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► **To cite this version:**

Laura Pinson, Valéry Masson. Heat stress in urban area: data fusion of observations, modeling and geospatial information. First International Conference on Urban Physics (FICUP 2016), Sep 2016, Quito, Ecuador. 10p. hal-01483630

HAL Id: hal-01483630

<https://hal.science/hal-01483630>

Submitted on 6 Mar 2017

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Heat stress in urban area: data fusion of observations, modeling and geospatial information

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Keywords: Urban Heat Island, Heat wave, Representation, Indoor climate, model

Abstract. *Cities have a direct impact on the local climate. The heating of surfaces and materials in urban area and the production of heat by traffic and human activity contribute to the Urban Heat Island (UHI) effect. This local climate will be even more dangerous with climate change. Climate projections for the world suggest elevated minimum and maximum temperatures and more frequent day with higher temperatures (heat wave). Hence, climate change is threatening human well being and health. Today, more than 50% of the world population lives in urban areas and humans spend more than 80% of their time in confined spaces. This can be affected negatively by indoors temperatures. Indoor temperatures are of special importance for well-being and health in general.*

Quantitative information about outdoor thermal comfort, on various temporal and spatial scales, is required to design better cities and mitigate heat problems not only for warm as well as temperate climates. The overall objective of this study is to explore the relation between indoor and outdoor temperature by urban features such as geometry (type of urban structure), housing areas, building arrangements and several other factors.

We use the SURFEX model (that is implemented in several weather prediction models and can also be used alone) to estimate urban temperatures (in street canyons and inside buildings). Therefore, two questions arise: how to represent the outputs of the SURFEX model both spatially and temporally? This work is part of a study conducted in summer 2015 which gathered data from air temperature sensors in five apartments. So for our study, the information given by the model is completed by measures to study the influence of building characteristics and situation on temperatures. Furthermore, it highlights the importance of thermal comfort in climate scenarios to describe the combined effects of changes in multiple apartments and to more realistically measure its impact on humans.

1 Introduction

Climate change does not only increase temperatures, it is becoming a regular phenomenon with noticeable maximum length of heat waves. Besides, a significant increase in mortality due to heat stress has been proved by Almeida et al. (2013), Gabriel and Endlicher (2011). Thus, heat stress is a serious risk to human societies. For instance, the summer of 2003 was the hottest seen in Europe for 53 years causing 14802 deaths in France (In VS, 2003; World Health Organization Europe, 2003). In urban areas, heat waves are connected to the Urban Heat Island (UHI). This effect can be beneficial in winter, by reducing domestic heating needs; however, it becomes critical for thermal comfort (indoors and outdoors) in summer.

The influence of outdoor climate on indoor climate, especially during heat stress events, has been well investigated [Nguyen et al, 2014; Quinn et al, 2014]. Indoor is mainly influenced by outdoor but its diurnal evolution is inhibited by the physical characteristics of the building (Höppe 1993). Even though the urban spatial variability is not considered in other studies, [Fenner et al. 2014] found significant spatial and temporal differences outdoors during heat waves in Berlin. It is therefore likely that indoors climate differs within the urban areas of any given city.

2 Meteorological data and model

The purpose of our study is to evaluate the heat wave risk in dense urban areas and produce data which could be used as an information tool for cities in the future. For that purpose, we will make an analysis of the data collected (visualize it and realize processing GIS to cross data in the notion of dangerousness). All results will be included into the geographical space. From the meteorological model mesh, we will create several mappings to improve the representation of the heat waves with the aim of estimating exposed areas and to classify their level of dangerousness. An index of dangerousness is calculated from sufficient duration and threshold (night/day and outdoor/indoor), and is computed to this mesh via a compute-dangerousness method. In this section we present the meteorological data we have used to estimate heat wave and series of measures made in specific flats during the heat waves in Paris.

