Investigating the Urban Heat Island Phenomenon in High-Density Cities: A Study on Macao SAR

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Abstract: This study investigates the Urban Heat Island phenomenon in Macao SAR, a region with one of the world's highest population densities, amidst rapid global urbanization driven by capital and labor flows. We utilize surface temperature data from five points in time (2000, 2005, 2010, 2015, 2020) to analyze the UHI effect's intensity and its correlation with land use patterns and population density. Findings show the pronounced dual-core structure of the UHI effect in Macao, heavily shaped by the variety in urban land utilization and the spread of the population. The city's green areas and water features significantly contribute to the reduction of the UHI impact.

Keywords: Heat island effect, land utilization, urbanization, environmental protection, population density.

1 Introduction

The rapid urbanization characteristic of the 21st century has precipitated a myriad of environmental challenges, one of which is the Urban Heat Island (UHI) phenomenon. This effect, where urban centers experience significantly higher temperatures than their rural counterparts, primarily results from alterations in land surfaces and increased emission of heat from urban activities. High-density cities like Macao SAR, with their labyrinthine agglomerations of concrete, asphalt, and scant vegetation, serve as quintessential incubators for UHIs. Furthermore, the implications of UHIs extend beyond mere discomfort, influencing energy consumption, public health, and environmental quality.

Macao Special Administrative Region (SAR), renowned for its dense urban fabric and precipitous population growth, presents an exemplary case for investigating the dynamics of UHIs within the ambit of high-density urban environments. This study seeks to elucidate the relationship between the UHI phenomenon and the urban morphology of Macao SAR by synthesizing surface temperature data across two decades, from 2000 to 2020. The study's focal point is the intensity of the UHI effect and its interrelation with factors such as land use patterns and population density, which are emblematic of high-density urban settings.

The academic and policy relevance of this research is underscored by the global impetus to create sustainable and livable cities amidst the escalating threat of climate change. The United Nations' Sustainable Development Goal 11 specifically targets the sustainment of cities that are inclusive, safe, resilient, and sustainable. In this context, understanding the UHI effect is pivotal

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for urban planning and the implementation of mitigation strategies in Macao SAR and cities alike. Through a meticulous analysis of temporal spatial data, this investigation aims to furnish empirical insights that could guide the formulation of urban planning policies and sustainable development initiatives. The findings are anticipated to contribute to the broader discourse on environmental protection, urban sustainability, and the optimization of urban living conditions in the face of unrelenting urbanization and climate change exigencies.

Given the complex interplay between urban development and environmental sustainability, this research serves as a conduit for understanding how high-density cities can navigate the exigencies of urban expansion while mitigating the adverse effects of UHIs. It also seeks to inform policy interventions that can reconcile the relentless march towards urbanization with the imperatives of ecological and human well-being.

2 Research Background

Following the industrial revolution, the widespread use of fossil fuels has triggered an increase in global temperatures, with profound implications for the planet's ecosystem and socio-economic compositions. To tackle this problem collectively, the *United Nations Framework Convention on Climate Change (UNFCCC)* was instituted in 1992. To reinforce the implementation of the UNFCCC, the *Kyoto Protocol* was initiated in 1997, serving as the inaugural international legal instrument to set specific greenhouse gas emission caps for developed nations. However, growing discord during climate discussions paved the way for the *Paris Agreement* in 2015. This agreement created a post-2020 global response strategy for climate change and defined a flexible emission reduction pathway, dependent on voluntary commitments from each party.

The *Paris Agreement*'s goal is to curb climate change threats by keeping the global temperature rise this century below 2°C, with additional efforts to limit the increase to less than 1.5°C. China, as a significant global greenhouse gas contributor, has pledged under the Agreement to cut its carbon intensity by 60%-65%, aiming to reach peak carbon dioxide emissions by 2030, and striving for carbon neutrality by 2060. Recognizing that greenhouse gas emissions emerge from different geographical areas within countries, it's crucial to consider cities as primary players in mitigating global climate change and executing the *Paris Agreement*.

The rapid pace of global urbanization has heightened the role of cities in societal progress and their contribution to environmental degradation. While global cities cover just 3% of the earth's surface, they are home to over half of the global population and generate roughly 70% of GDP. This results in an uneven consumption of resources, accounting for around 60% of the world's energy use and 75% of carbon emissions, intensifying the greenhouse effect [1]. The IPCC (2018) affirms that human-induced greenhouse gas emissions are the leading contributors to global warming [2], causing problems like sea-level rise, extreme weather conditions, and biodiversity loss, affecting both natural and human systems [3]. By 2050, the projected urban population of 6.7 billion will significantly escalate energy use and carbon emissions [4], amplifying the occurrence and intensity of extreme weather events, and thus making urban regions particularly vulnerable to climate change.

