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## Sustainable Urban Future in Southern Europe - What About the Heat Island Effect?

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# **Sustainable Urban Future in Southern Europe - What about the Heat Island Effect?**

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**ABSTRACT:** In general cities, and especially cities in hot zones, as the Mediterranean, suffer from raised temperatures in the city core, generally known as the heat island effect. Raised temperatures, especially in summer, may turn city centres into unwelcome hot areas, with direct effects on energy consumption for cooling buildings and morbidity and mortality risks for the population. These raised temperatures in the city centre derive from the altered thermal balances in urban spaces, mainly due to the materials and activities taking place in cities, by far different to those in rural areas. The notably raised thermal capacity of urban materials, their low albedo and their lack of porosity are of the main characteristics of urban materials, responsible for the formation of raised urban temperatures. The general lack of vegetation and the low albedo of urban surfaces are strong characteristics of the formation of the heat island effect. If building surfaces, which are greatly responsible for the formation of raised urban temperatures are covered with either high albedo materials or vegetation it is expected that urban temperatures could lower significantly. With the case study of the city of Athens, this paper explores quantitatively how raised urban temperatures could reduce in the hot and dry Mediterranean summer, when the building envelope is covered with either high albedo paint or vegetation. The most effective technique is then examined in detail, with the use of a prognostic, two-dimensional, micro-scale heat and mass transfer model, its effect in urban canyons with different geometries and orientations is explored and how this could be applied at an urban scale. The effect of this cooling technique is examined on the outdoors thermal comfort and the energy consumption for cooling. Conclusions are drawn about how the heat island effect could be mitigated, depending on the urban geometry and whether such a proposal could prove beneficial for cities in the South of Europe.

**Keywords:** heat island effect, albedo, vegetation, green roofs, green walls, urban temperatures

**Topic:** Environment, Natural Resources and Sustainability

## **1 Introduction**

Any alteration on the earth's surface can lead to quite significant transformations of the local or global climate. These alterations can be due either to natural causes (e.g. tectonic activity, which changes the position of the land and oceans) or anthropogenic activities. One of the greatest changes on the Earth's surface due to human activity, with a direct effect on the energy absorbed

by the planet, has been the deforestation of the Northern Hemisphere's temperate forest zone. It began on a small scale more than 5,000 years ago, when forests started being converted to land for cultivating grasses. This was responsible for causing climate change at that time (Lamb, 1995). On a more local scale, the formation of cities in places usually covered with vegetation fatally causes alterations of the climatic characteristics of its area, generally known as the *heat island effect*. Although the differences between the rural and the urban environment from an air quality point of view had been observed since the Roman times (Watkins, 2000), it was only until 1820 that the temperature irregularities of the urban climatology were scientifically established by Luke Howard (Chandler, 1965). One of the main characteristics of the heat island effect is the generally raised temperatures in the city centre. This might have a positive effect for cities in the North, but for cities in Southern Europe, with their hot and dry Mediterranean summers, might prove to be a very unsustainable factor, leading to excessive energy use for cooling and putting urban population at great morbidity and mortality risks.

This paper explores what causes the formation of the heat island effect in cities around the world. It mainly focuses on whether actions should be taken for mitigating raised urban temperatures in cities in Southern Europe, especially in hot period. It points out, through theoretical models what these actions could be and how effective at lowering temperatures they can be, so that the city planning is not altered. With the case study of Athens, techniques that had been used successfully in the past for mitigating temperatures around buildings are looked into for the hot and dry Mediterranean summer.

## **2 The Heat Island Effect**

The main differences between an urban environment and a rural one are governed, in general, by altered factors which affect heat exchanges in a local scale. Factors such as optical and thermal properties of materials (albedo, emissivity, heat capacity) are of different magnitudes for materials in rural and urban areas. In addition, urban areas are characterised by lack of evapotranspiring surfaces (vegetation) and materials of low porosity. The geometry between a vegetated area and the density-morphology of an urban area are completely different, which has a direct effect on wind and shade distributions. Human activities taking place in urban areas are responsible for anthropogenic heat release (transport, space and water heating, cooling etc) and air pollution, the latter affecting cloud cover. The combination of these factors determines the way in which heat is absorbed, stored, released and dispersed in the urban environment, expressed as a temperature increase in the urban area. The importance of these factors for the formation of the heat island effect is analysed below.

## **2.1 Optical and Thermal Properties**

The albedo of a surface determines how much solar energy is absorbed by the system. The higher the albedo of a surface, the lower the energy absorbed by the medium. Generally, urban surfaces tend to have lower albedo than surfaces in the rural environment (e.g. vegetation), thus absorb more solar radiation. This causes higher surface temperatures than air temperature; they can become 30°-40°C higher than ambient air temperature (Akbari et al., 2001). Ambient air temperature is then increased, due to the heat convected by them. Thus the albedo of urban surfaces is quite responsible for the cooling energy consumption within cities.

Emissivity defines the long-wave radiation (thermal radiation) from a body, of a specific temperature. The higher the emissivity is the larger the thermal radiation emitted from the body. It is thus important for the redistribution of the heat inside the system and for its radiative heat exchanges with the atmosphere. As the radiative heat emitted between bodies is conversely proportional to the square of the distance between them, the role of emissivity on the formation of the heat island depends on the geometry of the urban structure and its view factor to the sky. Systematic urban-rural differences in surface emissivity have been reported to be the potential cause of part of the heat-island effect (Watkins, 2000). However Grimmond et al. (1991) simulated the effect of optical and thermal characteristics of materials responsible for the heat island intensity and found that the role of emissivity is minor. As emissivity increased from 0.85 to 1.00 there was a slight increase of 0.4K in the temperature difference between the urban and rural environment, during night, for very tight canyons. For canyons with higher view factors there was practically no change.

Heat capacity is the ability of a body to store heat. Structures in the urban environment tend to have quite high thermal capacity. On the other hand, the thermal capacity of vegetation is almost negligible, so generally is its mass. Due to the high heat capacity of building materials, the energy received in the urban structure is primarily stored in its mass and released when the ambient temperature is lower than the surface one. On the other hand, a vegetated surface stores practically no heat. The extensive heat storage in the urban environment can block night cooling on extremely hot days with high irradiance and a clear sky. Heat stored in the urban fabric during the day is released into the environment at night, raising the ambient temperature. This results in slower night cooling of surfaces or, in extreme conditions in no night cooling at all.<sup>1</sup> In

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<sup>1</sup> This is a quite typical phenomenon during very hot days, in ancient, stone, open theatres around the Mediterranean. In the instance of the theatre of Herodes of Attica in Athens, which is exposed to solar gains and raised urban temperatures all day in summer, the heat stored in its

dense urban geometries with limited vegetation and shade, this phenomenon is quite usual.

In rural areas which are attractive for human habitats, their main characteristic is the existence of vegetation, which tends to be a secondary characteristic in the urban environment. The existence of vegetation modifies the local climate, due to the latent heat flux produced by plants. The surface temperature of plants is usually not significantly different to ambient air temperature. Furthermore, they are also able to cause further cooling through evapotranspiration, the combined procedure of evaporation and transpiration happening simultaneously at the vegetal surface. When evapotranspiration occurs, a certain amount of water is lost from a cropped surface. The energy (heat) required to vaporise water is known as the latent heat of vaporization. This energy consumed during evapotranspiration is responsible for lowering the temperature of the air in the vicinity of plants. Apart from plants and water surfaces, porous surfaces, which absorb water (e.g. soil) account for quite significant latent heat flux in the atmosphere. Materials mostly used in the urban texture are generally waterproof. Rainwater in cities is mostly channelled away from the city system through sewers and not through latent flux from the surface.