2.1 SURFEX model

In our study, the surface is modeled by the SURFEX model (SURFEX (SURFace EXternalise)), as the first meteorological data. Its goal is to compute the exchanges of momentum, heat, water, CO₂ concentration or chemical species. These exchanges are performed by mean of fluxes. SURFEX has been developed for the representation of surface processes in numerical weather prediction models. So it is designed as a modular scheme that can incorporate various parametrization (via name list options). Each of the following surface is modeled with a specific surface model:

- Nature (natural land surface) with the ISBA model [Noilhan and Planton 1989]
- Towns (built areas) with the TEB model [Masson 2000]
- Lakes treated either with the KLAKE model [Mironov 2010]
- Sea treated with the SEAFLUX model [Gaspar and al.1990]

The coverage of each of these surfaces is known through the global ECOCLIMAP database [Masson et al 2003], which combines land cover maps and satellite information. The Surfex fluxes are the average of the fluxes computed over nature, town, sea/ocean or lake, weighted by their respective fraction. These four surface types may occur simultaneously in the same grid with different percentages. SURFEX uses atmospheric forcing to estimate temperature, humidity, wind speed, etc., through the Meso-NH model.

Moreover, thermal comfort (or thermal stress) for inhabitants is calculated during the indoor and outdoor universal thermal climate index (UTCI) implemented in TEB model 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). According to Bröde et al [Bröde et al. 2012] values, ranging from 282.15K to 299.15K, represent conditions with *no thermal stress*, values between 299.15K and 305.15K suggest *moderate heat stress* and values between 305.15K and 311.15K indicate *strong heat stress*. In this project, the thermal comfort is integrated to represent a threshold of discomfort or heat stress.

2.2 Measured data and measurementsite

In order to study the variation of temperature inside cities, we installed sensors in specific apartments in Paris during the summer of 2014 and 2015. In this instance, we used measurements from 2015 which was the hottest summer. The aim was to complete the prediction given by SURFEX on indoor temperatures. To assess the variability of indoors heat stress, measurements were executed in five different buildings, with 21 sensors localized in the centre of Paris. The meteorological data comes from the Tynitag sensors (Figure 1). We collected the data using the Tynitag software. The measurement started in 29 June 2015, at 12 am and lasted 34 days.

The The research focuses on the heat stress characterization. Only data from July were evaluated. Indoor temperatures in residential buildings have recently been studied by [Bokenes 2009] and [Kavgic et al 2012]. From this research and studies, we obtained a detailed and deeper knowledge of indoors temperature and its variations. For our experiments, apartments were chosen according to their variability to a priori knowledge on apartments' characteristics on temperature [Bokenes 2009 ; Yohanis 2010] : number of exposition, floor level, ventilation, isolation and sun exposition. These apartments characterize the A variable defined in section 2.2. The number of apartments is limited but our aims is to study the temperature variation between these main building types during a hot summer.

Basic calculations were made (besides graphics) on the data to qualify and quantify the temperature variations and to optimize the mapping. With these statistics, we created 5 types of apartment:

- Apart 1: Old building¹ <1850, one exposition only, ground floor, very poorly ventilated, no sun and isolated
- Apart 2: Haussmann² type building, well isolated and ventilated, 6th floor, N/S orientation

¹ Old building usually have 4/6 floors, in canyon street with a simple architecture, rectangular windows

- Apart 3: Old building <1850, well isolated and well ventilated, sunny and a N/S orientation
- Apart 4: Old building <1850, very well isolated, very poorly ventilated, 3th floor with a North orientation
- Apart 5: Old building <1850, isolated and poorly ventilated, under roof, N/S orientation

The measurements were carried out in various locations in figure 1 the same district in Paris. Measurements were performed, with sensor in several rooms with different exposure (to see the variability if any) and outside when possible to allow comparison with SURFEX model outputs in streets.

