VURCA PROJECT

Cities vulnerability to future heat waves & adaptation strategies

Vulnérabilité URbaine aux épisodes Caniculaires et stratégies d'Adaptation

Project methodology and results

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CIRED	(1)	**Centre International de Recherche sur l'Environnement et le Développement**
CNRS GAME	(2)	**Groupe d'études de l'Atmosphère MEtéorologique**
CSTB	(3)	**Université Paris-Est, Centre Scientifique et Technique du Bâtiment**

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Summary

Figures

Tables

SYNTHESIS

Project identification

Acronym	**VURCA**
Name	*Vulnérabilité URbaine aux épisodes Caniculaires et stratégies d'Adaptation* *Urban structure vulnerability to heat waves and adaptation strategies*
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Start date	January 2009
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Summary and key insights

Because more than half of the world population lives there, and because most of the economic activity takes place within them, cities appear of particular importance when looking at the potential impacts of climate change.

Climate change can threaten cities through many different ways. One of them is the increased risk of summer heat waves, which can be dangerous for human health and impact energy consumption. Such a risk is reflected in climate models simulations, for all emission scenarios, by both an increase in average summer temperatures and in temperature variability from one year to another. Cities are particularly vulnerable to heat waves because of the urban heat island effect, which magnifies the high temperatures in urbanized areas.

The impact will depend on the infrastructure in place, planning policies, types of homes and lifestyles. Several policies can be undertaken to mitigate this risk: the development of air conditioning is one of them, and may enable to greatly decrease the health burden of heat waves; the promotion of better building insulation or land-use policies promoting green spaces may also be means to attenuate the negative effects of the urban heat island.

VURCA project studies cities vulnerability to future heat wave events. Through an interdisciplinary team consisting of climatologists, atmospheric physicists, economists and specialists in construction, it was able to develop a framework to analyze prospective effects of different policies aiming at reducing heat waves impacts. This project takes Paris urban area as a case study.

Based on a demographic scenario and a scenario of transport prices evolution, Nedum-2D, a simulation model of urban expansion developed in CIRED, was used to develop scenarios of prospective urban expansion, distribution of the population, and average level of rents in the city.

These scenarios were then used by TEB-SURFEX model, developed at CNRM-GAME, to simulate, for different heat waves computed by climate models, the effect of urban heat island. This enabled to compute energy consumption related to air conditioning use, and the temperatures inside buildings and in the streets.

A number of results are available from this work, answering three main questions:

1. To what extent will Paris be vulnerable to heat waves?

Paris can be strongly affected by heat waves. We computed that, without air conditioning, at the end of the century, **almost 11 heat wave days per year in average** should be expected to be spent in Paris urban area. During these days, in residential buildings, if no AC is used, almost **7 hours and a half** would be in average spent in **high heat stress** conditions, i.e. with an apparent air temperature (UTCI) greater than 32°C. This could lead to serious health consequences. In the streets, even in shadow, this duration is higher, and **almost 15 hours** have to be spent in these conditions.

Urban expansion, through an increased heat island effect, could worsen heat waves impacts. We computed that, in the scenario of high city densification (the “compact city scenario”), in the streets, **20 minutes in high heat stress conditions should be added**.

2. What would be the effect of a massive development of air-conditioning?

If a massive development of air conditioning happens happens to create more conformable indoor ambiance and to prevent health issues, about **1.1 TWh** per year of extra final energy consumption should be expected, if a 23° temperature is to be maintained in all residential and office buildings.

Heat released by AC systems causes a degradation of external thermal comfort, and the duration spent under high heat stress conditions in the streets is increased by about **20 minutes**.

These results were computed with the hypothesis that existing urban green spaces are adequately watered, and this plays an important role in reducing Paris sensitivity to heat waves. In case of water shortage, (which is almost equivalent to an urban green spaces removal), we simulated that energy consumption would be **increased by about 8%**, and that **almost one hour** of outdoor thermal discomfort would be added.

3. Could alternative adaptation policies enable to reduce energy demand for air conditioning and thermal discomfort?

Energy demand for air conditioning could be an important burden in a context of greenhouse gases reduction efforts, but **adaptation policies** could be implemented to reduce this demand. We computed that:

- a massive creation of parks and green spaces in Paris urban area (devoting 10% of land surface to new parks),
- stricter building insulation rules and the use of reflective materials for walls and roofs,
- and effective recommendations or policies leading to air conditioning used to maintain 28°C in residential buildings and 26°C in offices instead of 23°C,

could together enable to reduce energy consumption by 0.7 TWh, i.e**. reduce energy consumption for AC by more than 50%**. This would also **reduce outdoor thermal discomfort time by about 1 hour**.
However, these policies could not a priori totally replace AC use, as **6 hours per day would still have to be spent in high heat stress conditions** in residential buildings if no AC is to be used at all.

In conclusion, several alternative options to air-conditioning are able to significantly reduce the vulnerability of the city in terms of both indoor and outdoor comfort. Nevertheless, at best, a third of the day is spent under conditions of strong heat stress inside buildings without air-conditioning.

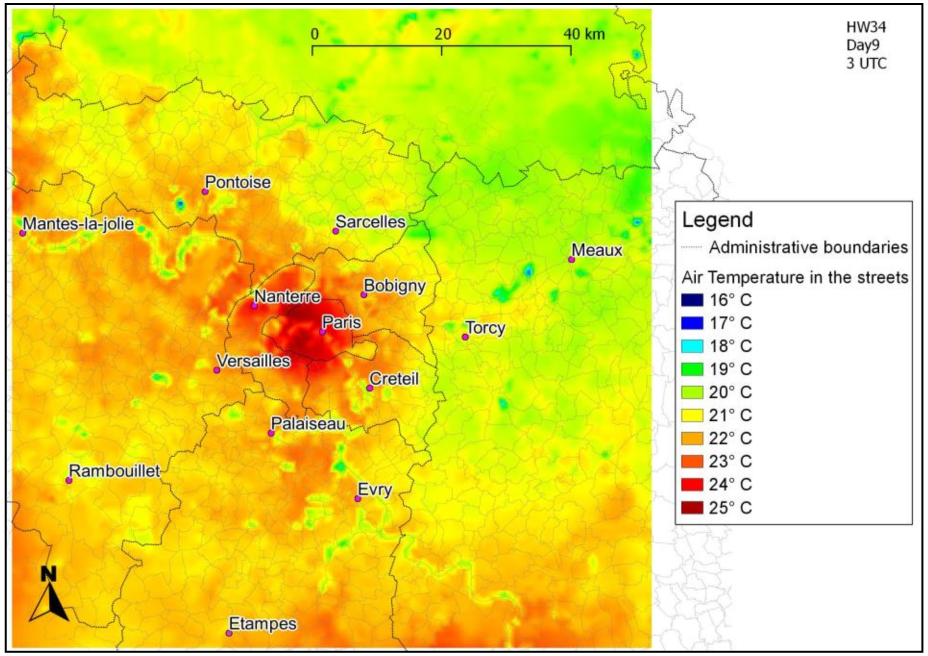
Adaptation policies efficiency depends on the heat wave characteristics

Various adaptation policies have efficiencies which vary according to the type of heat wave. For instance, cities sensitivity to heat waves varies greatly with the duration of the event. Continuously high temperatures are required during a few days before indoor temperatures reach their maximum equilibrium value. This duration was found to be about 5 days in Paris. Building insulation enables to increase this duration and therefore to be less sensitive to short heat waves.

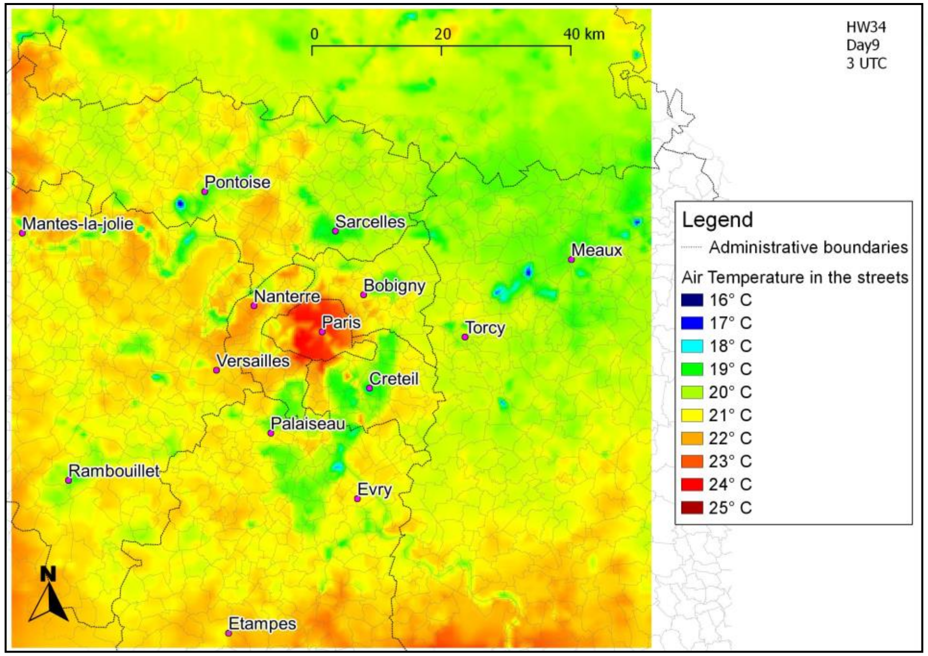
Adaptation policies implementation issues

Implementing these policies is however not an easy task. Beside the operational difficulty to limit the use of air conditioning, the reinforcement of building insulation would be expensive, and green spaces creation would have a high cost in terms of land use (by decreasing residential land supply, it could increase all rents and real estate prices by 2 %, when compared to reference scenario). Green spaces creation would also reduce the city density and could lead to increased urbanized surface, and to increased transport-related greenhouse gases emissions (+10%). They would finally require a huge amount of water to be efficient. If water availability stops, green spaces are found to have almost no effect.

Among the three policies we have studied, the **change in AC use** (increasing temperature set points) is the policy which has the greatest impact when considered alone. This policy, moreover, has none of the costs or collateral effects that the two other adaptation policies have. However, it is rather unclear how such a policy could be implemented in practice.



***A. Reference scenario**: urban heat island effect is clearly visible, with a 6 °C temperature difference between the center of Paris and the countryside.*



***B. With the three adaptation policies:** this simulation was done with the exact same conditions as map A, except that the three adaptation policies are supposed to have been implemented.*

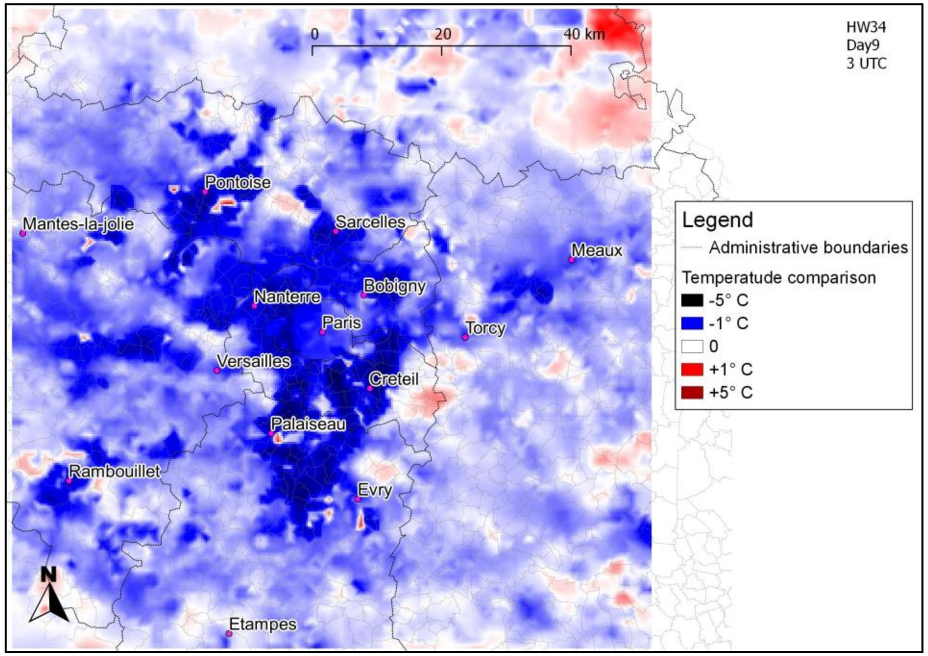


Figure 1: example of simulation maps for Paris in 2100. Maps represent air temperature at 4 a.m. in the streets, after 9 days of a heat wave similar to the 2003 heat wave.

These temperature maps were computed for a projection of what Paris could be in 2100, with and without the implementation of the three specific adaptation policies

***C. Difference between both simulations:** this map shows the difference between maps A and B. Air temperature decrease can be up to 5°C thanks to adaptation policies.*

SCIENTIFIC REPORT

INTRODUCTION

Because more than half of the world population lives there, and because most of the economic activity takes place within them, cities appear of particular importance when looking at the potential impacts of climate change. (C. Rosenzweig et al. 2010; Hallegatte et Corfee-Morlot 2010)

Climate change can threaten cities through many different ways. One of them is the increased risk of summer heat waves, which can be dangerous for human health and impact energy consumption. Such a risk is reflected in climate models simulations, for all emission scenarios, by both an increase in average summer temperatures and in temperature variability from one year to another. Cities are particularly vulnerable to heat waves because of the urban heat island effect, which magnifies the high temperatures in urbanized areas. (IPCC 2007a; Cynthia Rosenzweig et al. 2011)

The impact will depend on the infrastructure in place, planning policies, types of homes and lifestyles (Riberon et al. 2006). Several policies can be undertaken to mitigate this risk: the development of air conditioning is one of them, and may enable to greatly decrease the health burden of heat waves; the promotion of better building insulation or land-use policies promoting green spaces may also be means to attenuate the negative effects of the urban heat island.

However, an air conditioning policy may lead to a great increase in energy consumption, and, hence, in greenhouse gases emissions, conflicting with climate change mitigation efforts (McEvoy, Lindley, et Handley 2006; Salagnac 2007; Hamin et Gurran 2009) ; building energy performance improvement or green spaces policies direct costs, benefits and side effects (e.g. the modification of urban landscape) are difficult to assess, in part because it requires a broad interdisciplinary approach.

In this project, we aim at dealing with this issue. Through an interdisciplinary team of researchers combining atmospheric physicists, urban economists and construction specialists, we have developed a quantitative prospective framework that enables to assess many different aspects of these policies, using Paris urban area as a case study.

In the first section of this report, we present the urban expansion model and the urban climate model that we have linked and used together to do this study. In the second section, we focus on the description of the future heat waves used in the analysis. In the third section, we explain how we measured the future vulnerability to heat waves. We present in the fourth section various adaptation policies, and finally in the last section how these policies can mitigate heat wave consequences, and what are the associated direct or indirect costs.

CHAPTER 1
Urban climate and urban economic models

The systemic approach within VURCA project has been developed through a core of models into a unique investigation framework: a socioeconomic urban expansion model, and an urban climate model. A major effort has been made to:

- improve of our models: see sections 1.1 and 1.2
- prepare their integration: see section 1.3

1.1 NEDUM Socioeconomic urban expansion model

Urban structure and its evolution is a crucial determinant of cities vulnerability to heat waves, through. **NEDUM-2D** has been developed in this project to model how the inhabitants choose to locate in a city, how policies can influence their choice, and what are the socio-economic effects associated to these policies.

This has been designed to create long-term scenarios for city expansion, based on scenarios describing future land-use and transport policies in the city, on demographic scenarios on the future total population, and on global "techno-economic" scenarios on future income, construction cost and transport cost evolution. These techno-economic scenarios can be produced through global general equilibrium prospective models, such as Imaclim-R developed in CIRED (Rozenberg et al. 2010), or Markal/TIMES developed by IEA ETSAP[1]. NEDUM-2D can therefore be seen as a tool to downscale at city scale global scenarios produced by such models.

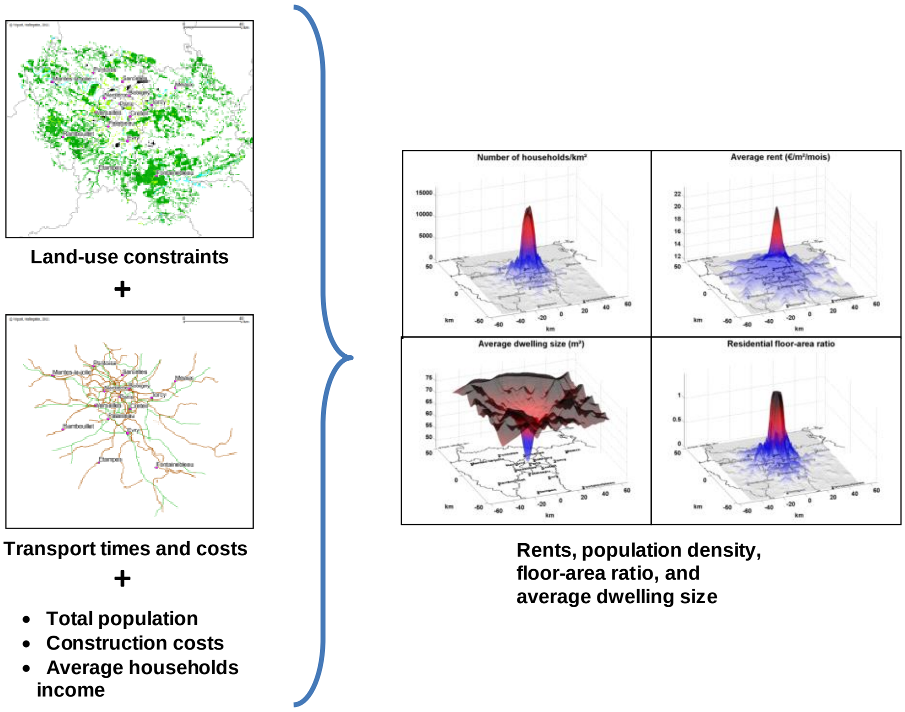


Figure 2 - Description of NEDUM-2D model.

