Assessment of adaptation strategies to climate change impacts in a big city: the case of Paris

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Abstract

The EPICEA project is a joint collaboration between the City of Paris, the French Meteorological Office (Meteo-France) and the French Scientific and Technical Centre for Building (CSTB). The general objective is to quantify the impact of climate change in Paris city as well as the influence of the built environment on urban climate. The project addresses three subjects: (1) the long-term evolution of the Parisian urban climate in a changing climate; (2) a sharp analysis of the 2003 heat-wave and (3) the interactions between the characteristics of the built environment and the urban climate. Numerical models describing heat and mass transfer between the urban area and the atmosphere were used. For subject (2), a fine scale description (250m x 250m) of the area was chosen to allow a precise definition of the physical properties of the built environment which rule the urban energy balance (thermal mass, radiative properties of roofs, walls and streets cover, green areas ...). A comparison with recorded meteorological data demonstrated the robustness of this simulation which was then chosen as a reference situation. This reference situation helped assessing the impact on the heat wave intensity and other meteorological parameters of modifications of the built environment. Several scenarios were elaborated: “shining Paris” (increased albedo of surfaces), “greener Paris” (increase of green surfaces), “watered Paris” (water on the street surfaces). Simulations were run for each of the scenarios using the same numerical environment than for the reference situation. Differences in results reflect the impacts of the modified characteristics of the built environment. This paper presents these results which confirm the importance of (watered) vegetation as a very influent factor. The impact of other factors such as high albedo surfaces and water is also tangible. These results are analysed in an economic perspective taking investment and maintenance conditions into consideration.

Keywords: urban-heat-island, adaptation, heat-wave

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1. Introduction

An urban area is a very complex dynamic structure that supports a great number of social, economic, symbolic and technical functions. The share of world population living in urban areas was 13% in 1900, a bit less than 30% in 1950, close to 50% in 2005 and is expected to reach 60% in 2030 (UN, 2005). This trend now concerns all countries. The number of both large cities (population ranging from 5 million to 10 million) and mega-cities (with at least 10 million) is expected to increase in the near future: numbers should jump respectively from 40 to 59 and from 23 to 37 between 2011 and 2025 (UN 2011). Originally, urban areas developed from a natural environment experiencing local climate. The concentration of a huge mass of construction material on a relatively small area as well as the presence of multiple sources of energy (e.g. heating/cooling of buildings, traffic of vehicles, production activities) modified the local urban climate. This evolution of local climate mainly results from the modification of the exchange of energy with the atmosphere. The urban-heat-island (UHI) phenomenon is one of these modifications that has for long been described and documented (OKE 1988). The building fabric, the topography of the urban tissue, bare ground surfaces, green and blue areas embedded in the urban tissue, wide and narrow streets with or without trees along are some of the parameters that participate in UHI development.

The on-going growth of the urban population and the concomitant climate change perspectives create an unprecedented context. Global warming is already observed (IPCC 2007) and will very likely become particularly significant beyond 2070. Heat waves comparable to or even more intense than the August 2003 event could concern Western Europe every other year from 2070. The conjunction of both urban growth and more intense and frequent heat-waves triggers reflection on how to cope with future climatic situations. Moreover, the time scale of urban interventions is several decades so that decisions should be prepared from now in order adaptation measures to be timely implemented and operative by the end of the century.

The aim of the EPICEA project (French acronym for “pluridisciplinary study of the impacts of climate change at the scale of Paris region”) is to address such issues and to provide scientific background to decisions. This project results from a joint effort of Meteo-France and the French Scientific and Technical Centre for Building (CSTB). It was launched in 2008 and funded by the City of Paris.

