Influence of air-conditioning management on heat island in Paris in a global warming perspective

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Abstract —Urban heat island (UHI) is an increasingly important public health problem which could be even more severe in a near future due to global warming. Air conditioning (A/C) is a key parameter for health problems in case of heat waves since, on one hand, it reduces mortality but, on the other hand, depending on the heat rejection management, it can increase the street temperature.

This communication, based on simulations, addresses the influence of A/C management on the street temperatures of Paris in the case of the severe heat wave which occurred in August 2003.

Results show that A/C affects the UHI depending on its management. A detailed analysis on selected districts shows that the local temperature variation resulting from heat island is proportional to the sensible heat rejected locally by A/C, indicating that a clever A/C management is all the more important to provide comfort and to mitigate heat island.

Moreover, the incidence of the sky view factor is also discussed.

Keywords —air conditioning, heat island mitigation, Paris heat wave

1 INTRODUCTION

It is now well established that, due to human activity, the urban climate is modified with respect to that of surrounding rural areas. This effect is named urban heat island (UHI) and results in an increase of the ambient temperature. For example, in Athens, the mean heat island intensity exceeds 10°C but in the very central Athens area, the heat island intensity may reach 15°C [1].

Heat wave impact on mortality, especially in densely areas in big cities, is a major issue and the National Weather Service, in US, claims that heat wave is becoming a "major killer". In France, the 2003 heat wave killed 14 802 persons [2]. Jianguo Tan et al. [3] studied the 1998 and 2003 heat waves impacts on mortality in Shanghai. Interestingly, the authors note that the mortality was much more pronounced during the 1998 heat wave although the 2003 one was slightly warmer than the 1998's. Amongst the reasons for less mortality in 2003, the authors note that there was an increase in air-conditioning use, larger living spaces and a higher coverage of urban green space. Between 1998 and 2003, the number of air conditioners in Shanghai jumped from 68.6 to 135.8 per household. In that case, the authors claim that A/C undoubtedly lessens heat stress, protecting large portions of the population from the heat wave.

However, the role of A/C on heat waves is subject to controversy. On one hand, it protects from heat stress inhabitants who are in coolers spaces but, on the other hand, it can contribute, depending on the A/C management, to increase the street temperature if air-source A/C, which discards condensing heat into the air, is used. Due to that effect, several authors [4,5] suggest to use ground-source or water (river, lake or sea) cooled A/C so as to evacuate the condensing heat elsewhere than into the air.

Last but not least, there exists two trends which could contribute to UHI extension. The first one is global warming which suggests that within a few decades, the extreme temperatures observed in France during the august 2003 heat wave should no more be an exception. The second trend is the emergence of many mega cities, favourable to UHI, in countries like China. It is the reason why UHI mitigation corresponds to an important present challenge.

The aim of that paper is to analyse the role of A/C

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management on the street temperature taking into account the case study of the meteorological conditions of the august 2003 heat wave in Paris.

2 Methodology

MESO-NH, a meso-scale meteorological model developed by Lafore *et al.* [6] and Stein *et al.*[7] was used to reproduce meteorological conditions for the 2003 heat wave (9-13 August). This model is coupled, for city, with an urban energy balance model : the Town Energy Balance model (TEB) [8]. TEB is designed to simulate thermodynamical interactions between the city and the atmosphere. Within TEB, the urban landscape is simplified as a network of street canyons. TEB simulates exchanges of heat and water for three generic surfaces : road, wall and roof.

The model was first used to run a reference scenario (NO-AC) using the anthropic energy due to human activity without A/C.

Implementation of A/C within TEB was based on the heat released by A/C and an indoor target temperature of 26°C for buildings with A/C (Fig 1).