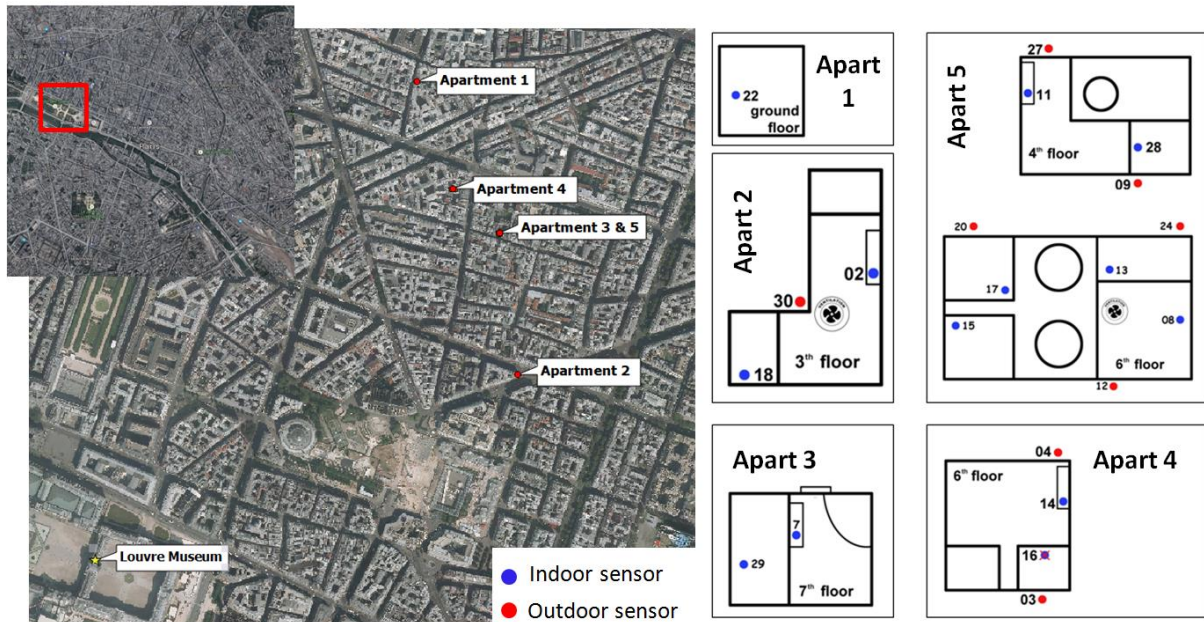


Figure1: Localization and apartments type and sensors for temperature measurements

3 Methodology

3.1 Recontextualization of output's SURFEX

The recontextualization (assignment of estimations in space) of the resulting data is important for a better understanding of the information provided and to visualize several data at the same time. To be able to contextualize this information, we have structured it under a DBMS (DataBase Management System). Every grid cell is described by a set of meteorological indications (stemming from SURFEX) amongst which some represent the temperature in the street 2 metres from the ground, temperature in buildings and on roofs.

There are more than about fifty parameters or indications. The creation of a geo-referenced grid allowed us to allocate to every grid cell of the grid, the value of the punctual datum stemming from SURFEX. For the SURFEX's outputs, we propose to represent the

² Haussmann style building usually have from 5/7 floors, along the wide boulevards, with facades built out of cut stones, possess a continuous balcony on the second and fifth floor and the mansard roof are with roof hatches

temperature in a continuous plan, like apartments. To do so, each point is transformed into a mesh of the same size as the grid cell.

We then allocated the geographical objects (of Topographic data) the values corresponding to this grid. If an object (a building) is located in the intersection of two meshes, we allocate it. We then weighed the average by the surface of the value of both meshes (Figure 2).

