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A Lemonsu, J M Alessandrini, Julie Capo, M Claeys, E Cordeau, Cécile de Munck, S Dahech, J C Dupont, F Dugay, V Dupuis, et al.

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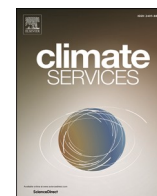
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## News

**The heat and health in cities (H2C) project to support the prevention of extreme heat in cities****Introduction**

Urban populations are exposed to multiple environmental stresses (Rojas-Rueda et al., 2021) that adversely impact health and well-being. Heat is one of the most challenging risks, rapidly changing under climate change, and aggravated by the urban heat island (UHI). Exposure to heat in both outdoor and indoor environments can lead to severe health impacts, for instance on perinatal health, mental health, cardiovascular, respiratory or renal diseases. It is associated with an increase in both health care consumption and mortality. In addition, strong UHIs in summer are frequently associated with air pollution conditions, with evidence of negative synergies between both risks. Extreme heatwaves are among the deadliest extreme weather events worldwide.

Few epidemiological studies have investigated the influence of UHI and temperature contrasts within a city on health. The meta-analysis by Schinasi et al. (2018) highlighted the aggravating effect of micro-UHI on mortality risk during heatwaves. For the 2003 heatwave, Laaidi et al. (2012) showed the role of night-time temperature and urban overheating in Paris area on mortality risk based on satellite data. To support urban planning, a heat vulnerability map has been produced for the Paris region by cross-referencing urban typology data with socio-demographic and environmental criteria (Cordeau, 2017). However, these different approaches do not consider the direct information on air temperature (combined with other microclimate variables) which nonetheless determines the actual exposure of people. The difficulty lies in understanding and assessing temperature variations spatially across the region and down to very fine territorial levels, as well as their temporal variability in relation to local weather conditions (He, 2018). The complex interactions between urban canopies, the atmospheric boundary layer dynamics (Lemonsu and Masson, 2002) or synoptic-scale atmospheric circulations (Céspedes et al., 2024) largely govern the day-to-day local-scale environmental conditions but are very poorly documented. A major obstacle is the lack of dedicated observational data in urban areas for long-term and multi-scale monitoring. Added to this is a lack of awareness of the ability of current meteorological and air quality models to reproduce the processes involved (Varentsov et al., 2018).

While current prevention focuses on warnings and communication during heatwaves, the evolving characteristics of summer heat and heatwaves calls for more structural adaptation to heat (Pascal et al., 2021). UHI mitigation is essential to contribute to the prevention of heat-related health impacts. Consequently, we need to be able to predict the contrasts in exposure conditions on different spatial and temporal scales in order to better support prevention, and to understand the variability factors linked to surface properties or meteorological conditions that modulate exposure in order to guide planning choices.

**Objectives of H2C**

The main goal of the Heat and Health in Cities (H2C) French project is to improve the urban climate services to support preventive actions and policies to deal with the risk of heat and extreme heat in cities, with the Paris region (France) as a case study. In response, the three scientific objectives are identified:

- Improve our understanding of the impacts of urban covers and surface heterogeneities in the city on UHI, local meteorology and air quality.
- Strengthen the synergy between numerical modeling and multi-source observations to study the environmental phenomena in detail, and assess the spatial and temporal variations in population exposure to heat and air pollution, and the associated health risks.
- Develop and provide information that is useful for decision-making, in terms of UHI assessment, consequences on exposure in both outdoor and indoor environment, associated health impacts, and opportunities for prevention.

The project adopts a multi-disciplinary and multi-sectoral approach, bringing together partners from academic research (atmospheric physics, urban climate, building sciences, air quality, epidemiology), prevention, and public action (with the national public health agency and the region institute for urban planning and territorial development). The main results expected are (1) a database of daily exposure and health data at the scale of the municipalities and the Paris neighborhoods, (2) a prototype system for forecasting environmental conditions and exposure in the city (down to hectometric resolution), and (3) a multi-criteria analysis mapping platform for use by stakeholders.