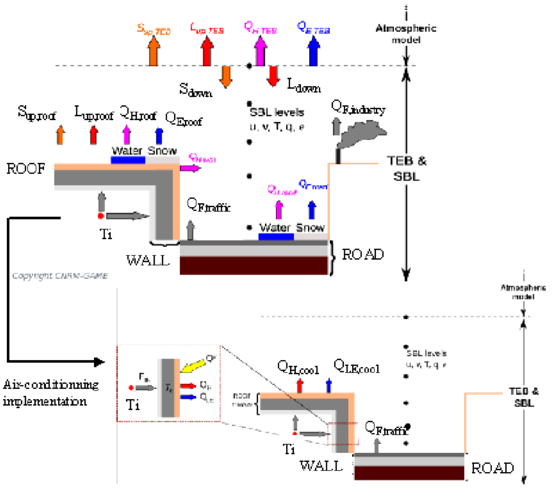

Fig. 1. Simplified description of TEB model implemented with A/C [9]

Simulations based on a realistic spatial cartography of air-cooled chillers and cooling towers in the city of Paris and its surroundings (simulation domain) have been performed. Several sources were used to determine the heat released into the air from A/C for Paris and its surroundings. First, for large A/C units and wet towers, official statements do exist. For other A/C units rejecting heat into the air, Google tools were used for the visualization. Data from district cooling were obtained from Climespace. About 5.6 GW of heat released from A/C for Paris and its surroundings has been implemented in the model according to the types of air-conditioning systems existing in the city : dry air cooling for individual systems, wet towers and a district cooling network using either wet towers or water-cooled A/C with the river Seine (technique known as free-cooling).

With those data, a real scenario was run (REAL). In the case of cooling towers, 5% of the heat released is sensible heat and 95% is latent heat.

To study the impact of A/C management another present-time scenario was run. It is the DRY AC scenario : all the heat released is converted into sensible heat. The overall heat released over the simulation domain is the same as for the REAL scenario but the latent heat released into the air with the wet towers during the REAL scenario is converted into sensible heat with the DRY scenario.

Two other scenarios correspond to a future situation where A/C is doubled : one assumes that all the heat is rejected as sensible heat in the atmosphere (DRY ACx2 scenario), the other, on the contrary, assumes that all the heat is rejected underground or in the river Seine (NOREJ scenario)

For the DRY ACx2 scenario, to avoid a non realistic case, a heat rejection limit of $126 W/m^2_{floor}$ (corresponding to a ratio of $90 W_{cold}/m^2_{floor}$) is imposed into the model. Furthermore, the 10.32 GW of sensible heat reject is distributed with 68% in Paris and 32% outside of central Paris.

All scenarios are compared to the baseline (NO-AC scenario) referring to a situation without air-conditioning.

3 Results

3.1 Impact on street temperatures

When compared to the NO-AC scenario without A/C, the three scenarios considered in Fig. 2 show an increase in 2m street temperatures which is greater at night than during day time. Compared to the NO-AC, temperature elevation at night in Paris is about 0.5°C, 1°C and 2°C for the REAL, DRY AC and DRY ACx2 scenarios respectively. The average temperature variation is about +0.25°C, +0.5°C and +1°C outside of Paris.

As expected, temperature in central Paris is more influenced by A/C than outside, due to a strong concentration of air-conditioned buildings in Paris. The future projection scenario (DRY ACx2) impacts wider zones in the city.

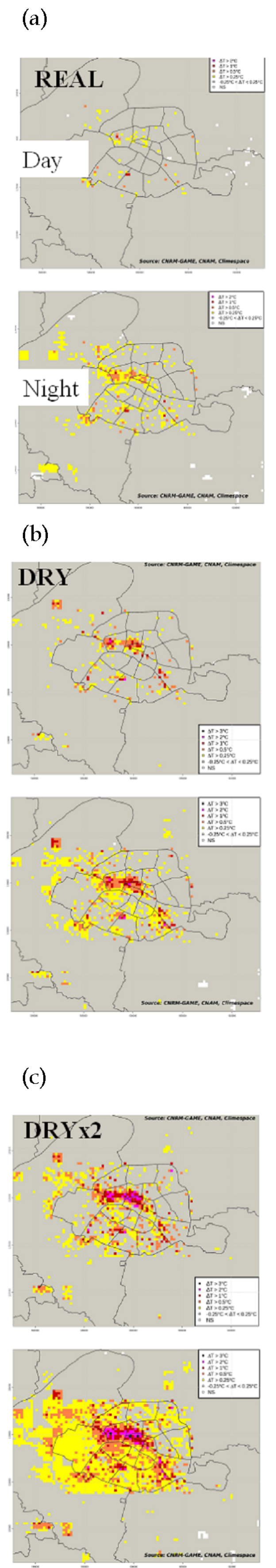

Fig 2. Average variation of temperature at 2m for 3 A/C scenarios at daytime and night-time [9]