## **2.2 Anthropogenic Heat Release**

Anthropogenic heat release is the concentrated heat produced by human activities in urban areas all year-round. Anthropogenic heat is a quite crucial factor in the heat island effect when both the per capita energy use and the population density are high (Watkins, 2000). In certain high density areas, anthropogenic heat release can be equal to or even more than the solar input in winter and on some occasions in summer also, because of the high use of air conditioning systems. Harrison and McGoldrick (1981) determined the anthropogenic heat fluxes (transport, service, industry and domestic sectors) for the United Kingdom. For the city of London, the results showed a wide range of heat release from less than  $1\text{W/m}^2$  on the outskirts to more than  $300\text{W/m}^2$  at the centre of London. Comparatively, the average global solar radiation on a horizontal plane in London, in June, is  $455\text{W/m}^2$  (Page and Lebens, 1985). It was found that in the centre of London (a diameter of 5 km) the artificial heat flux exceeds the natural flux for every month of the year. Oke (1987) also compared summertime anthropogenic heat release from all sources within certain cities with the net radiation (short-wave and long-wave) received from the sky. He observed that anthropogenic heat can be of similar or higher magnitude to net sky radiation. Meteorological simulations conducted by Taha (1997), showed that

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fabric during extremely hot days is released during the early night hours, giving an uncomfortable feeling of thermal stress to both audience and performers.

anthropogenic heat emissions in a large city core can be responsible for a temperature increase of 2-3°C both during day and night.

Due to human activities in the urban environment a lot of particulates are produced, mostly by industry, vehicles and the burning of fossil fuels for heating, cooling or electricity generation. The significance of each source varies according to the characteristics of each city. In the instance of Mumbai and Delhi, in India, the major source is vehicles (Singh and Kumar, 2001). For Paris, the major source had been the industry, but since the 1980ies, Sundays are equivalently polluted as the rest of the weekdays, leading to the conclusion that cars are also a major source of urban air pollution (Escourrou, 1991). The level of the particulates concentration depends on several factors, such as the type and amount of fuels consumed, geographic and topographic particularities, town planning, meteorological factors, etc. Those particulates, under solar radiation and certain humidity concentrations react and cause numerous issues in the urban environment, such as sulphurous dioxide, smoke (suspended particulates with a diameter less than 2  $\mu\text{m}$ ). Cities in the Mediterranean latitudes also experience photochemical smog, chemical substances formed in the atmosphere under the influence of solar radiation, when nitrogen oxides and hydrocarbons are present, which is also fatal for human lives, with serious morbidity and mortality risks caused by them (Moussiopoulos et al., 1995; Diaz et al., 2005). In addition, some particulates tend to absorb, reflect and scatter short-wave radiation. Their high concentration influences the solar radiation reaching the surface, by decreasing the direct, and increasing the diffuse radiation (Sachsamanoglou, 1999).

### 2.3 Heat Island Intensity

All these altered factors discussed above, lead to new energy balances in urban areas, which lead to different air temperature distributions in the urban areas. It can be said that in general the differences of the air temperature between urban and rural area, regarding distance, for a large city with clear sky, exhibit a steep temperature gradient to the centre of the urban area, forming an “island profile” (Oke, 1987), as can be seen in Figure 1.

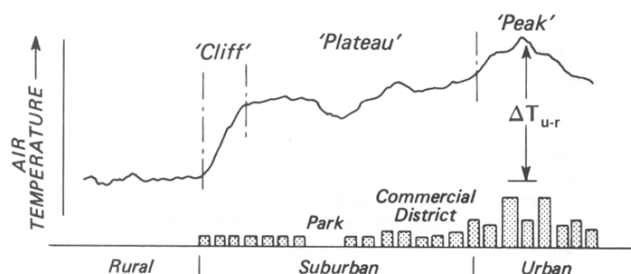


Figure 1. Typical sketch of an urban heat-island profile (Oke, 1987)

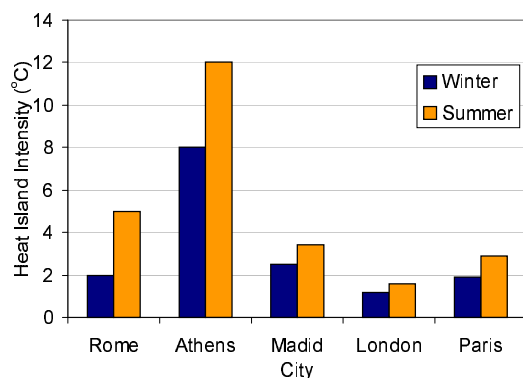
It is quite difficult to define the size of the heat island effect. Theoretically it could derive from a set of pre-urban measurements of the climate of the area before urbanisation and present measurements after urbanisation (Oke, 1987). In most cases this is an impossibility, as most cities have been founded before the establishment of meteorological measurements. Instead, it is common to compare climatic data from the centre of the urban area with those from a rural or a non-urban station in its surrounding area. The temperature difference between the urban and rural environments is called the *heat island intensity* and it is an indicator of the magnitude of the heat island effect. It is usually calculated from the maximum urban temperature at the canopy layer and its respective rural temperature (ibid.).

In the instance of Paris, the average annual heat island intensity is of the magnitude of  $+2^{\circ}\text{C}$  to  $+3^{\circ}\text{C}$  compared to the countryside. It is estimated that only a very strong wind with an average speed of more than 11m/s or a very intense rain can eliminate the heat island effect of Paris almost completely but even then only temporarily (Cantat, 1989). Chandler (1965), when examining the heat island effect of London came to the conclusion that there were more days with exceptionally high temperatures and fewer days with lower temperatures in the city centre. The estimated London heat island density is of the magnitude of  $+1.4^{\circ}\text{C}$  (ibid). For the hotter climate of Athens and its more significant absence of vegetation the heat island effect becomes larger, reaching the magnitude of  $+10^{\circ}\text{C}$  (Santamouris, 2001). For Hong Kong, the day-time heat island intensity reaches  $+1.5^{\circ}\text{C}$  in summer (Giridharam et al., 2004), and Tel-Aviv's heat island intensity is of a similar magnitude ( $+1.5$  to  $+2.5^{\circ}\text{C}$ ) (Saaroni et al., 2000).

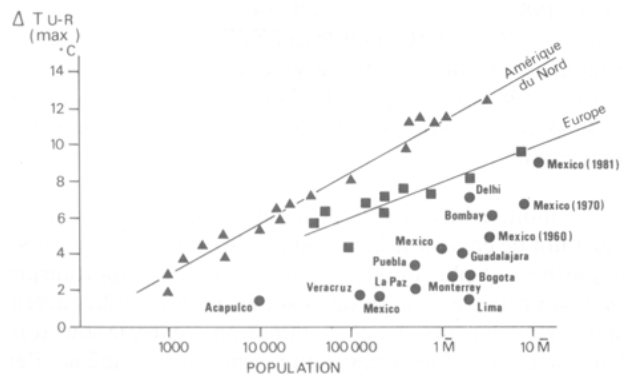
Due to the great inhomogeneity of cities there are great spatial differences within the same city. Air temperature is determined by the microclimate of different areas of the city, which is defined by their density, geometry, materials, and the existence of vegetation. Generally, the city centre tends to be hotter than the suburban area. Apart from that, the heat island intensity changes throughout the day, following a diurnal and a seasonal pattern. The diurnal pattern is mostly characterised by greater temperature differences between rural and urban areas during nighttime, due to the great heat capacity of urban materials and to the evapotranspiration of plants in rural areas. The seasonal pattern of the heat island effect depends on the climate and the local characteristics of the area of the city. Generally, for cities with warm and hot climates, the heat island intensity is usually larger in summer than in winter. Cities in the south of Europe suffer from heat islands of greater intensity in summers than cities in central and northern Europe (Figure 2). In the example of Athens, the heat island intensity in summer has a mean value of  $12^{\circ}\text{C}$ , while in winter it is  $8^{\circ}\text{C}$ , with  $4^{\circ}\text{C}$  difference between the two seasons (Santamouris, 2001). In Rome, the heat island intensity becomes smaller, with a winter heat island intensity of  $5^{\circ}\text{C}$  for summer and  $2^{\circ}\text{C}$  for winter (Bonacquisti et al., 2006). However, the difference between the two seasons is very close to that of Athens, reaching  $3^{\circ}\text{C}$ . According to Yague et al. (1991) for Madrid the heat island intensity is  $3.4^{\circ}\text{C}$  for the hot season and  $2.5^{\circ}\text{C}$  for the cold season, with an increasing trend, leading to  $0.9^{\circ}\text{C}$  difference between