[1] http://www.iea-etsap.org/web/tools.asp

More precisely, NEDUM-2D simulates the spatial distribution of land and real estate values, dwelling sizes, population density, building height and density, and their evolution over time (Figure 2). (Gusdorf et Hallegatte 2007; Viguié et Hallegatte 2012; Viguié, Hallegatte et Rozenberg 2011) It is a dynamic model which relies on the classical urban economics framework (Fujita 1989), but is able to capture the dynamics of urban systems, and the importance of inertia. To produce scenarios going until the end of the century, it uses only general and fundamental economic principles, which are likely to remain constant over the long term. A more detailed description of the model is available in the technical report (see Project deliverables).

Three main mechanisms drive the model. First, we suppose that households choose their accommodation location and size by making a trade-off between the time and money they spend for transport (i.e. to commute to their jobs) and the real estate price level (or, equivalently, between the proximity to the city center and the housing surface they can afford).

Second, real estate developers choose to build more or less housing (i.e. larger or smaller building) at a specific location, depending on the local level of real estate prices. When these prices are low, developers tend to build low density buildings, and when these prices are high, they tend to build high density buildings.

Third, we suppose that various city characteristics do not change and adjust at the same speed. For instance, rents can change very quickly, whereas buildings characteritsics evolve over a much longer timescale. Building depreciation is also very slow, leading to path dependency and lock-ins in city evolution.

Using these mechanisms, it is possible to determine the structure of the city from information on population size, households' income, transport network location, building construction costs and developers behavior parameters.

In this project, this model has been first calibrated on Paris urban area (Viguié et Hallegatte 2012). A validation of the model over the 1900–2010 period shows that the model reproduces the available data on the city's evolution fairly faithfully, suggesting that the model captures the main determinants of city shape evolution. It also well reproduces the spatial distribution of dwelling size, population density, and rents in the urban area (Viguié, Hallegatte, et Rozenberg 2011; Viguié 2012, see also Project deliverables)

VURCA's outcome

A great part of the development of NEDUM-2D model was performed thanks to VURCA project. An important part of the work was devoted to calibration and validation of the model on Paris urban area.[2]

The development of a methodology for long-term scenarios building for cities, and for the assessment of adaptation policies over the long-term was also developed thanks to the project.[3]

[2] Deliverable 2.1: "Technical report on economic-urban model development".

[3] Deliverable 4.1: "Report on the long-scenario for cities, including the adaptation strategies and their economic side-effects".

1.2 TEB SURFEX Urban climate model

Urban climate modeling has been a research topic studied at Météo France/GAME for about ten years. A specific urban canopy model was developed, the Town Energy Balance (TEB, Masson 2000), in order to parameterize radiative, energetic, hydrologic, and turbulent processes at the interface between built-up surfaces and atmosphere.

TEB is included in the surface numerical module SURFEX, and is based on a simplified geometry description of urban covers. Built areas are represented as mean urban canyons composed of 1 flat roof, 1 road, and 2 identical walls with isotropic street orientations (Figure 3).

Radiation and energy balances are resolved independently for each of these urban facets and then aggregated for the whole urban canyon. Mean geometric parameters describe the urban arrangement. The radiative and thermal properties of materials are associated with each urban facet.

In the VURCA project, several improvements have been made in order to model in a more realistic way some aspects of urban microclimate, so that the model is able to evaluate and compare different adaptation strategies linked with urban planning.

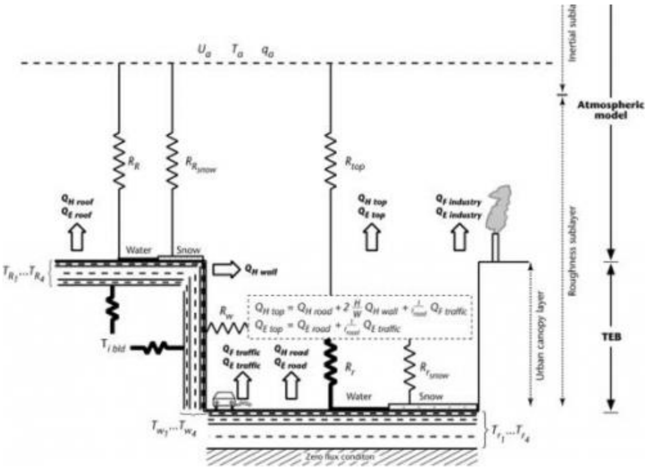


Figure 3 - TEB scheme

Urban green space in TEB

The original version of TEB is only applied to built-up covers. To model the microclimate for urban environments that include some urban green spaces, TEB is coupled with the ISBA vegetation model but without direct micro-scale interactions between built-up and natural covers (Figure 4, left): each model calculates the surface fluxes over the cover types it deals with, and then these fluxes are aggregated according to the respective cover fractions.

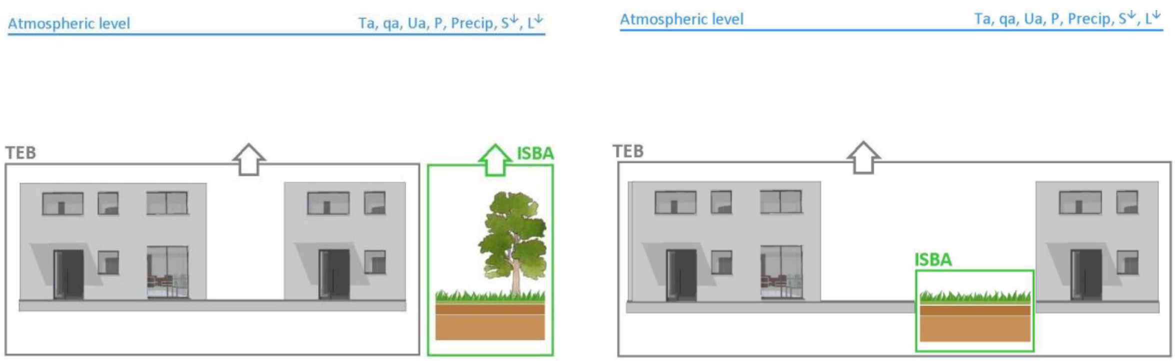


Figure 4 - Left: Initial version of TEB without interaction between built-up covers and vegetation; Right: New version of TEB including vegetation inside the streets.

TEB has been improved in order to integrate explicitly the low vegetation (gardens) between buildings (Figure 4, right) so that the geometric parameters of the urban canyon are more realistic (especially, the canyon is wider). The radiation calculations are modified to account for the shadow effects of buildings on vegetation, and the contributions of vegetation in the short and longwave radiation budget. The turbulent fluxes over vegetation are still computed with ISBA but inside the TEB's code by providing ISBA the right atmospheric conditions inside the canyon. Finally, these microclimatic variables (temperature, humidity, wind) are recomputed by including the contributions of gardens.

Both versions of TEB have been confronted to experimental data issued from a field campaign conducted in Israel (Lemonsu et al. 2012). A significant improvement in the modeling of surface temperature and street-level air temperature has been highlighted. In conclusion, this new version is better suited to study greening strategies.

Air conditioning in TEB

While the original version of TEB considered the need for heating inside the buildings and proposed estimates of the associated energy demand (Pigeon *et al*. 2008), it did not take into account the need for air-cooling. For this project focused on heat waves, it has been essential to develop its calculation inside TEB to evaluate:

- Energy demand associated to air conditioning for the different scenarios of urban expansion and adaptation measures for buildings proposed;
- Environmental impact of a massive air conditioning strategy in order to mitigate the indoor heat stress. Indeed, according to De Munck et al. (2012), the heat releases associated to massive air conditioning over Paris increase up to 2 °C the urban heat island, and the associated outdoor discomfort.

During the VURCA project and in association with the MUSCADE[4] project, a **building energy model (BEM)** has been developed inside TEB (Figure 5). This model (TEB-BEM) uses the same homogenous urban morphology as the original TEB but now resolves an indoor building energy balance for a unique thermal zone with a single thermal mass that represents the thermal inertia of construction materials inside a building (e.g. partition walls and floors). It is based on the following processes:

- Solar heat gain through the glazing for a uniform glazing ratio over the façade,
- Heat gain through specific use of energy inside the building,
- Heat exchanges by infiltration and ventilation with outdoor air,
- Air cooling or heating according to user specified temperature set points.

The accuracy of the model has been evaluated against energy consumption data collected for Toulouse during the Capitoul field campaign leaded by the GAME (Bueno et al. 2012).

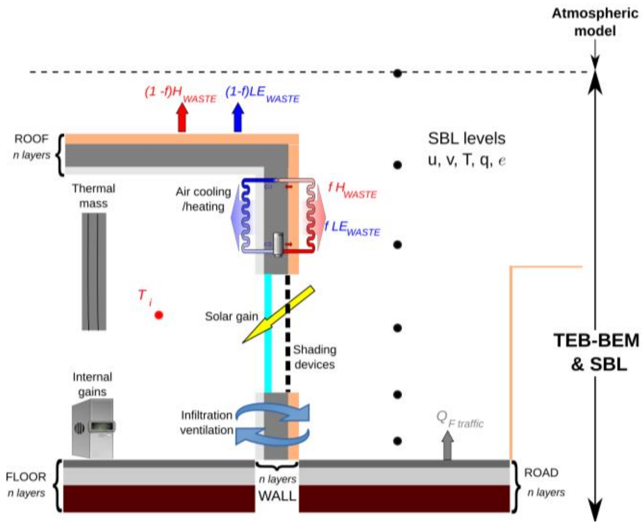


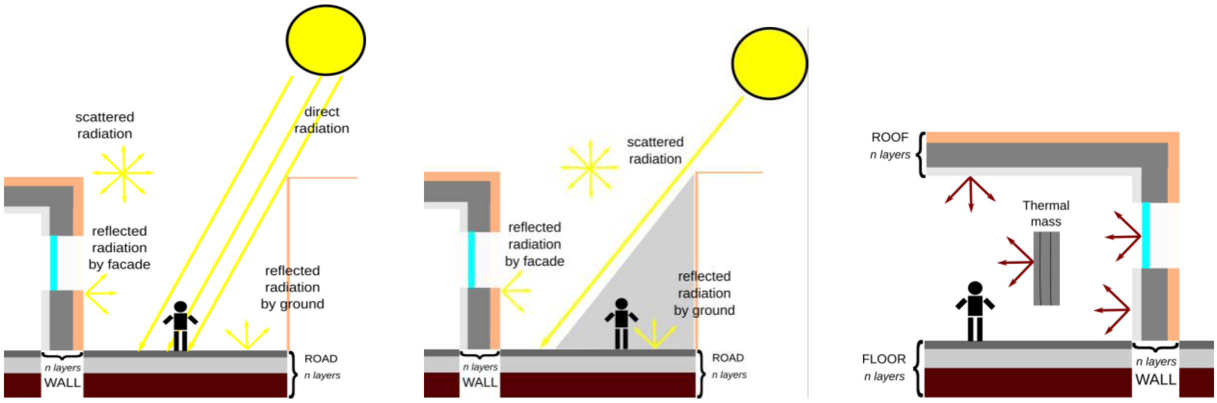
Figure 5 - Diagram of the new version of TEB including the Building Energy Model.

[4] MUSCADE is a research project, funded by ANR (reference ANR-09-VLL-003) : Modélisation Urbaine et Stratégies d'adaptation au Changement climatique pour Anticiper la Demande et la production Energétique

Thermal comfort model in TEB

Human body thermal comfort is not only related to air temperature but also to other local meteorological variables (radiation, moisture, wind) and to the activity level of people. Among the huge number of existing procedures for evaluating thermal comfort, we chose the **Universal Thermal Climate Index** (**UTCI**, www.utci.org). This index has been developed by the COST Action 730 for public weather service, public health system, precautionary planning, climate impact research in the health sector, and should become an international standard.

UTCI follows the concept of an **equivalent temperature** of a reference environment that would generate the same heat stress than the actual environment. The reference environment is defined with 50% relative humidity, with still air and a radiant temperature equaling the air temperature. The heat stress is evaluated from the multi-node Fiala thermoregulation model (Fiala et al. 2012) and for a person walking at 4km/h with a metabolic rate of 135 Wm^{-2}. Since the response of the model is multidimensional (body core temperature, sweat rate, skin wettedness, etc...) a single dimensional index is calculated by principal component analysis. Then, to be applied to numerical weather predictions without running a thermoregulation model, a polynomial regression equation (6^{th} order, available as a software source code on www.utci.org) has been developed with less than 1°C of error with the exact solution of the model (Bröde et al. 2012).



a. Outside, sun-exposed people — *b. Outside, people in the shade* — *c. Inside building*

Figure 6 - Representation of the 3 environments considered to evaluate UTCI in TEB

This equation has been implemented in TEB, and three possible environments are considered in order to evaluate outdoor and indoor comfort: people outside exposed to the sun, people outside in the shade and people inside buildings (Figure 6). For each environment, the meteorological variables to compute UTCI are adapted and especially the radiant temperature.

VURCA's outcome

A considerable work of TEB model development and evaluation against experimental data was performed for implementing:

1. Urban green spaces [5]
2. Energy budget of buildings and air-conditioning systems[6]
3. Indoor and outdoor thermal comfort indicator for human body [7]

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[5] Deliverable 1.1: Inclusion of vegetation in the TEB urban canopy model for improving urban microclimate modeling in residential areas. Aude Lemonsu.

[6] Deliverable 4.2 : Analyse préliminaire de l'impact de scénario du bâtiment. Grégoire Pigeon

1.3 How to link urban expansion and climate models?

NEDUM-2D model simulates the urban expansion and provides projections of the evolution of various city characteristics, such as dwelling sizes, population density, building height and building density (see description in Section 1.1). These outputs must be used to feed the SURFEX land surface modelling system, but SURFEX also requieres some other data(Figure 8):, in particular in order to describe the morphology of urban covers

- Building height
- Building density
- Fraction of roads
- Fraction of gardens
- Wall density (surface of walls vs ground-based surface)

Some NEDUM-2D outputs can be provided directly to TEB but most of them must be translated into meaningful data for TEB (SURFEX). Simple rules are then applied to deduce the fractions of buildings, roads, and private gardens required by TEB starting from the surface area actually devoted to residential space (excluding gardens, lobbies, etc.) divided by the constructible surface area (referred to as S_{hab} / S_{build}) simulated by NEDUM-2D. These rules are based on the analysis of accurate data available for Paris intra muros (source: Agence Parisienne d'Urbanisme (APUR)), which indicate that buildings cover 62% of the Parisian urban areas (excluding parks); the remaining 38% are assumed to be covered by roads and courtyards in Paris center and by roads and private gardens in the suburbs (Figure 7). The buildings are 18 m high in average in the city center, and 6 m high in the suburbs.

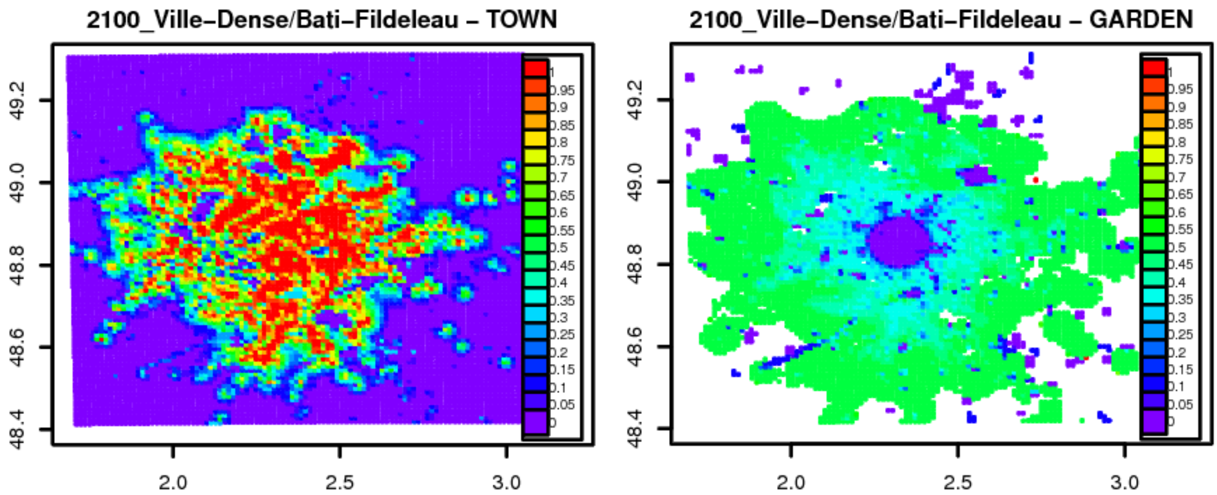


Figure 7 – Example of surface fields defined according to NEDUM's outputs for the sprawl city scenario: fraction of impervious covers (left) and of private garden(right).

NEDUM-2D allows only defining the parameters related to land use and morphology in urban areas. For natural areas (forests, crops, rivers), the project relied on the Corine Land Cover classification.[8] This classification is used in order to define the fractions of land use and land cover outside the city for the SURFEX simulation; the descriptive and physiological parameters of vegetation are prescribed based on the ECOCLIMAP database (Masson et al. 2003) that associates look-up tables to the Corine Land Cover classes. No

[7] Deliverable 1.2: Computation of a thermal comfort index in the TEB urban canopy model. Grégoire Pigeon.
[8] http://www.eea.europa.eu/publications/COR0-landcover

specific information is available for private gardens. They are assumed to be composed of a fraction of grass and a fraction of trees. Their characteristics are prescribed using homogeneous properties all over the domain coming from literature.