3.2. Impact on Urban Heat Island (UHI)

Fig 3 represents for a cross section an average night-time street temperature profile for four scenarios including the scenario without A/C (noted NO-A/C on the figure). This figure shows the influence of air-conditioning on the heat island in Paris, especially on the spatial expansion and the intensity. For the NO-AC, scenario UHI amplitude reaches 3.75°C and it increases to 4.5°C for DRY AC and 5.5°C for DRY ACx2.

For the REAL scenario corresponding to an actual situation of the air-conditioning development in Paris and its surroundings, the amplitude of the UHI is not modified notably compared to the baseline. However, this scenario shows that A/C still influences the temperature profile with an increase in temperature in the hottest areas in central Paris.

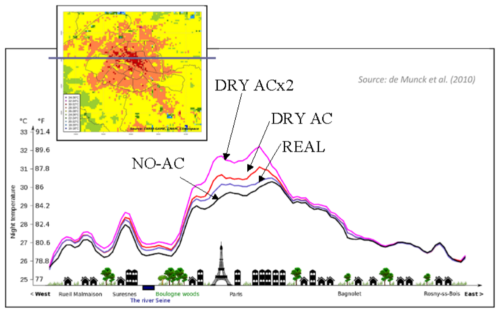

Fig 3. Temperature profiles at night-time for a West-to-East cross section [9]

4 LOCAL ANALYSIS

Fig. 2 and 3 show that UHI is not at all constant. To analyse the impact of A/C on local street temperature variation, 12 meshes (250X250m^2) downtown Paris corresponding to districts where the A/C management differs have been selected. Over the heat wave period, the maximum temperature difference (ΔTmax) between the daily average temperature of a scenario and that of the reference was extracted for each mesh and each scenario. Taking these 12 meshes with 3 scenarios with heat rejection due to A/C, 36 points were obtained. Results of that maximum temperature difference (ΔTmax) are presented in Figure 4 for each mesh under each scenario.

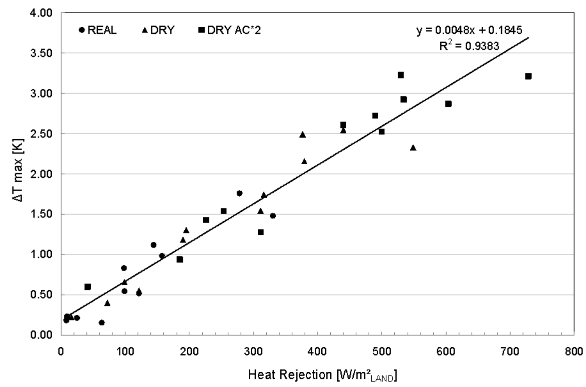

Fig. 4. Variation of local temperature as a function of sensible heat rejection for a subset of 12 meshes

Interestingly, a linear variation of the temperature increase due to A/C versus the sensible heat rejection is obtained. This tends to prove that the local street temperature increase due to A/C depends, to the first order, on the heat rejection. Note that for zero heat rejection, we do not get zero temperature increase. This could prove that, in densely areas, even without heat rejection due to A/C, a mesh experiences a temperature increase due to the next meshes where A/C may exist.