the two seasons. Nonetheless, the authors point out that this difference might be higher, since the urban station used for calculating the city's heat island effect was close to a park, leading to possible underestimation of the urban effect, especially for summer (ibid.). In central and northern European cities there is little difference between summer and winter intensities (Watkins, 2000), as solar radiation and air temperatures are not as high as in southern parts. In the instance of London, the winter heat island intensity is  $1.2^{\circ}\text{C}$ , while the summer one is  $1.6^{\circ}\text{C}$ , with only  $0.4^{\circ}\text{C}$  difference between the two seasons (Chandler, 1965). The heat island intensity of Paris is  $2.9^{\circ}\text{C}$  in summer and  $1.9^{\circ}\text{C}$  in winter (Cantat, 1989), with  $1^{\circ}\text{C}$  seasonal difference, slightly higher than London's but lower than Athens' and Rome's. It can be noted that cities in the Southern part of Europe suffer more from the heat island effect in summer, than in winter. With the raised temperatures of the Mediterranean summer, cities in South Europe undergo even greater summer temperatures than their surrounding areas.

The intensity of the heat island effect depends on the factors discussed above, the economic growth of a city, the activities occurring within the city and at its outskirts, the topography, its climatic zone as well as its local climate, its density and amplitude. In the Figure 3 measurements of the heat island intensity, compared to the population from cities in Europe, North America, Japan and cities in tropical latitudes are given.



**Figure 2. Winter and summer heat island intensity for selected European cities [source: Bonacquisti et al., 2006; Santamouris, 2001; Yague et al., 1991; Chandler, 1965; (Cantat, 1989]**



**Figure 3. Relationship of the maximum heat island intensity with urban population in European, North American and tropical cities (Escourrou, 1991)**

It is obvious from Figure 3 that regardless of the climatic zone of a city the higher its population is (which makes the city larger and/or denser) the greater is the heat island density. It has been observed that cities with populations of thousands have maximum heat island intensities of  $2$  to  $3^{\circ}\text{C}$ , while cities with population of one million the intensities can be  $8$  to  $12^{\circ}\text{C}$  (Watkins, 2000). As Givoni (1998) concludes, the larger and denser the city the greater the difference which is commonly observed between the city centre and its surrounding area. Urbanisation can therefore be considered to be a major factor affecting the heat



island effect. In most cities that have expanded dramatically in the 20<sup>th</sup> century, a significant rise of air temperature has been noticed. In the instance of Paris, from measurements for the period from 1891 to 1968 it is found out that there has been a 1.1°C raise for the maximum temperatures and a 1.9°C rise for the minimum temperatures with a 0.8°C reduction for the diurnal amplitude. During this period the city expanded significantly, particularly after the second half of the 19<sup>th</sup> century when the surface of its inhabited area increased from 100 km<sup>2</sup> to 2300 km<sup>2</sup> (Cantat, 1989).

Due to economic and social factors, the tendency is for urban population to augment significantly. According to statistics, in mid-2004, 48% of the total world population (6.396 billion people) lived in urban spaces (Population Reference Bureau, 2004). By comparison, in the year 1950 only 30% of the 2.5 billion people were urban dwellers (Population Reference Bureau, 2000). It is estimated that by the year 2030 more than 60% of the world's population will be living in urban spaces (Nash and De Souza, 2002), as there is no sign of the shift from rural to urban spaces of slowing or reversing (Ashford, 2004). As urban centres grow over their surrounding rural areas, it is expected that the heat island effect and its consequences will be stronger in the future, unless action is taken to mitigate the raised urban temperatures.

## **2.4 Should the Heat Island Effect Be Mitigated?**

In cold climates the heat island effect may influence beneficially the heating energy demand of buildings (Givoni, 1998). As higher ambient air temperature is produced, less energy is required for heating. As Cantat (1989) concludes *"if it was not for the atmospheric pollution, the heat island effect in the area of Paris would be a pleasant effect for the inhabitants by creating a local climate warmer, less humid and less windy"*. Chandler (1965) also points out that thanks to the raised temperatures of London, the active growing season of crops and the frost-free periods are extended. However, due to global warming becoming a sensitive issue over the last few years, this perspective has changed. It is estimated that the combination of global warming and the heat island effect of London might be responsible for more energy being expended for cooling the city than the energy saved for heating and it could also lead to a parallel increase in summer stress and mortality (Clarke et al., 2002). With a rising trend, especially in nocturnal heat island intensity and with the combined warming experienced in Britain in the recent years, these raised urban temperatures cannot be as beneficial as believed in the past, even for the high latitude of London. However, for cities in lower latitudes, such as the Mediterranean area, the heat island effect has proved to be disagreeable, both from an energy consumption and a quality of life point of view.

For warm and hot climates, the resulting higher temperature can lead to increasing demands for air-conditioning during hot period which exceeds by far the energy savings in winter (Santamouris, 2001) and may cause unbearable levels of heat stress. The amount of energy consumed for heating and cooling buildings in cities in both western and southern Europe has increased significantly in the last two decades (Dimoudi and Nikolopoulou, 2000). Due to the heat island effect, the cooling degree hours in the central area of Athens are approximately 350% greater than in the suburban areas and the heating degree hours are only 40-60% less (Santamouris, 2001). Rosenfeld et al. (1995) showed that in American cities for each 1°C rise in daily maximum temperature above a threshold of 15°C to 20°C, the peak urban electric demand rises by 2–4%. The additional use of air-conditioning caused by this urban air temperature increase is responsible for 5–10% of urban peak electricity demand. The use of air-conditioning for cooling buildings removes the heat from the building to the urban environment. In very dense areas with excessive use of air-conditioning systems this leads to a significant rise of the ambient air temperature (Papadopoulos, 2001), and thus to a rise of the cooling demand, leading to a vicious cycle of rising ambient air temperature and energy demand.

Apart from that, this extensive need for cooling energy leads to increasing emission of pollutants from power plants and air-conditioning systems such as sulphur dioxide, carbon monoxide, nitrous oxides and suspended particulates. Especially in cities with hot climates, during summer, this combination of extreme temperatures and pollutants can even be responsible for high rates of morbidity and mortality risks, especially respiratory-related mortality, cardiac arrests, stroke, and a variety of direct heat-related illnesses (Kalkstein and Sheridan, 2003). With the future climate change expecting to increase the number and intensity of extreme events, such as heat waves, and increased maximum and minimum temperatures (White et al., 2001), urban dwellers are bound to suffer from excessive heat stress. With most deaths caused by heat waves occurring in urban centres (Koppe et al., 2004; Kalkstein and Sheridan, 2003), urban populations health is bound to be at risk (White et al., 2001; Koppe et al., 2004). In the instance of the population of New York City, the death rates are higher on days when the 4:00 p.m. city temperature exceeds 30°C (Davis et al., 2003). The heat waves experienced in Europe in 2003 cost the lives of 14,603 people in France and 3,134 in Italy (Koppe et al., 2004). These casualties were not only in the most vulnerable groups of the population but also in parts of the population classified as healthy people under heavy activity (Diaz et al., 2005). It has been reported that the 10-day heat-wave in Athens in 1987 resulted in 926 deaths classified as heat-related, while the attributable excess mortality was estimated to be more than 2000 (Koppe et al., 2004).

