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Urban heat islands: Potential effect of organic and structured urban configurations on temperature variations in Dubai, UAE

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A R T I C L E I N F O

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A B S T R A C T

Urban heat islands are phenomena that occur coupled with rapid urban developments. The study was carried out to show the effect of organic and structured urban configurations on temperature variations throughout the year, especially in summer. The study investigated a larger area of the city rather than merely building-to-building relationships. It went beyond the confinement of street and building geometries and investigated how a number of these geometries put together in one context contributed to temperature variations. Computer simulation software was used to simulate three different urban configurations, representing an organic configuration in the Bastakiyah model and two structured configurations represented in the Orthogonal and Volume Ortho configurations. The simulations were carried out in Dubai, UAE for summer, winter, and autumn with fixed initial input temperature value of 32 °C and varying initial wind speeds (0.1 m/s and 3.6 m/s; and 7 m/s for summer case only).

Assessment of the results showed that the organic configuration recorded lower temperatures in summer than both the structured configurations. The Orthogonal structured configuration did not behave as an intermediate configuration between the organic and highly structured grid configurations. The Volume Ortho configuration, though recorded the highest wind speeds, did not result in lower temperature values. It was shown that different configurations manipulated the behavior of the wind within the configuration. The sky-view factor and standard deviation were plausible explanations in the absence of obvious trends in some cases, and showed how urban configurations impacted temperature variations. It was concluded that, given this specific site location and the alignment of prevailing winds parallel to the roads, the organic configuration showed the better thermal performance amongst the three configurations.

1. Introduction

Urban heat islands (UHI) are phenomena tightly associated with the development of cities and urban expansion. This topic was and still is the focus of researchers in the fields of architecture, urban design, engineering and climatology, to name a few. This is true because of its vast impacts and implications on energy efficiency, the environment, and ultimately human comfort and health.

The urban heat island phenomenon, in its basic definition, is the increase in temperature of urban areas in comparison to its rural surroundings. Wanphen and Nagano [1] report that “temperature difference between urban and rural areas can be as high as 5–15 °C”. These “islands” are pockets or areas within an urban context that are characterized by increased temperature creating a slightly warmer micro-climate. Another definition of UHI is one stated by Kolokotroni [2] indicating that the urban heat island phenomenon is caused by micro-climatic variations due to “man-made” intervention and modification to the natural environment. Landsberg [3] described it as “a reflection of the totality of micro-climatic changes brought about by man-made alterations of the urban surface”. Akbari [4] defined it as areas that “tend to have higher air temperatures than their rural surroundings as a result of gradual surface modifications that include replacing the natural vegetation with buildings and roads”. Another definition was by Synnefa et al. [5] who defined the urban heat island effect as the increased ambient temperature of an urban area caused by warmer surfaces.

This variation in temperature was first noted as the population moved from rural areas creating urban centers higher in density and activity levels. According to Kolokotsa [6], “approximately 50–60% of the world population lives in cities or towns” with urbanization increasing from 160 million people to 3 billion in the last 100 years. This figure is expected to increase to 5 billion by the year 2025 [6]. With this shift, the nature of the land, surface types,

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land uses, and urban configurations changed to meet the demands and needs of the population.

This research was designed to understand the impact of various urban configurations on the micro-climate. At present, there is a trend for urban plans to take a structured layout as it is perceived and promoted as the requirement for a better sustainable life style. The image associated with sustainable urban development is that of structured square building plots, an abundance of vegetation, water bodies, structured roads and offset right-of-ways. It is almost never seen represented in dense compact irregular building plots, meandering and winding roads, and overshadowed open spaces. However, not all climatic conditions allow for large water bodies and vegetated areas to be planned. Not all economies support such infrastructure. And not all have the availability of land for expansive planning. More "evolutionary" types of urban configurations, namely organic forms, can also support the components of the triple bottom line: the environmental, economic, and social, and be considered as sustainable urban forms. Even though the organic form seems to promote a denser configuration, there are cities planned on a grid-configuration and still have a high-density issue. It can then be argued that the urban configuration of the city is not a measure of its sustainability. The dynamics of the city and the factors in play are far too complex to deduce that one urban configuration is more sustainable than another solely based on its layout.

2. Literature review

Literature on the topic of UHI is most often targeted at investigating major contributing factors one at a time, due to the complexities of these factors. Che-Ani [7] summarized the factors affecting the occurrence and intensity of UHIs. Those are divided into two broad categories:

1. Meteorological factors which also include wind speed and direction, humidity, and cloud cover.
2. Urban parameters such as density, built-up areas, aspect ratio, sky-view factor, building material, and urban structures.