Finally, the TEB model needs some information on the material properties and characteristics of buildings and air conditioning systems. These parameters are directly defined through look-up tables that refer to the types and ages of buildings. According to theses criteria, all buildings of the area are classified according to four different typologies:

1. Haussmanniens buildings dating from end of 19th century
2. Multi-family housings
3. Single-family housings
4. Offices

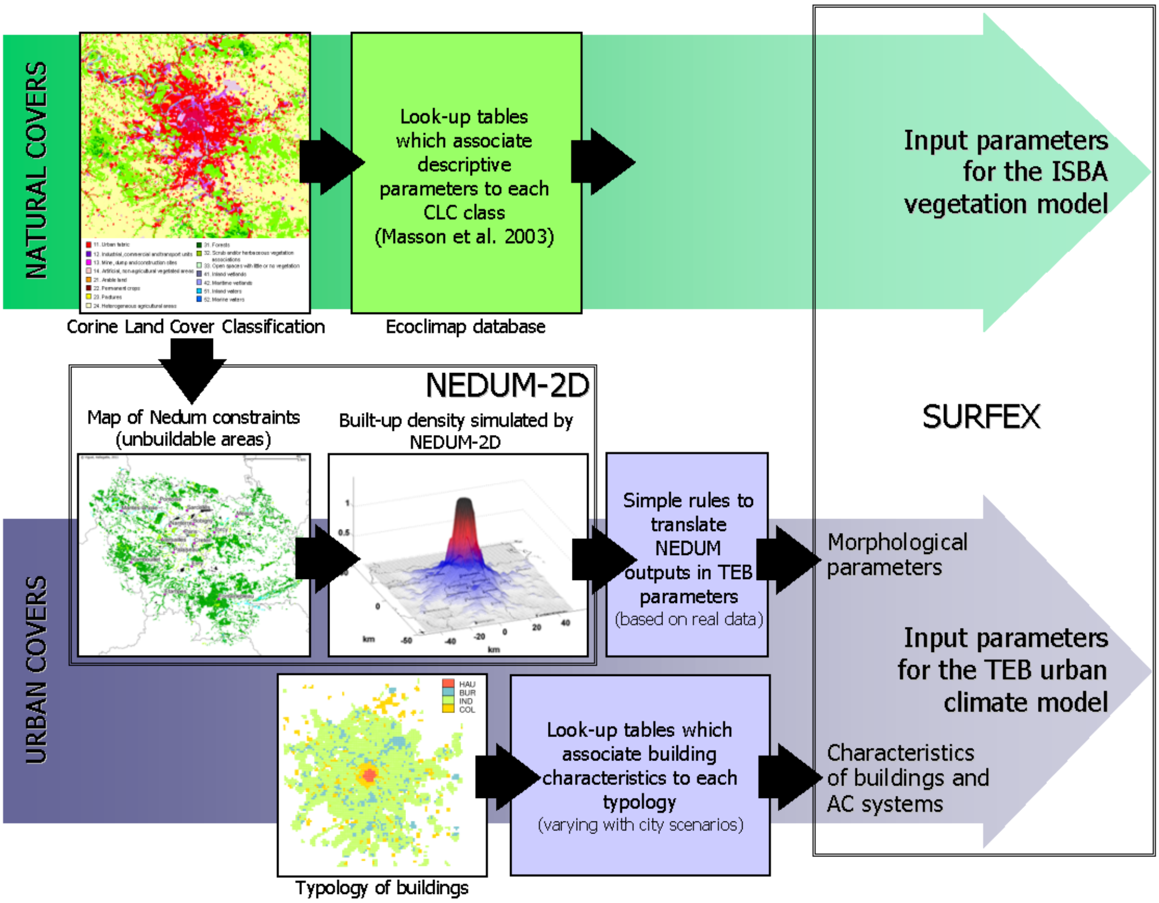


Figure 8 – Description of the methodology applied to translate the results of the NEDUM urban expansion model in input parameters for the SURFEX model.

VURCA's outcome

A methodology has been developed in order to produce in a semi-automatic way the surface fields required for the SURFEX simulations for any integrated city scenario[9], starting from data provided by the NEDUM-2D urban expansion model (plus complementary information linked to typology of buildings).
This systemic approach and framework then allows investigating the complex problem of city vulnerability to heat waves by coupling tools and disciplines.

[9] Deliverable 3.2 : Préparation des champs de surface pour les simulations SURFEX. Aude Lemonsu.

CHAPTER 2
Heat waves events in future climate

As the objective is to study the city vulnerability to future heat waves, a set of climate model projections is analyzed in order to define occurrence probability of future heat waves over the region. A definition for heat wave events is first set, and a methodology is then proposed to extract such events from temperature time series. The same methodology is finally applied to a large number of climate model projections to provide a statistical distribution of heat waves at the end of the century.

2.1 Heat waves definition

Different methodological approaches exist to determine, from observed or simulated temperature time-series, the existence of a heat wave (HW) event (characterized by a peak of intensity and a duration): there is no universal definition in the literature. For the present study, a new heat wave definition is proposed in agreement with recommendations of Robinson (2001). It combines different approaches based on climatic studies and the definition used in French operational heat wave warning system (Plan National Canicule, PNC):

- It fits with the constraints imposed by the analysis of climatic projections (only some meteorological variables are available and with a limited temporal resolution) by using daily minimum and maximum temperatures (Tn and Tx, see Table 1).

- It integrates in a simple way information on sanitary impacts: it computes minimum and maximum temperature indicators (TIn and Tix, see Table 1) as moving averages of minimum (Tn) and maximum (Tx) daily temperatures, respectively, over three consecutive days (D, D+1, D+2). These indicators allow taking into account the heat-stress cumulative effect over time during a heat wave.

The peak of a heat wave event is first identified when either TIn or TIx exceed their respective temperature thresholds (TI1, see Figure 9) applied by the PNC for the corresponding country, i.e., 18 and 34°C for TIn and TIx, in this project (Figure 9).

The heat wave duration is then determined by all adjacent days to the peak for which TIn and TIx values are not, during more than two consecutive days, smaller than the first temperature threshold minus 2°C (TI2=TI1-2, see Table 1). A minimum duration of three days is however imposed.

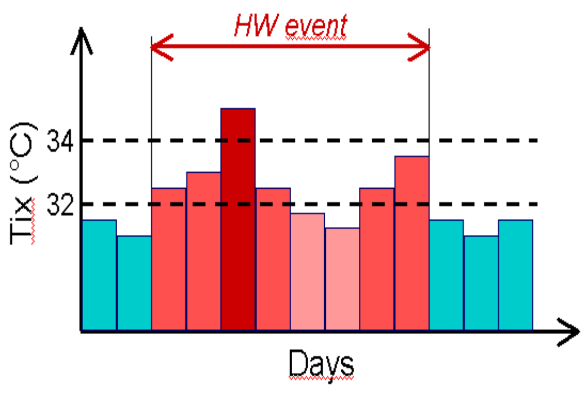


Figure 9 - Methodology of HW extraction. Example for TIx.

This methodology is evaluated via the extraction of observed heat waves from historical time-series of temperature recorded at Chartres and Montereau from 1950 to 2009. The majority of past heat waves listed in the Meteo Fance database (at the country scale) are correctly extracted. Estimated durations are also satisfactory. The main differences are obtained for heat waves that have mainly affected the south of France, and are consequently not extracted or shorter.

Indicator	Definition
Tn Tx	Daily minimum (Tn) and maximum (Tx) air temperatures provided by observed time-series issued from operational meteorological stations or by simulated time-series issued from climate model projections
TIn TIx	Moving average over three consecutive days (D, D+1, D+2) of daily minimum (TIn) and maximum (TIx) temperature
TIavg	Daily average temperature indicator (calculated as the average between TIn and TIx)
TIn1	Threshold of heat wave detection for the daily minimum temperature indicator time-series TIn1 = 18°C for Paris region (according to PNC standards)
TIx1	Threshold of heat wave detection for the daily maximum temperature indicator time-series TIx1 = 34°C for Paris region (according to PNC standards)
TIavg1	Additional threshold defined in VURCA in order to detect a heat wave from the daily average temperature indicator TIavg1 = 26°C for Paris region (calculated as the average of TIn1 and TIx1)
TIn2	Second threshold used to define the heat wave duration for the daily minimum temperature indicator time-series TIn2 = TIn1 - 2°C = 16°C for Paris region (according to PNC standards)
TIx2	Second threshold used to define the heat wave duration for the daily maximum temperature indicator time-series TIx2 = TIx1 - 2°C = 32°C for Paris region (according to PNC standards)
TIavg2	Same as TIavg1 but computed from TIn2 and Tix2 TIavg2 = TIavg1 - 2°C = 24°C for Paris region

Table 1 – Definition of all indicators used in the methodology of HW detection

2.2 Heat waves extraction from climate projection

The evolution of heat waves in a changing future climate (2021-2050, 2071-2100) is analyzed based on a set of 12 climate model projections:

- 9 projections performed with several combinations of regional climate models (RCMs) forced by GCMs following the A1B scenario only (source: ENSEMBLES European project)
- 3 projections performed with the ARPEGE variable-resolution global climate model (GCM) following three emission scenarios (A2, A1B, B1)

TIn and TIx time-series are calculated from Tn and Tx time-series issued from climatic simulations for the closest model grid point to Paris (spatial resolution of 25 and 50km according to the models). Evolution of heat wave events is foreseen over both time-periods 2020-2049 and 2070-2099.

Nine RCM-GCM combinations following one emission scenario (A1B)

According to all climatic projections, a systematic and continuous increase in number of heat waves and cumulated number of heat waves is observed between the 1960-1989 period and the end of the century. By gathering the results of all projections, we extract in average:

- 0.11 HWs per year (and 0.62 HW days) over 1960-1989 i.e. a return period of 9 year;
- 0.44 (2.84 days) over 2020-2049 i.e. a return period of a little more than 2 years, and 1.36 (10.84 days) over 2070-2099.

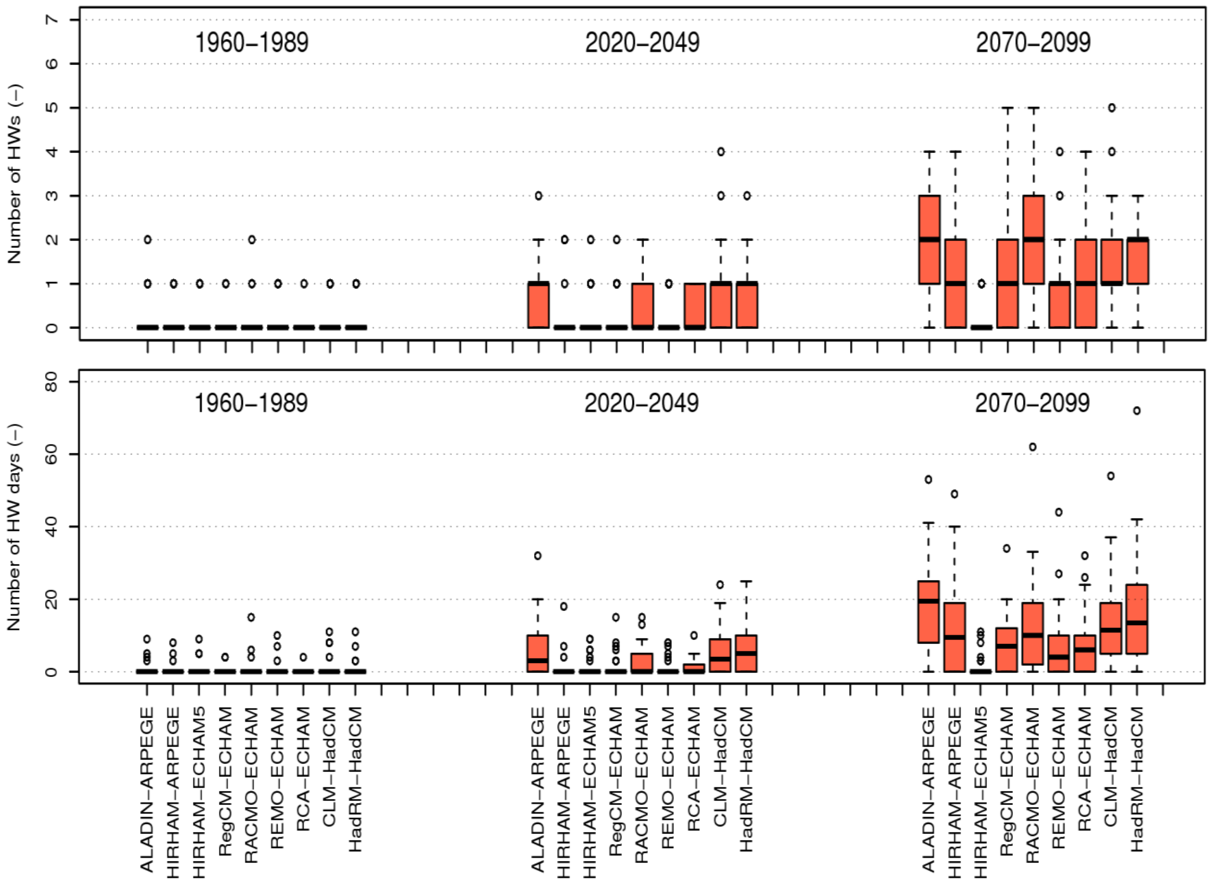


Figure 10 - Number of HWs (top) and of cumulated HW days (bottom) calculated by year over the control period (1960-1989) and both future periods (2020-2049 and 2070-2099) for the 9 climatic projections from ENSEMBLES.

However, a large diversity of results is displayed between the projections (Figure 10): in average, the number of heat waves (heat wave days) by year varies between 0.03-0.17 (0.27-1.03 days) over 1960-1989, between 0.17-0.83 (0.97-5.93 days) over 2020-2049, and between 0.20-1.90 (1.30-17.77 days) over 2070-2099. Some trends are observed depending on the GCMs that force RCMs. More especially, most of RCMs forced by ECHAM5 foresee an increase that is less important than those forced by HadCM or ARPEGE .

One GCM following three emission scenarios (B2,A1B,A2)

An increase in heat wave events and cumulated heat wave days number is also observed using ARPEGE model and three emissions scenarios (Figure 11). Whereas a return period of more than 14 years is obtained in average over the control period, heat waves become much more frequent over 2020-2049 (about 0.53-0.77 heat waves per year in average, and 3.9-4.3 heat wave days) and especially over 2070-2099 (about 1.43-2.27 heat waves per year in average, and 12.5-32.6 heat wave days).

the end of the century, the climatic projection based on A2 scenario (that is the most pessimistic scenario in terms of emission hypothesis) foresees nearly 50% more heat waves and more than the double of heat wave days than the projection based on B2 scenario (that is the most optimistic).

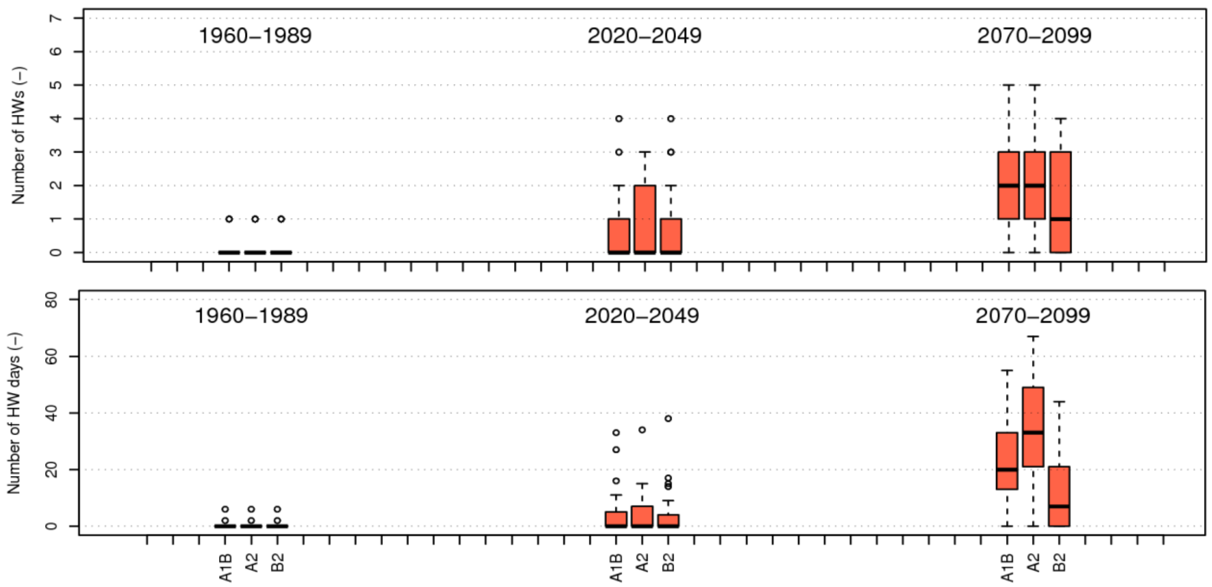


Figure 11 - Number of HWs (top) and cumulated HW days (bottom) calculated by year over the control period (1960-1989) and both future periods (2020-2049 and 2070-2099) for the 3 climatic projections of ARPEGE following 3 different emission scenarios.

2.3 Heat waves classes definition

We define the intensity of a heat wave as the daily maximum temperature averaged over the event. Four classes are then built: less than 36°C, 36-40°C, 40-44°C, and more than 44°C.

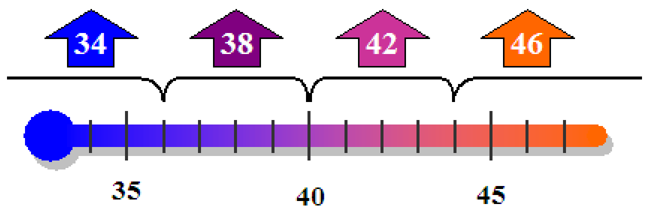


Figure 12: HW proposed classes

The future heat waves extracted from the climate projections are classified into 4 classes according to their intensity (distribution presented in Figure 13). The heat wave durations vary between 3 days (by definition) and 60 days. But the majority of heat waves have a duration which is smaller than two weeks.

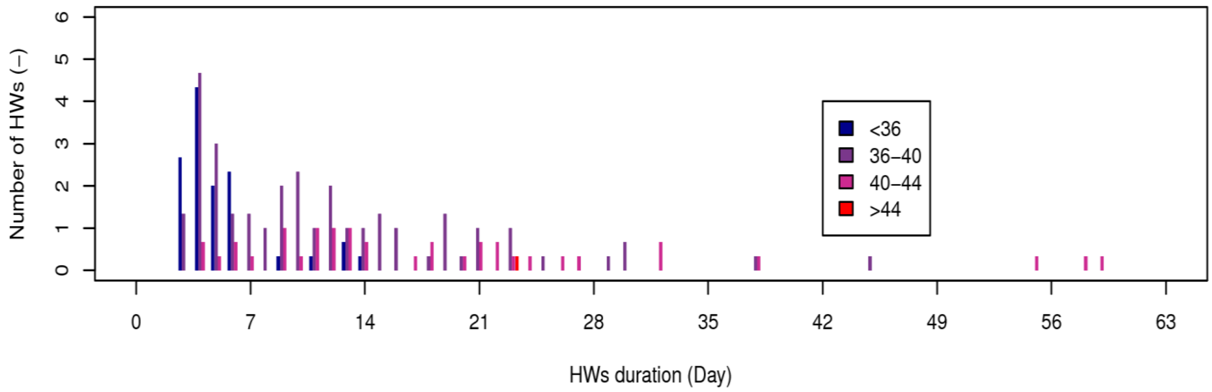


Figure 13- Distribution of future HWs (over 2070-2099) by class of intensity.

