Building Mitigates Urban Heat Island

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A consequence of urbanization was the intensification of urban heat islands, especially in tropical cities. There have been rapid developments in infrastructure that have displaced open spaces.

Keywords: urban heat island (UHI) ; tropical climate ; Indonesia ; passive design ; urban planning ; building ; architecture design

1. Introduction

Cities all over the world are experiencing urban heat islands (UHI). In urban environments, the phenomenon of UHI is characterized by increased temperatures at surface, sub-surface, or air levels compared to their undeveloped rural counterparts [1][2]. It has been observed that UHI phenomena are more prevalent during the summer when the weather is clear and calm [3]. UHI has been shown to directly decrease thermal comfort and healthiness among city dwellers [4]. As a result of the Paris Agreement in November 2016, both adaptation and protection have finally been recognized as equally important, thereby pushing many countries that have already developed national adaptation strategies to also adopt their own [5].

The rapid development of infrastructure has led to the replacement of open space in many developing countries [6]. As a result of urbanization and climate change, the UHI effect in tropical cities has grown [1][7]. Climate change has already created hotter summers and different patterns of rainfall in these regions [1]. An increase in the intensity of UV-induced heat stress in tropical climates can result in a significant increase in both indoor and outdoor heat stress [8]. In the long run, high temperatures in urban areas lead to inconvenient living conditions [6]. The World Meteorological Organization (WMO) has long recognized the importance of studying tropical urban climate, and commissioned a series of bibliographies on the topic in 1993 [9] and 1996 [10].

2. Causes of UHI in Tropical and Global Cities

An intense urbanization process in the 20th century led to pollution-related problems and temperature increases in cities, resulting in a UHI [11]. Urban areas with dense populations and built-up areas are more likely to suffer from climate change, since natural surfaces are mostly replaced by sealed surfaces and construction sites [1][4][12]. Furthermore, UHI intensities are affected by factors such as wind speeds, cloud cover, season, city size, and time of day [4]. Typical urban climates are characterized by the presence of thermal, wind environments that can pose wind danger or serious overheating issues [13].

UHI has caused environmental changes in many cities as well as societal challenges [2]. Increasing UHI in urban areas is also influenced by human behavior. Through the activities of industrialization and transport, human beings contribute directly to urban overheating, and indirectly through air pollution that alters the radiative properties of the atmosphere [3]. Additionally, street canyons contribute to UHI in urban areas. A street canyon is a U-shaped space between two adjoining structures that can also be used to trap longwave radiation due to a reduction in sky view factors (SVFs) that increases the temperature [14]. There is an urgent need to develop urban planning guidelines that are based on the geometric parameters of urban street canyons, which have a significant effect on microclimates and thermal comfort at the pedestrian level [15].

Climate interaction with buildings has always been complex and dynamic. Buildings located in urban areas consume significantly more cooling energy than those located in rural areas [16][17][18][19]. In urban areas, air conditioners are an important cooling and adaptation strategy, especially for citizens with pre-existing medical conditions or the elderly [19][20]. The use of air conditioners, however, also increases energy consumption [1][8]. Due to the exhaust heat from an air conditioner's outdoor unit, this could contribute to climate change and could actually raise the outdoor temperature [3][20]

[21]. During the night, this phenomenon is particularly strong, reducing the building's ability to cool [3][22]. A closer look at climate-based design for reducing UHI is also essential.

Cities in the tropics are constantly hot and sunny, and heat islands can make urban areas more uncomfortable [23][24]. The highest intensity (medium magnitude) occurred during the daytime in tropical environments during the rainy season [11]. In contrast with tropical climates, temperate climates are the most intense at night and during months of greater temperatures and low precipitation [11].

As illustrated in Figure 2, the causes and consequences of UHI affect global and tropical climates. These analyses show that the UHI effect is higher in tropical climates than in temperate climates. In urban areas, rapid urbanization changed the land's function from vegetated areas into buildings and streets. Moreover, rapid urbanization led to unplanned buildings that were mainly designed without understanding the conditions of the current climate. Building owners, architects, designers, and even the government do not seem to be knowledgeable about this issue. Consequently, high cooling energy is consumed to provide indoor thermal comfort. This led to an increase in outdoor temperatures not only during the day but also at night. The need to mitigate this in tropical climates cannot be overstated. In light of these analyses, strategies for creating healthy building designs are recommended, especially in cities, to reduce UHI and increase thermal comfort in buildings.

3. Mitigation of and Adaptation to UHI Phenomena

3.1. Weather Data Research and Modeling

Weather data are one of the primary inputs used in analyzing UHI. In some studies, experimental tools were used to collect data. HOBO dataloggers (U23-002, protected under the same RS3 brand) and Davis Vantage PRO weather stations were used to measure and calculate hourly air temperature data [11]. These results calculate the hourly temperature average for both cities for 2016 and illustrate the differences in season and synoptic conditions [11]. Other than using that equipment, humidity traces and solar radiation time series were obtained from selected Malaysian sites [25]. Anemometers with ultrasonic waves were used to measure the weather [25].