2. Objective and methodology

2.1 Objective

As in many cities in Europe in August 2003, as well as in other country during past intense heat-waves (e.g. in Chicago and Philadelphia in 1995, (Kahn-Thornbrugh 2001)), a high number of extra fatalities was recorded in the city of Paris. Between August 1 and August 20, 1 910 deaths were recorded whilst the statistical number during the same period was expected to be 843.1 (Hémon, Jougla 2003). These figures reflect the vulnerability of the population exposed to extreme temperature during long periods. These extreme temperatures result first from the temporary meteorological conditions at a regional scale and are increased in urban areas due to the UHI effect.

The general objective of EPICEA is to address the evolution of the Parisian urban climate within the context of climate change with a particular focus on temperatures as a main driver of observed heat-wave related extra fatalities. The project does not directly address the vulnerability of persons but as the link between extreme urban temperatures and extra fatalities is qualitatively established, we will use the expression “vulnerability of the city” (to heat-waves) as a shortcut.

2.2 Coupling atmospheric and urban area systems

The description of the energy exchange between the atmosphere and the urban area is essential to explain observed climate and to anticipate the effects of future global climate on local urban climate. Several numerical models developed by Météo-France were used during the EPICEA project.

The French Meso-NH atmospheric simulation system (Lafore et al. 1998) is designed as a research tool for small and meso-scale atmospheric processes. The dynamics of the model is based on the non-hydrostatism hypothesis and the anelastic approximation. The physical part of the model consists in the parameterization of microphysics, convection, turbulence, radiation and surface. Surface treatment is externalised and specific surface schemes are coupled with the atmospheric model: the Town Energy Balance (TEB) scheme for the urban part (Masson 2000), the ISBA scheme for the vegetation (Noilhan, Planton 1989), and two other specific schemes for lakes, sea and oceans.

The TEB scheme is designed according to the canyon approach (figure 1). Walls (w), flat roofs (R) and streets (r) are described by layers of construction materials. Liquid water (W) or snow (W_{snow}) can be accumulated on roofs and streets. The temperature (T) of the different layers is calculated using the laws of heat transfer. The TEB scheme was upgraded during the project so as to integrate low growing vegetation in the streets (Lemonsu 2010). Topographic data as well as data referring to the building fabric reflect the characteristics of the Parisian urban area.

A main driver of the UHI phenomenon is the thermal inertia of the urban area as a whole. The TEB scheme is then designed to well represent heat exchanges at the urban/quarter scale. Recent upgrade allows a better representation of building physics but the initial design proved to be accurate enough to simulate the observed UHI effects at the scale of urban areas (Masson et al. 2002).

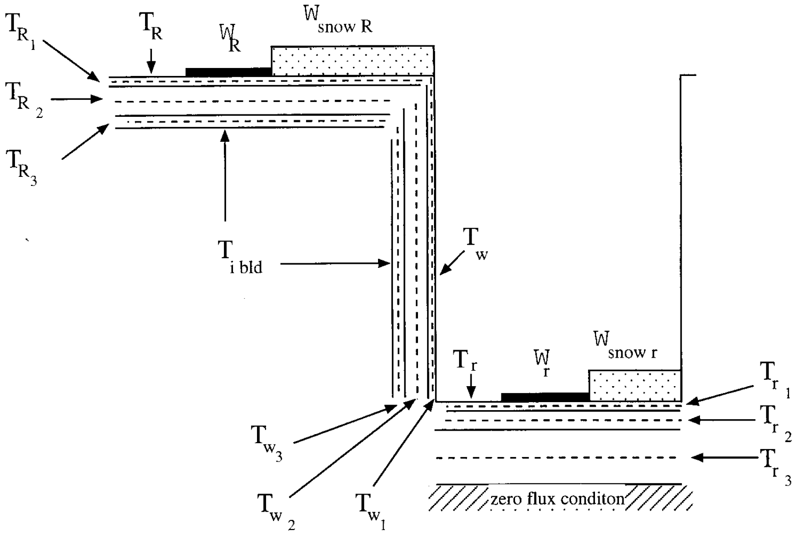

Figure 1: the TEB canyon street (adapted from Masson 2000)