2.4 Heat waves modeling methodology

The objective is to simulate the urban climate of the "Paris today" and of Paris in the future (under different scenarios of urban expansion, adaptation measures for buildings, and use air conditioning) for different heat wave conditions in order to assess the vulnerability of the city to such events.

The simulations are performed with the SURFEX land surface modeling system that is run in offline mode (in order to achieve a large number of simulations) over a spatial domain of 100 x 100 points, centered on Paris, with a horizontal resolution of 1 km. A set of synthetic (or idealized) heat waves is modeled, based on the 2003 heat wave but corrected in duration and intensity in order to replicate the different classes of heat waves that are statistically representative of future climate (see 2.3). A 3 steps comprehensive methodology (Figure 14) is developed in order to build the atmospheric forcing and to implement the simulations.

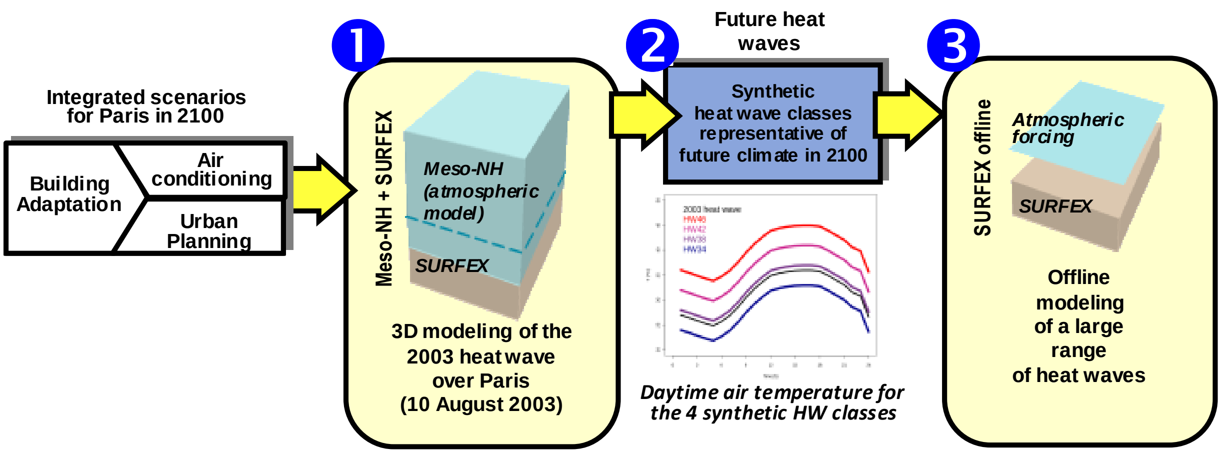


Figure 14 - Description of the modeling methodology

Step 1. Meso-NH simulation of a heat wave day

For each city scenario, a 3D atmospheric simulation of the 10th August 2003 is run with the Meso-NH non-hydrostatic model. This day has been selected among the six successive days of the 2003 heat wave (8th-13th August) that was already studied in previous projects

(EPICEA/CLIM2)[10], because it is a sunny day with clear sky and weak wind. This numerical configuration enables to simulate the impact of the city on the atmospheric boundary layer. This impact is directly related to the city scenarios, considering that for each simulation the surface data are computed in accordance with the studied scenario.

Step 2. Construction of synthetic heat waves

The meteorological fields required to force SURFEX are extracted from the Meso-NH simulations: air temperature, humidity, wind, and pressure at 15 m above the top of the canopy, and solar and infrared incoming radiation.

The hourly temperature fields are then corrected in order to readjust the maximum daily temperature to that of the heat wave classes that have been defined in Section 2.3, (i.e., Tmax=34, 38, 42, and 46C as shown in Figure 15). The specific humidity is also corrected to maintain constant the relative humidity value, and the infrared incoming radiation is recomputed to account for the modification in air temperature (and thus in emission by the atmosphere).

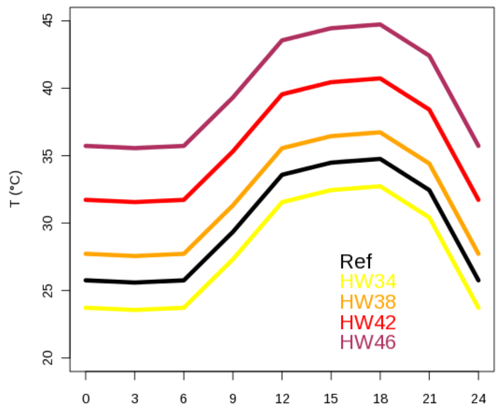


Figure 15 - Example of daytime evolution of air temperature for 2003 HW (referred to as REF) and the four classes of HWs

Step 3. Urban climate simulation with SURFEX

A 21-days offline simulation is performed with SURFEX for each scenario and each class of intensity (by duplicating the 1-day forcings built based on the Meso-NH simuations). A previous analysis indicated that beyond 21 days, the microclimatic variables reach a plateau. As a result, their evolution for the next days can be easily extrapolated which enables to limit the length of simulations.

VURCA's outcome	The originality of the methodology is to combine the approaches from climatic studies and the definition used in an existing operational heat waves warning system: heat wave events are extracted from climate model projections taking into account in simple way the heat-stress cumulative effect in time associated with heat waves. The methodology has been evaluated from historical long-term series and has shown its ability to accurately identify past heat waves over Paris' region[11].

[10] See http://www.cnrm.meteo.fr/ville.climat/spip.php?article175 and http://www.cnrm-game-meteo.fr/spip.php?article271&lang=en

[11] Deliverable 3.1: Note on the analysis of heat waves events in present and future climate. Anne Lise Beaulant, Aude Lemonsu

CHAPTER 3
Definition of indicators related to urban heat waves

Before introducing VURCA indicators, it is important to make clear the difference between “hazards” that may occur as a result of climate change and “vulnerability”. According to IPCC (2007b):

- **Hazard** is a particular climate-related event, such as floods or heat-wave. This type of event is characterized by a probability of occurrence and a magnitude.
- **Exposure** is defined as *“the nature and degree to which a system is exposed to significant climatic variations.”*
- **Sensitivity** is *“the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli.”*
- **Vulnerability** (or **risk**) is *“the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity”.*

The vulnerability is then the result from the three components hazard, exposure, and sensitivity in the face of the event (Figure 16). Reducing the vulnerability requires action in each of these components. Mitigating a hazard or its probability is directly linked to mitigating climate change, i.e. reducing GHG emissions. Acting on exposure and sensitivity to reduce the vulnerability is what is generally known as "adaptation" to climate change.

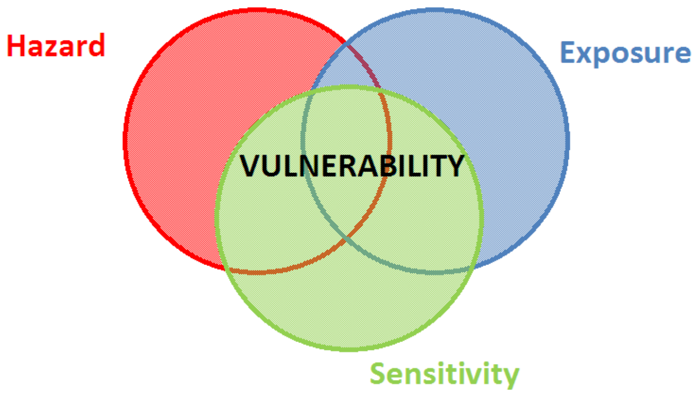


Figure 16 - Representation of vulnerability

Note that we use here the definition often used in the climate change community (cf. glossary in IPCC 2007a). It should be noted that other definitions also exist in the literature (cf. for instance Füssel 2007). For example, "vulnerability" is often used as an equivalent of "sensitivity ", with, therefore, a meaning differing from the meaning of “risk” (Kron 2002).

3.1 VURCA's indicators

In this project, here is how the definitions of "hazard", "exposure" and "sensitivity", (cf Figure 17) are translated into indicators:

Hazard	As explained in chapter 3, Heat wave events are defined by their intensity (maximum daytime temperature), duration (number of days), and probability of occurrence (that are affected by climate change).
Exposure	We do not consider the impact of heat waves on goods and properties, neither on businesses. The exposure is therefore given by the population exposed to heat waves: in this project, we suppose that it is the entire urban population. This population is defined by the total number of inhabitants and its spatial distribution. Some demographic hypotheses are used to foresee the population of Paris urban area in 2100 (see Project deliverables).
Sensitivity	For any given heat wave, a set of **heat wave sensitivity (HWS) indicators** is proposed to evaluate the sensitivity of the city, i.e. the degree to which the city is affected by this heat wave, which is characterized by its intensity and its duration. This sensitivity is measured in terms of: • thermal stress for the population, • energy consumption due to air conditioning, • water consumption for gardens watering.
Vulnerability or **Risk**	Degree to which a city will be affected by a set of heat waves statistically representative of future climate: it is given by the expected value of the sensitivity indicators, when averaging over all the heat waves, taking into account their probability. A set of **heat wave vulnerability (HWV) indicators** is defined, which measure the vulnerability in terms of: • thermal stress for population, • energy consumption due to air conditioning, • water consumption for gardens watering.

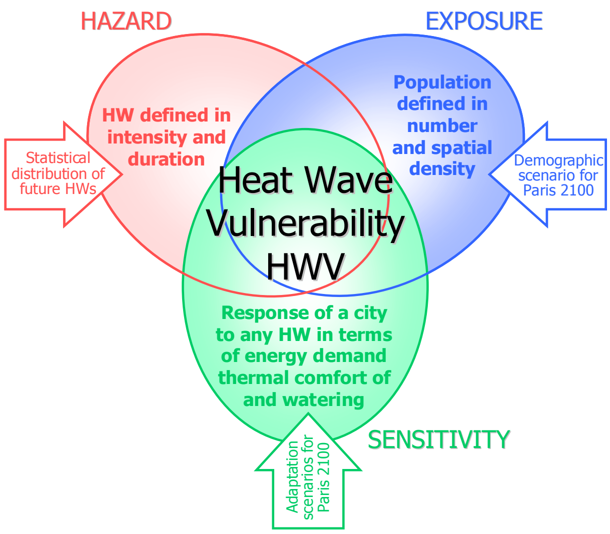


Figure 17 - Risk framework in VURCA project.

The **heat wave sensitivity set of indicators** is computed for **each class of heat wave** (duration/intensity) so that one should be able to deduce the seriousness of any heat wave (for combination intensity/duration) that could affect the city.

The **heat wave vulnerability set of indicators** is computed from the **sensitivity indicators weighted** according to the occurrence probability of heat wave classes in future climate (as shown in Figure 13 and in the matrix plotted in Figure 18).

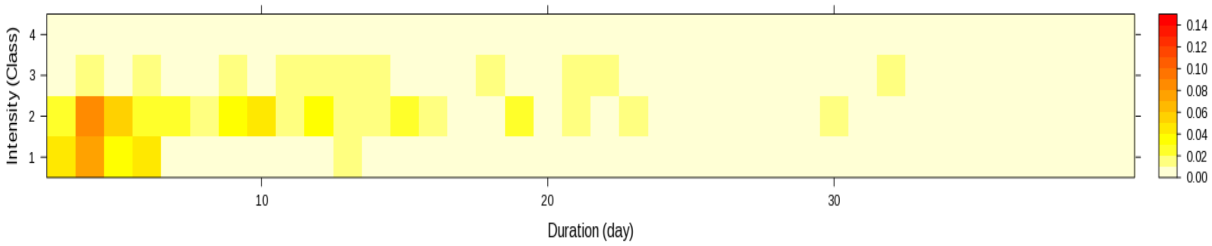


Figure 18– Matrix of occurrence probabilities for future HWs (computed for the period 2070-2099) depending on their durations and intensities.

In the VURCA project, the proposed methodology does not pretend to cover all components that can describe the vulnerability of the city of Paris to future heat waves. Indeed, because of the models that are used to simulate the impact of heat waves on Paris (see Section 1.2), the vulnerability is quantified only in terms of thermal stress for population, energy consumption related to air-conditioning and water consumption. On the other hand, the exposure component is addressed in a very simple way since only the impacts on the population are assessed (and not the impacts on goods, properties, or businesses) and only one demographic scenario is considered for Paris in 2100. Similarly, the population is considered as a whole, and no distinction is made between various socio-economic groups whereas some may be more sensitive to heat stress than others (elderly people, especially).

3.2 Evaluation of thermal comfort

Thermal comfort (or thermal stress) for inhabitants is calculated using the indoor and outdoor universal thermal climate index (UTCI) implemented in TEB (see Section 1.2), and depending on air temperature, air humidity, wind, and radiation.

The assessment scale for the UTCI has been established and categories of heat stress responding the terms from the Glossary of Terms for Thermal Physiology (2003) have been assigned for levels of UTCI according to Figure 19.

UTCI (°C) range	Stress Category	
above +46		extreme heat stress
+38 to +46		very strong heat stress
+32 to +38		strong heat stress
+26 to +32		moderate heat stress
+9 to +26		no thermal stress
+9 to 0		slight cold stress
0 to -13		moderate cold stress
-13 to -27		strong cold stress
-27 to -40		very strong cold stress
below -40		extreme cold stress

Figure 19 - UTCI assessment scale in terms of thermal stress

In the project, the thermal comfort is assessed for 5 different daily profiles of activity (Figure 20). Time series of UTCI are built at each grid point of the modeling domain (preferentially covered by housings) according to these daily profiles by associating to each hour of the day the UTCI that corresponds to the location of people (cf. Figure 20). These times series are used to calculate the number of hours per day spent over the different thresholds of discomfort or heat stress. The results are integrated spatially over the city according to a weighting depending on the population density provided by NEDUM.

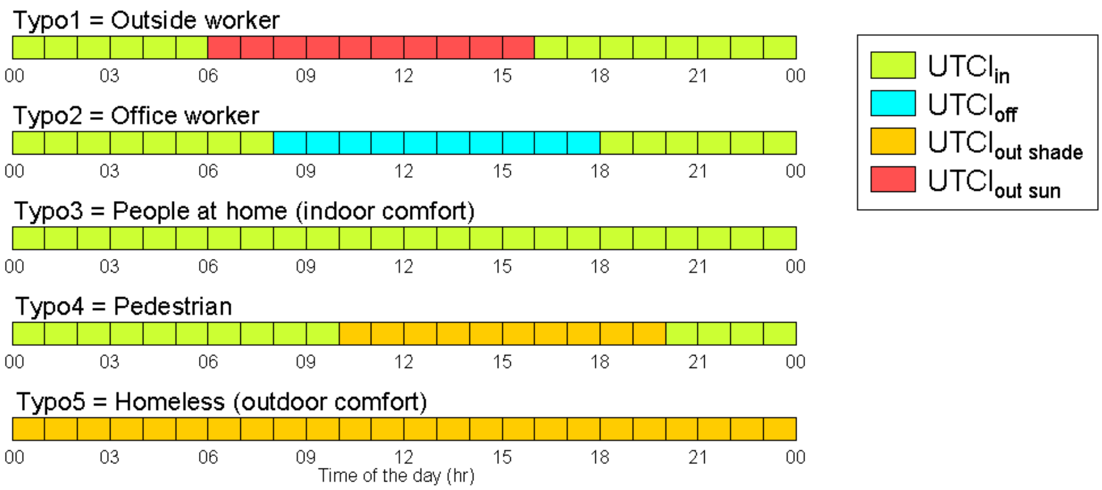


Figure 20 – Daily profiles of activity (and associated UTCI) for the 5 typologies of people.

3.3 Evaluation of energy consumption

Four indicators are identified to evaluate the energy consumption due to air conditioning:

INDICATOR	UNIT	DEFINITION
Cumulated energy consumption **E_{cum}**	Wh_{EF}	This indicator is integrated with time over all the duration of the heat wave event, and integrated spatially over the city by weighting the energy consumption according to the population density.
Cumulated energy consumption per m² of floor **E_{cum/m^2}**	$Wh\ m^{-2}_{EF\ or\ EP}$	The same methodology than for E_{cum} is applied but relative to the m^2 of floor (evaluated from the building heights coming from the NEDUM simulations and from the height of a standard floor).This energy can be converted in primary energy (in order to relate the results to the requirements of the French Grenelle de l'Environnement law, for instance) by using the standard conversion coefficient of 2.56 used for electric energy
Instantaneous maximum power **P_{max}**	W_{EF}	It is the instantaneous maximum power reached over the city during a heat wave event. It is computed from the energy consumption spatially integrated over the city at each time step
Maximum overpower **ΔP_{max}**	$W\ °C^{-1}_{EF}$	It is the variation in maximum power generated by an 1°C increase in air temperature. It is calculated according to the maximum powers reached during two heat waves of same duration but of different intensities. The maximum powers are compared by couples of heat waves that are part of two successive classes of intensity, i.e. HW34 vs HW38, HW38 vs HW42, and HW42 vs HW46. For instance: $\Delta P_{max\ [HW38]} = (P_{max\ [HW38]} - P_{max\ [HW34]}) / 4$

3.4 Evaluation of water consumption

Water availability of natural soils is essential for an optimal role of green spaces in the city in terms of cooling effect and improvement of outdoor comfort. Especially, during heat wave events which are frequently associated with a dryness of natural soils, the vegetation watering and consequently the assessment of water consumption are key issues.

For the present study, gardens watering is simply simulated in the model by maintaining the water content of the soil reservoir to 50% at least. Thus, the vegetation is never under water stress conditions.

