climate-science information. *Weather, Climate, and Society*, *5*(1), 14–26.

Climate services transdisciplinarity

Last, but not least, climate services are transdisciplinary projects,

Table 7
Public and private actors in Toulouse's observation-based urban climate service and their associated participation levels. TM refers to Toulouse Metropolis technical departments.

Actors	Sector	Participation	Component
TM: Environment and Energy	Public	Co-construction	All components (product owner)
TM: Green Areas	Public	Consultation	-choosing sites -applications
TM: Territorial Centers	Public	Consultation	-choosing sites -applications
TM: Regulation	Public	Co-construction	-choosing sites -sharing -applications
TM: Streetlights Department	Public	Co-construction	-choosing sites -communication technologies -choosing sensors
TM: Construction of Public Buildings	Public	Coordination	-choosing sites -applications
TM: Mobility Network Management	Public	Consultation	-choosing sites -applications
TM: Numerical and Innovation	Public	Co-construction	-communication technologies -database -sharing -applications
National Meteorological Research Center	Public	Co-construction	-choosing sites -applications -sharing
Interdisciplinary Laboratory on Solidarity, Societies, and Territories	Public	Co-construction	-choosing sites -applications -sharing
Institute for Research in Computer Science of Toulouse	Public	Consultation	-communication technologies
Deposits and Consignments Fund	Public	Co-construction	-sharing -applications -database
National Center for Space Studies	Public	Consultation	-applications -sharing
National Society for Connected Objects	Private	Consultation	-communication technologies
HD-rain	Private	Consultation	-choosing sensors
Urban Canopy	Private	Consultation	-choosing sites
Volx	Private	Co-construction	-choosing sensors
WaltR	Private	Consultation	-choosing sensors

including multiple actors involved with climate science production and delivery. As expected for an emerging field, many recent references are available to conceptualize and assess the goals and stakes of projects through this transdisciplinarity prism; however, there is less experience feedback concerning their application.

Guidelines exist to develop these services, including co-construction methods. Experience feedback can give examples of climate services applied to specific territories via multiple aspects (e.g., observations, delivery, and data transmission).

In addition, researchers have studied the development of climate services as general science services (Harjanne, 2017), questioning their forms, stakes, utilities, languages (Vaughan, 2014; Lugen, 2020) and applications.

Co-construction applied to urban departments in Toulouse

Here, we present an application of this conceptual framework to the co-construction of an IUS based on observations in the Toulouse metropolitan area. Indeed, this section presents the expressed needs of the urban departments, their participation levels, and the final climate services governance. The governance (Fig. 4) and participation levels (Table 7) illustrate how the urban departments are connected to each component of the network and how they interact.

We first explain the organization of the local authority and the three participation levels we used to describe the form of interaction with the urban departments. Once the list of stakeholders is presented (including external partners as private companies), we structure the climate services using a governance chart where only the urban departments appear because they are the owners of the climate services.