**Environmental and social drivers of heat-related health impacts in the Paris region**

A good understanding of the health impacts but also of the influence factors is needed to support evidence-based prevention strategies. Capturing the spatial variations in heat exposure over several years is key to improving current epidemiological studies. In order to characterize the spatial and temporal contrasts in exposure to warm weather and air pollution but also clarify the most relevant environmental factors, long-term simulations and observations were compiled to provide spatial maps of meteorological and air-quality indicators over the Paris region. The meteorological data (including minimum and maximum near-surface temperature, average humidity, daily comfort index, etc.) were provided with a 1-km horizontal resolution for the time period 2000–2020. Daily mean and maximum concentrations in O<sub>3</sub>, PM<sub>10</sub>, PM<sub>2.5</sub> and NO<sub>2</sub> were derived over 2015–2020 from air-quality

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simulations with two systems: ESMERALDA, based on the models MM5 for meteorology (Grell et al., 1994) and CHIMERE (Menut et al., 2021) for chemistry and transport, with a 3-km resolution over the region; and HORAIR based on ESMERALDA and the ADMS model (Carruthers et al., 1994) for estimating concentrations near road traffic, with a 50-m resolution over Paris and its suburb.

First, these data were used to describe the exposure of the population over time in each neighborhood (census district) and municipality of the region. They were combined with other environmental data (e.g. vegetation) and social data (e.g. social deprivation) to identify *a priori* areas presenting similar drivers of vulnerability to heat. Vulnerability is here defined as the result of an exposure and individual susceptibility, mitigated by adaptive capacity (Forceville et al., 2024). The analyses revealed two types of *a priori* highly vulnerable areas, where different strategies may be relevant: 1) areas experiencing the warmest temperatures of the region, but with low social deprivation, and 2) areas less exposed but highly socially deprived (Fig. 1, right). A time-series temperature-mortality analysis found that mortality risks at very high temperatures were higher in those areas: a mean daily temperature of 29.4 °C was associated with a mortality risk 3.03 times higher than at temperature of 16.6 °C [IC 95 % 2.82:3.25] in the most vulnerable areas, and 2.82 times higher [2.69:3.04] in the second most vulnerable areas. In total, 8,021 deaths were attributable to heat (mean daily temperatures higher than 23.2 °C corresponding to the 95th percentile of the temperature distribution) in the Paris Region during summer between 2000 and 2017, representing 1.3 % of the total mortality.

Mortality and morbidity data (hospitalisations, emergency room visits) were collected for several causes, age groups and sex, for each of the municipalities (including Paris arrondissements). The influence of heat on those health indicators is investigated through time-series analyses, taking into account non-linear, time-lagged effects, and exploring for effect modification by urbanicity (from rural to very dense municipalities), vegetation (greening density, tree canopy, land use), and social deprivation.

## Synergy between observation and modeling to assess environmental conditions

To achieve a more robust and accurate assessment and forecast of environmental conditions over the Paris region from the regional to the neighborhood scale, the project combines multi-source observations and numerical models.

A large experimental component has been implemented, which took place in a cross-lab and cross-project research initiative named PANAME (Masson et al., 2022), in connection with the Paris 2024 Research Demonstration Project accredited by the Weather Meteorological Organization. A complete observation database was built, with the acquisition of near-surface meteorological parameters and atmospheric pollutants, and vertical profiles within the atmospheric boundary layer (temperature, humidity, wind, aerosols) in contrasted urban, *peri*-urban and rural environments. The contribution of Netatmo's citizen weather stations was also explored, the advantage being the density of the network particularly in populated and therefore urbanized areas. During summers 2022 and 2023, innovative observation systems and protocols were deployed especially in Paris city center to investigate the role of urban parks in regulating the microclimate and their efficiency depending on weather conditions. The cooling effect was studied by cross-referencing measurements of air temperature and humidity collected by fixed weather stations in the streets and parks of Paris, by on-board sensors along cycle routes, and according to vertical profiles in the near-surface atmosphere performed with instrumented quadcopter drones and radiosondes.