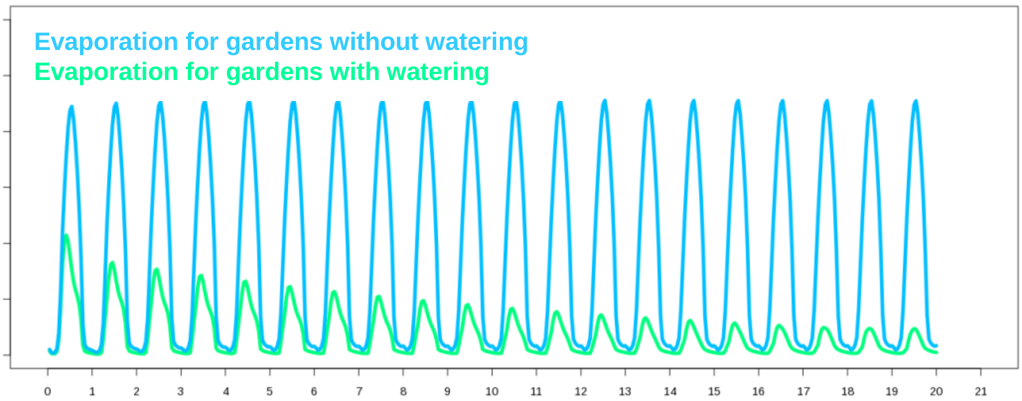


Figure 21 – Comparison between evaporation from gardens simulated for the scenarios with (blue) and without (green) watering.

Water consumption related to watering is quantified by comparing the total amount of evaporation from gardens during two simulations performed with or without watering (but for a same integrated scenario for the other trends). It is assumed that the excess in evaporation obtained for the scenario with watering compared to the one without watering (Figure 21) is directly equal to the amount of water supplied for gardens.

VURCA's outcome	The indicators developed within VURCA's project link large-scale climate information to local seriousness of a heat wave event, but also the characteristics of urban morphology, buildings and inhabitant's behaviors to the vulnerability of a city to such events[12]. Thanks to models improvements, VURCA's indicators take into account 3 key impacts: thermal stress for population (indoor and outdoor), energy consumption due to air conditioning, and water consumption for gardens watering, but also the specifics of urban climate.

[12] VURCA deliverable DEL5.1 : Indicateurs VURCA : Méthodologie et résultats. Aude Lemonsu.

CHAPTER 4
City adaptation strategies

Regarding urban structure, adaptation strategies can be related to urban compactness and to the introduction of green or blue areas. As far as buildings are concerned by adaptation strategies, elementary actions can for instance address the urban tissue geometric characteristics (i.e. size, location and orientation of buildings), and the radiative properties of urban surfaces materials (roofs, walls, streets, free spaces).

These strategies then address complex and potentially contradictory issues (e.g. search for coolness versus energy consumption related to cool production, implementation of high albedo surfaces versus outdoor visual comfort, search for coolness through vegetation versus water consumption).

Within the VURCA project, we focus on the following adaptations strategies:

- Land use policy
- Transformation of the built environment
- Air conditioning usage

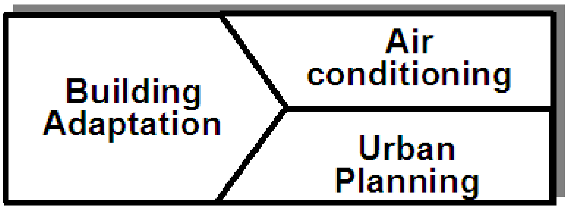


Figure 22- VURCA's adaptation strategies

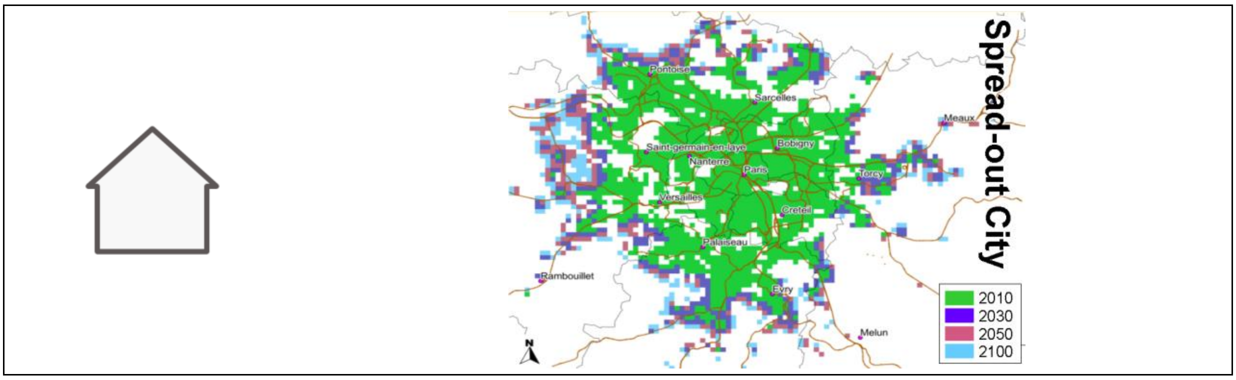
The potential impact of proposed adaptation measures (i.e. influence on outdoor and indoor temperatures and heat balance) is assessed through numerical simulation using the TEB-SURFEX environment presented in 1.2. The output of such simulation does not pretend to be an "exact" temperature mapping over the urban area in a given situation. The added value is a comparison of outcomes corresponding to various sets of input data.

4.1 Urban structure adaptation strategies

NEDUM-2D model was used to simulate three alternative scenarios for urban structure development. All three are based on the same demographic and techno-economic scenario, but three different hypothesis have been used for future land-use policies:

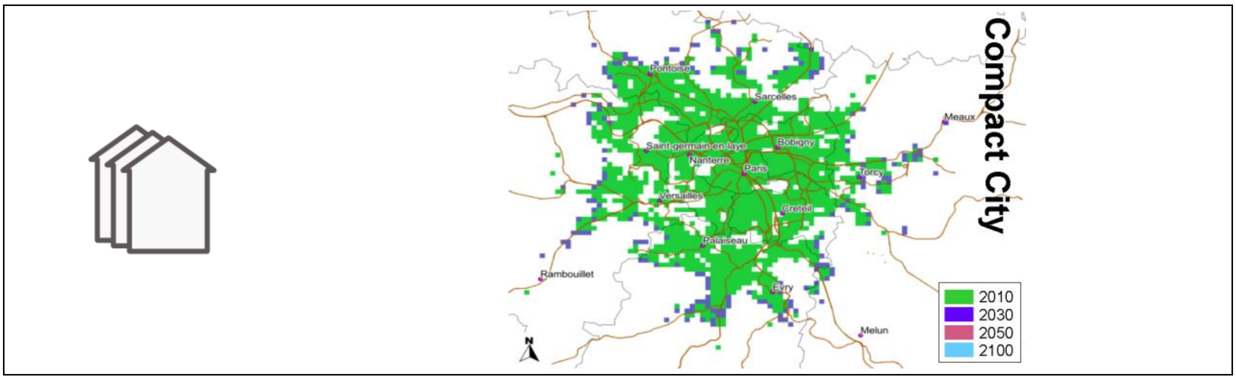
Spread-out city (S)

No effective containment policy is carried out. Urbanization is supposed to be driven only by market forces.



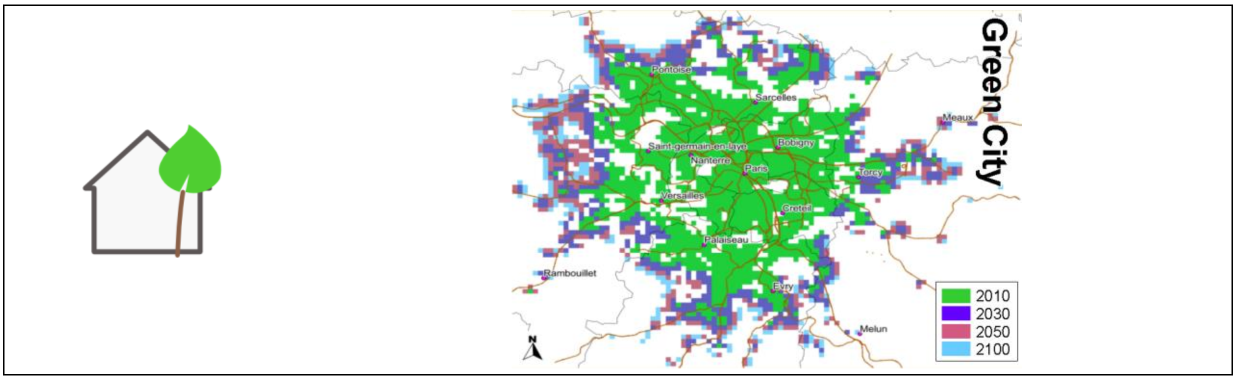
Compact city (C)

A “green-belt policy” forbids from 2020 on any new construction in locations which are not already densely inhabited. Additional development is therefore carried out through densification of the city center. The city expansion is therefore the same in 2030, 2050 and 2100, and the maps of the city are similar for these three years.



Green city (G)

No effective containment policy is carried out, but numerous parks are introduced in the city. We suppose that, in 2020, 10% of all built surfaces is not built to leave space for urban parks. After 2020, 10% of all newly urbanized surfaces have to be doted to parks. Urban extension is therefore bigger in this scenario than in the « Spread-out city » scenario.



The assessment of related socio-economic costs is made through the analysis of the policies that could lead the city development into this direction (e.g., transportation taxation, land-use regulation, etc.), with their final and transitory costs. In VURCA's deliverable DEL4.1, you can find a detailed presentation of the simulations.

Urban scenarios cross-comparison

Land-use policies promoting green spaces in the city: the "Green city scenario". In this scenario, the obligation to devote 10% of land to new urban parks increases land scarcity, and therefore leads to increased rents, when compared to the reference "spread-out" scenario (**Erreur ! Source du renvoi introuvable.**).

In this scenario, because of the lack of construction space, households have to locate further in the suburb than in the reference scenario. Urban sprawl is therefore increased. This leads to an increase in total transport demand in the city. Because of green spaces, city population density is lower than in the reference scenario, which leads to a decreased modal share of public transport. Because of these two factors, private car use and transport-related GHG emissions are higher in this scenario than in references scenario (Figure 24).

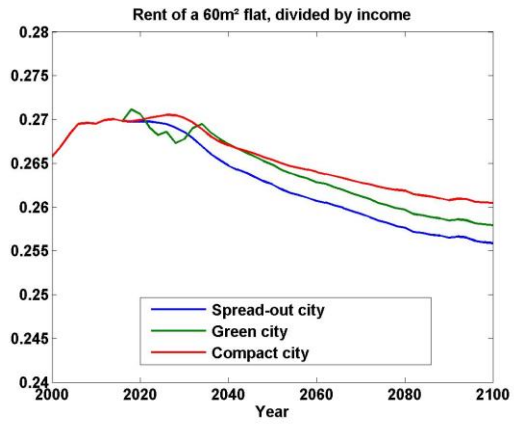


Figure 23 - Comparison of rents level in the center of Paris in the three scenarios

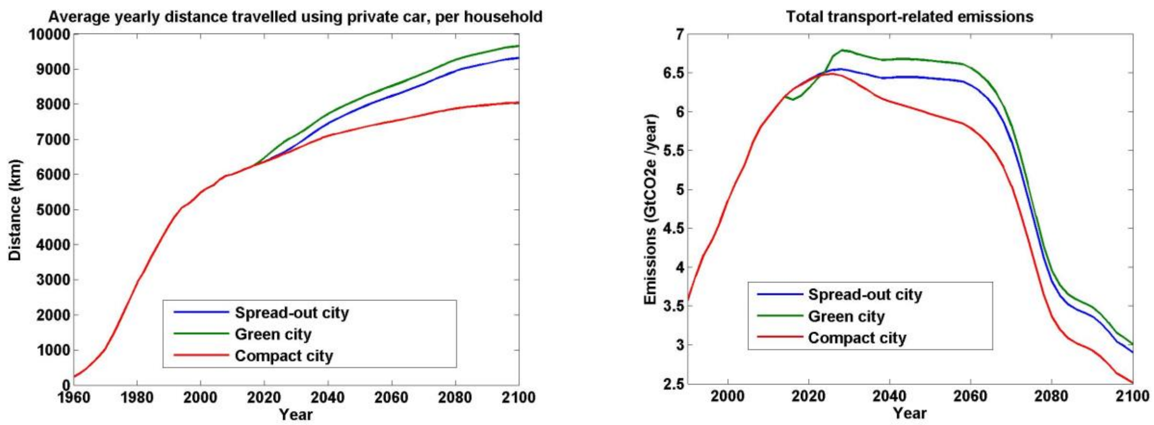


Figure 24 - Average distance traveled by car per household and total transport-related GHG emissions in the three scenarios.

Land-use policies densification over urban sprawl: the "compact city scenario". In this scenario, city extension is much smaller than in the two other scenarios, but total garden surface is also much smaller, and city is denser (Figure 25). The effect of such a policy on UHI is therefore a priori unclear.

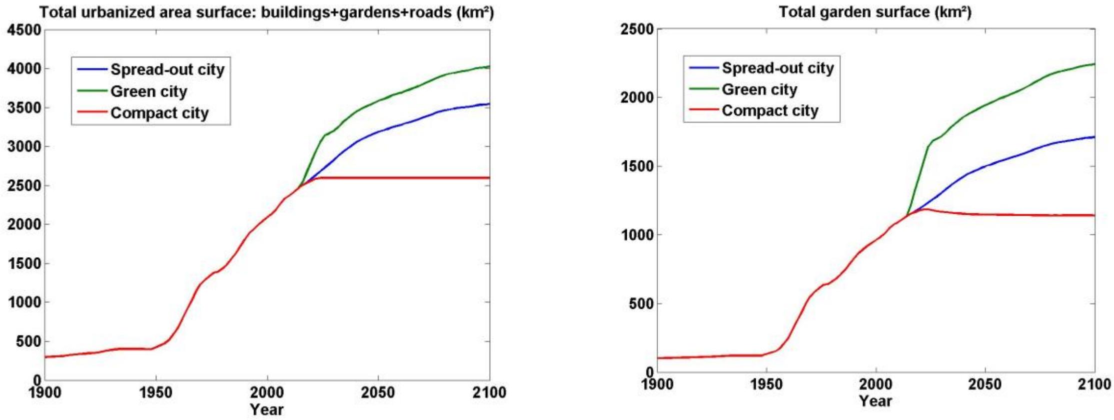


Figure 25 - Total urbanized area, and total garden surface in the three scenarios

In such a policy, as the city is denser, transport-related GHG emissions are lower than in the two other scenarios (Figure 23). However, such a restrictive land-use policy leads high rents because of the lack of available building space (Figure 23).

4.2 Building adaptation measures

Improvements of performance materials up to 2100

The Paris built environment can be presented according to main building characteristics associated to periods of construction. They reflect the evolution of the know-how, the introduction of innovation and the architectural choices. Since 1974, regularly more demanding thermal performance regulations introduce a new factor of evolution (Figure 26).

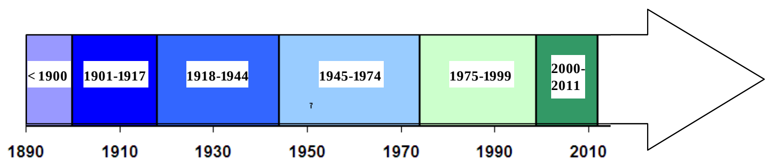


Figure 26 – Construction periods in the past

Within the VURCA project, the following parameters were chosen to reflect these evolutions:

- wall and roof insulation
- internal thermal loads
- ventilation rate
- glazing ratio
- wall and roofing structural material
- air conditioning equipments performances
- type and location of air conditioning condensers

For the future, the VURCA project assumes that new regulations and technical improvements are likely to contribute to the definition of adaptation measures.

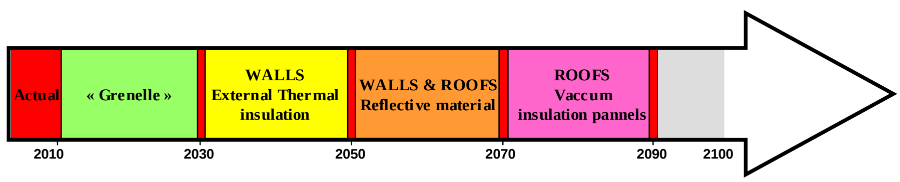


Figure 27 – Regulations and improvements steps in the future

The “Grenelle” period is a major current step concerning building energy performance improvement that will shape the built environment during the next decades. The current regulation will be followed by others at periods which are unknown. We cannot know the content of these future regulations, but we made assumptions concerning possible evolutions of the characteristics of buildings envelopes (mainly walls and buildings) both for new and existing constructions (Figure 27). These measures are said to be the base for adaptation measures.

For obvious technical and economic reasons, the implementation of adaptation measures cannot be instantaneous over a whole urban area. Time is needed to progressively introduce relevant technologies: this time is called “technology introduction time constant” and its value varies according to building types and scenarios.

We suppose, that, for any given year, all buildings of the same class (offices, individual buildings, collective buildings or Haussmanian buildings) have identical properties, and that these properties correspond to the regulation enforced a few years earlier, this number of years being equal to the “technology introduction time constant”.

The VURCA project defines two scenarios related to buildings: **“Business as usual” and “Virtuous”.** They correspond to two contrasted dynamic introduction schemes of adaptation measures up to 2100.

Business as usual building scenario

New and existing buildings meet known regulatory requirements and comply with progressive improvements in performance materials, without significant disruption in technologies or inhabitants behavior. This corresponds to an extension of current trends.

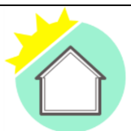
Technology introduction time constant is the same as currently

Progressive improvements in performance materials are introduced following the same pace

Business as usual building

Virtuous building scenario

A more proactive implementation of proposed solutions is proposed, with time constant of technologies introduction evolution shorter than in the past: buildings are then renovated more quickly that in the past.



Technology introduction time constant shorter than in the past

Proactive implementation of efficient solutions

Virtuous building

Figure 28 is an overview of the projected 2100 situation, showing the main characteristics of buildings according to these two scenarios.

