Local climate change: Assessing the impact and mitigating the heat

The main characteristics of the local climatic change and, in particular, of the urban heat island phenomenon. The implications of the urban heat island on energy consumption in buildings, and on the indoor and outdoor environmental quality and health. The actual research and the existing application aiming to develop and apply mitigation technologies to counterbalance the urban temperature increase and its impact on man

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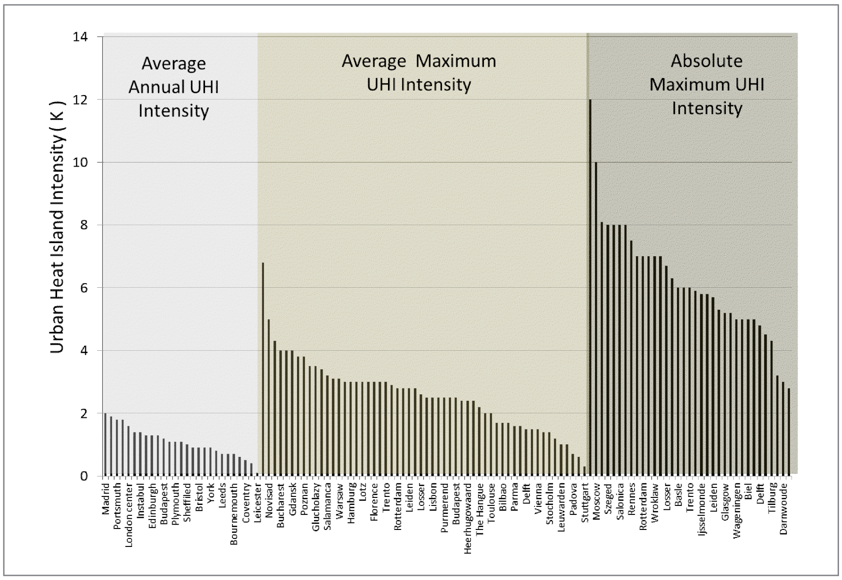

Fig 1 Measurements based on Standard Fixed Stations

The urban heat island is the most documented phenomenon of climate change. Actually, there are more than 400 cities around the world where specific measurements are performed and the existence and the characteristics of the phenomenon are documented and analysed. Urban heat island deals with the development of higher ambient temperatures in the dense zones of cities compared to the surrounding suburban and rural areas as a result of the more positive thermal balance in the urban than in the rural environment. Accumulation of solar heat in the dense urban fabric, excessive generation of anthropogenic heat, lack of green spaces and water, and reduced convective flows because of the inability of the wind to penetrate into the city are among the main reasons contributing to the development of the phenomenon (Santamouris, 2001).

The Urban Heat Island Phenomenon

Urban heat island exists in all geographic locations, from low to high latitudes, it reaches its maximum during the warm summer period and may be present during the day or the night as a function of the local thermal balance. It achieves its maximum peak during clear days with low wind speed, whereas it is highly affected by the sea breeze and precipitations. Its magnitude is measured in terms of 'Urban Heat Island Intensity', which is the maximum measured difference between the urban and the reference rural station. Unfortunately, there is not a universal agreement on the way that the Urban Heat Island Intensity has to be measured and reported. Such an inconsistency creates a certain confusion and results in false interpretations. Actually, three experimental protocols are used to determine the characteristics of the phenomenon. The first one is based on the use of standard meteorological stations usually installed in undisturbed urban and rural zones, the second on non-standard stations placed in various zones of the city fabric, and the third one involves the use of mobile stations moving inside the city to map the temperature distribution. The first protocol has the advantage of multiyear measurements, however, the position of the stations does not permit to collect temperature information in the dense urban zones. The second experimental protocol offers data of limited time period, compared to the first protocol, however it allows to map the temperature regime of the thermally sensitive urban zones. Finally, the third protocol may offer data for a very short time period, but can collect information in most of the urban areas. The magnitude of the urban heat island intensity is reported either as a function of the average maximum annual temperature difference between the specific urban zone and the reference station, or the absolute maximum difference between the corresponding stations. In rare cases, the average annual temperature difference is reported.

The intensity of the local climate change in the European cities is quite high and may reach values close to 10 K, depending on the measurement protocol and the reporting format used. Figure 1 summarizes the known magnitude of almost all European cities where urban heat island measurements are carried out using standard fixed stations, and reported in credible scientific fora.

As shown, an average intensity of the phenomenon varies between 4 to 7 K. It is evident that such a temperature increase may have a serious impact on the energy consumption of buildings during the summer period and also on the overall environmental quality of the cities.