Calculated as a function of the ground surface, the ratio of maximal street temperature variation is about : 5 $K.m^2_{land}.kW_{heat}^{-1}$. Kikegawa et al. [10] reported temperature differences, in Tokyo, due to A/C reaching 0.6 or 1.15°C depending on the sky view factor. More recently Kikegawa et al. [11] claim that the sensitivity of downtown air temperature, in Tokyo and Osaka, to anthropogenic heat is 7 to 9 $K.m^2_{land}.kW_{heat}^{-1}$ which is of the same order of magnitude as the 5 $K.m^2_{land}.kW_{heat}^{-1}$ reported herein. In the model developed herein, the heat is assumed to be rejected on the roof (which corresponds to the most important fraction of heat released by A/C in Paris) but Kikegawa et al. note that when the heat is rejected to the ground levels rather than from the rooftop, the daily surface-air temperature increases by 0.62°C [4]. This could explain the difference between the results herein and the data by Kikegawa et al. on the sensitivity of air temperature to anthropogenic heat.

The analysis of the results shown on Fig. 3 and 4 suggests that in the NO-AC scenario, the UHI is mainly due to the impact of the urban structure (including the disappearance of green spaces) whereas, in the other scenarios, the heat rejected plays a major role. The results show that the extra UHI due to heat rejected by A/C may be as high or even more than the structural UHI when air cooled A/C is intensively used. This proves the challenge for a clever A/C management to avoid UHI pockets intensification in districts whith a high A/C level.

Four typical meshes have been selected to present their relative hourly street temperature variation, in the REAL scenario (Fig. 5-8), and their average excess temperature due to A/C (Fig.9-12) during the heat wave period. Mesh 4129 (Fig. 5 & 9) corresponds to a business district where A/C is very important (330W/m^2_{LAND} sensible heat rejected in the REAL scenario). On the contrary, mesh 3465 (Fig. 6 & 10) corresponds to a residential popular district where very little A/C exists (9$W/m^2._{LAND}$ sensible heat rejected in the REAL scenario). Meshes 4692 (Fig. 7 & 11) and 6207 (Fig. 8 & 12) correspond to cases where district cooling represents more than 90% of the A/C. As observed on Fig. 5-8, the trend for the temperature swing is the same for all the meshes but the relative temperature swing between day and night is not the same for the four meshes and it can reach and even overpass 15°C. For all the meshes, the minimum temperature during night time goes through a maximum on the same night during the heat wave peak. The meshes 4129 and 3465 experience a smaller temperature swing than meshes 6207 and 4692, this point will be discussed later on.

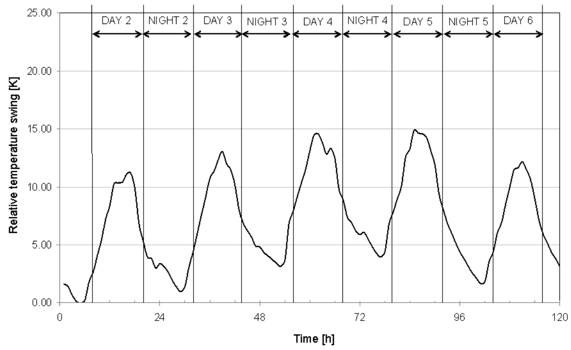

Fig. 5. Relative hourly temperature swing for mesh 4129 deduced from the model for the REAL scenario during the august 2003 heat wave in Paris

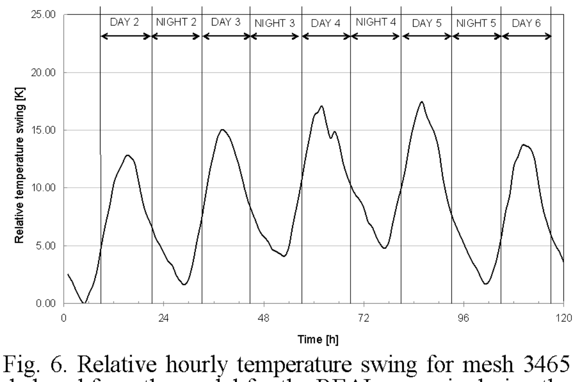

Fig. 6. Relative hourly temperature swing for mesh 3465 deduced from the model for the REAL scenario during the august 2003 heat wave in Paris