From studies done in the United States, regarding the effect of reducing the heat island effect on mortality risks, it has been estimated that a 0.5-1.0°C<sup>2</sup>

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<sup>2</sup> 1-2°F, in the original text.

reduction in outdoor temperature, in combination with other meteorological changes, could reduce urban mortality by 10-20% (Kalkstein and Sheridan, 2003). Apart from energy saving and quality of life, when human life is put under such risk due to the heat island effect, it is impossible to discuss about sustainability in Southern European cities, unless these raised temperatures are mitigated.

### **3 Mitigating the Heat Island Effect in Southern European Cities**

As has been pointed out in the previous paragraphs it is the nature of the city, its geometry, materials and activities which cause the formation of raised temperatures in the city core. Unless cities change, these raised temperatures will only get greater, as cities expand. Changing existing cities in a city-planning point of view is an impossibility; such an attempt would demand the existence of many small parks in the urban fabric, according to the direction of the prevailing winds (Givoni, 1998), which could mean the demolition of buildings and the fundamental change of cities. On the other hand, if alterations capable of lowering urban temperatures could happen on building scale, this would not affect the city planning. If the urban building fabric is altered, the heat island intensity could lower. As had been noted in paragraph 2.1, the most important properties for the formation of raised temperatures are low albedo and lack of transpiring surfaces. If urban buildings are covered with high albedo materials or vegetation, temperatures could lower quite effectively in the Mediterranean area. As most cities in the Mediterranean are characterised by hot and dry summers, with the use of the climatic characteristics of the city of Athens, both methods are investigated as a case study in the following paragraphs.

#### **3.1 *Increasing the Albedo of Building Materials***

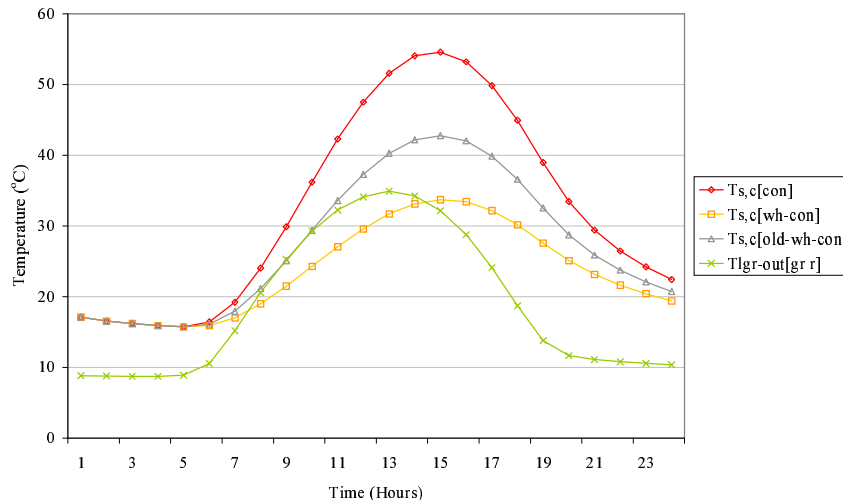
As has been discussed in paragraph 2.1, the albedo of a surface is responsible for the amount of solar radiation it absorbs. High albedo building surfaces (such as white ones) have been proven to cool down urban temperatures (Akbari et al., 1997; Taha, 1997; Konopacki et al., 1998). By decreasing surface temperature, with a coating which reflects a large part of incoming radiation, air temperature is also lowered. On the urban scale, Rosenfeld et al. (1995) simulated the effects of raising average urban albedo in the Los Angeles Basin. The average albedo that was identified as 0.13 increased to 0.26. The results showed that central Los Angeles became 2-4°C cooler at midday in summer. Peak power consumption for Los Angeles can then be reduced by 0.6-1.2GW (Konopacki et al., 1998). Taha et al. found out that

materials covered with high albedo coating of 0.72 were 45°C cooler than materials with coating of a 0.08 albedo (cited in Santamouris, 2001). Nonetheless, such coatings need frequent maintenance, as, in most cases they lose 25% or more of their albedo within three years (Cool Roof Rating Council, 2003).

The question is which technique could be more effective for reducing raised urban temperatures in Southern cities; covering the building fabric with high-albedo coating or with vegetation, in the forms of green roofs and ivies on walls? With the use of a one-dimensional, dynamic heat and mass transfer model, the thermal effect of a green and a white roof are compared with a plain, concrete roof without any coating (with a 0.23 albedo). The white roof is a concrete roof covered with white coating (0.70 albedo) and a concrete roof with white coating, 3 years after the coating has been applied, its albedo drops to 0.53. All four cases are examined for the climatic characteristics of Athens for a typical day in July.

As can be observed in Figure 4, both the surface temperatures of the green and the white-coated roof are much smaller than the surface temperature of the plain concrete roof in Athens, in July. The difference between the surface temperatures of the white and the plain concrete roof reach a maximum of 20.9°C, with a 14.8°C day-time average. For the air layer 1m above the roof these differences become 4.1°C and 2.8°C, respectively. For the green roof, the temperature decreases are greater, reaching 26.2°C maximum and 17.0°C for the surface and 11.3°C and 3.7°C, respectively for the air layer 1m above the roof. The surface temperature of the green roof is higher than the white concrete's temperature in the morning, for 7 hours, with a 3.5°C average difference at this time of the day. For the air layer 1m above the roof, this difference becomes only 1.3°C. Later on during the day, as heat is stored up in the white concrete roof, its surface and air temperatures become higher than those of the green roof's, reaching a much larger average difference of 8.8°C for the surface and 2.7°C for the air layer 1m above the roof.

Three years after the coating has been applied, temperature decreases between the white-painted and the plain concrete roof become smaller; The maximum surface temperature decrease is 11.9°C, with a 8.4°C day-time average. For the air layer 1m above the roof, these numbers become 2.3°C and 1.6°C, respectively. The surface temperature of plants exceed that of the white-painted roof's only by a negligible 0.2°C, while the air above it slightly exceeds it by 0.6°C, in the morning. The rest of the day, the green roof shows much lower temperatures, by an average difference of 10.1°C for the surface and 3.2°C for the air layer 1m above the roof.



**Figure 4. Comparison of surface temperature distributions of a concrete roof [con], a white concrete roof [wh-con], a 3-year old white concrete roof [old-wh-con] and a green roof [gr r], for a typical day in Athens, in July**

For the Mediterranean hot and dry summer of Athens, white painted roofs may prove very beneficial, when compared with plain concrete roofs. Yet again, the periods when green roofs offer cooler effects than the white painted roofs are longer and of larger intensity, as can be observed in Figure 4. Apart from having a higher albedo than most urban materials, vegetation releases water vapour when it needs to keep its temperature below a certain level. Thanks to the dry Mediterranean summers, the increase in water vapour is able to lower temperature much more effectively in the unsaturated air, making green roofs cooler urban elements than high-albedo roofs. In addition, the white coating loses its high albedo relatively quickly, and the amplitude of its difference with green roofs becomes much larger three years after it has been applied. It could therefore be concluded, that covering roofs with vegetation than with high-albedo materials could prove more effective, from a thermal point of view, for the Mediterranean climate.