One of the major factors related to this research is urban geometry. Shashua-Bar et al. [8] investigated the effect of urban geometry on the micro-climate by quantifying what defines an urban geometry in terms of "geometric ratios". The findings show that areas with shallow open spaces and wider spacing recorded temperatures 4.7 K higher than baseline measurements taken from a meteorological reference. Other research used field measurements to study how urban form may affect the microclimate in different areas in Dubai [9]. The researchers concluded that the built form (ventilated, shaded, and transitional), vegetation, water bodies, and adaptive activity zones all influence the microclimate by lowering temperatures. In a similar research, different spatial configurations were investigated ranging from completely exposed spaces to spaces next to large water bodies [9]. Comfort surveys have showed that higher relative humidity levels are more acceptable by people when there is substantially more airflow. However, the increase in airflow does not necessarily increase the acceptance of higher temperature levels [10].

Unger [11] and Montavez et al. [12] studied the impact of sky view factor (SVF) and aspect ratio, respectively, on temperature variations. Ratti el al. [13] addressed major variables including: surface to volume ratio, shadow densities, daylight accessibility, and sky–sky view factors. These variables address, from an environmental perspective, "solar radiation, thermal comfort, and urban temperatures". The conclusions of this research highlighted that the performance of surface to volume ratio represented in the thermal mass has a positive effect on thermal performance. Other conclusions included that having a lower sky view factor resulted in better thermal comfort in the narrow streets and open spaces during the day. Some other researchers expressed this factor in terms of street geometry and approximation to other external environmental factors such as street orientation and location [14,15]. Bourbia and Boucheriba [16] investigated street design and its impact on urban microclimate in semi-arid climate and found that the higher the aspect ratio the lower temperature. They suggested that the SVF should be incorporated in urban geometry design as it plays a role in mitigating the effect of urban heat islands [16]. Other researchers studying the impact of SVF on UHI and its intensity also include Mills [17] and Sakakibara and Sato [18].

Ratti et al. [13] reiterated that there are "infinite combinations of different climatic contexts, urban geometries, climate variables, and design objectives. Obviously there is no single solution, i.e. no universally optimum geometry". Ratti et al. however highlighted that there are associated building forms with certain climatic types, "such as the courtyard type and the hot-arid climate" [13]. In a research investigating the relationship between thermal performance and urban morphology and linking them to climatic responses, Golany stated that the configuration of a city can assist wind circulation and affects wind velocity which in turn impacts temperature variations. He pointed out that city morphology directly affects the movement of the wind within it depending on its design, shape, and orientation of the roads within it [19].

Another factor impacting UHI is building form. Research addressing building forms usually refer to the shape of buildings, their footprint, orientation and grid azimuth, height, building length ratio, and aspect ratio as expressed and investigated by Okeil [20], Panao et al. [21], Hamdi and Shayes [22], and Yamashita et al. [23]. Eliasson [24] suggested that the major difference in temperature was reported between urban areas with different land uses. He demonstrated that the difference in air temperature of an average of 4 °C between a large park southwest of the city and the city center was similar to the average temperature between urban and rural readings which was in the order of 3.5–6 °C [24].

One research conducted that particularly compared an old city fabric to a new one was carried out by Johansson in Fez, Morocco. Field measurements gave conclusions in line with previous findings. During the day, the high aspect ratio gave cooler readings than the lower aspect ratio canyon. This is mainly due to the geometric proportion of the deep canyon which allows for shadows and shade to continue throughout the entire day. It was also noted that although the compact urban form gives protection from the sun and reduces solar exposure resulting in lower temperatures during the summer, it is disadvantageous during the winter [25].

Morris and Simmonds [26] investigated the association between urban heat island intensity and wind speed and cloud cover. Their main findings were that calm winds and clear skies result in increased means of urban heat island values. In summer, when the results were most pronounced, it was found that an increase of wind speed by 1 m/s the UHI variation was −0.139 °C, i.e. a reduction in the value of UHI. Furthermore, an increase of 1 octa of cloud cover the UI variation was −0.122 °C, i.e. a reduction in UHI as well. Figuerola and Mazzeo [27] carried out a research to investigate how urban heat islands are affected by factors such as cloud cover, wind speed and direction, the day of the week, and different seasons. They reported that in winter the temperature difference between a day with little sky coverage with weak wind speed was 1 °C higher than a day with windy and cloudy conditions. Also, the maximum temperature difference occurred when the direction of the wind was from the rural areas towards the urban.

Among the factors contributing to the urban heat island effect is material and surface properties as investigated by Wong [28], Bretz