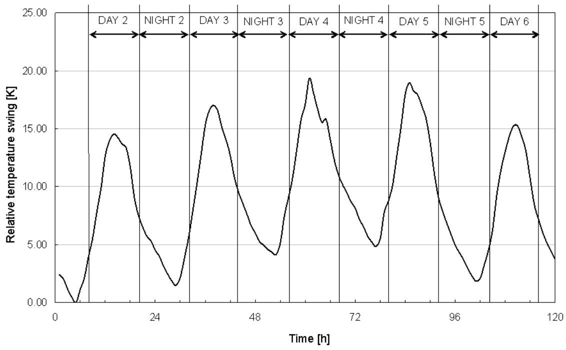

Fig. 7. Relative hourly temperature swing for mesh 4692 deduced from the model for the REAL scenario during the august 2003 heat wave in Paris

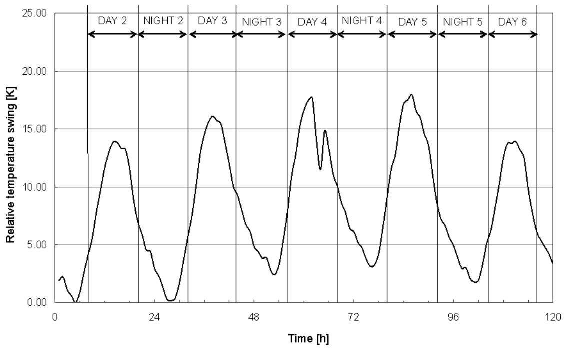

Fig. 8. Relative hourly temperature swing for mesh 6207 deduced from the model for the REAL scenario during the august 2003 heat wave in Paris

On Fig. 9-12, the average excess temperature due to A/C, for day time and night time on periods of 12h, is now presented for each mesh as the temperature difference between a given scenario and the reference scenario. Doing so, the main focus is put on the effect of the A/C management as it was performed on Figure 4. In the mesh 4129 where A/C is very important, the sensible heat released by A/C is high ($330W/m^2_{LAND}$ in the REAL scenario). The temperature increase spans between 1.5 (REAL) and 3.5°C (DRY ACx2). On the contrary, mesh 3465 corresponds to a residential popular district where very little A/C exists ($9W/m^2._{LAND}$ sensible heat rejected in the REAL scenario). The temperature increase is very small, between .3 (REAL) and .7°C (DRY ACx2). Meshes 4692 and 6207 correspond to cases where district cooling represents more than 90% of the A/C. With district cooling, the REAL scenario does not show significant temperature increase with respect to the NO-AC scenario because the sensible heat released is very low. But, when the condensing heat is rejected into the mesh, as depicted by the DRY scenario, a temperature increase between 1.5°C and 3°C, with respect to the reference, is observed.

Note that in meshes 4692 and 6207 (Fig. 11 & 12), the temperature increase due to the heat rejected due to A/C is higher during the night as should be expected from the analysis presented on Fig.2 whereas in mesh 4129 (Fig. 9), there is no significant difference between day and night. At the moment, we have no explanation on this local behaviour.

From those data, important conclusions can be drawn:

- the local street temperature increase is strongly, and linearly, dependent on the sensible heat released through A/C and UHI pockets do exist
- dry air cooling A/C represents a strong penalty in districts where A/C is highly used since it induces temperature increase which can reach 2.5°C in the DRY scenario.
- Areas where district cooling is mainly used are not subject to significant temperature increase due to A/C preventing UHI pockets.