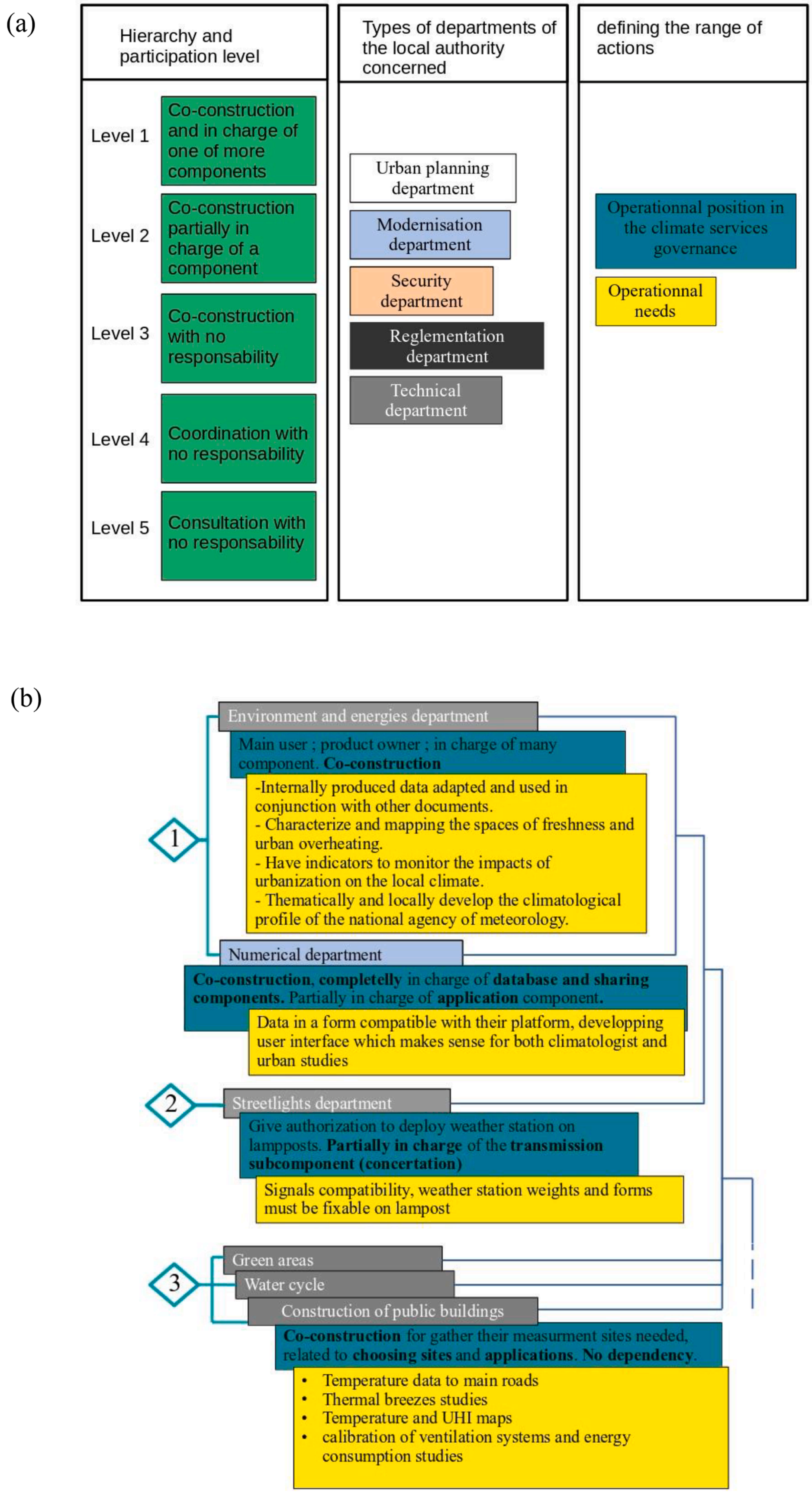

Fig. 4. (a) Governance based on the hierarchy and participation level of the departments. The department type and name and the range of actions in the climate services is indicated. (b) Levels 1–3 of the governance using co-construction. (c) Levels 4 and 5 of the governance using coordination or consultation as defined in the text.