In light of this, the study focuses on Macao, one of the world's densest cities, and uses surface temperature data from five intervals over the last 20 years (2000, 2005, 2010, 2015, 2020) to examine the city's vulnerability to the UHI effect and its correlation with land usage and population concentration. The objective is to furnish empirical support for future considerations in urban planning, ecological design, and sustainable development policies.

3 Literature Review

3.1 Implications of Urbanization on Environment

Urbanization, the transition from rural to urban societies, began during the first Industrial Revolution in the 1760s. Various scholars have provided insights into urbanization [5] [6] [7]. As urban growth surged, issues such as overpopulation, pollution, and disease outbreaks became evident, impacting the relationship between urbanization and the environment. Historical works emphasized the imperative of environmental protection and sustainability in urban planning and industrial development [8] [9] [10] [11].

The environmental repercussions of urbanization extend beyond the confines of cities, contributing to regional and worldwide environmental deterioration and restoration efforts. This understanding led the United Nations in 1980 to introduce sustainable development, a principle that emphasizes meeting the needs of the present generation without jeopardizing the ability of future generations to meet their own [12]. The UN (2019) disclosed that urban populations had surged from 751 million in 1950 to 4.2 billion in 2018 and projected an additional 2.5 billion by 2050, predominantly in India, China, and Nigeria [13]. In terms of geographic distribution, North America holds the highest urbanization level, while Asia, despite a lower urbanization rate, is home to 54% of the worldwide urban population. Regrettably, cities, which occupy less than 2% of Earth's surface, account for 78% of global energy consumption and generate over 60% of human-caused greenhouse gas emissions, posing potential threats to the global environment's future [14].

Currently, the swift advancement of urbanization is a significant global concern. Over recent years, researchers have delved into the connection between urbanization and environmental changes from various angles. Seto et al. (2017) revealed the direct impacts of urban growth on biodiversity and carbon pools from a global forecasting viewpoint, underlining land-use alteration as a central factor in global environmental shifts [15]. Meanwhile, Güneralp et al. (2017) investigated the effects of urbanization on building energy consumption, presenting a global scenario related to urban compactness and underscoring that urban regions generally exhibit increased temperatures compared to rural areas, subsequently jeopardizing urban inhabitants' health and living standards [16]. By examining the influence of urbanization on water resources, Liu et al. (2016) highlighted the growing demand and intensified competition for water resources triggered by rapid urban sprawl [17]. Additionally, Zhang et al. (2017), through their research on urbanization in China, exposed the relationship between urbanization and ecological footprint, emphasizing the impact of urban development on resource exploitation [18]. Liu et al. (2014), through their analysis of urbanization's impact on rural regions in China, unveiled urbanization's influence on the ecological environment of these areas [19]. Niemelä et al. (2010) studied the effect of urbanization on biodiversity and proposed a model concerning the correlation between urbanization and biodiversity decline [20]. These studies offer a holistic view of the relationship between urbanization and environmental implications and underscore potential directions for future inquiry, such as a more in-depth understanding of the influence of urbanization on various aspects and the creation of more sustainable urban growth strategies.

Hence, urbanization embodies a spatial environmental vector reflecting economic and demographic transformations. The relationship between urbanization and the environment is reciprocal; urbanization propels environmental degradation, which, in turn, inhibits urbanization. This relationship necessitates harmonization with the environment to achieve sustainable development in future urbanization.

3.2 The Urban Heat Island Phenomenon

The investigation into the UHI effect dates back to the early 19th century when Howard (1833) observed elevated temperatures in London's urban regions relative to its suburban areas [21]. Manley (1958) first introduced the UHI concept [22], while Oke (1982) defined the UHI intensity [23]. UHI formation correlates with numerous factors, with urbanization playing a key role due to structural changes affecting heat exchange processes between the soil and atmosphere [24] [25].

UHIs are present in over 1,000 cities worldwide, affecting every latitude in both hemispheres [26]. UHI doesn't trigger natural disasters directly but can alter local climate characteristics and indirectly impact human productivity and life [27]. Furthermore, UHIs interact with atmospheric pollution, intensifying air pollutants concentration and increasing respiratory and cardiovascular diseases incidences [28]. Therefore, mitigating the UHI effect, both nationally and locally, has gained much attention under the *Paris Agreement*. Promising mitigation strategies include improving urban heat storage capacities, augmenting urban green spaces and parks, and utilizing vegetation, wind, and water [29] [30].