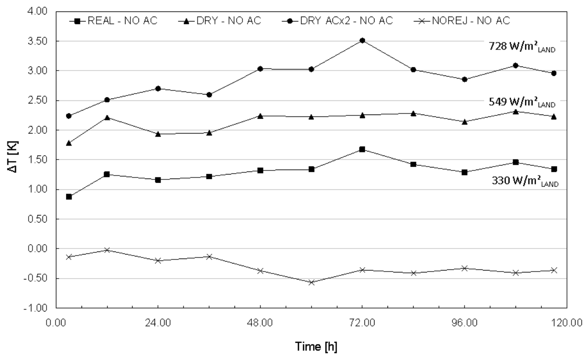

Fig. 9. 12 h-average temperature difference between each scenario with A/C and the reference scenario without A/C for mesh 4129 during the august 2003 heat wave in Paris

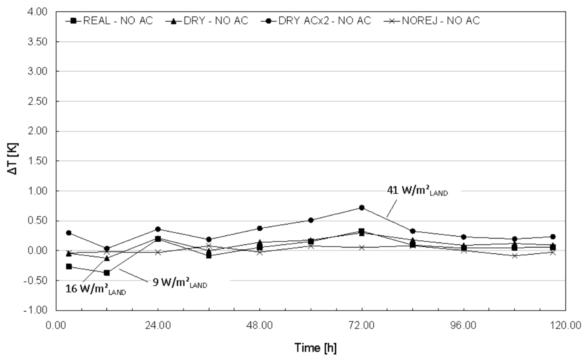

Fig. 10. 12 h-average temperature difference between each scenario with A/C and the reference scenario without A/C for mesh 3465 during the august 2003 heat wave in Paris

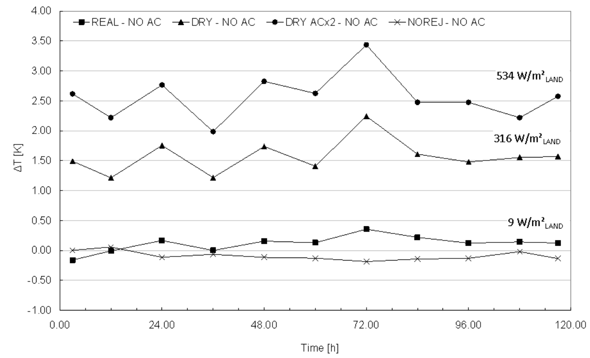

Fig. 11. 12 h-average temperature difference between each scenario with A/C and the reference scenario without A/C for mesh 4692 during the august 2003 heat wave in Paris

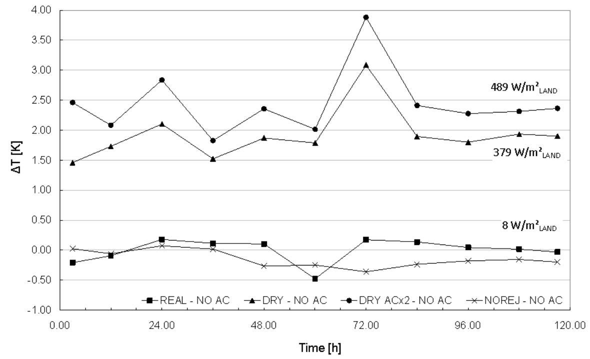

Fig. 12. 12 h-average temperature difference between each scenario with A/C and the reference scenario without A/C for mesh 6207 during the august 2003 heat wave in Paris

In Fig. 4 some dispersion on the points was observed and in Figures 5-8, it was noted that the temperature swing between day and night differed significantly depending on the meshes. The influence of other parameters than heat rejection was analysed to find if some could play a role. Herein, the influence of the sky view factor is reported. For that purpose, the temperature swings observed in Figures 5-8 were analysed in more detail. The temperature swing between the average temperature of a half day and that of the following half day has been extracted and is presented on Fig. 13-15, for three different sequences during the heat wave, versus the sky view factor of the mesh (which varies from 0.126 to 0.68 for the 12 meshes). Note that the information contained in those figures differs strongly of that contained in Fig. 4-8. In the previous figures, the temperature difference was that existing between the scenario with A/C under study and the reference one without A/C. That means that the existing temperature swing of the reference case was subtracted. Therefore, effects due to parameters like architecture or urbanism were excluded. On the opposite, the results shown, in the REAL case, on Fig. 13-15 include not only the effect of heat released by A/C but also the characteristics of the mesh (architecture, urbanism, etc.). For the 4 meshes under study, all the scenarios yield typical similar results as those reported herein on Fig. 13-15 for the REAL scenario. The temperature swing between day and night increases linearly versus the sky view factor from 8°C to 10°C at the beginning (Fig. 13) or 8°C to 12°C at the end (Fig. 15) of the heat wave. It is reduced to 7°C and does not show any significant dependence on the sky view factor when the heat wave is the strongest (Fig. 14).