2.3 A three-fold approach

A three-fold approach was followed so as to achieve the previously exposed general objective of EPICEA: part 1) investigation of the long-term evolution of the Parisian urban climate under global climate change; part 2) detailed simulation of the August 2003 heat wave as an example of extreme meteorological event that is likely to become more frequent in the future; part 3) exploration of the impact on local urban climate of adaptation measures aiming to influence the intensity of the UHI in future climate. The following subsections provide a brief overview of the context of the simulations for each of the three aspects as well as some results. More detailed results of part 3 are presented in section 3.

2.3.1 Paris city in a future climate

The objective of this first part is to simulate the impact of climate change by comparing the urban system response in two different climatic contexts: one in the recent past, one in the future. Our methodology relies on simulations over long-time periods using the same surface model (i.e. the characteristics of the city remain unchanged).

The surface model is forced by meteorological conditions derived from an analysis system called SAFRAN (Durand et al. 1993) and validated over France (Quintana Segui et al. 2007). It is a spatial and temporal interpolator which gives analyses of meteorological variables (temperature, humidity, wind, precipitation, pressure, and solar and atmospheric radiation) on a 8km*8km grid over France with an one hour resolution, using CORINE Land Cover (Heymann et al. 1993) and associated parameters from the ECOCLIMAP (Masson et al. 2003) database. Our simulations are run on a 48km*48km grid with the city of Paris in its center. The spatial resolution is 1km.

Simulations of past/present climate of the city of Paris start on 01/08/1970 to end on 31/07/2007. Simulations of the future climate for the period 2046-2065 were run using ARPEGE-Climat, the French global climate model developed by Météo-France. Emission scenarios A2 and A1B produced by IPCC in its Special Report on Emission Scenarios (IPCC 2007) were considered. Meteorological forcing for each scenario was issued from downscaling techniques used in the RExHySS project (Ducharne et al. 2009).

Simulation results highlight a significant increase of the outdoor temperature (between 2 to 4 °C) which depends on the urban density (central city, suburb, countryside) (table 1) as well as a clear trend towards milder winters and much hotter summers by the end of the 21st century.

Table 1: present and future minimum / maximum annual average temperatures 2m above ground according to IPCC SRES A1B and A2

		Urban area		Near suburb		Rural	
		T_{MIN}	T_{MAX}	T_{MIN}	T_{MAX}	T_{MIN}	T_{MAX}
Present (1971-2006)		9,4	15,8	8,0	15,5	6,9	14,6
Future (2072-2098)	A1B	11,8	18,7	10,3	18,6	9,2	17,8
	A2	12,4	19,4	11,0	19,3	9,9	18,5
Temperature increase : Future - Present	A1B	+2,4	+2,9	+2,3	+3,1	+2,3	+3,2
	A2	+3,0	+3,6	+3,0	+3,8	+3,0	+3,9

2.3.2 Detailed simulation of the August 2003 heat wave

The goal of this simulation is to try reproducing the observed August 2003 heat wave effects over the Paris area. Doing so, we get a reference situation that will be used to assess the effects of adaptations measures in part 3. The simulation period corresponds to the peak temperature period from August 8 to August 13 (during which the highest mortality rate was recorded (Hémon, Jougla 2003)). The simulation domain is smaller than for the part 1 and the resolution of the grid covering Paris inner city is much finer: 250m*250m.

The description of the urban fabric also needs to be much more detailed. A specific database of the Parisian urban canopy was developed by CSTB to represent the city in a realistic way. It was elaborated in close collaboration with the Parisian Urban Planning Agency (APUR). These data include the altitude of each grid point, the presence of vegetation, of streets and of water, the height of buildings as well as the types and surfaces of roofs and walls, etc. They have been re-analysed and incorporated into the TEB urban scheme using geographic information software.