Numerical modeling is the complementary tool for understanding the processes, their interactions, and assessing the environmental conditions combining meteorology and air quality. It also extends the scope to indoor thermal comfort and exposure to heat, for which measurements are not available. The project implements existing models (in each discipline) which are improved using available observations, and applied to case studies from the field campaign in order to validate an

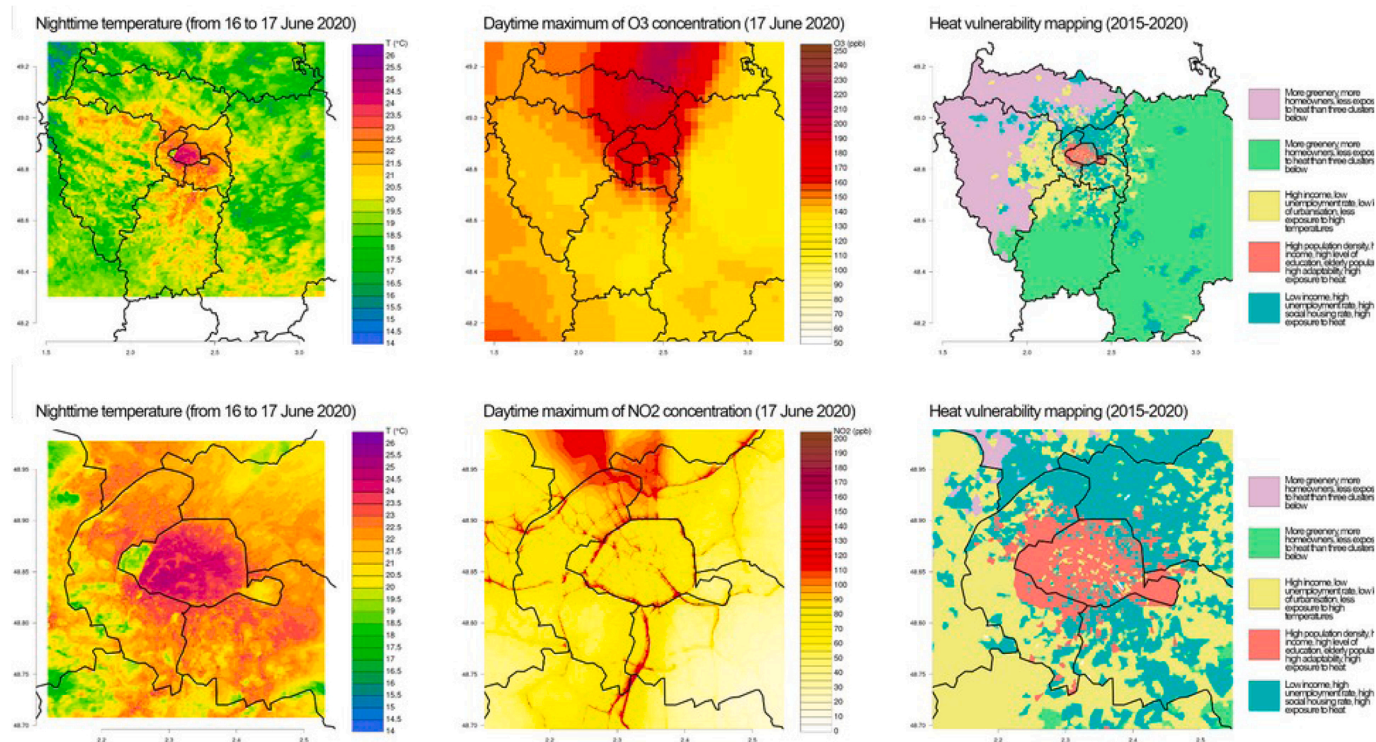


Fig. 1. Example of indicator maps produced at regional (top) and local (bottom) levels: night-time temperature simulated for the heatwave night from 16 to 17 June 2022 (left), maximum daily O<sub>3</sub> concentration over the region and maximum daily NO<sub>2</sub> concentration over Paris simulated for the 17 June 2022 (middle), and classes of vulnerability to heat based on cluster analysis for the period 2015–2020 (right).