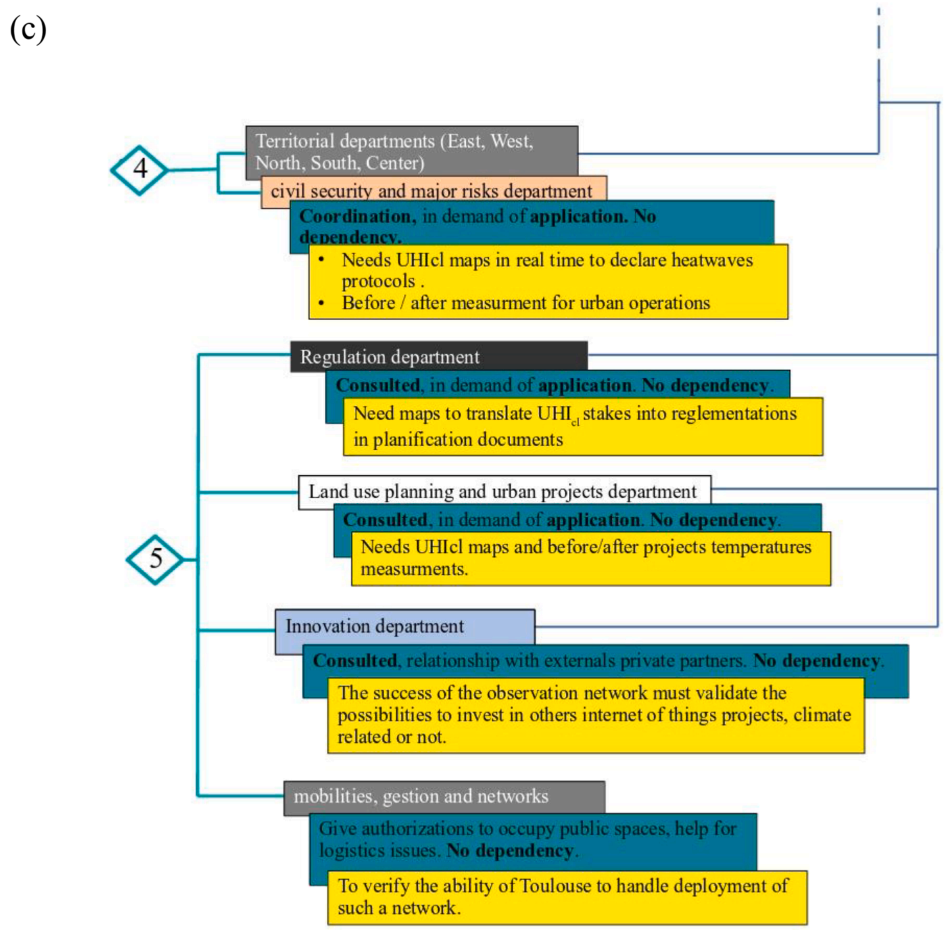

Fig. 4. (*continued*).

Organization of the metropolis

This project involved various partners at different levels of involvement and participation, including urban departments from the Toulouse Metropole and public organizations, such as NMHS (Météo-France and its national climate research center), universities[1], and private companies (mostly equipment suppliers). Public organizations provided economic support, and some organizations were interested in developing softwares solutions around the data produced, such as the Deposits and Consignments Fund. Several private companies showed similar interests (e.g., Capgemini). Because the data were intended to be freely accessible on an open data platform[2], external software developers were not directly related to the climate service. The NMHS and the universities bring expertise and knowledge to the co-construction process, while the urban departments are the main actors and stakeholders. Indeed, because they own the observation network, the urban departments play multiple roles, including as product owners, users, and data producers.

The Toulouse local authority is divided into departments, themselves subdivided into smaller sub-departments. For example, there is the Environment and Energy Department (EED), which manages climate plan, air quality, and sound quality teams. There are also specific teams in charge of rivers and hydrological structures. In France, there is no legislation to concretely organize a metropolitan area, just a list of possessed competences that are described within the law[3] (Le Bras et al., 2016; Chabrot, 2013). Each department can be organized by the mayor of the city and its board as they see fit. The challenge therefore is to identify where the competences are in each department with respect to the components of the IUS.

Participation levels

The participation levels of the urban departments are not homogeneous. Some are only consulted, others are coordinated with, and still others participate in the co-construction. These terms reflect the different levels of participation. Here, we develop the terms we used to define three levels of participation: consultation, coordination, and co-construction.