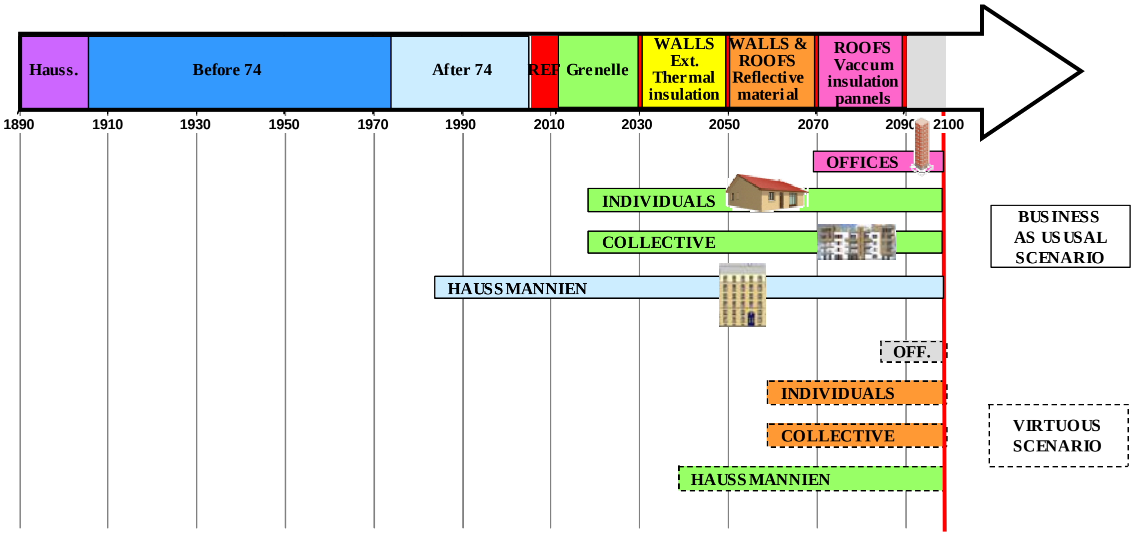


Figure 28 – Overview of building adaptation measures versus building type and scenarios

As shown in Figure 28, such an approach leads to a situation in which, in 2100,

- in the Business as usual building scenario, offices comply with the 2070 legislation, Individual and collective buildings comply with the 2010 legislation, and Haussmanian buildings with the 1974 legislation
- in the Virtuous building scenario, offices comply with the 2070 legislation and Individual and collective buildings with the 2050 legislation. We supposed that external thermal insulation was not possible for Haussmanian buildings, because of their historical value. They therefore comply with the 2010 legislation.

4.3 Air conditioning usage adaptation measures

Air conditioning use has an impact on both energy consumption, indoor comfort, but also on outdoor air temperature (De Munck, 2011). Air conditioning use is determined by the temperature set point and assessed through numerical simulation using the TEB-SURFEX environment. Three scenarios are proposed within the VURCA project.

Intensive use of air conditioning

The use of air conditioning continues and is event faster than its current growth curve so that all buildings are equipped with air conditioners in 2100, and all inhabitants set a temperature set point lower than recommendations

Moderate use of air conditioning

Air conditioning usage is limited: all buildings are equipped with air conditioners, but inhabitants set a "moderate" temperature set point equal or higher to recommendations.

No air conditioning

No building is air-conditioned.

	T= 23°C	AC intensive use
	T= 26 or 28°C	AC moderate use
		No AC

4.4 Combined adaptation strategies

The set of adaptation strategies proposed here to address the various issues of urban expansion, buildings adaptation, and air conditioning use lead to a total of 24 integrated scenarios, plus a reference case scenario corresponding to today's Paris (ie, Paris simulated with NEDUM-2D in 2006), as described in Table 2.

As land use policies are highly dependent on vegetation management, watering of urban green spaces has been studied for most of the integrated scenarios.

For each scenario, 21-day simulations corresponding to the four classes of heat wave intensity are performed (following the methodology described in section 2.4), and the HWS and HWV presented in Section 3.2 are calculated.

VURCA's outcome	VURCA's team has performed a systemic analysis based on interdisciplinary exchanges: the proposed integrated scenarios combine assumptions describing different urban planning or building adaptation policies, as well as inhabitant's behaviors[13]. Scenarios are thus created up to the end of the century, in a consistent and contrasted way to be evaluated by the systemic framework tool.

[13] Deliverable 4.3: Les scénarios "Bâti et usages de la climatisation" et leur simulation. Colette Marchadier, Grégoire Pigeon, Jean Luc Salagnac.

Year	Urban expansion	Adaptation measures for buildings	Usage for air-conditioning	Watering	Simulation code	Combination of action levers
2006	NEDUM-Paris	Business as usual	Intensive (offices only)	No watering	RNFFN	
2100	Sprawl city	Business as usual	Intensive	No watering	CFFFN	
				Watering	CFFFA	
			No AC	No watering	CFFNN	
				Watering	CFFNA	
		Virtuous	Moderate	No watering	CFVMN	
				Watering	CFVMA	
			No AC	No watering	CFVNN	
				Watering	CFVNA	
2100	Compact city	Business as usual	Intensive	No watering	CDFFN	
				Watering	CDFFA	
			No AC	No watering	CDFNN	
				Watering	CDFNA	
		Virtuous	Moderate	No watering	CDVMN	
				Watering	CDVMA	
			No AC	No watering	CDVNN	
				Watering	CDVNA	
2100	Green city	Business as usual	Intensive	No watering	CVFFN	
				Watering	CVFFA	
			No AC	No watering	CVFNN	

Table 2 - Description of the 25 integrated scenarios

CHAPTER 5
Evaluation of adaptation strategies

Adaptation strategies have been evaluated in 2 steps. First, the impact of heat waves has been analyzed on present day Paris urban area (as simulated by the models), without any adaptation measure, in order to estimate the heat stress and energetic sensitivities of any possible heat waves.

Then, the integrated scenarios have been simulated in order to evaluate the city vulnerability to future heat waves, taking into account their probability of occurrence. Comparison of the vulnerabilities then allows evaluating the adaptation strategies.

5.1 Analysis of heat waves impact on present day Paris

Sensitivity to heat stress

The number of hours per day spent in the different conditions of heat stress is presented in Figure 29 for the five typologies of people and the four classes of heat wave intensity.

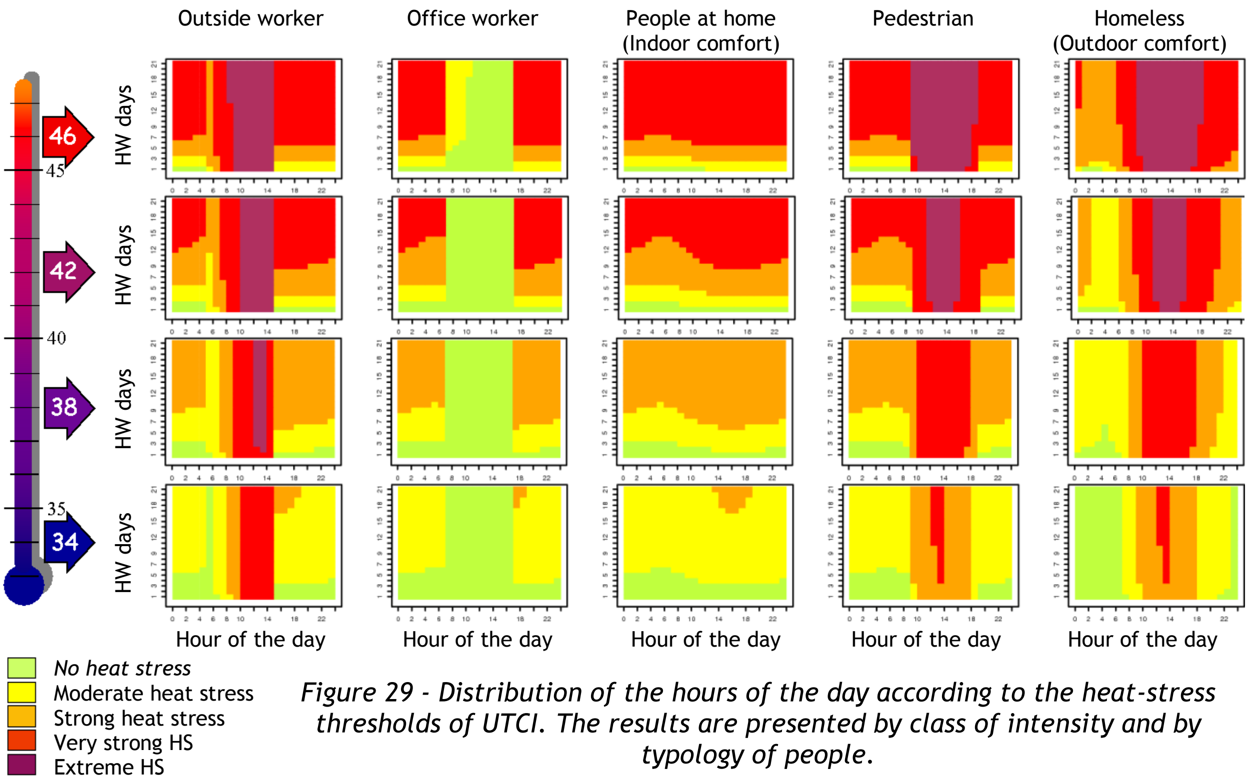


Figure 29 - Distribution of the hours of the day according to the heat-stress thresholds of UTCI. The results are presented by class of intensity and by typology of people.

Different findings are highlighted:

- For all profiles, thermal discomfort increases with both duration and intensity of heat waves. But the evolution over time varies according to the typology of people: a plateau of discomfort is reached after several days of heat waves; this number of days depends on the typology of people and heat wave intensity.

- Generally, the least vulnerable people are "office workers" because they spend the hottest hours of the day in air-conditioned buildings, and to a lesser degree "people at home" which are not exposed to uncomfortable outdoor conditions.
- The most vulnerable people are "Outside Worker" which are always in the sun during working hours, and "Homeless" that are exposed to additional nighttime discomfort.

The most extreme discomfort conditions are reached outdoor, but for the longest heat waves, the nighttime indoor discomfort increases sharply due to inertia of buildings without air-conditioning. Buildings warm gradually until heat stress conditions exceed high (HW38) or very high (HW42 and HW46) thresholds.

Finally, two types of conditions are opposed:

- The outdoor comfort is characterized by a significant daily variability of comfort/discomfort conditions. For the longest and most intense heat waves, several hours of extreme heat stress are accounted (up to 8 hours per day for HW46), but inversely a portion of the day is spent in conditions of high stress "only ".
- The indoor comfort/discomfort conditions are much more homogeneous. Although the threshold of extreme heat stress (>46°C) is never reached, all the day can be spent in conditions of very high heat stress (between 38 and 46 °C).

Figure 30 represents the number of hours spent at least in conditions of high heat stress, for the 4 intensity classes and for durations up to 21 days; data is cumulated day by day, and then expressed for an average day.

In terms of outdoor comfort, the HW46 intensity class is always more serious in terms of thermal stress than other classes, whatever the duration of the event.

For other typologies of people (which spend at least 14 hours per day at home or at home/office, see Figure 20), the same number of hours in high heat-stress condition can be obtained between two heat waves of different intensities and durations (except for HW34 Vs HW46). For example, a 3-day HW46, a 5-day HW42, and a 9-day HW38 are comparable in terms of number of hours in a high heat-stress condition. The same is true of a 7-day HW46, a 11-day HW42, and a 19-day HW38.

This indicator enables certainly comparing heat waves, but not concluding on their health impact. For the same number of hours spent in high heat-stress condition, which event induces the most serious consequences for health? A heat wave that is very hot but short, or a heat wave that is less hot but much longer?

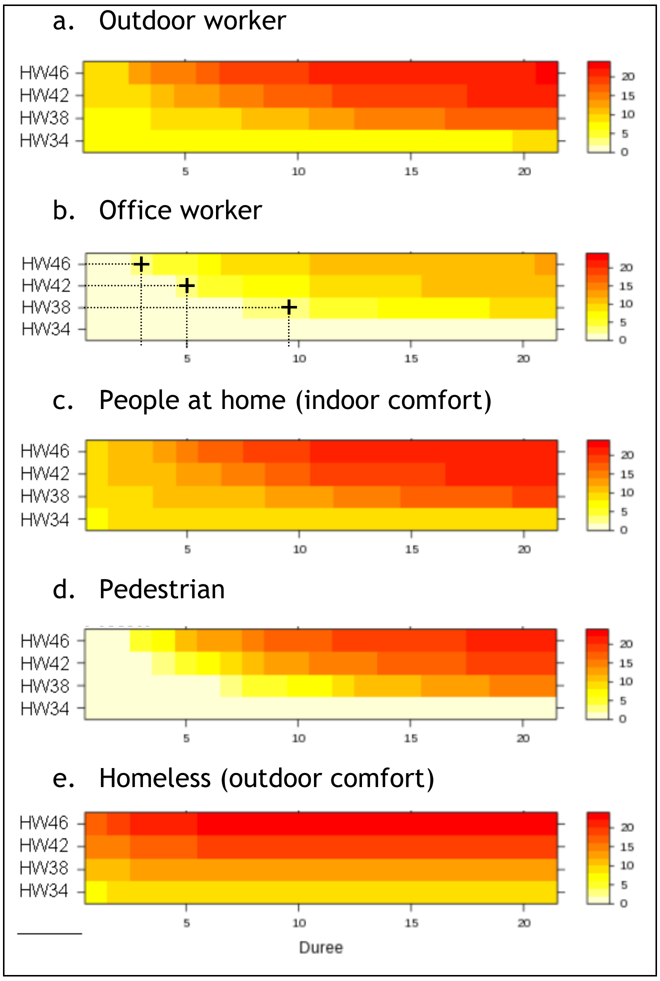


Figure 30 - Number of hours spent in high heat-stress condition, cumulated day-by-day and expressed for an averaged day. The diagram represents HW duration on the X-axis and HW intensity on the Y-axis

Energetic sensitivity of heat waves

The day-by-day evolution of the four sensitivity indicators during a 21-day heat wave is presented in Figure 31. These indicators are calculated for Paris 2006 (simulated by NEDUM) and for the four classes of heat wave intensity. Data are spatially integrated over the city, and calculated as final energy.

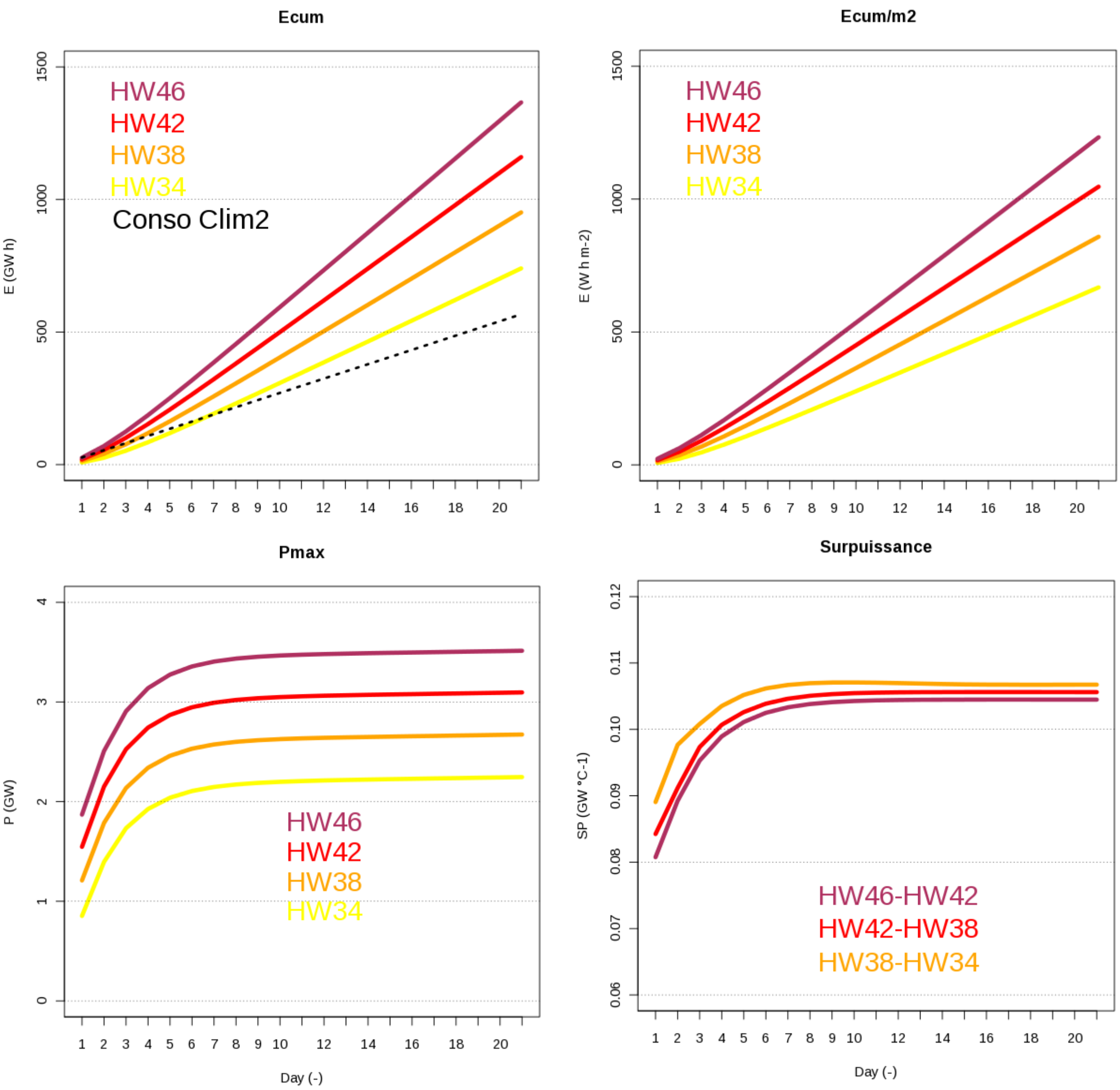


Figure 31 – Day-by-day evolution of cumulated energy (top, left), cumulated energy per m^2 of floor (top, right), maximum over-power (bottom, left), and over-power (i.e. variation in maximum power generated by an 1°C increase in air temperature: bottom, right) for 2006 NEDUM-Paris according to the four classes of intensity.

The analysis highlights the following results:

The electricity consumption cumulated in time (E_{cum}) increases with the intensity of the event. This increase rapidly becomes linear. Indeed, a plateau of daily consumption is reached after several days (Figure 32).