As an additional step, the input weather data for urban areas have been simulated using several tools. The Weather Research and Forecasting (WRF) model was used to assess mitigation scenarios for the tropical city of Singapore during April 2016, including two heat waves [26]. Simulated results show that the canopy layer UHI intensity in Singapore can reach up to 5 °C in compact areas at night [26].

Using another simulation tool, the Urban Weather Generator Tool (UWG), exploratory UHI simulations were performed in Duran, Ecuador [8]. A sensitivity analysis was conducted on the four clusters to study the relevance of the main UHI driving factors [8]. The urban heat island profile of Duran was quite typical, based on the analysis results. At noon, the thermal inertia effect and heat emitted from traffic combined to produce a negligible effect and increased during the afternoon and night [8]. Duran appears to be strongly affected by the urban heat island effect, especially in informal settlements with a high anthropogenic heat release [8].

Planning and development professionals may also benefit from weather data analysis by improving building construction designs for thermally comfortable zones and by avoiding development in hotspots [26]. Medium-rise building areas are strongly affected by UHI. Due to the rising outdoor temperature as well as the heat produced by air conditioners in nearby high-rise buildings, these buildings suffered. When planning an urban area, these areas should be the main focus.

3.2. Simulation Tools for Urban Planning

Simulation tools have been helpful in analyzing the behavior of radiative cities and their effects on residents [27]. Increasing availability of urban area data has led to a more comprehensive analysis of urban microclimates and thermal comfort [27]. The Discrete Anisotropic Radiation Transfer model (DART) is used to model the spatial distributions of The Mean Radiant Temperature (TMRT) [27]. The model can simulate TMRT across a range of scales and parameters including coverage, shape, spectral signature, Leaf Area Index, and Leaf Area Density of vegetation (for example, ground, walls, and roofs) [27]. Simulations using accurate vegetation properties are therefore essential [27].

4. UHI Impacts on Building Energy Consumption

4.1. Weather Data as Input Data for Building Simulation

The standard meteorological year helps in the design of new buildings and the assessment of energy efficiency [3]. With dynamic software it is possible to simulate the energy performance of buildings based on a wide range of weather data [3]. It is desirable to have more localized meteorological data available inside big cities (affected by UHI phenomena). Data of this nature can be used to produce more accurate and consistent climatic data for improving predictions of building simulation models, as well as for improving the estimation of energy costs, internal environmental conditions, and making more rational assessments of energy conservation measures affecting existing buildings [3]. The results of this study indicate that climatic data collected from airports should not be used to assess the energy performance of buildings located at the center of cities (if possible) [3]. Moreover, standard weather information must be updated regularly to prevent air conditioning systems from being oversized during the winter and undersized during the summer [3].

4.2. The Importance of User Behavior

Data are collected via surveys and questionnaires. Human behavior can often be understood using this method. In response, one paper provides research on the relationship between residents' mitigation and adaptation behaviors around cooling in Fukuoka, Japan, and draws lessons for communicating to encourage those behavior changes [20]. Participants were asked about issue perceptions, evaluation of mitigation measures, and behavior related to mitigation and adaptation [20]. Study findings suggest that there is a lack of information regarding how to use air conditioning appropriately in a manner that saves energy, and that energy-saving behavior is more likely to be coupled with practices such as relaxing in the shade or using a cooler [20]. Providing direct evidence of the benefits of appropriate air conditioning usage on electricity bills may be helpful for engaging citizens that may be unaware [20].

The study studied the effects of urban sustainability in ten countries worldwide using semi-structured interviews with experts in the field [28]. The results of an interview indicated that countries and different actor groups differ in their awareness of adaptation measures [28]. Politicians and citizens are less aware than urban planners and designers [28]. Public awareness must be raised through media campaigns, further education, and a display of best practices [28].

The level of education in a country can predict its sense of urgency as well as its climate experience [13]. According to survey results, urban planners and designers are aware of the problems concerning urban climate in most countries, showing that formal education places enough emphasis on this topic [13]. Various countries have urban climate experts who can also advise politicians, urban planners, and designers [13]. Urban climate phenomena are relatively poorly understood in less developed countries despite the higher urgency of adopting climate adaptation measures [13]. The most effective way to increase people's awareness is through education and communication [13].

4.3. Experiment Tools and Calculation

In the tropical city of Mérida, Yucatán, Mexico, the NDVI values can be used as an indicator of how changes in urban land cover affect the spatiotemporal variations in surface temperatures [29]. Through remote sensing technology, this study sought to discover how weather patterns and land cover change affect land surface temperatures during the rainy and dry seasons. The NDVI data obtained suggest that vegetation vigor has decreased in the region since 1994 due to land use changes. The results suggest that the hottest temperatures are found in the Mérida urban zone, whereas they decline in peripheral areas that maintain vegetation cover [29].