Simulations show that the most urbanised quarters in the center of Paris are the seat of intense UHI. A 4 to 7 °C temperature difference is observed at the end of the night between these areas and the low urban density areas around Paris. The influence of the Seine river flowing through the city as well as of the two main green areas on the east (bois de

Vincennes) and the west (bois de Boulogne) of Paris are also visible. Local UHI can also be observed in the inner city (differences of 2 to 4 °C). Peripheral quarters as well as close suburb urban areas situated downwind are also impacted by high temperatures due to the convective energy transfer from the city core.

2.3.3 Adaptation strategies

Previous research helped identifying actions on the built environment that have a potential impact on urban climate and more precisely on the UHI development (Colombert 2008). The most promising interventions are the modification of the surfaces albedo and infra red emissivity (roofs, walls and streets), the greening of urban surfaces with low growing plants (e.g. grass-type vegetation) and the introduction of water in the city (e.g. watering of street surfaces). These interventions are named adaptation measures, i.e. they are said to be effective to reduce the UHI intensity in the future. Doing so, the urban area local meteorological conditions during a heat wave is intended to be more bearable for inhabitants.

Part 3 aims to assess the potential impact of adaptation measures based on these interventions. Our methodology is to simulate the effects of these modifications using the same meteorological context than for part 2 (i.e. during the peak temperature period of the August 2003 heat wave). The comparison between the results of these simulations and the results of the part 2 reference situation provides the assessment we are looking for.

Four scenarios have been investigated as indicated in table 2. Two options are considered for the S2 scenario: green surfaces can be watered or not. The geometrical and topographical parameters (i.e. the size and height of buildings, the width of streets) of the virtually modified Paris city remain unchanged for all these scenarios.

The additional green surfaces have two origins. Firstly we virtually “green” all existing bare-ground surfaces, i.e. 862 hectares. Secondly we also virtually green half of the surfaces of wide enough streets (wider than 15 m), i.e. 305 hectares. The total additional surface increase represents 89% of the present surfaces covered with low-growing vegetation.

Table 2: adaptation scenarios

Name	Reference	Description
Shining Paris	S1	increased albedo and infra-red emissivity of artificial surfaces
Greener Paris without watering	S2	increase of green surfaces
Greener Paris with watering	S2 bis	increase of green surfaces
Watered Paris	S3	water spraying on the streets during the day
Complete	Stot	combination of the three first scenarios

3. Impacts of adaptation measures on UHI

The comparison of part 3 simulations with the part 2 reference situation allows the analysis of the effects of adaptation measures on several meteorological parameters during the development of UHI in the Paris city. We report some of these effects on urban heat balance, outdoor temperature and UHI characteristics.

3.1 Impacts on the urban heat balance

The heat balance expresses the fact that the net radiative flux (difference between incident and reflected/emitted short/long wave radiations) over the urban area is counterbalanced by the sum of the sensible heat flux (energy transferred by convection), the latent heat flux (energy involved in the evapotranspiration of vegetation) and the stored energy (in the thermal mass of the built environment). Under stationary conditions, an equilibrium temperature would be reached. It would be higher in the urban area than in the surrounding rural area. The diurnal cycle creates dynamics so that the terms of the balance are constantly changing. The difference of the dynamic balances between these two areas creates the conditions for the UHI development.

All scenarios (refer to table 2 for description) influence the heat balance of the urban area. In scenario S1, the net radiative flux strongly decreases due to the influence of the increase of surface albedo and of infra red emissivity. The stored energy decreases as well. On the contrary, the net radiative flux increases in woods at the east and west of Paris.

In scenario S2/S2bis, the resulting effect highly depends on the availability of water for the low-growing vegetation. If the vegetation is not watered (S2), it quickly experiences water stress and the contribution of the concerned surface to the heat balance is unchanged compared to the reference situation. If the low-growing vegetation is watered (S2bis), latent heat flux becomes more intense and “consumes” part of the incident solar energy.