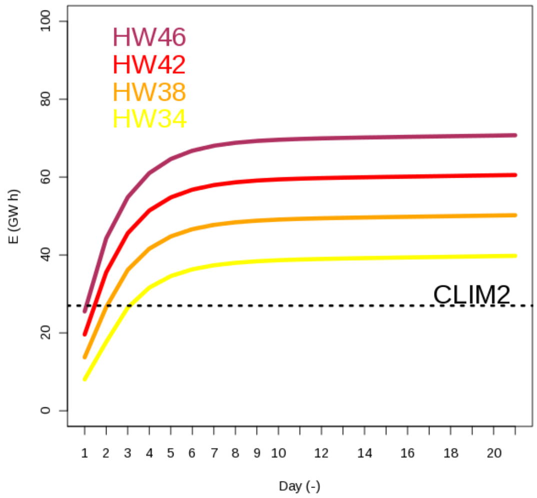


Figure 32 - Daily energy consumption compared to the CLIM2 value.

These values can be put into perspective with the daily consumption evaluated by CLIMESPACE and CNAM for the $CLIM^2$ project[14]: energy consumption associated with air conditioning is estimated to 70 GWhEP per day, i.e. about 27 GWhEF per day.

According to Figure 32, the simulated energy consumption is systematically higher than that estimated for $CLIM^2$. However, the $CLIM^2$ methodology enables to provide a mean consumption for summertime. It is therefore possible that this consumption is underestimated for heat wave conditions.

The maximum daily power (p_{max}) also increases depending on the heat wave intensity (Figure 31). As for E_{cum}, it increases during the first days (~ 1 week) and then reaches a plateau. It increases more rapidly for the strongest heat waves.

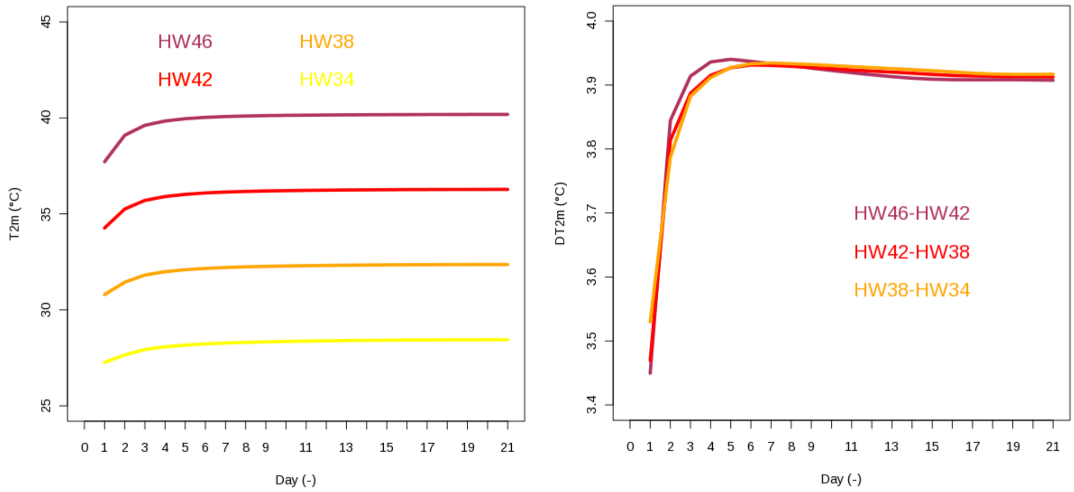


Figure 33 - Mean daily 2-m air temperature averaged for grid points with air-conditioning i.e. offices only (left) and difference between 2-m air temperatures of heat waves from different classes of intensity (right).

[14] $CLIM^2$ project has been co-funded by CLIMESPACE, METEO FRANCE and CNAM. It studies the impact, in term of air temperature in streets, of air conditioning releases, on Paris area, during an heat wave event similar to the 2003 one's. http://www.cnrm-game.fr/spip.php?article370

This dynamics is related to the evolution of air temperature during the heat wave (Figure 33). A systematic increase in 2m-air temperature occurs at the beginning of the simulation because the model variables are initialized based on summertime conditions (the same for all simulations) but not heat-wave conditions. After several days, a plateau in temperature is reached in response to atmospheric forcings whose diurnal cycle is constant over time (see Section 2.4: Heat waves modeling methodology).

The overpower (ΔP_{max}), as the other indicators, increases during the first days and then reaches a plateau (Figure 31). It is greater for lower intensity heat waves but this difference decreases with time. The plateau is higher for HW38-HW34 than for HW42-HW38 and HW46-HW42 because the urban heat island, for grid points with air-conditioning, becomes slightly smaller for more intense heat waves (Figure 33). Therefore, the demand for cooling increases a little less between HW42-HW38 and HW38-HW34 (and so on).

5.2 City vulnerability Vs adaptation strategies

The vulnerability of the city to future heat waves is assessed by weighting the sensitivity indicators according to the occurrence probabilities of the four classes of heat waves in future climate (2070-2099).

The analysis of the results puts in perspective two antagonist policies of adaptation:

1) Air-conditioning for all

   The comparison of scenarios with air-conditioning informs us on how to efficiently reduce the impacts of air-conditioning on energy demand and outdoor comfort.

2) Alternative to air-conditioning

   The comparison of scenarios without air-conditioning informs us on how to efficiently reduce the city vulnerability evaluated in terms of outdoor and indoor comfort without air-conditioning.

In order to evaluate the adaptation scenarios, each of them is compared to a scenario taken as a reference that reflects what the city would be in 2100 if it would evolve according to a set of "business as usual" trends. In addition, these adaptation scenarios can be considered as combinations of different action levers, so that they can be compared with each other by evaluating the contribution of each action lever independently, and then of the different combinations of action levers.

Air-conditioning for all

Table 3 lists the ensemble of scenarios that is analyzed in this issue, i.e. the reference case and the other scenarios classified according to the action levers.

	Expansion sc.	Building + AC sc.	Watering sc.
REF	Sprawl city	Business as usual measures for buildings + intensive use of AC	No watering
1 action lever	Compact city	Business as usual measures for buildings + intensive use of AC	No watering
	Green city	Business as usual measures for buildings + intensive use of AC	No watering
	Sprawl city	Virtuous buildings + moderate use of AC	No watering
	Sprawl city	Business as usual measures for buildings + intensive use of AC	Watering
2 action levers	Compact city	Virtuous buildings + moderate use of AC	No watering
	Green city	Virtuous buildings + moderate use of AC	No watering
	Compact city	Business as usual measures for buildings + intensive use of AC	Watering
	Green city	Business as usual measures for buildings + intensive use of AC	Watering
	Sprawl city	Virtuous buildings + moderate use of AC	Watering
3 action levers	Compact city	Virtuous buildings + moderate use of AC	Watering
	Green city	Virtuous buildings + moderate use of AC	Watering
	Green city	Virtuous buildings + intensive use of AC	Watering

Table 3 – Description of the scenarios analyzed for the case "Air-conditioning for all". They are classified according to the number of implemented action levers.

For the reference scenario, indoor comfort is provided by a massive use of air conditioning. Thanks to a set point temperature of 23°C both for housings and offices, UTCI values never exceed the thresholds of heat stress (even moderate). The analysis of outdoor conditions during a mean future summer (i.e., by weighting the seriousness indicator according to occurrence probabilities of future heat waves) displays that the threshold of strong heat stress is exceeded during 15.5 hours per day. Finally, this reference scenario foresees a cumulated energy consumption of 2.66 TWh_{EF} for operating air-conditioning systems.

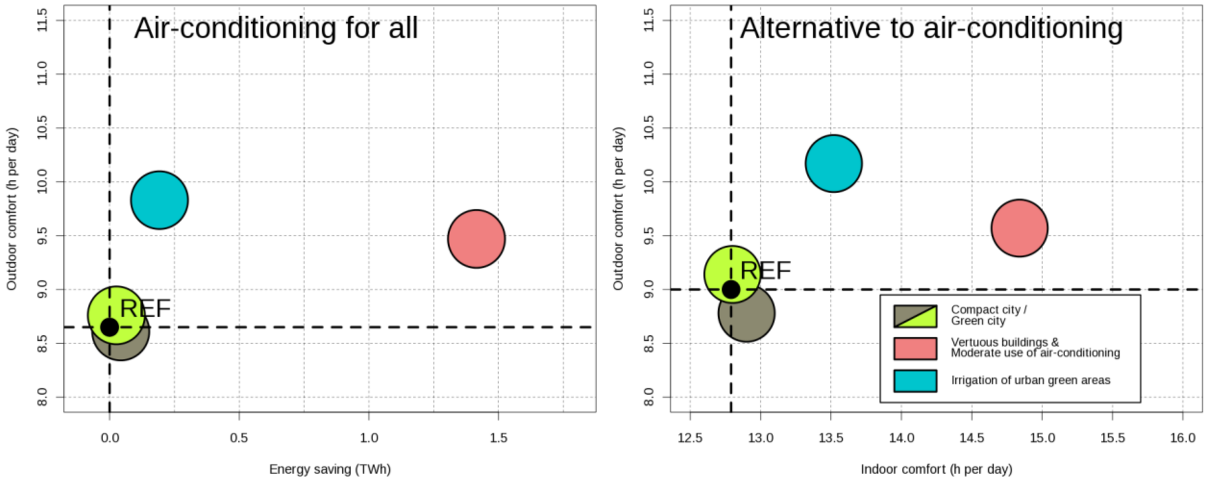
Based on the comparison of scenarios that integrate only one action lever (Figure 34a and Table 4), the main impact on energy consumption comes from the scenario that combines adaptation measures for buildings and use of air-conditioning. The implementation of virtuous buildings, associated with a moderate use of air-conditioning, enables saving 1.42 TWh, i.e. more than 50% of the energy demand related to the reference scenario. This action lever also improves the outdoor comfort by reducing of 50 minutes the time spent under strong heat-stress condition. But the main gain is obtained by watering of gardens (-70 minutes namely almost 8% of gain with the reference case).

The combination of two action levers (Figure 34b) indicates that:

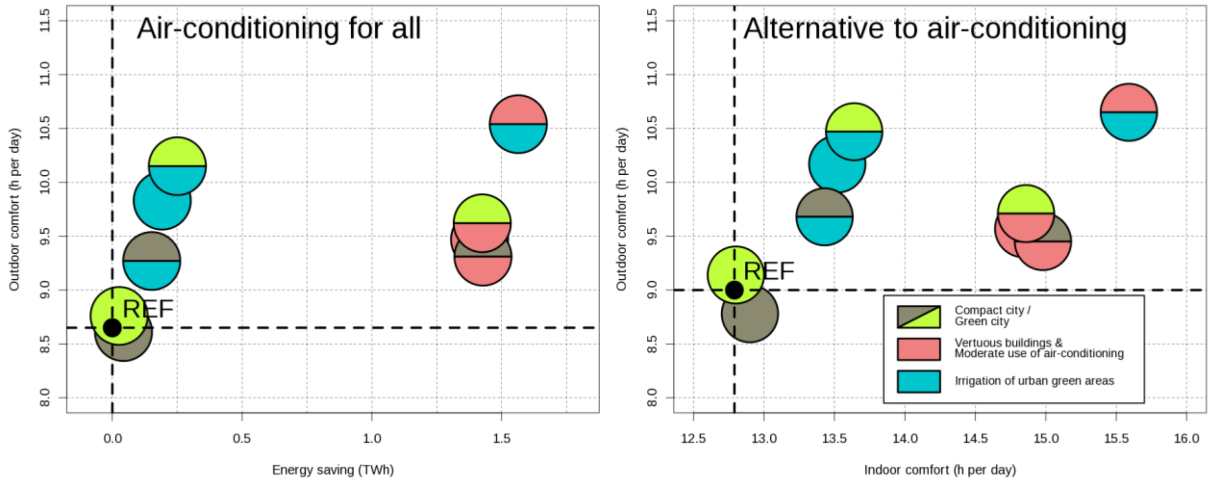
- The urban expansion scenario “Green city” makes sense when it is associated with watering of gardens. Indeed, the more there is vegetation in the city, the more the effect of watering becomes significant. The urban microclimate is less hot thanks to watering so that a gain in comfort of 90 minutes per day is obtained in this case. It is interesting to note that the combination of the two action levers has a much stronger impact than each lever separately. In addition, the energy consumption is reduced by -0.25 TWh.
- The addition of garden watering in the scenario that implements virtuous buildings enables significantly improving both energy saving (+59% vs REF) and outdoor comfort (+22%) although the combined impact is a bit less than that of the two levers separately.

Finally, thanks to an optimal combination of the three action levers "Virtuous buildings" + "Green city" + "Watering" (Figure 34c), the energy saving reaches 60% compared to the reference scenario and the outdoor comfort is improved by almost 15%, i.e. by more than 2 hours per day.

a. 1 action lever



b. 2 action levers



c. 3 action levers

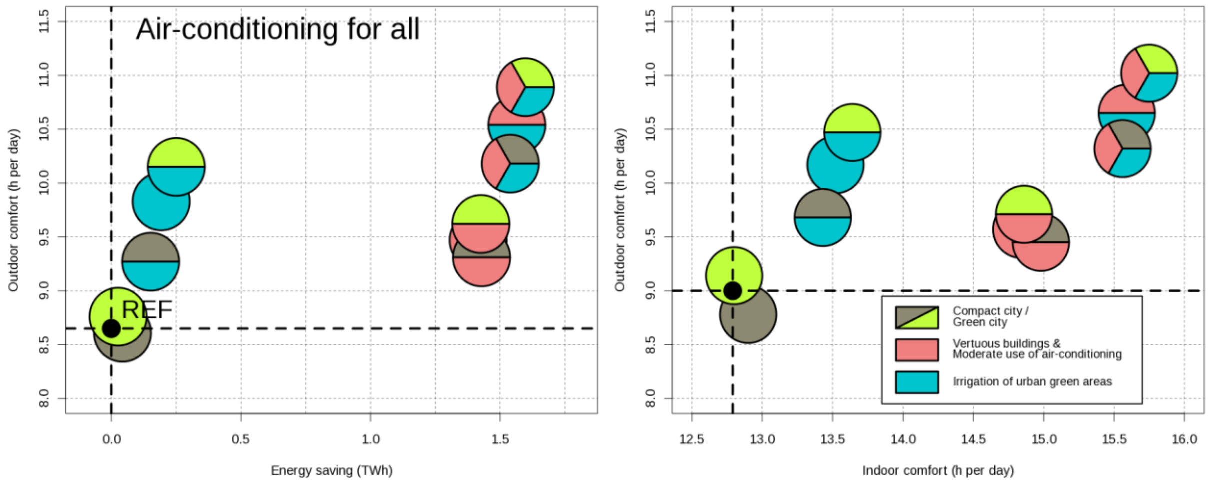


Figure 34 – Impacts of scenarios on both energy saving (X-axis) and gain in outdoor comfort (Y-axis) compared to the reference scenario for the case "Air-conditioning for all".

The building scenarios defined initially for this study do not separate adaptation measures for buildings and use of air-conditioning. An additional scenario is run in order to only evaluate the contribution of adaptation measures for buildings by maintaining an intensive use of air-conditioning (Figure 35). This test is performed for the most efficient combination of action levers, i.e. for a "Green city" with "Watering". In this case, outdoor comfort is slightly affected with a gain of 12.2 % instead 14.6% for the most efficient scenario. But the energy saving is now only 23% when it was 60% with moderate use of air conditioning. This highlights that a simple regulation favoring a moderate use of air-conditioning can significantly reduce energy demand.

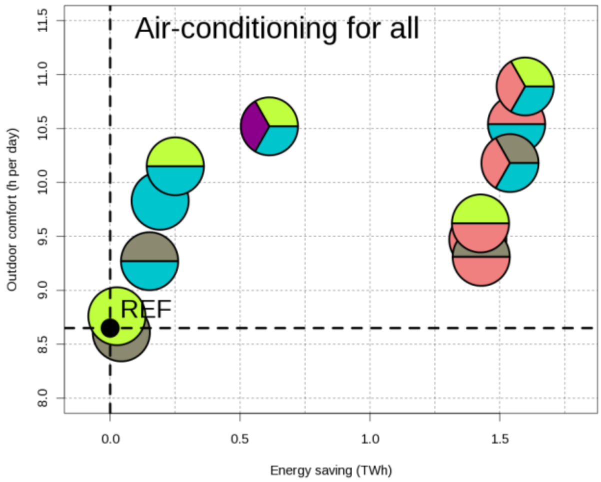


Figure 35 – Same than Figure 34 for 3 action levers (left) but with an additional case: the pie chart with colours blue/green/purple refers to the scenario combining "Green city" + "Watering" + "Virtuous building" but with an intensive use of AC.

			Urban expansion « Compact city »		Urban expansion « Green city »		Virtuous buildings + moderate use of AC		Watering	
Air-conditioning for all	All HWs	Ecum (TWh)	+2.6	+2%	+2.6	+1%	+1.2	+53%	+2.5	+7%
		Outdoor comfort (minutes)	-2	-0.3%	+7	+0.7%	+49	+5.3%	+71	+7.7%
	Extreme HWs	***Ecum (GWh)***	***+14***	***+1.4%***	***+8.8***	***+0.9%***	***+400***	***+41%***	***+59***	***+6.1%***
		Outdoor comfort (minutes)	***-7.2***	***-1.9%***	***+7.2***	***+1.9%***	***+52***	***+14%***	***+70.***	***+19%***
Alternative to air-conditioning	All HWs	Indoor comfort (minutes)	+7	+0.9%	+1	+0.1%	+120	+18%	+44	+6.5%
		Outdoor comfort (minutes)	-13	-1.5%	+8	+0.9%	+34	+3.8%	+70	+7.8%
	Extreme HWs	***Indoor comfort (minutes)***	***+4.8***	***+1.7%***	***0***	***0%***	***+88***	***+31%***	***+26***	***+9.4%***
		Outdoor comfort (minutes)	***-18.0***	***-4.6%***	***+9.6***	***+2.5%***	***+41***	***+11%***	***+69.***	***+18%***

Table 4 – Contributions of the different action levers (analyzed separately) in terms of energy saving, and gain in indoor and outdoor comfort.

Alternative to air-conditioning

Table 5 lists all scenarios analyzed in this issue, i.e. the reference case and the other scenarios classified according to the action levers.