These results suggest that the heat stored in the buildings and other infrastructures should be at its maximum value for the heat wave peak. At that moment, the influence of the sky view factor could be minimum.

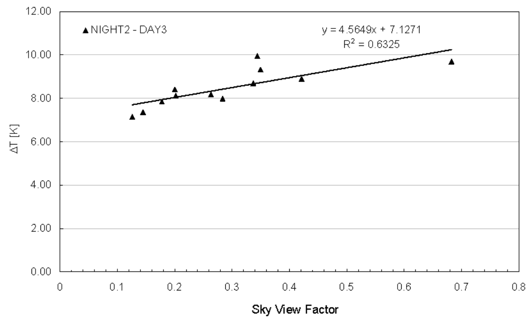

Fig. 13.Absolute temperature swing between the average temperature of the second night and the third day of the heat wave for the REAL scenario and the12 meshes versus their sky view factor

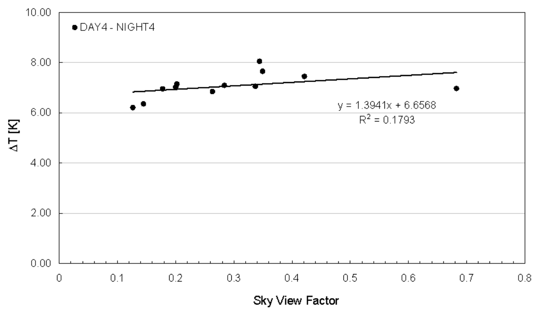

Fig. 14. Temperature swing between the average temperature of the fourth day and the fourth night of the heat wave for the REAL scenario and the 12 meshes versus their sky view factor

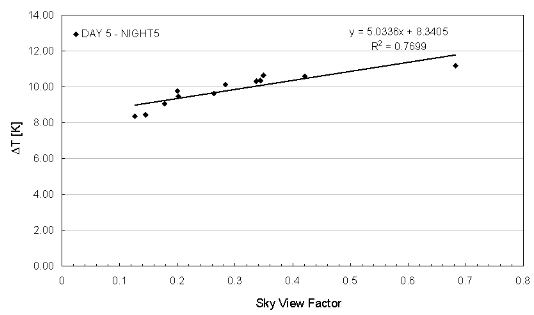

Fig. 15. Temperature swing between the average temperature of the fifth day and the fifth night of the heat wave for the REAL scenario and the 12 meshes versus their sky view factor

Coming back to Fig. 5-8, the temperature swing was noted to be smaller for meshes 4129 and 3465. The explanation could be that the sky view factor of meshes 4129 and 3465 equals to respectively 0.126 and 0.26 is smaller than that of meshes 6207 and 4692 which equals 0.34 and 0.35.
Results shown on Fig. 13-15 tend to prove that the urban characteristic of the mesh plays a role, as well as heat released, on the temperature increase and confirms that the sky view factor is a pertinent parameter to take into account for UHI. Areas with higher sky view factor experience higher temperature swings, which is favourable for the health. But when the effect of the heat wave is the highest, the influence of the sky view factor seems to be reduced.