Similarly, the energy needed to evaporate the water sprayed on the street surfaces (S3) increases the latent heat flux and decreases the stored energy as well as the sensible heat flux. The complete scenario (Stot) cumulates these effects.

3.2 Impacts on outdoor temperature

3.2.1 Temperature at 2 m above the ground

Impacts on this parameter highly depend on the scenario. The effect we are mainly looking at is the reduction of the highest temperatures. The following results refer to average trends; a more detailed analysis allows more nuanced conclusions. S1 causes a strong decrease of the highest temperatures at 2m above ground. Even more important decrease can be observed with S2bis whilst S2 does not generate significant signal. The effect of S3 is moderate. The combination of all identified adaptation measures (Stot) can locally and temporarily lead to more important temperature decrease: up to 6°C.

An example of a local analysis introduces the nuances we previously mentioned. The selected location is in the south-east of Paris (13th district) where vegetation, buildings and streets surfaces respectively represent 28 %, 40 % and 32 %. In this particular place (simulation grid square surface 250m*250m): 1) S1 and S3 have comparable limited impacts (i.e. a slight temperature decrease during the day with a maximum of 1°C at mid-day, 2) S2 has no impact but S2bis causes a maximum decrease between 2 and 2.5 °C, 3) the decrease can reach 3.5 °C for Stot.

3.2.2 Vertical temperature gradient

Vertical temperature profiles (up to 30 m corresponding to the average height of buildings in Paris) can be plotted for any point of the grid. They reflect the impacts of scenarios according to the following global trends.

All scenarios lead to temperatures along the vertical lower than in the reference situation. For all scenarios, the maximum difference is observed during the day and the night of August 11. Figure 2 presents typical profiles in two contrasted situations: a dense built environment (arr9) and an area (arr7) that offers important green surfaces on wide avenues when S2 is implemented. Days and nights temperature profiles resulting from S1 are rather flat along the vertical. S2 shows no difference with the reference situation (doted lines superpose on figure 2). The impact of S2bis obviously depends on the importance of watered green surface at a given location: the temperature difference between the bottom and the top can reach 3.5 °C during the day and 2.5 °C during the night in green districts while it remains flat in densely built districts. The effect of S3 is more modest (0.5 to 1°C at low altitude) and is limited to lower altitudes. Stot cumulates the effects of all scenarios: vertical temperature differences up to 5°C during the day and 4.5°C during the night can be observed.

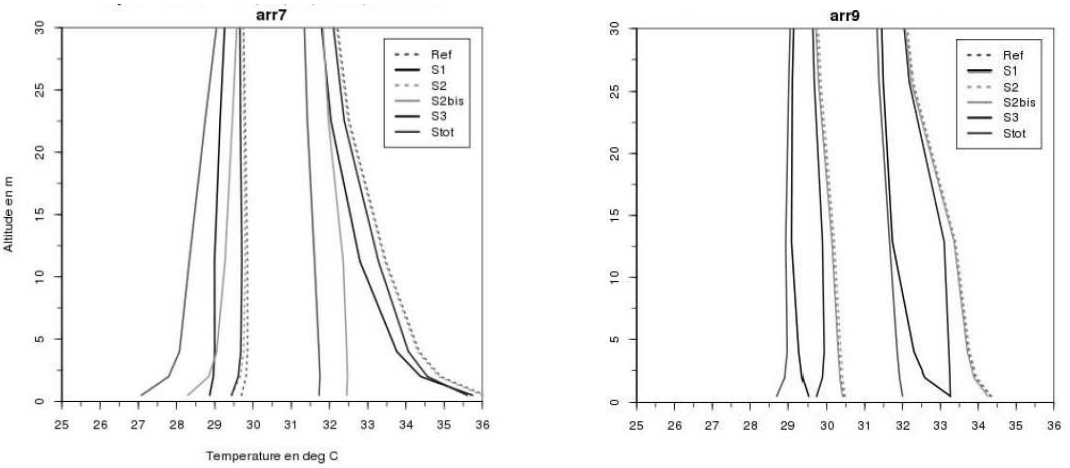

Figure 2: typical vertical temperature profiles in a green area (left) and in a dense district (right). Day/night profiles are represented by left/right groups of curves.