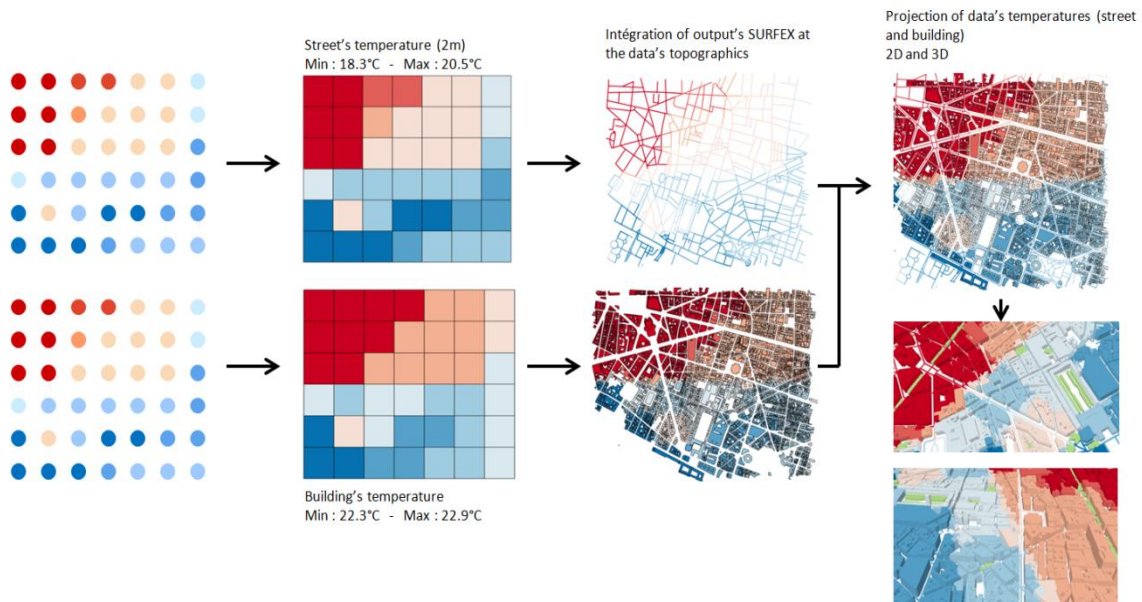


Figure 2: Recontextualisation of output's SURFEX

3.2 Integration of punctual observations

In our study, it is necessary to include sensor measurements and predictive model outputs in the same grid. For the measurements series in Paris, we created 6 categories of apartments by considering various characteristics such as the floor or the exposition, etc. This class is computed from SURFEX prediction and sensors in order to adjust the indoor temperature compute from SURFEX according to each buildings' characteristics type (as SURFEX can run for one type of building only, the dominant one). So, one type of building is described by its attributes. The building's description is given in part 1.2. These apartments are characterized by their indoor and outdoor temperatures. To be able to understand the phenomena more clearly, we represented these data in the meshes below (250m*250m) with an extrapolation. We extrapolate the results obtained in one apartment to the whole mesh. We created surfaces based on measured point. So, from a punctual observation, we move to a mesh in a surface representation.

To observe the punctual observation of the *apart-type* in the *SURFEX's outputs*, it is necessary to compute the temperature by two types of extrapolation. To integrate punctual observations, our approach is to add SURFEX's outputs in the mesh (*self*) with the difference between the punctual observations and temperatures of the apartment type (Figure 3). Thus each mesh contains a set of values (outdoor – indoor temperatures, UTCI index, etc. for the

SURFEX's outputs) An example is given below to calculate the indoor temperature of the mesh (mesh) for the Apartment Type (AT):

$$\text{indoorTemp} (AT, \text{mesh}) = \text{indoorTemp-surfex-Haus} (\text{self}) + (\text{indoor-temp-obs} (AT, m) - \text{indoor-temp-obs} (\text{Haus}, m))$$

Indoor-temp-obs corresponds to the punctual observation included in the mesh (*self*)

IndoorTemp-surfex-Haus corresponds to SURFEX's outputs included in the mesh (*self*)
m being the neighbors mesh

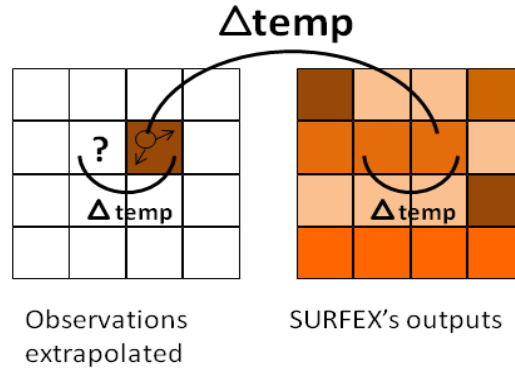


Figure 3: Assimilation's representation

Blending measured data with simulated information is necessary for a better estimation and the mapping of heat wave phenomenon.