optimal model chaining configuration. Meso-scale meteorological conditions and the urban microclimate are simulated using the MesoNH atmospheric model (Lac et al., 2018) and a differentiated representation of natural covers with the ISBA-DF model (Decharme et al., 2011) and urbanized areas with the TEB urban canopy model (Redon et al., 2020, Schoetter et al., 2020). Two nested domains are defined to cover the Paris region and to zoom on Paris and inner suburbs with respective horizontal resolutions of 300 and 100 m (Fig. 1, left). These meteorological fields are fed into Airparif's local (HORAIR) and regional (ESMERALDA) operational air quality modeling systems (Fig. 1, middle), replacing current MM5 model which does not specifically use an urban canopy model. The aim is to improve atmospheric conditions likely to influence pollutant distribution, particularly in urban environments. The link between outdoor microclimate and indoor comfort conditions is investigated through thermo-aerodynamic modeling of dwellings selected for their sensitivity to heat exposure and their representativeness. The meteorological conditions surrounding the buildings are supplied to the Cometh model (Videau et al., 2013, Da Silva et al., 2016) by the urban microclimate simulations or by available urban-scale observations. Simulations of these dwellings make it possible to calculate indoor thermal comfort in order to assess the level of vulnerability to heat by calculating how often the conditions acceptable to individuals are exceeded over the summer period. One of the main challenges will be to design relevant multi-criteria forecasting products, based on the modeling chain supplemented by observation.

### Knowledge transfer to stakeholders and support decision-making

Transferring the scientific knowledge produced to stakeholders in order to raise awareness and support decision-making is an important outcome of the project. Supported by the Paris region urban planning agency, a mapping of potential users was first established identifying more than 200 organizations and 300 stakeholders in a wide variety of fields (health, social, environmental and urban planning, air quality, energy-climate, construction, etc.). A survey was carried out to identify their needs. Through the analysis of the 60 responses to an online questionnaire, several priorities have been pointed out: neighborhoods exposed to heat, periods of heatwaves, the night-time period, sensitive or fragile populations (isolated and vulnerable people, homeless, young children, etc.). At the end of the research, a workshop will be held with stakeholders to co-construct an information and decision-making tool for risk management and the promotion of adaptation and prevention. It will be supplied with data from the project, cross-referenced with other existing data (geographical, urban, socio-demographic, etc.), so that it can be used to support the heatwave warning plan by helping to allocate resources or design local adaptation strategies, and provide recommendations for documents relating to town planning, health and the environment.

### CRedit authorship contribution statement

**A. Lemonsu:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Conceptualization. **J. M. Alessandrini:** Writing – original draft, Software, Methodology. **J. Capo:** Writing – review & editing, Validation, Data curation. **M. Claeys:** Validation, Software, Methodology. **E. Cordeau:** Writing – review & editing, Methodology, Conceptualization. **C. de Munck:** Data curation, Methodology. **S. Dahech:** Writing – review & editing, Investigation, Formal analysis, Data curation. **J.C. Dupont:** Investigation, Formal analysis, Data curation. **F. Dugay:** Software. **V. Dupuis:** Investigation, Formal analysis, Data curation. **G. Forceville:** Visualization, Investigation, Formal analysis. **S. Garrigou:** Methodology. **O. Garrouste:** Data curation. **M. Goret:** Methodology, Data curation. **S. Gorla:** Writing – review & editing, Investigation, Formal analysis. **M. Haeffelin:** Methodology, Investigation, Formal analysis, Conceptualization. **S. Host:** Writing – original draft, Methodology. **C. Joly:** Software. **P. Keravec:**