### 3.2 Placing Vegetation on Buildings

When vegetation is placed on urban surfaces, thermal balances can shift to new conditions, closer to the cooler conditions of rural areas. It is estimated that 1460kg of water is evaporated from an average tree during a sunny summer day, consuming about 860MJ of energy; this offers a cooling effect outside a building that is equal to five average air conditioners (Santamouris, 2001). Papadakis et al. (2001) measured the effect of trees on walls in Athens, in August. On a vertical wall with south-east orientation the measured peak solar radiation at the exposed parts of the wall to direct solar radiation was  $600\text{W/m}^2$  while at the same time at the shaded by trees parts it was under  $100\text{W/m}^2$  with a surface

temperature difference of 8.5°C. Relative humidity was higher by 7% in the area with trees, due to transpiration, keeping air temperature in this area lower by 0.5°C to 3.0°C during daytime (ibid.). Chrisomallidou (2001) points out that placing plants on the building envelope can provide urban buildings with beneficial shading. She mentions that especially for the green roof the benefits are great for the interior of the building as well, improving internal temperatures both in winter and summer.

This technique, of lowering temperatures near a building by the use of vegetation has been applied since antiquity and might be one of the most efficient methods. Fylaktou-Cataneo (2002), when investigating the microclimate of three courtyards of the Alhamra palace in Granada, found that the most vegetated courtyard (Lindaraja) has the lowest temperatures in summer (3.5°C lower than the air temperature in the external space), while the courtyards with only water features have practically the same air temperature as the external, unmodified space. Similar results were reached by Shashua-Bar and Hoffman (2002), when conducting experiments in courtyards in Tel-Aviv. They estimated that the thermal effect of trees in courtyards causes a 3.0°C temperature difference in the afternoon between a courtyard with and without trees.

In most cases, vegetation within cities can be found contained within the limited space of parks. Although urban parks can be extremely beneficial for a city from a social and city planning point of view, from a thermal point of view they can mitigate the heat island effect only at their micro or meso scale, rather than the local scale of the city. The air temperature is reduced significantly inside the park, but only the few buildings which are in the neighbouring area of the park can benefit from the reduction of air temperature due to the park's vegetation. The rest of the city is not affected thermally by the presence of the park (Dimoudi and Nikolopoulou, 2000; Ahemed, 1995; Giridharam et al., 2004; Bruse and Fleer, 1998). The heat island effect is moderated only locally, within the core of the park and its immediate surroundings. The rest of the buildings and the city itself remain practically unaffected by the presence of the park from a thermal point of view. From an exaggerated thermal point of view, parks in the city could thus be paralleled to oases in the desert. No matter how many oases there are, temperature is still high in the desert, away from the oases. Numerous oases could have a larger thermal impact on the desert enclosing them, but they could not lower its temperature as much as if they were part of the desert, if the oases and the desert could not be so separated. Although this cannot happen in the desert, it could happen quite easily in existing cities, by covering its impermeable, hot surfaces, such as the roofs (Figure 5) and walls (Figure 6) of buildings, with vegetation. In the following paragraph, the thermal effect of this transformation is examined thoroughly, with the use of a micro-scale, heat and mass transfer model.



**Figure 5. Residency of the architect Elli Georgiadou with extensive green roofs, in Thessalonica**



**Figure 6. Green wall in Athens**

### ***3.3 Covering Urban Roofs and Walls with Vegetation; Temperature Decreases***

In order to assess the potential of lowering urban temperatures through green roofs and green walls, a parametric study is done, exploring how the amount and geometry of vegetation, the urban geometry and orientation affect temperature decreases. This is made with the use of a two-dimensional, prognostic (dynamic) micro-scale model, describing heat and mass transfer in a typical urban canyon. The differential equations describing heat and mass transfer in the air, building materials (considered as capillary -porous bodies), soil and vegetation have been solved with finite differences approximations. Climatic characteristics, such as air temperature, relative humidity and wind speed, are set as the boundary nodes of the model, 10m above the upper part of roofs. Solar radiation is input onto the surfaces, according to their orientation, inclination and shading pattern. The shading pattern, determined by the canyon geometry and the geographic latitude, is calculated with the software ECOTECT (Marsh, 2003). The air velocities in the vicinity of the canyon are calculated with the CFD code WinAir4 (Welsh School of Architecture, 2003).

Four types of vegetation covering the building envelope are examined for each canyon geometry: a) a base case, where no green is placed in and around the canyon, referred to as the “no-green” case, b) the “green-roofs” case, where both roofs are covered with vegetation (ground-covering grasses) c) the “green-walls” case, where both walls inside the canyon are covered with vegetation (ivies) and d) the “green-all” case, where both roofs and walls are covered with vegetation.

Three types of canyon geometries are examined, according to the wind flow developed in each; a) a canyon with ratio of building height (H) to street width

equal to 2 ( $H/W=2.00$ ), where, according to Oke (1988) skimming flow is developed, with very low air velocities, and sun shaded surfaces b) a canyon with ratio  $H/W=0.50$ , where wake interference flow is developed, with greater air velocities and more exposed surfaces to direct solar radiation and c) the  $H/W=0.33$ , where isolated roughness flow is developed, with much larger air velocities, and greater exposure to solar radiation.

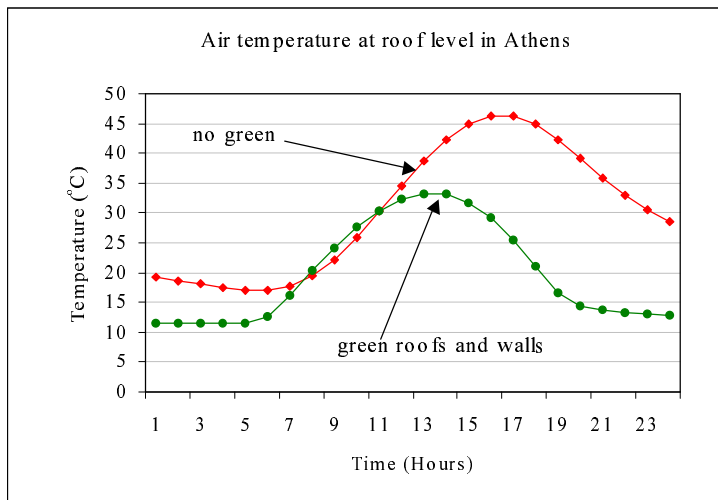
The canyons are examined with two orientations: a) one where the canyon's axis was parallel to the East-West axis (referred to as the EW canyon) and b) one where the canyon's axis was parallel to the North-South axis (the NS canyon). Building and street materials are the typical urban materials in Northern Europe; concrete and asphalt. A summary of the hydrothermal properties of the materials and vegetation considered in the canyons has been presented in Alexandri (2005).