In recent times, there have been notable advancements in UHI effect research, covering a diverse range of research domains and methodologies. Varquez and Kanda (2018) illustrated through a global study covering 286 cities from 1960 to 2009 that the UHI effect is triggered by both a rise in sensible heat and significant thermal inertia [31]. Li et al. (2019) found that the spatial fluctuations of daytime UHI intensity are largely governed by differences in the ability of urban and rural areas to evaporate water, implying that green infrastructure can effectively alleviate urban heat [32]. Conversely, Zander et al. (2018) provided proof of the social impacts of escalating heat in urban areas in the Philippines by examining the correlation between population density and heat stress [33]. Additionally, Memon, Leung, and Li (2008) highlighted the significance of selecting suitable materials for constructing urban envelopes to mitigate the adverse effects of the heat island phenomenon. In a separate study [34], Jenkins et al. (2014) underscored additional benefits, such as reduced mortality and residential discomfort, associated with mitigating the UHI effect by decreasing albedo and anthropogenic heat emissions [35]. Amorim (2020) posits that UHI analysis will facilitate the subsidizing of territorial management and urban planning, fostering healthier city development, thereby enhancing societal sustainability [36]. These research findings provide various techniques and strategies to comprehend and mitigate the impacts of the UHI effect and emphasize the importance of multidisciplinary research and knowledge dissemination in urban planning and management.

In short, as urbanization, an irreversible globalization trend, continues, a crucial future consideration involves maintaining societal development while mitigating UHI effects and safeguarding the natural environment.

4 A Case Study of the Urban Heat Island Effect: Macao SAR

4.1 Macao SAR: An Overview

Macao, an emblematic SAR of China practicing "One Country, Two Systems", holds a significant geographical location on China's southeast coast within the Pearl River Delta's western coastline. Following a sustained history of systematic land reclamation since 1840, the city's area has expanded from 2.78 km^2 to 33 km^2, housing a population of roughly 681,700 with an extraordinarily high population density of approximately 20,645 individuals per square kilometre [37] [38] [39].

Macao's administrative division includes Nossa Senhora de Fátima, Santo António, São Lázaro, Sé, São Lourenço, Nossa Senhora do Carmo, and São Francisco Xavier. As per the statistical division, it encompasses numerous areas such as Ilha Verde, Tamagnini Barbosa, Areia Preta e Iao Hon, NATAP, Móng Há e Reservatório, among others. The city's geography, characterized by low hills and flatlands, displays a declining gradient from south to north, with Alto de Coloane as its pinnacle point (172.4 meters) and the South China Sea level as the lowest point (0 meters). Influenced by its geographical proximity to the sea, Macao's subtropical maritime climate primarily exhibits warmth and humidity with an average annual rainfall of 1,966 mm [40].

The previous two decades have seen Macao experience a distinct period of rapid economic expansion and urban spread, achieving an urbanization rate of 100% [41]. Nonetheless, such rapid urban growth has triggered significant environmental shifts impacting the climate, hydrology, biology, and air quality. These changes pose serious challenges to the city's sustainable progression. Hence, this study uses Macao as a case study to examine the spatial distribution of the UHI effect, its association with land-use patterns, and population density.

4.2 Decadal Analysis of UHI Phenomenon: Spatial Differentiation within Macao

Utilizing remote sensing and Geographical Information System (GIS) methodologies, this research dissects the temporal progression of the UHI effect across Macao SAR at five-year intervals spanning from 2000 to 2020. The data bank includes Landsat5 TM data (for years 2000, 2005, 2010) and Landsat8 OLI/TIRS data (for 2015 and 2020) acquired from the Landsat series. The mean-standard deviation technique was employed to classify UHI intensity into five levels: high land surface temperature (LST) zone, sub-high LST zone, medium LST zone, sub-low LST zone, and low LST zone, enabling statistical interpretation of the data.

Historical data spanning two decades indicate that UHI distribution tends to be governed by a principle wherein regions of high built-environment and population density showcase pronounced high-temperature effects, whilst lower temperature effects are dominantly observed in the vicinity of water bodies. This phenomenon is sporadically observed across Macao, with high, sub-high, and medium LST zones being omnipresent, enveloping the entirety of the city. Essentially, a binary heat island thermal region, extending from north to south, is discernible, encapsulating the Macao Peninsula and Cotai (refer to Figures 1 to 5). Notably, high and sub-high LST zones exhibit sporadic intensifications, spanning the parishes of Nossa Senhora de Fátima, Santo António, São Lázaro, Sé, São Lourenço, Nossa Senhora do Carmo, and São Francisco Xavier, specifically in densely constructed and populated zones with sparse vegetation cover and high concentrations of anthropogenic heat sources. Over time, UHI spatial distribution across Macao has exhibited diverse patterns of growth, with a surge followed by a stagnation phase, more prominently in the pre-2010 era compared to the post-2010 period.