3.3 Impacts on UHI

The temperature curves on figure 3 illustrate the global impacts of the four scenarios. The structure of the UHI remains unchanged with highest temperatures over the dense city centre. A global decrease down to -2,2 °C can be seen over Paris for the complete scenario Stot. The analysis of results over the entire area show that the structure of the UHI is slightly modified as the highest temperatures, located over the centre of Paris in the reference situation are located in the south-west and south-east of the city for Stot. The most intense temperature diminutions are situated over places where vegetation fraction is increased and watered. UHI varies from one day to another in terms of intensity and spatial structure.

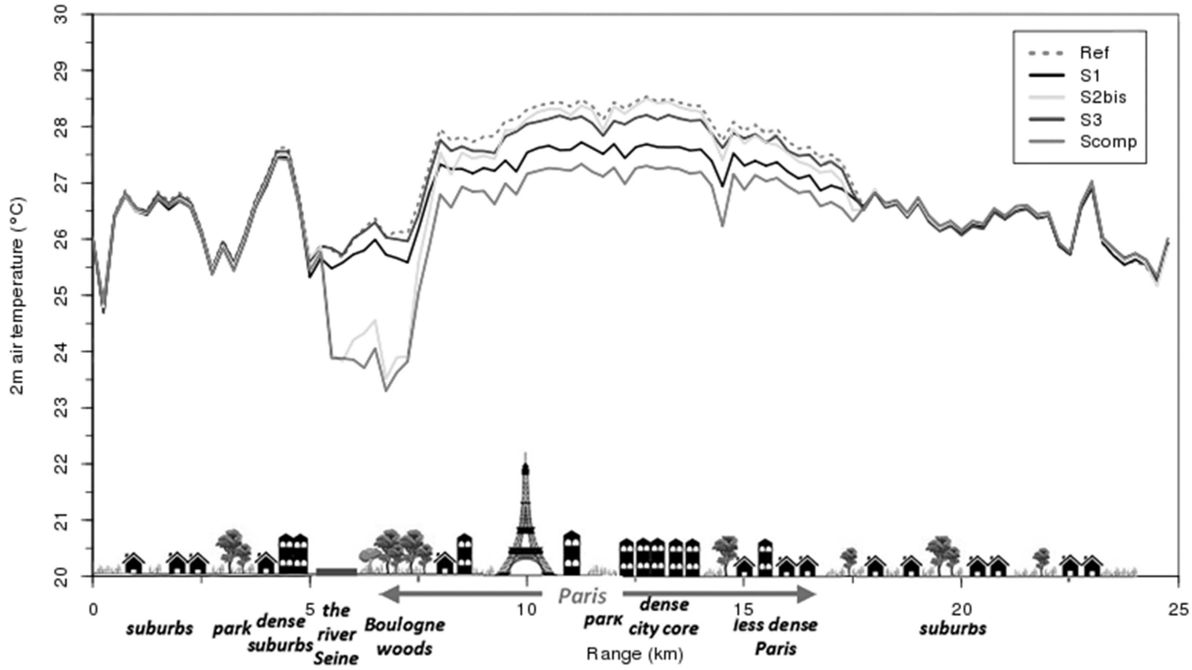

Figure 3: west (left) - east (right) cross section of Paris city showing the influence of scenarios on average temperature profiles

4. Discussion of results

Presented results are part of the outcomes of the project. The influence on other parameters such as relative humidity, wind speed, precipitations (thunderstorm), soil water content has also been addressed. This section introduces a discussion on the presented results.