4 A more detailed view of the estimation

If the SURFEX's model allows us to calculate temperatures in the streets according to the topography and the surrounding weather conditions, we are completing it with the impact of apartments types on indoor temperature. The output's SURFEX are valid averages in the mesh and a little differentiated. However, we wish to go towards a more accurate estimation. For that purpose, it is necessary to re-interpret the values in light of hypotheses and knowledge. This section aims to map indoors and outdoors temperatures.

4.1 Output's sensors: temperatures spatially differentiated

In order to analyze the huge volume of collected data, we need a well-organized data representation model with a swift data processing which abstracts local data. We used different software. We calculated and represented the thermal behaviour for each sensor.

The first graphs (Figure 4) display the outdoors temperatures for all sensors; we notice an important homogeneity between temperatures. The thermal amplitude between day and night is present. This amplitude rises in approximately 6K. Even inside the Paris city core, the phenomenon of UHI is visible between different neighbourhoods. The temperatures of the MontSouris Station, located in a park a few kilometers from the city centre, are lower than our sensor's temperatures in the oldest part of Paris centre. Concerning the matrix of outdoor temperature temporal evolution, we notice that the highest temperatures are occurring between 2pm and midnight with a peak of heat at 7pm. The lowest temperatures are concentrated between 3am to 9am.

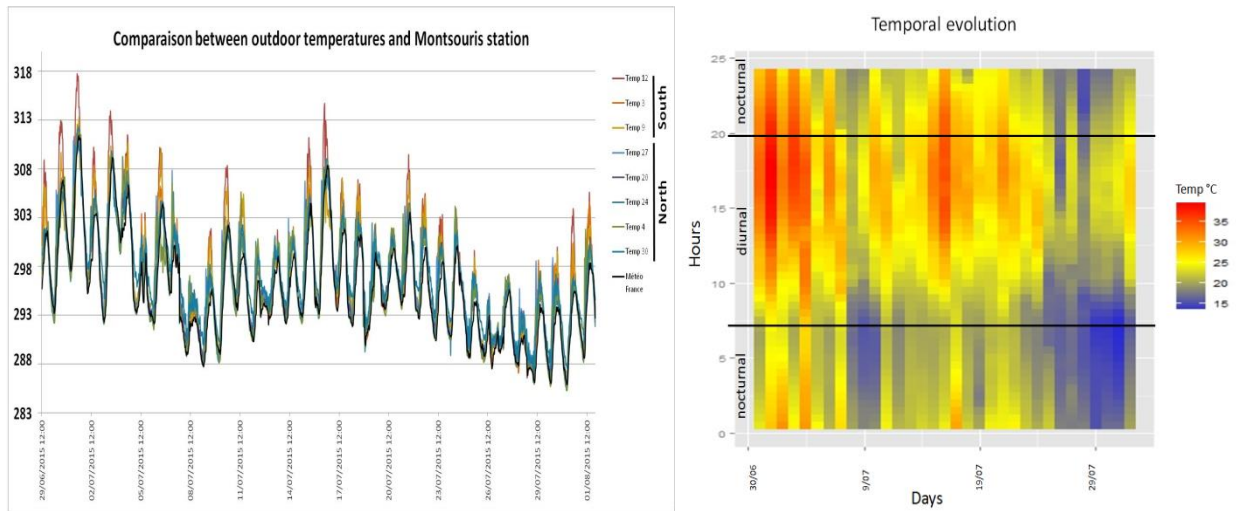


Figure 4: Graphics of outdoors temperature

The second graph (Figure 5) on inside temperatures shows a lower difference between sensor and lower thermal amplitude. Concerning the matrix of inside temperature, we notice that the highest temperatures concentrate between 5pm and 2am with a peak of heat at 8pm. The lowest temperatures concentrate approximately at 10am.