Terraced housing research at Kuching University found that when air well configurations are explored with several experiment tools, natural ventilation can be maximized in single-story terraced houses [30]. HOBO U12 air temperature and air humidity were measured, and the HOBO U12 anemometer was used, as well as the Delta Ohm HD32.3 Wet Bulb Globe Temperature meter to determine the existing indoor environmental conditions and thermal performance. The purpose of this study was to investigate the thermal performance of a real-world case study house during field testing.

5. Reducing UHI through Building

5.1. Roof Greening and Cool Roof

A building's thermal energy performance can be significantly impacted by UHI. Material in urban areas absorbs solar and infrared radiation, and in turn the accumulated heat is dispersed in the atmosphere, raising the ambient temperature [31]. Specifically, roofs are envelope components that are capable of reducing indoor temperature and providing significant energy savings in air-conditioned buildings by incorporating advanced solutions such as cool roofs and green roofs [12][31].

Approximately 20–25% of the urban surface area is covered by roofs of buildings [31]. Adding green roofs to buildings has been found to be an effective solution for improving environmental quality [32]. Typically, green roofs are covered with a layer of soil over a waterproofing membrane. The benefits of green roofs include decreased energy consumption within a building due to reduced solar absorption (as green roofs are more reflective) and evapotranspiration of plants [31]. Typically, green roofs are covered with a layer of soil over a waterproofing membrane. The benefits of green roofs include decreased energy consumption within a building due to reduced solar absorption (as green roofs are more reflective) and evapotranspiration of plants [31].

5.2. Green Facade

A green facade has the ability to reduce indoor temperatures due to its shading ability. The first design concept is focused on the window. When window areas are not shaded by external shading devices, the window size has a greater effect than thermal mass. A building's height should be considered in relation to shading of south- and west-facing facades through facade greening and trees, shading of rooftop extensions, and the correct orientation of buildings and streets to reduce solar irradiation and improve natural ventilation [12]. Wind directions are to be considered when planning building orientation and design [12]. Evaluation of individual wind comfort and microclimate must be required [12]. Facade greening should be considered in conjunction with renewable energy sources, since summer comfort in buildings is enhanced by shading during hot periods [12].

Researchers in Vienna are investigating the use of "plus-energy" and modern smart buildings, capable of generating, storing, and using energy conveniently within a building's constraints, which will provide more efficient and economical solutions [21]. Architectural solutions include external shading, ventilation at night, and a large thermal mass of construction materials. According to the detailed analysis, combining these three measures provides the best results [21]. Moreover, the external shading must not be neglected at any cost. As part of this planning process, it is essential to consider shading, greening, ventilation, and densification to ensure that buildings can provide comfortable summer temperatures inside [21].

5.3. Ventilation Design

Passive cooling plays a crucial role in reducing the energy consumption during the operational period of a building, especially in tropic countries [30]. Thermal comfort can be achieved by implementing good ventilation. A natural ventilation system can provide the building with a cooling effect via airflow or air pressure differences as well as temperature differences between the inside and outside of the building, based on the design of the building at the pre-construction stage [30]. Providing fresh air to an indoor environment is essential to preventing levels of carbon dioxide (CO_2) from exceeding undesirable levels [30].

A terraced house is the most common type of residence occupied by citizens in Malaysia, and its design does not consider the problem of single-sided ventilation [30]. In Malaysian terraced houses with one floor, a solar chimney was studied in order to improve natural ventilation [30]. Researchers found that the combination of a solar chimney and a louvre window geometry could enhance the stack ventilation of a residential building, resulting in a better thermal comfort for occupants [30].

5.4. Air Conditioning Control

In the tropics, ventilation is very helpful in reducing cooling loads, but the effectiveness of air movement depends on the air pollution levels [33]. As a result of a lack of quality air, the windows will be closed and internal and solar gains will accumulate. Despite shading or ventilation, the savings achieved by this scenario will be marginal because internal and solar gains will be eliminated with only air conditioning [33]. Future urban areas will need to utilize renewable energy sources, such as photovoltaic electricity generation, to power air conditioning, and other sustainable methods to reduce heat exposure [19].

Around half of the total electricity produced in Singapore goes to buildings, and for cooling alone, buildings consume about 30% of the country's total electricity production [31]. AC systems contributed significantly to the air temperature in the urban environment during the night by releasing waste heat [26]. Increasing the thermostat setting from 21 to 25 °C can mitigate the effect [26]. Singapore could not achieve a thermally comfortable future without limiting the density of less compact areas, and measures to mitigate UHI are necessary if urban densification is inevitable [26].

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