- Consultation (first level)

In consultation, a need is expressed without continuous exchanges,

[1] -Toulouse University II: Jean Jaurès (Social and Human Sciences) and its Interdisciplinary Laboratory on Solidarity, Societies and Territories (LISST)-Toulouse University III: Paul Sabatier (Medical, Engineering, and Technological Sciences) and its Institute for Research in Computer Science of Toulouse (IRIT)

[2] https://data.toulouse-metropole.fr/pages/accueilv3/, we recommand to use « station » as keyword to find the data.

[3] LAW n° 2014–58, January 27, 2014: "Modernization of territorial public action and affirmation of metropolises"

only when the work is finished are the results presented. Take, for example, the departments consulted concerning the choice of site locations for measurements. These departments have specific needs that correspond to an envisioned application and to particular locations. For example, actors in Green Areas want to observe data from parks, in particular during the summer, to compare temperatures in different parks. Meanwhile, actors in Territorial Centers prefer to place sensors in urban projects, renovations, or new neighborhoods to monitor temperature changes. Their needs are considered but, because there is no feedback to them concerning the validation of the locations, their role is limited to consultation.

- Coordination (second level)

At the second level, there is coordination. Here, needs are expressed and the results are shown, followed by the collection of opinions, however, without any obligation to take these opinions into account. In this category, we see departments that are involved for the selection of sensors for specific applications. Requested locations can considered and evaluated on a case-by-case basis for validation with the departments. For example, the department concerned with construction and new buildings may request sensors located on school grounds to compare outdoor temperature data to indoor data from their sensor network. Coordination is a intermediary level of participation, were the relationships are discontinuous but the exchanges and the implications from the contacted departments are consequents.

- Co-construction (third level)

The final level is co-construction. Here, needs are expressed and exchanges are continual until a solution is found. This concerns several components. The suggestions of the involved urban departments significantly impact the structure of the IUS. They may change the size of the network, its objectives, or any other specifications. For example, the Streetlights Department could invalidate the entire network if its needs are not met. The network must comply with European directives regarding wireless emissions; however, the weight of the stations and their mounting brackets cannot jeopardize the stability or integrity of the streetlight poles.

Work organization

For all levels of participation, the necessary exchanges cannot be completed in a single meeting with all the urban departments in the same room. Indeed, these departments do not have the same needs. Consequently, meetings need to be spread out over several months with the relevant people in each department to build an interface where feedback is appreciated and solicited. Note that each urban department may mobilize a particular disciplinary field; therefore, the language of the meetings needs to be adapted to each discussion. The project may therefore be constantly renegotiated, especially if its content and contours are co-constructed in a dynamic process. In meetings, there was an attempt to emphasize the multi-faceted co-construction prism developed by Bremer and Meisch(2017); Bremer et al. (2019) because discussions covered multiple topics. In addition, we benefitted from being an agent of the local authority. This facilitated our connections and links with the urban departments.

As an example of co-construction, one focus of the Numerical Department of the Toulouse metropolitan area was to integrate any data into their open data application and their future “Artificial Intelligence Data” internal application. The weather station network provides a proof of concept for their platform, which is presently under construction, and they integrated the storage of the data components into their Geographic Information System platform architecture. Discussions with the Numerical Department cover topics such as software, data organization according to their point of view, and their capacity. It is important to communicate in appropriate terms when specific points arise with specific departments. During work with the Numerical Department, design and graphics questions were also evoked, which is an aspect that has already been studied in the scientific literature of climate services (Christel et al., 2018).

The results of the co-construction process, and in general any participation level, reveal the real expectations of the contacted departments in addition to their aspirations. The number of partnerships and urban projects related to the observation network has grown as the study has progressed. This has not really modified the technical solution itself; however, it has changed the extent of the applications of the network as a tool for many departments. The main consequence has been an increase in the number of weather stations in the network. To illustrate this size modification, two projects linked to the network are presented below.