### *3.3.1 Air Temperatures inside the Canyon and at Roof Level*

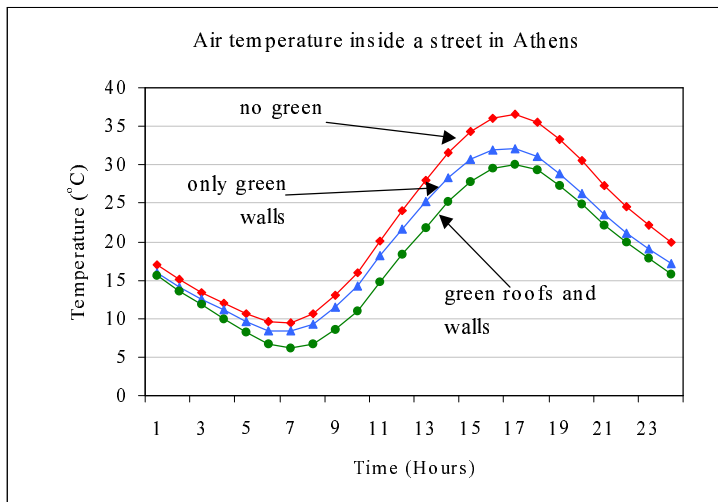
Mediterranean summer, being hot and dry, leads to high air temperatures and relatively low relative humidity. For the case study of Athens, from all the vegetated cases examined, the most effective one is when both roofs and walls are covered with vegetation. When both roofs and walls are covered with green, the air masses enter the canyon cooled by the vegetation on the roofs and not warmed by the high temperatures of concrete roofs as in the rest of the cases. In Figure 7 the air temperature 1m above a green and a concrete roof is presented. It can be observed that there is a great difference between the two temperatures; the air above the concrete roof reaches a maximum of  $46.2^{\circ}\text{C}$  and a day-time average of  $35.3^{\circ}\text{C}$ , while these values become only  $33.2^{\circ}\text{C}$  and  $25.4^{\circ}\text{C}$ , respectively, for the green roof. In Figure 8 the averaged air temperature distribution in an East-West oriented canyon, with ratio  $H/W=0.50$  is presented for three cases; for the base case, where no green is placed, for the case of the green walls and for the case where both roofs and walls are green. It can be noted that for the first case the maximum air temperature reaches  $36.5^{\circ}\text{C}$  inside the canyon, with a day-time average of  $25.7^{\circ}\text{C}$ . In comparison, the respective air temperature input meteorological data are  $30.1^{\circ}\text{C}$  and  $27.3^{\circ}\text{C}$ , building and street materials being responsible for significant temperature raises inside an urban canyon. When only walls are covered with vegetation, temperatures inside the canyon lower, leading to a maximum air temperature of  $32.1^{\circ}\text{C}$  and  $22.7^{\circ}\text{C}$  day-time average. When both roofs and walls are covered with vegetation the thermal effect is even greater; the maximum air temperature inside the canyon  $29.9^{\circ}\text{C}$  with a  $20.1^{\circ}\text{C}$  day-time average. The case where only walls are covered with vegetation is responsible for a day-time average temperature decrease of  $3.0^{\circ}\text{C}$ , with a  $4.5^{\circ}\text{C}$  maximum decrease, when compared with the base case. When both roofs and walls are covered with green, these decreases increase to  $5.6^{\circ}\text{C}$  and  $6.6^{\circ}\text{C}$ , respectively, achieving a  $2.6^{\circ}\text{C}$  larger temperature decrease for the day-



time average and  $2.1^{\circ}\text{C}$  for the peak temperatures. By comparing Figure 7 and Figure 8 it can be observed that the highest air temperature decreases occur at roof level. Roofs are more exposed to direct solar radiation than canyons and the amount of solar radiation horizontal planes receive in summer months is by far greater than that of vertical planes. Vegetation on roofs can relief the great amounts of heat generated by these surfaces, which directly affects air temperature both inside and outside the urban canyon.



**Figure 7. Air temperature 1m above a concrete and a green roof in Athens**

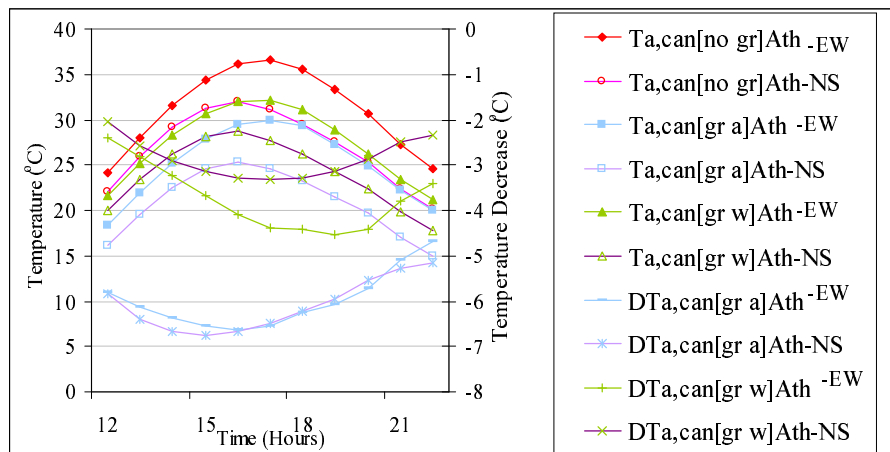


**Figure 8. Averaged air temperature distribution in an East-West oriented canyon with ratio  $H/W=0.50$ , when no vegetation is placed, when only the walls are covered with vegetation and when both walls and roofs are covered with vegetation**

### 3.3.2 Canyon Orientation

The amount of irradiation received on the east and west oriented vertical planes is much larger than on the south and north orientations in Mediterranean latitudes. For Athens in July, the maximum solar radiation received by the south-oriented vertical plane is  $374\text{W/m}^2$ , while for the east-oriented plane reaches the magnitude of  $617\text{W/m}^2$ . This has a direct effect on the way the canyon orientation affects temperature decreases caused by vegetated surfaces. For the two orientations examined, their difference in temperature decrease is very small, when both roofs and walls are green. The difference between the temperature decrease of the air inside the canyon reaches only  $0.1^\circ\text{C}$  for the day-time average (temperature decrease being  $5.6^\circ\text{C}$  for EW and  $5.5^\circ\text{C}$  for NS), and  $0.2^\circ\text{C}$  for the maximum (temperature decrease being  $6.6^\circ\text{C}$  for EW and  $6.8^\circ\text{C}$  for NS orientation, Figure 9). For the case where only the walls are green these differences become larger, reaching  $0.8^\circ\text{C}$  for the day-time average (temperature decrease being  $3.0^\circ\text{C}$  for EW and  $2.2^\circ\text{C}$  for NS) and  $1.2^\circ\text{C}$  for the maximum (temperature decrease being  $4.5^\circ\text{C}$  for EW and  $3.3^\circ\text{C}$  for NS). It can be observed that the difference between the two cases of vegetation (only green walls or both green roofs and walls) is more crucial than the difference between orientations.

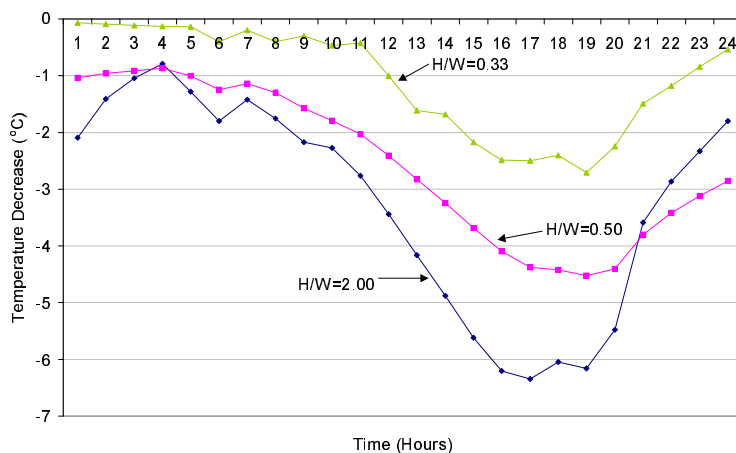
In general, it can be concluded that the orientation may play an important role in temperature decreases due to vegetation, only when the amounts of solar radiation received on vertical planes differ significantly. Yet again, concerning temperature decreases, the amount of vegetation placed on buildings is more crucial than the orientation of the canyon, with the case when both roofs and wall are covered with vegetation leading to much larger temperature decreases.