Impact of the Urban Heat Island Phenomenon

Higher urban temperatures increase energy consumption in buildings during the summer period, intensifiy the peak electricity demand, deteriorate indoor and outdoor thermal comfort conditions, increase the concentration of harmful pollutants and especially of the tropospheric ozone, affect the health of vulnerable populations, and has a negative impact on the local economy while it increases the ecological footprint of urban areas.

Exposure of population to high ambient temperatures has a significant impact on health and increases mortality rates. Medical research carried out in Southern and Northern European zones has concluded that over a threshold ambient temperature mortality rates increase rapidly. The critical temperature is found to be much higher in the Mediteranean countries, 29.4 °C, than in the Northern and Continental European areas where it was close to 23.3 °C, (Baccini et al, 2008). It is characteristic that a possible increase in the ambient temperature by 1 K above the threshold temperature may increase the mortality rate by 3.12% and 1.84% in the Mediteranean and Northern Europe, respectively.

The impact of the local and global climate change on energy consumption in buildings has been recently assessed using almost all available published data (Santamouris, 2014). It was found that for the 1970-2010 period, the increase in the cooling demand of buildings induced by the global climate change was significantly higher than the corresponding decrease of the heating load. On average, the calculated increase in the cooling demand of selected buildings was 23 %, while the total increase in the heating and cooling load was 11%. In parallel, it was calculated that the increase in the cooling load induced by the urban heat island is in the order of 13%. Finally, it was found that the global energy penalty caused by the UHI per unit of the city surface and per degree of the UHI intensity is 0.74 kWh/m^2, (±0.67) while the Global Energy Penalty per person, is close to 237(±130) kW h/p.

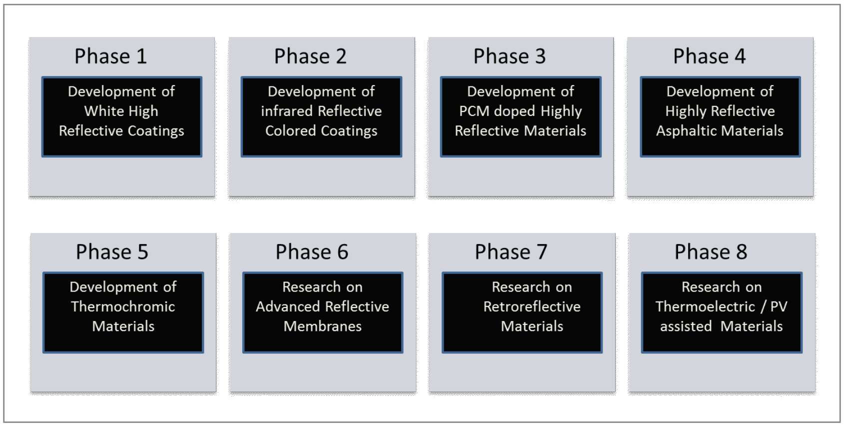

Fig 2 Eight different clusters of the research on reflective materials

Urban Heat Island Mitigation Technologies

Several techniques and technologies are proposed to mitigate the urban heat island. The main technologies used to deal with the implementation of green spaces in the city scale like additional parks and trees in the streets, or the use of green roofs in buildings and also the use of reflective materials for buildings and open spaces that reflect the incoming solar radiation back in space. In many cases, the use of environmental heat sinks presenting a temperature lower than the ambient one is proposed (Santamouris and Kolokotsa, 2015).

Among the different proposed mitigation technologies, the development and use of reflective materials has gained the highest scientific interest. In general, research on reflective materials can be classified in eight different clusters, as shown in Figure 2.

During the first phase of the research, white coatings were developed in an effort to enhance the solar reflectance of the external surface of buildings and pavements. The specific coatings have an increased solar reflectance value by 15% compared to the commercially available white coatings. Comparative measurements of the surface temperature of the advanced white coatings showed that during the day period, the maximum temperature difference between the white coatings was around 5 °C as a function of their reflectivity. The difference between the white and aluminum tiles was up to 11 °C. During the night period, the maximum temperature differ-