- The first is an urban planning project led by the Garonne River and Canals Department, which is a sub-department of the EED in charge of the Garonne River, the Canal du Midi, and the Canal de Brienne, the three of which run through the city. This department wants to measure the impact of future renovations along both sides of the Canal du Midi. They plan to remove a large amount of vehicular traffic, create larger green spaces, and plant thousands of trees. Currently, the project is in the design phase and there will be a five-year construction period from 2021 to 2025. Therefore, 10 stations have been bought and specifically designed to observe this operation.
- The second is both an urban planning project and a scientific project: the transformation of an island in the center of Toulouse into a park. Currently, this island is home to a huge parking structure and an exhibition center. This is a location that includes a large amount of impermeable surfaces and few trees that will be transformed into an urban park. Approximately 10 stations are related to this project, which is called the “Project LIFE île du Ramier” or the “LIFE project Ramier Island.” The goal is to conduct microclimatic simulations with high-resolution models in combination with additional meteorological stations to assess the impact of future changes on the region.

Altogether, the project involves 11 departments (Table 7). Some departments (as future users) are directly concerned by the choices of the measurement sites and expect results from the “sharing” component for specific applications, while other departments participate in meetings but are still waiting for results to prove the utility of climate services as applied to their technical fields. The “data transmission,” “data storage,” and “sharing” components are strongly connected to the Numerical Department (as climate service user interface developers). The “data transmission” component is also related to the Streetlights Department to ensure compatibility with their networks and to validate each pole.

In parallel, three departments are waiting on the results from other departments either to evaluate the climate services or to start developing their own services.

- The Innovation Department is in charge of overseeing all “smart-city” projects (they are a sub-department of “Modernization” in the Numerical Department).
- The Regulation Department is in charge of all urban areas built by public authorities and the writing of urban planning documents.
- The Civil Security and Major Risk Department is awaiting protocols from the EED to efficiently manage heatwaves.

Table 7 shows all the partners involved in the climate services and their associated participation levels.

Governance of the urban climate service

Co-construction involves multiple urban departments; however, they are not hierarchically organized in the metropolis. A hierarchy needs to be created to direct the IUS and its components. In addition, even if some departments may only be integrated into the consultation or coordination of specific components of the network, their role can still be crucial and highly hierarchical.

Figure 4 shows the governance of the climate services. To construct this governance, we used two criteria: the participation level and the dependency of a component on a department. The dependency can be:

- Complete, which means that, if the department stops its work on the IUS, the component also stops;

- Partial, which means that the department is not fully in charge of a component, if it stops, the component can still work; and

- Null, which means that the department, even if it is involved in a component with any level of participation, has no impact on that component if it leaves the climate services.

The hierarchy was constructed by prioritizing the dependency criterion over the participation. For example, a department partially in charge of a component and involved in coordination processes will rank higher than a department with a null dependency but with co-construction involvement. Therefore, the governance chart contains five levels in our case (Fig. 4a). Each level is associated with the name of the department involved, its operational needs, and the climate service component with which it is interacting.

The first level is for co-construction and total dependency. The second is for coordination and partial dependency (Fig. 4b). Levels 3, 4, and 5 are for co-construction, coordination, and consultation, respectively, with no dependency (Fig. 4c).

Conclusions

This paper described work done on the expansion of climate services for the Toulouse local authority in partnership with Météo-France and local universities. Its main objective was to show how the different components of climate services can be integrated into urban departments using the co-construction process. In this case, it was the development of an automated weather station network in real time for microclimatological studies.

From our point of view, as well as that of the metropolis, co-construction is a long-term process, here relating to a long-term project including multiple stakeholders over multiple years. This work was developed in the framework of a three-year PhD project. In the two previous years, the local authority also funded a masters-level internship and a student group to conduct a feasibility study and to find technical solutions. Currently, the local authority provides funds for a full-time position in the Climate Research Center to finalize the implementation of the climate services. At the same time, they have started an audit to evaluate the possibility of building a specific IoT team and, in two years, recruiting individuals for one or two full-time positions to internally produce climate information, achieving an internalization of the climate services competence. This demonstrates how the integration of climate services via an automated station network into the administration of a local authority and its urban departments is an exercise mobilizing multiple disciplinary fields.