Writing – review & editing, Validation, Data curation. **S. Kotthaus:** Writing – review & editing, Investigation, Formal analysis, Data curation. **N. Laruelle:** Methodology. **M. Madelin:** Writing – review & editing, Methodology, Investigation, Formal analysis. **V. Masson:** Writing – review & editing, Methodology, Investigation. **C. Mauclair:** Methodology. **T. Nagel:** Writing – review & editing, Validation, Software, Investigation. **M. Pascal:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **J.F. Ribaud:** Methodology, Investigation, Data curation. **G. Roberts:** Methodology, Data curation. **A. Rosso:** Software, Methodology. **A. Roy:** Validation, Data curation. **M. Sabre:** Methodology. **O. Sanchez:** Software. **M. Stempflet:** Writing – review & editing, Methodology, Formal analysis. **W. Wei:** Software. **R. Wilson:** Investigation, Formal analysis, Data curation. **J. Wurtz:** Methodology, Software, Validation.

### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Aude LEMONSU reports financial support was provided by French National Research Agency. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability

Data will be made available on request.

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- A. Lemonsu<sup>a,\*</sup>, J.M. Alessandrini<sup>b</sup>, J. Capo<sup>a</sup>, M. Claeys<sup>a</sup>, E. Cordeau<sup>c</sup>, C. de Munck<sup>a</sup>, S. Dahech<sup>d</sup>, J.C. Dupont<sup>e</sup>, F. Dugay<sup>f</sup>, V. Dupuis<sup>g</sup>, G. Forceville<sup>h</sup>, S. Garrigou<sup>c</sup>, O. Garrouste<sup>a</sup>, M. Goret<sup>a</sup>, S. Gorla<sup>h</sup>, M. Haeffelin<sup>i</sup>, S. Host<sup>c</sup>, C. Joly<sup>f</sup>, P. Keravec<sup>j</sup>, S. Kotthaus<sup>k</sup>, N. Laruelle<sup>c</sup>, M. Madelin<sup>d</sup>, V. Masson<sup>a</sup>, C. Mauclair<sup>c</sup>, T. Nagel<sup>a</sup>, M. Pascal<sup>h</sup>, J. F. Ribaud<sup>k</sup>, G. Roberts<sup>l</sup>, A. Rosso<sup>f</sup>, A. Roy<sup>a</sup>, M. Sabre<sup>m</sup>, O. Sanchez<sup>f</sup>, M. Stempfelet<sup>h</sup>, W. Wei<sup>b</sup>, R. Wilson<sup>n</sup>, J. Wurtz<sup>a</sup>
- <sup>a</sup> Centre National de Recherches Météorologiques (CNRM), Université de Toulouse, Météo-France, CNRS, Toulouse, France
- <sup>b</sup> Centre Scientifique et Technique du Bâtiment (CSTB), Champ-sur-Marne, France
- <sup>c</sup> Institut Paris Région, Paris, France
- <sup>d</sup> Université Paris Cité, UMR PRODIG, Paris, France
- <sup>e</sup> Institut Pierre Simon Laplace (IPSL), Université Versailles Saint-Quentin-en-Yvelines, Palaiseau Cedex, France
- <sup>f</sup> Airparif, Agence de Surveillance de la Qualité de l'air, Paris, France
- <sup>g</sup> Sorbonne Université, UMR PHENIX, Paris, France
- <sup>h</sup> Santé Publique France, National French Public Health Agency, Saint Maurice, France
- <sup>i</sup> L'Institut Pierre Simon Laplace (IPSL), CNRS, Palaiseau Cedex, France
- <sup>j</sup> Nantes Université, École Centrale Nantes, CNRS, LHEEA, UMR 6598, F-44000 Nantes, France
- <sup>k</sup> Laboratoire de Météorologie Dynamique (LMD-IPSL), Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau Cedex, France
- <sup>l</sup> Scripps Institution of Oceanography, University of California, La Jolla, San Diego, CA, USA
- <sup>m</sup> Centre Scientifique et Technique du Bâtiment (CSTB), Nantes, France
- <sup>n</sup> LATMOS-IPSL, Sorbonne Université, Paris, France

\* Corresponding author.

E-mail address: [aude.lemonsu@meteo.fr](mailto:aude.lemonsu@meteo.fr) (A. Lemonsu).