ence between the white coatings was around 2 °C, while the maximum temperature difference between the white and the aluminum base paints was around 5 °C. In this case, the role of the emissivity is dominant.
During the second phase of the research, coloured coatings presenting a high reflectivity in the infrared were developed. The coatings were tested extensively in terms of durability, age problems and optical degradation, while the thermal performance of the coatings against conventional materials of similar color was extensively tested. During the day, all the cool colored coatings had surface temperatures lower than the colored-matched standard coatings. The best performing cool coatings were black, chocolate brown, blue and anthracite, which maintained differences in mean daily surface temperature from their respective standard color-matched coatings by 5.2, 4.7, 4.7 and 2.8 °C, during the month of August. The highest temperature difference was observed between cool and standard black and was equal to 10.2 °C, corresponding to a difference in their solar reflectance of 22%. The lowest temperature difference was observed between cool and standard green and was equal to 1.6 °C (for August) corresponding to a difference in their solar reflectance of 7%.
During the third phase of the research, and in order to further decrease the surface temperature of highly reflective colored coatings, phase change microcaplules containing parafins (phase change T = 18 °C), were incorporated in the cool coatings. Microcapsules have a diameter of 17-20 μm and are protected externally by a polymeric material. The optical and thermal performance of the materials was tested extensively. The surface temperature of the black cool material with PCM microcapsules was almost 3.8 °C lower than the temperature of the cool black and 13.3 °C lower than the common black. Also, the surface temperature of blue cool material with PCM microcapsules was almost 1.8 °C lower than the temperature of the cool blue.
During the fourth phase of the research, cool asphaltic materials were developed and tested. The materials can replace conventional asphaltic materials and are available in different colours. They present a much higher reflectivity and also a lower surface temperature compared to conventional asphalt materials.
During the fifth phase, thermochromics coatings were developed and tested. Thermochromic coatings change colour as a function of the ambient temperature. For low outdoor winter temperatures , the coatings may be dark, presenting a high absorptivity. For higher ambient temperatures, summer, the coating becomes white, presenting a high reflectivity. Thus, when applied on roofs or walls, it may present the best performance all year round. Thermochromism is the reversible colour change of a substance induced by temperature change. The composition of organic thermochromic dyes includes : a) *the color former*: usually a cyclic ester which determines the color of the final product in its colored state, b) *the color developer*: usually a weak acid that imparts the reversible color change of the thermochromic material and is responsible for the colour intensity of the final product, and c) *the solvent*: usually an alcohol or an ester, that, when reachin the melting point, control the temperature at which the colour change occurs. Thermochromic coatings present a high reflectivity both in the visible and infrared spectrum, and avery strong absorption in the near-ultraviolet range of the spectrum.
The sixth phase of the research aimed at optimising cool membranes under varying conditions. Analysis of five different prototype membranes: (i) standard white, (ii) standard grey,

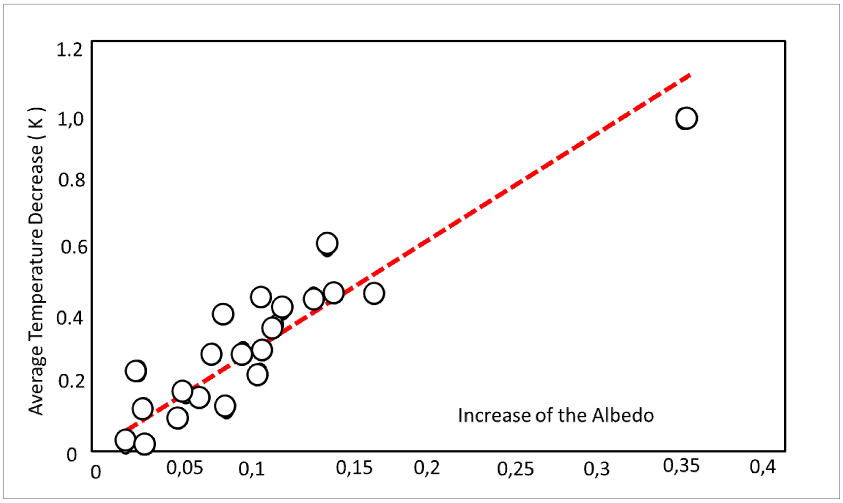

Fig 3 Increase in the local albedo and average temperature decrease

(iii) standard white with additional 30% white paste, (iv) standard white with additional 30% optimized white paste, and (v) standard white with 10% integrated paraffin as PCM material. The optimization of the cooling potential was performed by increasing specific components, i.e. titanium dioxide (TiO_2) and hollow ceramic microspheres. Additionally, the superficial finishing of the membrane, named "white paste", was improved in sample (iv) to minimize its sticky effect, typical of polyurethane-based products, affecting their self-cleaning capability.
During the next phase of the work, retroreflective materials were developed and tested. Different materials were investigated and tested and very promising results were obtained regarding the desired reflection angle.
Finally, there is an important research on the use of thermoelectric nanomaterials for pavements. The research has given some first interesting results that are not yet in the phase of exploitation.
The developed materials have been applied extensively in various large-scale projects around the world. A recent evaluation of the existing results from all monitored projects showed that it is possible to decrease the average ambient temperature in a place by 0.2 to 0.5 °C using a moderate increase in the local albedo (Santamouris 2014b).