4.1 Order of magnitude

A main interest of the EPICEA project is to provide credible orders of magnitude of the effects of some adaptation measures on meteorological parameters. This credibility lies in the proved capacity to simulate the August 2003 heat wave pattern (temperatures, relative humidity, wind, precipitations) over Paris and surroundings. These results consolidate previous validations of the TEB scheme (Masson et al. 2002). They also give indication on the pertinence of the description of the built environment that includes different types of buildings according to the date of construction. The computed decrease in temperature according to considered scenarios has to be further analysed taking into account other issues such as the economic and technical feasibility, the acceptability of proposed measures and side effects (e.g. on health).

4.2 Technical and economic feasibility

In the wake of the “cool-roof” conceptual and technical development, several technical solutions are at hand. We can then seriously consider the S1 option from a technical point of view even if architectural peculiarities of the Parisian roofs would create difficulties to implements these solutions (40% of the roof surfaces are covered with zinc (Colombert 2008)). Products with required properties (high albedo, high infra red emissivity) are not necessarily “white-looking” (Akbari et al. 2006). The present cost of cool watertight roofing membranes for flat roof is about 50% higher than traditional black bituminous or polymer products but this extra cost is very likely to decrease with the development of the market.

Beyond direct investment cost, the aging of reflectance and emissivity properties is a main concern as the expected decrease in temperature in the urban area highly relies on them. Tests show a rapid decrease of these properties due to air pollution and aging of materials (Akbari, Levinson 2008). An ad hoc maintenance consisting in a frequent cleaning could counterbalance this degradation of performance but it has to be organised and budgeted.

The presence of urban surfaces covered with low growing vegetation (e.g. trams railways) brings evidence of the feasibility of scenario S2. The expected contribution of green surfaces to the urban heat balance depends on the availability of water that may be a problem during hot and dry periods. But this is a more general problem to be solved as well for green roofs.

The implementation of S3 is likely to be feasible in Paris due to the existence of a distribution network of non drinkable water that runs along all the streets. It is used for street cleaning. Tests are planned during hot periods to measure the local effect and assess water consumption.

4.3 Acceptability and side effects

Scenario S1 using “white” materials would cause a radical change in the visual perception of the city (Erell, Pearlmutter 2012). The question must be raised of its impact on the attractiveness of the city for millions of visitors a year as well as for the citizens. Additional trees could be necessary to limit glare.

The abundant use of water for scenarios S2bis and S3 may also create unexpected situations impacting the life of citizens and pedestrians. The combination of heat and humidity could favour the development of unusual vectors of disease (e.g. insects).

5. Conclusion

The EPICEA project is a contribution to questions all urban areas experiencing hotter climate will have to face in some decades. We have explored some scenarios the technical feasibility of which is likely. Nevertheless, cost issues (investment and maintenance) and side effects have of course to be considered to assist decisions by the town authorities.

A town is nevertheless not just a thermodynamic system and decisions cannot be taken only on the results of simulations based on the law of physics, even if we can rely on these results. Many other concerns (e.g. symbolic, architectural and environmental) are at least as important for human groups as the simulation of the thermal behaviour of an urban area under extreme climatic conditions.

These results call for further works that are planned or under way in other projects by the EPICEA partners. The TEB scheme is being improved to integrate green roofs and a more realistic model of buildings. These improvements will allow considering the building scale and comfort issues that could not be approached properly during the EPICEA project.

Health issues deserve a particular attention. The impact of even slight decrease in temperature may have important effects on mortality rate. Prevention and protection of the most vulnerable population can also be organised by other means than the EPICEA scenarios, e.g. by temporarily hosting this population in naturally cool or artificially cooled places. This latter option addressed the important question of energy demand that must not only be analysed during heat wave period but during the whole year including heating and cooling needs. The positive effect of adaptation measures during the heat wave (e.g. use of high albedo and infra red emissivity surface materials) may not be as positive during the heating period.

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