This experience demonstrated that co-construction can be divided into the following three steps.

- First, there is the “birth” of the project, where the aims, goals, possibilities, and capacities of each stakeholder need to be defined for each partner even if they are clear to the stakeholders themselves. This step involves the carriers of the project.
- Second, there is the “growth” or development of the project, where more partners are integrated into the process, the specificities become more detailed, and the terms of providing and using the services are conceptualized. In this step, the disciplinary fields enable the clear separation of what is relevant with respect to good practice, standards, or needs, as well as the involvement of specific urban departments with respect to their technical domains.
- Third, there is the “maturity” of the project where the deliverables are realized. The project can stop at this step or can continue into a retroactive structure where feedback evaluations are made and the process of growth continues.

For each step, two parts emerged.

- The first is an acculturation part, where each partner comes with their own specificities, such as their own language, needs, and goals.
- A second part follows where both sides, the providers and the users, are connected. Their languages are common, and their separate capabilities are merged into one.

For example, in this project, there was an important **acculturation** step to explain to the urban departments the differences between remote sensing and air temperature in ground level UHI studies during the **birth** step of the project. Indeed, the air-temperature measurement method needed to be justified because of its large cost compared to remote sensors, which do not observe the same variable. This acculturation needed to occur because many other cities simply use surface UHI studies, and the urban departments were already familiar with these technologies. Moreover, in the same local authority, some urban departments were already using surface UHI studies with the belief that they were using air-temperature data. This resulted in misled decisions and communication issues. This point also informed the climate scientists of a gap in the communication associated with their research. After acculturation was complete, the **connection** step occurred. This was the moment when the urban departments in the **growth** step of the project directly asked for new measurement sites, specifying if they served thematic or transect studies, the important variables to observe, and even sometimes proposals for lampposts and local representatives to deploy the materiel. Acculturation also occurred in the other direction, from the users to the providers. For example, in the **maturity** step of the project, the Numerical Department explained how their internal data architecture worked and what was possible under what conditions.

Today, the main interest is to continue to capitalize on this work and on the network capacities and to prove its ability to last and to be pertinent to urban planning, which means strengthening the links between the urban departments. The work around the creation of the network has already brought urban departments together to a surprisingly level, proving its value with just this aspect, prior to obtaining any results. This validates the co-construction process, showing that meetings can have a greater value than their goals. The metropolis has financed a three-year position to continue work on the network from both research and operational points of view.

At this point of the IUS structure, the co-construction process can be considered a success. A strong choice was made by the local authority to internalize the service instead of buying a service solution from a private company or the NMHS. This point strongly diverged from a market approach for climate services. In addition, this particular point made this IUS a complete integrated climate service as a new competence for the local authority, where the role of the NMHS is only to provide knowledge and act as a scientific organism to validate a desired tool. This is a win–win relationship. In effect, urban department studies will be supported by science in exchange for access to data from a complete network built at scientific gold standards but maintained by urban departments with more significant technical support.

Our work was designed as a reproducible approach for any other city or structure that wants to develop its own climate services and does not know where to start or the scale of the task. We strongly hope to see other cities become empowered, becoming climate service and knowledge providers, in the same way they develop their competences in other fields. In addition, their feedback will provide interesting insights into methods to deal with network maintenance and management over long periods, which are key to the success of these types of climate services.

CRediT authorship contribution statement

Guillaume Dumas: Conceptualization, Methodology, Resources, Software, Writing – original draft. **Valéry Masson:** Conceptualization, Methodology, Supervision, Writing – original draft. **Julia Hidalgo:** Conceptualization, Methodology, Supervision, Writing – original draft. **Valérie Edouart:** Supervision. **Aurélie Hanna:** Supervision. **Guillaume Poujol:** Resources.

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.

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