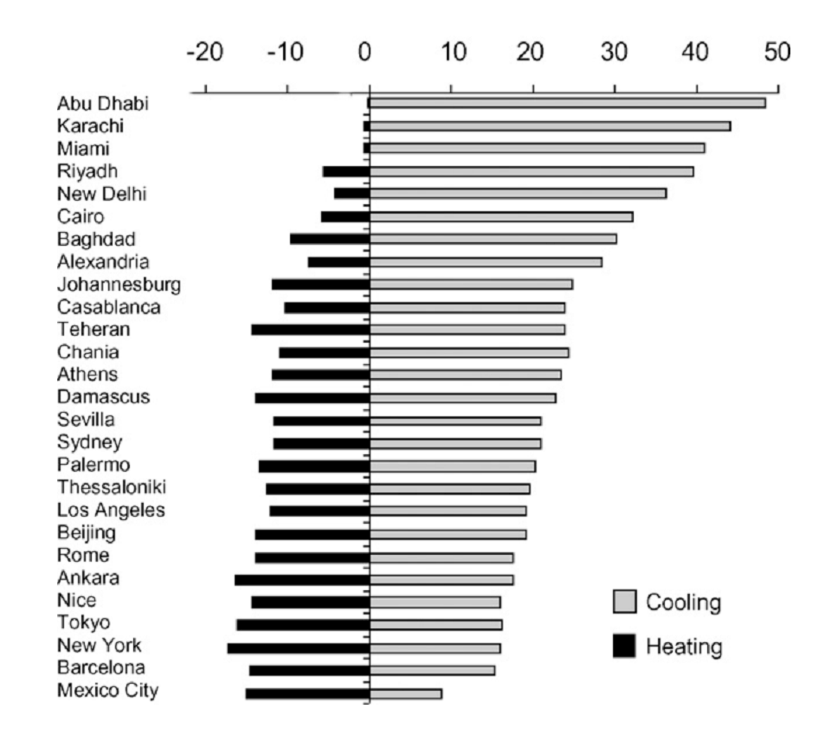

Fig 4 Changes in cooling and heating energy loads (kWh/m² year)

Use of Advanced Cool Materials in Buildings

Reflective materials are suitable for the roof of buildings in order to reflect solar radiation and decrease the heat input during the summer period. The cooling potential of the so-called 'coor roofs' strongly depends on the thermal conditions of the building, the local climatic conditions and the optical characteristics of the used cool roof. Thousands of applications have been performed all around the world and this is a very well established market that helps to decrease energy consumption in buildings.
An extended study aiming to investigate the cooling potential of cool roofs under different climatic and building boundary conditions is carried out and given in Synnefa et al., 2007. It was found that by increasing the roof solar reflectance the cooling loads are decreased by 18–93% and the peak cooling demandin air-conditioned buildings by 11–27%. In parallel, indoor thermal comfort conditions improve considerably by decreasing the hours of discomfort by 9–100% and the maximum indoor temperatures in non air-conditioned residential buildings by 1.2–3.3 °C. The contribution of cool roofs was found to be more significant for non-insulated buildings. The calculated heating penalty (0.2–17 kWh/m2 year) was less important than the cooling load reduction (9–48 kWh/m² year).

Conclusions

The Urban Heat Island is an extremely well documented phenomenon that affects the quality of life of cities and creates important energy and environmental problems. Significant research carried out especially during the last 30 years has allowed first to understand and quantify in detail the specific impact of the phenomenon, and second to develop advanced mitigation technologies that are commercially available. Large-scale mitigation projects aiming to decrease the ambient temperature during the warm period have been undertaken and extensive monitoring has shown that the achieved results are quite spectacular.

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REFERENCES

Baccini M, A. Biggeri, G. Accetta, T. Kosatsky, K. Katsouyanni, A. Analitis, H.R. Anderson, L. Bisanti, D. D'Ippoliti, J. Danova, et al., Heat effects on mortality in 15 European cities, Epidemiology 19 (2008) 711–719

Santamouris M, (Editor), Energy and Climate in the Urban Built Environment, Earthscan Publishers, London, UK, 2001

Santamouris M, On The Energy Impact of Urban Heat Island and Global Warming on Buildings, Energy and Buildings, Volume 82, October 2014, Pages 100-113, 2014

M. Santamouris, Cooling the Cities, A Review of Reflective and Green Roof Mitigation Technologies to Fight Heat Island and Improve Comfort in Urban Environments, Solar Energy, 103 (2014b) 682–703, 2014

Santamouris M and Kolokotsa D, Urban Mitigation Technologies, Taylor and Francis, London, UK, 2015

Synnefa. A, M. Santamouris and H.Akbari, Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions, Energy and Buildings, 39,11, 1167-1174, 2007