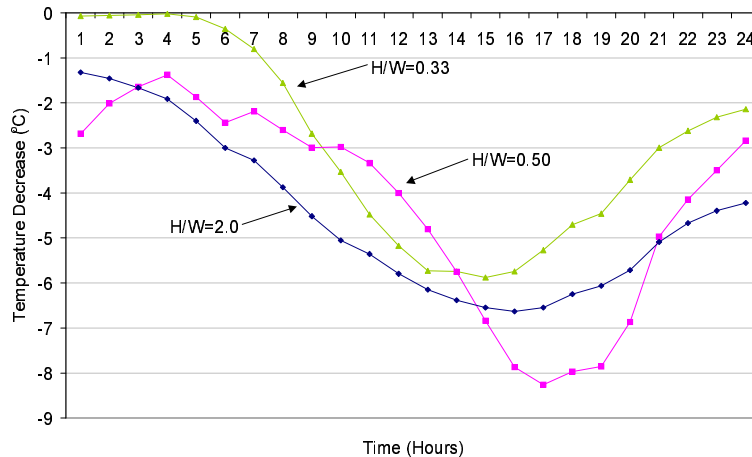
**Figure 9. Athens temperature distributions and decreases inside an urban canyon with ratio  $H/W=0.50$  for the case without any vegetation [no-gr], for the case where both roofs and walls are green [gr-a] and where only walls are covered with vegetation [gr-w], for East-West (EW) and North-South (NS) orientations**

### 3.3.3 Canyon Geometry

Regarding the geometric characteristics of the urban canyon, it can be concluded that the wider a canyon is, the smaller the effect of green roofs and green walls on it. For wider canyons, temperatures inside the canyon are dominated by the proportionally larger street surface and the fact that it is more exposed to direct solar radiation. Temperature decreases in the wide canyon with 0.33 ratio of building height to street width ( $H/W$ ) are of the magnitude of  $1.5^{\circ}\text{C}$  for the day-time average and  $2.7^{\circ}\text{C}$  for the maximum for the case where only walls are green (Figure 10). When both roofs and walls are green these numbers are greater, reaching  $4.2^{\circ}\text{C}$  and  $5.9^{\circ}\text{C}$  (Figure 11). For the narrower canyon with 0.50 ratio, the effect of green buildings is more apparent on temperature decreases; when only walls are covered with vegetation the day-time average air temperature decrease inside the canyon reaches  $3.0^{\circ}\text{C}$ , with a  $4.5^{\circ}\text{C}$  maximum. When both roofs and walls are covered with vegetation, these numbers become  $5.6^{\circ}$  and  $6.6^{\circ}\text{C}$ , respectively. For the narrowest canyon examined, where wall height is more dominant than street width ( $H/W=2.00$ ), the effect of green walls is the strongest (Figure 10). When only walls are covered with vegetation, air temperature decrease inside the canyon reaches  $4.2^{\circ}\text{C}$  day-time average, with  $6.3^{\circ}\text{C}$  maximum. When both roofs and walls are covered with vegetation these decreases become larger, reaching  $5.3^{\circ}\text{C}$  and  $8.3^{\circ}\text{C}$ , respectively.



**Figure 10. Air temperature decrease in canyons with different ratios of building height to street width ( $H/W$ ) when only walls are covered with vegetation**

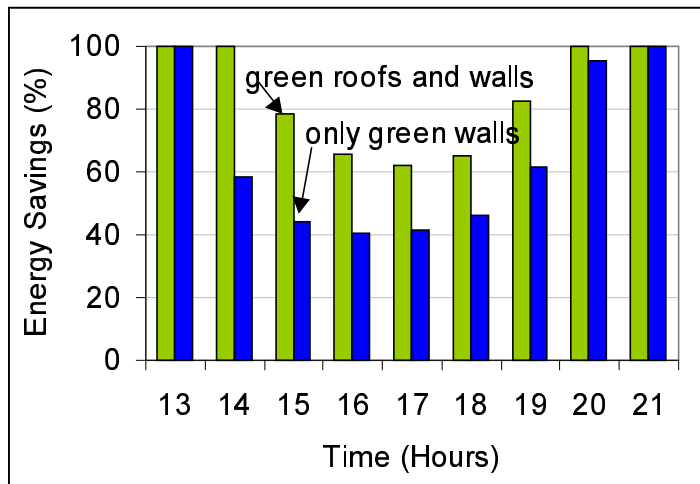


**Figure 11. Air temperature decrease in canyons with different ratios of building height to street width (H/W) when both roofs and walls are covered with vegetation**

### 3.3.4 Energy Savings

All these temperature decreases due to vegetation can only lead to energy savings from cooling and improvement of outdoors thermal sensation. The lowered urban temperatures can prove beneficial for indoor thermal conditions. They can decrease cooling load demands inside the building quite significantly. Considering an indoor limit temperature for cooling of 26°C for Athens, cooling load decreases due to vegetation placed only on walls and both on roofs and walls are given at an hourly basis for a typical day in July in Figure 12. As can be observed from Figure 12, the largest cooling load decreases occur for the case when both roofs and walls are covered with vegetation. The cooling load is lowered by 84% and by 4 hours, for the examined typical day in July. In the non-vegetated canyon cooling is needed for 9 hours per day, while in the green roofs and walls canyon, this is reduced to 5 hours. For the case where only walls are covered with vegetation, the energy savings from cooling reach 65% and the amount of hours that need cooling is reduced to 7 hours per day.

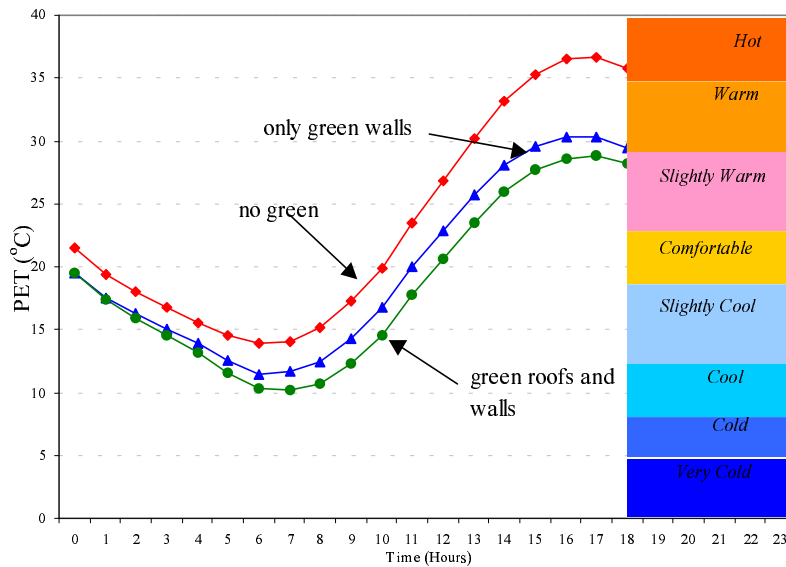
For both cases, when either only walls are covered with vegetation or when both roofs and walls are covered with vegetation, the cooling load decrease is of a great magnitude. Covering the building envelope with vegetation can only be a very successful sustainability policy.