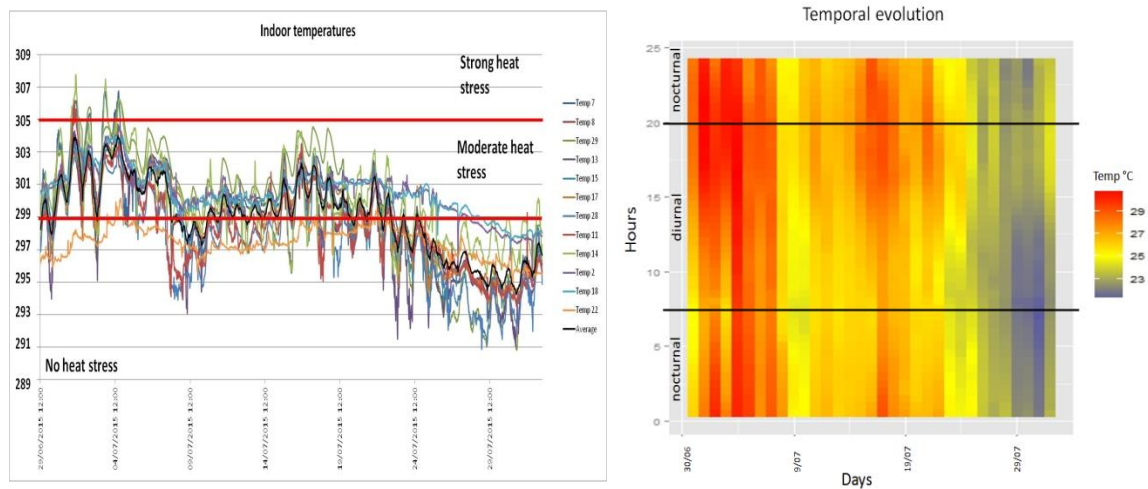


Figure 5: Graphics of indoors temperature

The data analysis shows that various factors such as the double exposure, the insulation, the floor and configuration of an apartment are affecting the changes in indoor temperatures and lead to atypical situations, even extreme configurations. Our findings show that during heat waves, indoor heat stress at night is higher than that outdoors temperature because of the thermal inertness of buildings. Those graphics prove that indoor climate is mainly governed by outdoor climate. In addition, we found temperature variations from one building to another (just a few metres apart) and variations between floors. For a more detailed analysis of the interactions between indoor and outdoor climate and the effect of buildings' characteristics, assimilation must be applied.

4.2 Towards mapping of the dangerousness

In the following, we present six cases to illustrate indoor temperature by using extrapolation and assimilation methods. Both phenomenon are temporal, but in this result, we will concentrate on the representation of one state. Similar to the measurement series, the spatiotemporal representation of the heat wave can be made out of the SURFEX model outputs. It is necessary to structure and store the data under a DBMS (Data Base Management System) then read in a GIS so that we can represent and visualize it. Our analysis also illustrates that the risk is related to the type of apartment. The most dangerous are not the ones exceeding automatically the threshold of 305.15K (UTCI) but those where temperatures remain high and stable during several days. So, the heat wave will not be, thus not lived in the same way. We have a differentiated experience, both specially and temporally (Figure 6).

In this study, we have created five types of building (part 2.2) and one type with the output's SURFEX (type 6). Indeed, figure 6 is represented in the indoor temperatures (average 15h-22h) between 1st and July 5th 2015, in the city of Paris according to types of apartments highlights the impact of the configurations on indoors temperatures. With these maps, we noticed an accumulation of areas of strong heat in the Parisian northwest. These regions of intense heat create zones of dangerousness due to the duration of the phenomenon. The indoor temperature is an aggregation of the temperatures measures over 8 hours to study the phenomenon during daytime or night time. This integration also enhances the results by contextualizing the data (to cross-reference temperatures refereeing to every object in the grid).