For the reference scenario, the indoor conditions exceed the threshold of strong heat stress during a bit more than 12 hours per day (i.e. approximately 13 hours of relative indoor comfort). Outside, the threshold is exceeded during 15 hours. One can note that outdoor comfort is a bit better than that evaluated for the previous reference case ("Air conditioning for all") probably because heat releases by air-conditioning warm the air outside.

By acting on a single action lever (Figure 34 a and Table 4):

- A maximum gain in indoor comfort is obtained thanks to adaptation measures for buildings: 2 hours more of comfort per day (i.e. +16% compared to the reference scenario).

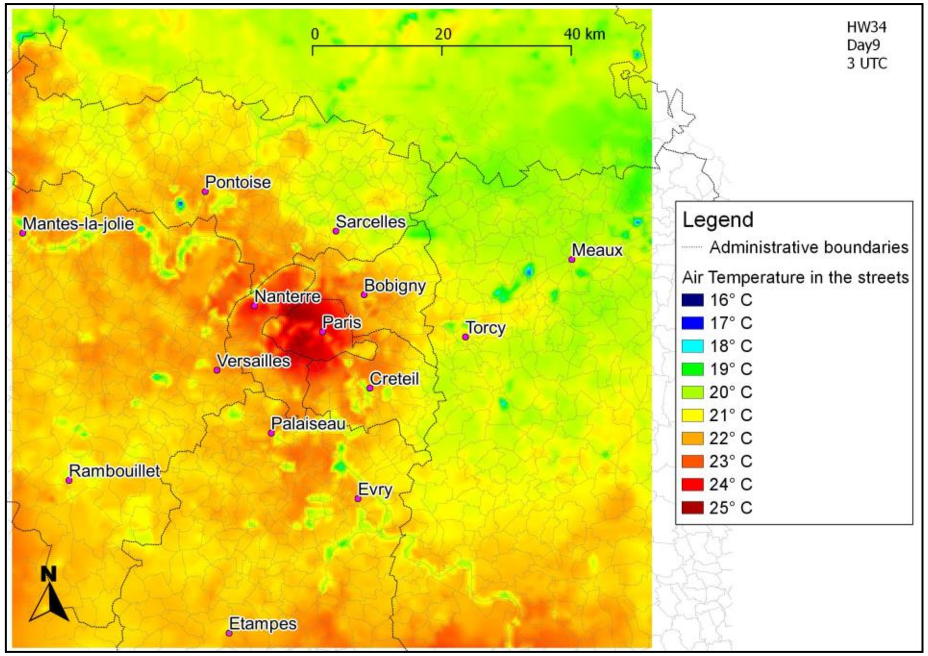
- A maximum gain in outdoor comfort is obtained thanks to gardens watering: 1 hour and 10 minutes more of comfort per day (i.e. +8% compared to the reference scenario). This scenario also induces a substantial improvement of indoor comfort of about 45 minutes.

The combination of adaptation measures for buildings and gardens watering (Figure 34b) provides a cumulated gain in indoor comfort of 2 hours and 48 minutes per day (i.e. +25% compared to the reference scenario) that is exactly the sum of gains provided by the two action levers separately. This is also this scenario that offers the best gain in outdoor comfort, namely 1 hour and 40 minutes per day (+11% compared to the reference scenario).

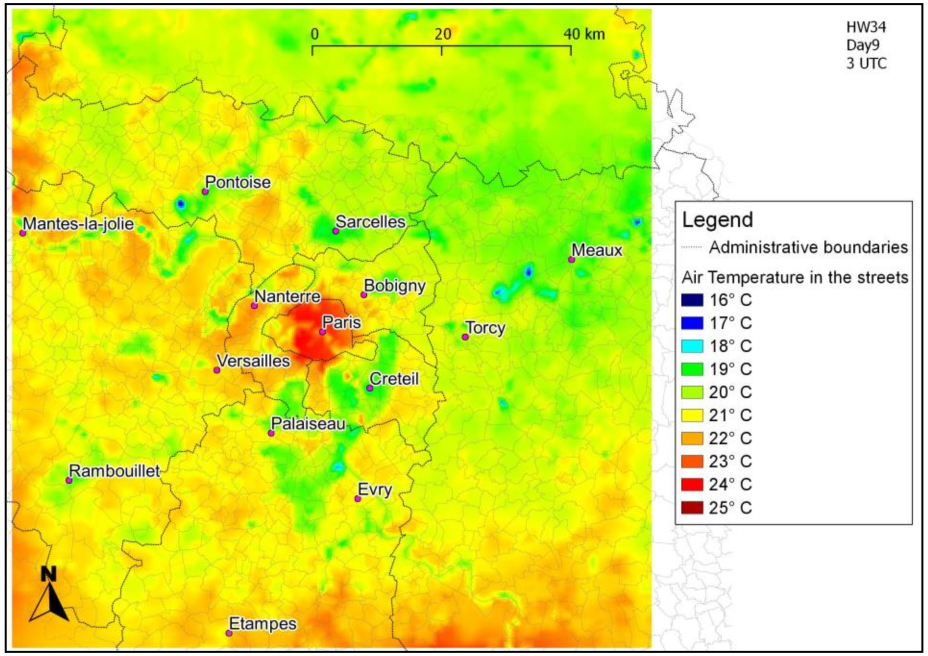
Finally, thanks to an optimal combination of the three action levers "Virtuous buildings" + "Green city" + "Watering" (as for the previous case, Figure 34c), the gain in indoor and outdoor comfort reaches 26.4% (3 hours per day) and 13.5% (2 hours per day), respectively, compared to the reference scenario. In conclusion, several alternative options to air-conditioning are able significantly reducing the vulnerability of the city in terms of both indoor and outdoor comfort. Nevertheless, at best, a third of the day is spent under conditions of strong heat stress inside buildings without air-conditioning.

	Expansion sc.	Building + AC sc.	Watering sc.
REF	Sprawl city	Business as usual measures for buildings + no AC	No watering
1 action lever	Compact city	Business as usual measures for buildings + no AC	No watering
	Green city	Business as usual measures for buildings + no AC	No watering
	Sprawl city	Virtuous buildings + no AC	No watering
	Sprawl city	Business as usual measures for buildings + no AC	Watering
2 action levers	Compact city	Virtuous buildings + no AC	No watering
	Green city	Virtuous buildings + no AC	No watering
	Compact city	Business as usual measures for buildings + no AC	Watering
	Green city	Business as usual measures for buildings + no AC	Watering
	Sprawl city	Virtuous buildings + no AC	Watering
3 action levers	Compact city	Virtuous buildings + no AC	Watering
	Green city	Virtuous buildings + no AC	Watering

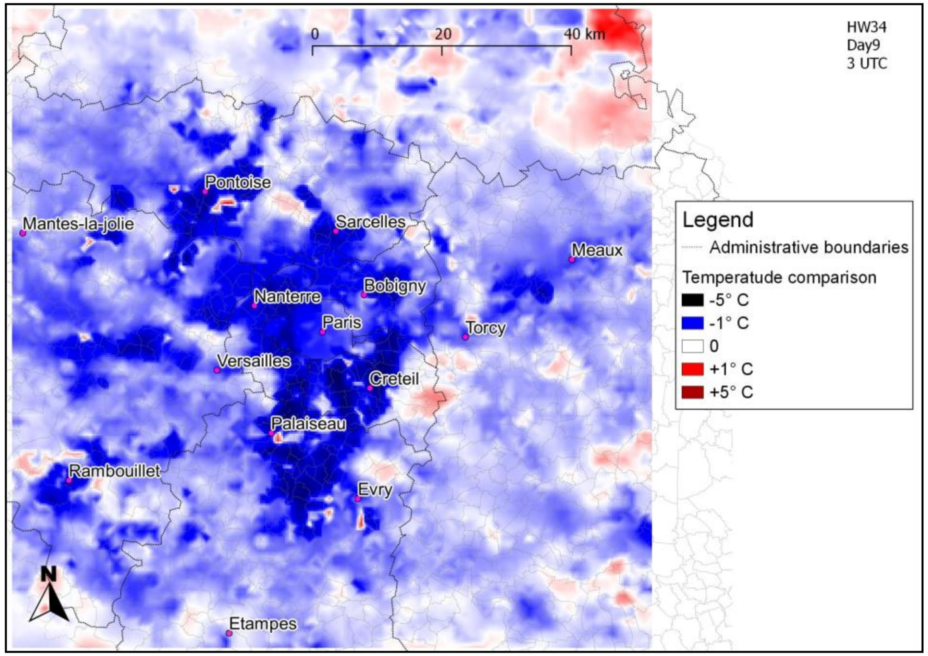
Table 5 - Description of the scenarios analyzed for the case “Alternative to air-conditioning”. They are classified according to the number of implemented action levers.



*A. **Reference scenario**: urban heat island effect is clearly visible, with a 6 °C temperature difference between the center of Paris and the countryside.*



*B. **With the three adaptation policies:** this simulation was done with the exact same conditions as map A, except that the three adaptation policies are supposed to have been implemented.*



*C. **Difference between both simulations** : this map shows the difference between maps A and B. Air temperature decrease can be up to 5°C thanks to adaptation policies.*

Figure 36: example of simulation maps. Maps represent air temperature in the streets after 9 days of an HW34 heat waves, at 3 a.m. UTC (i.e. 4 a.m. in Paris)

This shows the influence of the three combined adaptation policies, when compared to the reference scenario.

CHAPTER 6
Conclusions

6.1 Limits of the project, and future research

This project has several limits, that should be highlighted and that enable to build up a program for future research.

Models

Models used in the project could be improved. In TEB-Surfex, watering, and evaporation processes could be more finely simulated (cf. 1.2). Shadow effect of the vegetation is not accurately taken into account in the simulations. Water management strategies are also simplistic. No detailed analysis of various water management schemes (watering of only certain parts of the city, watering during only a few days etc.) was included in the analysis.

The same can be said about buildings. Windows were considered to have no solar protection. Further simulation should include such window features. There were only four building types, and a more detailed analysis (taking into account a variety of construction materials, shape etc) could be useful. It could also be interesting to focus on the vulnerability of badly insulated buildings. Such situations could be cross-analysed with socio-economic data (households revenues, age, …).

In NEDUM2D, the scenario of city development was based on several simplification hypotheses, and each of them can be criticized (cf. 1.1). Neither polycentric development of the city, nor any influence of socio-economic inequalities were taken into account. No modification of transport habits was modeled.

Scenarios

More deeply, the analysis relies on a small number of scenarios: there are only three city development scenarios, based on only one demographic scenario (cf. 4.1). There are only two building insulation and AC use scenarios, whereas these scenarios are found to have a major influence on the results (cf. 4.2 and 4.3).

All results are based on an average over different climatic projections: no deep analysis of the uncertainty related to the diversity of climatic projections has been made (cf. 2.4).

It would be useful to study a larger amount of scenarios (climatic scenarios, city development scenarios, and adaptation alternatives), and how our conclusions are affected by scenario choice. This would enable to determine the robustness of our conclusions.

Our results only analyzed the situation in 2100: it would also be interesting to study the city vulnerability over time, and whereas adaptation policies efficiency varies in the short or medium term. Such an analysis could take into account the time needed to implement adaptation policies.

Heat wave impacts

Heat wave impacts on health are taken into account using a simple indicator: the Universal thermic index (cf. 3.2). It would be interesting to refine the analysis of this impact. It could also be possible to take into account different households types, and to evaluate heat wave impacts for different categories. It would be especially interesting to focus on elderly people, for instance. Finally, it would be also interesting to study how recurrent heat stress conditions would be accepted by the population, and to what extent an evolution of existing heat wave emergency plans (the French “Plan Canicule”) could be an alternative response to costly adaptation measures concerning the modification of the built environment.

Several of these limitations are addressed in MUSCADE[15] project, as well as in Acclimat[16] project, in which TEB-SURFEX and NEDUM models are used.

6.2 Interpretation and key insights

In conclusion, here are some key insights that can be deduced from this project.

To what extent will Paris be vulnerable to heat waves?

Paris can be strongly affected by heat waves. We computed that, without air conditioning, at the end of the century, **almost 11 heat wave days per year in average** should be expected to be spent in Paris urban area. During these days, in residential buildings, if no AC is used, almost **7 hours and a half** would be in average spent in **high heat stress** conditions, i.e. with an apparent air temperature (UTCI) greater than 32°C. This could lead to serious health consequences. In the streets, even in shadow, this duration is higher, and **almost 15 hours** have to be spent in these conditions.

Urban expansion, through an increased heat island effect, could worsen heat waves impacts. We computed that, in the scenario of high city densification (the “compact city scenario”), in the streets, **20 minutes in high heat stress conditions should be added**.

What would be the effect of a massive development of air-conditioning?

If a massive development of air conditioning happens to create more conformable indoor ambiance and to prevent health issues, about **1.1 TWh** per year of extra final energy consumption should be expected, if a 23° temperature is to be maintained in all residential and office buildings.

Heat released by AC systems causes a degradation of external thermal comfort, and the duration spent under high heat stress conditions in the streets is increased by about **20 minutes**.

These results were computed with the hypothesis that existing urban green spaces are adequately watered, and this plays an important role in reducing Paris sensitivity to heat waves. In case of water shortage, (which is almost equivalent to an urban green spaces removal), we simulated that energy consumption would be **increased by about 8%**, and that **almost one hour** of outdoor thermal discomfort would be added.

Could alternative adaptation policies enable to reduce energy demand for air conditioning and thermal discomfort?

Energy demand for air conditioning could be an important burden in a context of greenhouse gases reduction efforts, but **adaptation policies** could be implemented to reduce this demand. We computed that

[15] MUSCADE is a research project, funded by ANR (reference ANR-09-VLL-003) : Modélisation Urbaine et Stratégies d’adaptation au Changement climatique pour Anticiper la Demande et la production Energétique (http://www.cnrm.meteo.fr/muscade/)

[16] ACCLIMAT is a research project, funded by STA RTAE (http://www.cnrm.meteo.fr/acclimat/)

- a massive creation of parks and green spaces in Paris urban area (devoting 10% of land surface to new parks),
- reinforced building insulation and the use of reflective materials for walls and roofs,
- and effective recommendations or policies leading to air conditioning used to maintain 28°C in residential buildings and 26°C in offices instead of 23°C,

could together enable to reduce energy consumption by 0.7 TWh, i.e**. reduce energy consumption for AC by more than 50%**. This would also **reduce outdoor thermal discomfort time by about 1 hour**.
However, these policies could not a priori totally replace AC use, as **6 hours per day would still have to be spent in high heat stress conditions** in residential buildings if no AC is to be used at all.

In conclusion, several alternative options to air-conditioning are able significantly reducing the vulnerability of the city in terms of both indoor and outdoor comfort. Nevertheless, at best, a third of the day is spent under conditions of strong heat stress inside buildings without air-conditioning.

Adaptation policies efficiency depends on the heat wave characteristics

Various adaptation policies have efficiencies which vary according to the type of heat wave. For instance, cities sensitivity to heat waves varies greatly with the duration of the event. Continuously high temperatures are required during a few days before indoor temperatures reach their maximum equilibrium value. This duration was found to be about 5 days in Paris. Building insulation enables to increase this duration and therefore to be less sensitive to short heat waves.

Adaptation policies implementation issues

Implementing these policies is however no easy task. Beside the operational difficulty to change air conditioning use habits, stricter building insulation would be expensive, and green spaces creation would have a high cost in terms of land use (by decreasing residential land supply, it could increase all rents and real estate prices by 2 %, when compared to reference scenario). Green spaces creation would also reduce the city density and could lead to increased urbanized surface, and to increased transport-related greenhouse gases emissions (+10%). They would finally require a huge amount of water to be efficient. If water availability stops, green spaces are found to have almost no effect.

Among the three policies we have studied, **changing AC use habits** (increasing temperature set points) is the policy which has, individually, the greatest impact. This policy, moreover, has none of the costs or collateral effects that the two other adaptation policies have. However, it is rather unclear how such a policy could be implemented in practice.

Two key trade-offs

Finally, this project highlights two key tradeoffs in the design of urban climate policies. First, there is a general **trade-off between mitigation and adaptation policies**. Adaptation to heat waves through AC use can be counterproductive from a greenhouse gases reduction objective point of view. Similarly, there is a trade-off between heat-wave vulnerability and transport-related emissions. Adaptation to heat waves through green space development would reduce the density of the city; conversely, active policies managing to stop urban sprawl and to make the existing city denser are found to increase the city sensitivity to heat waves

Second, there is a **trade-off between indoor and outdoor air temperature**: keeping indoor air temperature low can be easily made by air conditioning at the expense of outdoor temperature. Keeping outdoor temperature low requires reducing indoor air conditioning use. Keeping both indoor and outdoor air temperature low can be managed, to some extent, only if costing adaptation policies are implemented (green spaces development, stricter building insulation rules etc.). This trade-off can also be analyzed as an “efficiency-inequality” trade-off. Indeed, developing AC, whereas it is an efficient solution for households who can afford it, makes the situation worse for households who cannot or do not want to adopt it.

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Project deliverables

- **DEL 1.1**: Inclusion of vegetation in the TEB urban canopy model for improving urban microclimate modeling in residential areas. Aude Lemonsu.
- **DEL 1.2**: Computation of a thermal comfort index in the TEB urban canopy model. Grégoire Pigeon.
- **DEL 2.1**: Technical report on NEDUM model development. Vincent Viguié. *This document presents how the model was calibrated on Paris urban area, and how it was validated against independent data*
- **DEL 3.1**: Note on the analysis of heat waves events in present and future climate. Anne-Lise Beaulant, Aude Lemonsu.
- **DEL 3.2:** Préparation des champs de surface pour les simulations SURFEX. Aude Lemonsu.
- **DEL 4.1**: Long-term Paris urban area socio-economic scenarios using NEDUM. Vincent Viguié, Stéphane Hallegatte.
- **DEL 4.2** : Analyse préliminaire de l'impact de scénario de bâtiment. Grégoire Pigeon.
- **DEL 4.3** : Les scénarios "Bâti et usages de la climatisation » et leur simulation. Colette Marchadier, Grégoire Pigeon, Jean-Luc Salagnac.
- **DEL 5.1** : Indicateurs VURCA : Méthodologie et résultats. Aude Lemonsu.

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