**Figure 12. Energy savings for a 26°C indoor limit temperature for cooling in a canyon with H/W=0.50 ratio when only walls (only green walls) and when both roofs and walls (green roofs and walls) are covered with vegetation**

### 3.3.5 Thermal Comfort

As has been concluded by Nikolopoulou (1998) both air and globe temperature have a very significant effect on the thermal comfort of outdoors spaces. When both of them are altered, the new energy balances affect the thermal comfort in the same space. With the use of the Physiological Equivalent Temperature (PET), as defined by Matzarakis (2001) and Matzarakis et al. (2002), and its relationship with thermal perception as determined by Matzarakis (2003), the thermal comfort of a standing man inside the canyon with ratio H/W=0.50 for different amounts of vegetation is shown in Figure 13. As can be observed in Figure 13, a man standing in a canyon without any vegetation, in Athens, for a typical day in July, is for 4 hours in the “hot” zone, for 4 hours in the “warm” zone and for 5 hours in the “slightly warm” zone. He is in the “comfortable” zone for only 3 hours and for 7 hours in the night is he in the “slightly cool” zone. When only walls are covered with vegetation, thermal comfort in the urban canyon improves dramatically. Thermal perception does not reach the “hot” zone at all. It is for 4 hours in the “warm” zone, for 5 in the “slightly warm” zone and for 4 in “comfortable”. In the early morning and night it reaches “slightly cool” for 6 hours and “cool” for 4 hours. When both roofs and walls are covered with vegetation thermal sensation moves to even cooler zones. Neither the “hot” nor the “warm” zone are reached. The “slightly warm” zone is reached for 8 hours and “comfortable” for 4. Again, in the early morning and night hours “slightly cool” and “cool” zone are reached for 6 and 5 hours, respectively. These temperature decreases due to vegetation, which place thermal sensation to more comfortable levels can only lead to healthier urban environments with limited morbidity and mortality risks.



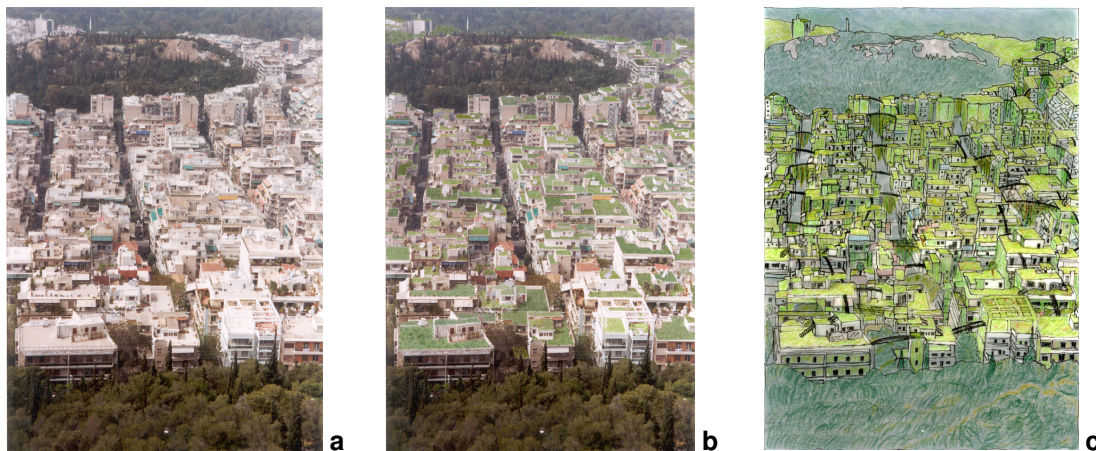
**Figure 13.** Physiological Equivalent Temperature inside a canyon with H/W=0.50 ratio, without any vegetation (no green), when only walls are covered with vegetation (only green walls) and when both roofs and walls are covered with vegetation (green roofs and walls)

## 4 Green Roofs Carried Further; Super-terrestrial Parks?

In 1902, Ebenezer Howard, with his theory and idea of *garden cities* was envisaging that “town and country *must be married* and out of this joyous union will spring a new hope, a new life, a new civilization” (Howard, 1970). In our times it is quite clear that social reforms cannot occur only through city planning. Garden cities, either in their vertical or horizontal form, naked from their beautiful social visions, have failed to succeed in marrying town and country in most modern cities. Nonetheless, the attempt of improving urban dwellers’ everyday life and trying to transform cities into viable and sustainable spaces is not abandoned. If the structure of the city stays as is, but its buildings are covered with vegetation, as this paper proposes, a new type of marriage of town-city could evolve (Figure 14a and b). With living building envelopes, not only by the presence of human beings, but also by their vegetated fabric, new relationships between city and nature could be born, new relationships of urban dwellers with nature and their habitat could evolve, in a healthier, more sustainable, cooler and maybe more human-friendly environment.

This could be carried on to an urban scale, with green roofs being transformed into superterrestrial urban parks, by linking them with footbridges (Figure 14c), which might be a very challenging urban planning project. The city roofs could be transformed into a public space, a public garden, through which people would be

able to commute, live, use as a recreational space with beautiful view and of course as a second entrance to buildings, from above. In this way the so much desired separation of pedestrian from the automobile (e.g. Le Corbusier, 1948) could be achieved; urban dwellers could be experiencing the city from above, having the view to the sky that all day-light creatures deserve, while vehicles would be left to move at the bottom of urban canyons. Urban inhabitants and users would then not need to use the “sunless” urban canyons that LeCorbusier detested, and their view to nature in their own habitat could mean the improvement of both physical and mental health of urban dwellers (Doernach, 1988).



**Figure 14. Partial view of the roofs of Athens in the city centre<sup>3</sup> (a) as are now, (b) covered with ground covering plants and (c) with foot bridges linking them**

## 5 Conclusions

As has been pointed out in this paper, cities suffer from climatic alterations, with main characteristic the raised temperatures in the city chore, a phenomenon generally known as the heat island effect. Cities in Southern Europe suffer more from the heat island effect during the hot season, with the summer heat island intensity being 0.9-4.0°C higher than the winter intensity in Southern European cities. With the morbidity and mortality risks these raised temperatures are responsible for, and the much greater amounts of cooling energy needed, it is an impossibility to talk about sustainability planning and policies in Southern European cities, unless these temperatures are mitigated.

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<sup>3</sup> The picture was taken in spring, under overcast sky. The colours of the green roofs were taken from ground covering vegetation of the area, under the same light conditions.



It has been shown in this paper, that the ways to mitigate the heat island effect in cities in Southern Europe, without altering the city planning, do exist. The only alterations that need to be done are on the building envelopes. By covering roofs and walls either with higher albedo and/or evapotranspiring surfaces, urban temperatures can decrease significantly. The latter can lead to greater temperature decreases, due to both plants' higher albedo and evapotranspiration, which acts as a very effective cooler in the dry Mediterranean summer. With a micro-climatic study, it has been shown in this paper, that, the amount of vegetation placed on a building and its position (roofs, walls or both) is a more dominant factor than the orientation of the urban canyon. Canyon geometry plays a more important role than orientation, with green roofs and walls having a fainter thermal impact on wider canyons. The greatest temperature decrease is noted for the case when both roofs and walls are covered with vegetation, with maximum decreases ranging from 5.9°C for the widest case examined to 8.3°C for the narrowest case examined. The day-time averages extend from 4.2°C to 5.6°C. When only walls are covered with vegetation, temperature decreases become lower with the maximum ranging from 2.7°C to 6.3°C and the day-time average from 1.5°C to 4.2°C. These temperature decreases can only lead to energy savings from cooling, extending from 65% for green walls to 84% for both green roofs and walls. Apart from that, much healthier and more comfortable, from a thermal point of view, outdoors conditions are reached; the thermal sensation zones "hot" and "warm" are not reached when urban roofs and walls are covered with vegetation, leading to more pleasant and safer temperatures for urban dwellers. These vegetated buildings can lead to new urban forms if their roof gardens are joined together to form superterrestrial urban parks. New urban spaces can then be formed on the roof layer, giving urban dwellers a much opener urban fabric than the one experienced at the other end of the urban canyon, the street.

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