The description of the variability of heat stress in the first part of the results indicates that some building characteristics may influence the indoor temperature like the floor level, the orientation and the ventilation. Type 1, situated in the ground floor and receiving no sun rays has low temperatures included on average between 297 and 302K contrary to the type 2 and 3, which have strong indoor temperatures and can achieve more of 310K on two consecutive days. Type 1 is the only one not exceeding the UTCI index thresholds of *moderate heat stress*. It will remain in the *no heat stress*. The third and fourth day, some zone will be in the fateful threshold *very strong heat stress* for type 2, 3 and 6.

So the model SURFEX (type 6), for temperatures is going to overestimate or underestimate the temperature according to the thermal characteristics of buildings.

It's important to know that people within the study rooms are affected by heat stress not only during day but also during night and the ability to cope with heat stress after a disturbed recovery phase at night is likely to decrease due to a possible accumulation effect of heat stress [Parson 2003].

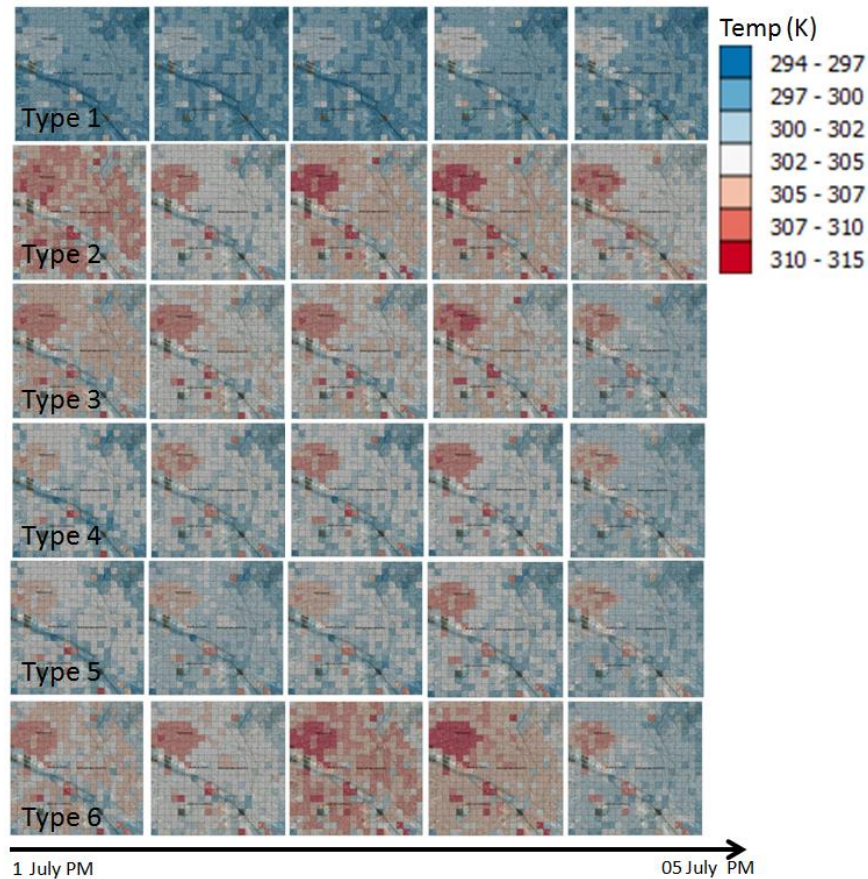


Figure 6: Mapping of indoors temperature by apartments type

5 Conclusion

The analysis shows that indoor heat stress during the summer of 2015 was unequally distributed regarding spatial and temporal variability, especially during the heat waves. The distribution of heat stress in indoor environments showed a small-scaled heterogeneity that was mainly governed by the characteristics of buildings and their surroundings. A significant influence of the outdoor urban heat island could not be found as it is only one factor amongst several other parameters responsible for the development of indoor thermal environment. To isolate and to ventilate the effect of the urban heat island, more buildings must be included in the study. Based on these results, it is suggested that the heat warming to indoor environments be adapted. It is important to recommend adequate adaptation strategies to reduce the heat stress risks. Risk assessments should not only analyze heat stress hazards but spatial variations of vulnerability to heat stress should also be considered.

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