The NOREJ scenario whose results are shown for the four selected meshes on Fig. 9-12 corresponds to the case when the heat released by A/C is the same as in the DRY ACx2 scenario except that, now, the heat is rejected elsewhere than in the air (in Paris, it can be underground or in the river Seine). In that case, the air temperature is found to be less than in the reference scenario for all meshes except mesh 3465 (Figure 10) where very little A/C does exist so that the external cooling load of the buildings is negligible and does not interact with the street. But when A/C is important, NOREJ A/C results in a slight cooling with respect to the reference scenario without A/C. For mesh 4129 (Figure 9), the maximum cooling effect reaches 0.5°C as depicted on Fig. 9. For meshes 6207 and 4692, the maximum external cooling loads as given by the model are lower than for mesh 4129 so that a smaller cooling effect of the order 0.2°C for mesh 4692 (Fig. 11) and 0.3°C for mesh 6207 (Fig. 12) is observed.
Those cooling values are higher than that which should be deduced using the 5 $K.m^2_{land}.kW_{heat}^{-1}$ correlation between heat exchange and external air temperature. The correlation would give respectively 0.13°C, 0.09°C and 0.08°C for meshes 4129, 4692 and 6207 instead of the values 0.5°C, 0.2°C and 0.3°C as given by the TEB model.
The TEB model used herein possibly underestimates the cooling external loads due to the exchange between indoor and the street. For all the scenarios discussed in this paper, the value of the external loads ranged from 2 to 9.5W/m^2.floor and in the NOREJ scenario they ranged from 2 to 7 W/m^2.floor which is a low value for a heat wave period when the street air temperature overpasses 40°C. Modifications of the TEB model are underway to better simulate the heat exchange between indoor building and the street. With higher external cooling loads, the external cooling effect due to NOREJ A/C would be higher.
Although small, according to the model, that effect does exist and contributes to mitigate slightly UHI. Interestingly, the mitigation effect is more important in areas where intensive A/C with heat released elsewhere than into the air is used. Obviously, district cooling rejecting condensing heat in a river or underground (or using the heat for domestic hot water) could be the appropriate technology to reach that goal of slightly cooling the city through A/C.

5 CONCLUSION

Heat waves will be reinforced due to climate change. In France, more probably, the temperatures observed during the august 2003 heat wave will be very frequent after 2050. Therefore, the need for A/C in large cities will be required to protect populations sensible to heat stress since it is proven that A/C can contribute to reduce mortality during heat waves. However, it is, as well, known that A/C can reinforce UHI. Therefore a clever management of A/C constitutes an important present challenge.
This study, based on a model using actual meteorological data [9], shows that, in Paris, the global UHI depends on the heat released by the A/C management. Moreover, this study also shows that, in densely areas, the local temperature variation due to A/C depends linearly on the sensible heat rate released by A/C. In districts where air cooled A/C is very intensive, the extra UHI due to A/C may be of the same order of magnitude as the structural UHI. This proves the importance of the challenge of a clever A/C management to avoid extra UHI.
In densely areas, dry air cooling A/C with heat rejection into the air represents a bad solution since it contributes to increase strongly the temperature creating UHI pockets. The districts more affected are those where the A/C is strongly developed. Doubling A/C as compared to the present situation, should produce, in some areas, local temperature increases due to A/C which should reach 2.5°C. The districts where very little dry air cooling A/C exist are far less affected but, nevertheless, are a little affected (a few 0.1°C) through coupling with nearby districts with dry air cooling A/C.
Wet towers A/C represent a much better solution than dry air cooling from the point of view of temperature variation since the sensible heat released is small , but the problem of Legionella must not be neglected.
However, the best solution is undoubtedly ground source or water cooled A/C in which the heat is released elsewhere than into the air (NOREJ scenario). Some cases of that technology do exist, in Paris for example where the river Seine is used for district cooling by Climespace. With the NOREJ scenario, A/C should contribute to slightly mitigate heat wave. The mitigation should be higher in areas where A/C is more developed.
The influence of the sky view factor has also be noted. A high sky view factor is more favourable for the existence of large temperature swings between

day and night which is favourable for health. However, during the warmest period of the heat wave, the influence of the sky view factor on temperature swing seemed to disappear.
In this work, the impact on energy consumption due to A/C was not addressed but further studies will develop this point since it is known that energy consumption due to A/C increases when the street air temperature increases [4 & 10]. Therefore, another advantage to dissipate the heat of condensation elsewhere than into the air will be energy saving.

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