In 2000, the UHI effect was acutely manifested, with high and sub-high LST zones permeating all parishes (Figure 1). By 2005, a slight easing of the UHI effect was observed on the Macao Peninsula (Figure 2), although the effect persisted in specific areas of Nossa Senhora de Fátima, Santo António, and Sé parishes, while an intensification was observed in Taipa Island and Cotai. By 2010, UHI effect in the Macao Peninsula experienced a slight intensification (Figure 3), predominantly in the parishes of Nossa Senhora de Fátima, Santo António, Sé, and São Lourenço. Conversely, a marginal relaxation of the UHI effect was observed on Taipa Island and Cotai, though they remained significantly impacted.

In 2015 and 2020, there was an observable decrease in the number of UHI-affected areas (Figures 4 and 5), primarily concentrated in the parishes of Nossa Senhora de Fátima, Santo António, Sé, and São Lourenço. Conversely, a substantial area of high and sub-high LST zones persisted in Nossa Senhora do Carmo, São Francisco Xavier parishes, among others. Notably, regions such as the Zona A dos Novos Aterros Urbanos and the Hong Kong-Zhuhai-Macao Bridge's Zhuhai–Macao Port Artificial Island began to show clear signs of UHI effect, with an increasing trend in high and sub-high LST zones.

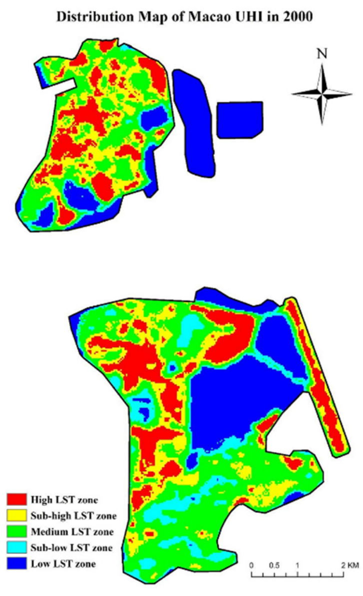

Figure 1. Temporal-spatial distribution map of Macao UHI phenomenon in 2000

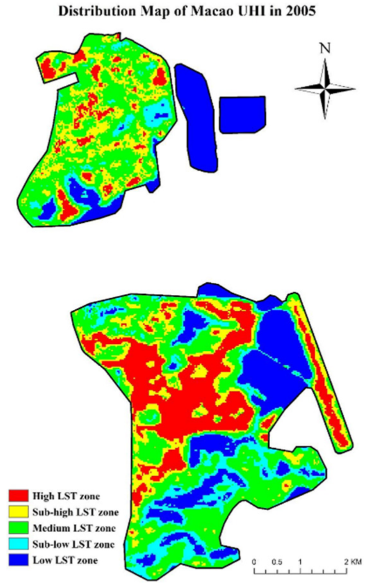

Figure 2. Temporal-spatial distribution map of Macao UHI phenomenon in 2005

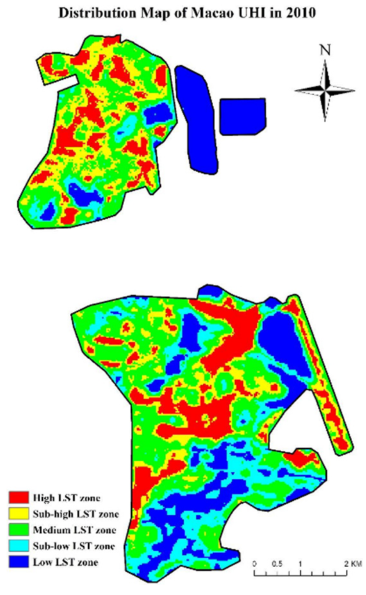

Figure 3. Temporal-spatial distribution map of Macao UHI phenomenon in 2010

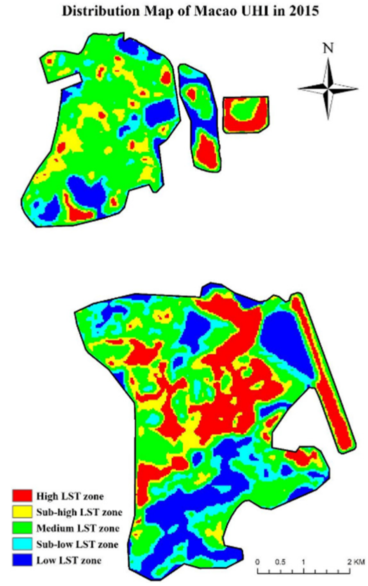

Figure 4. Temporal-spatial distribution map of Macao UHI phenomenon in 2015

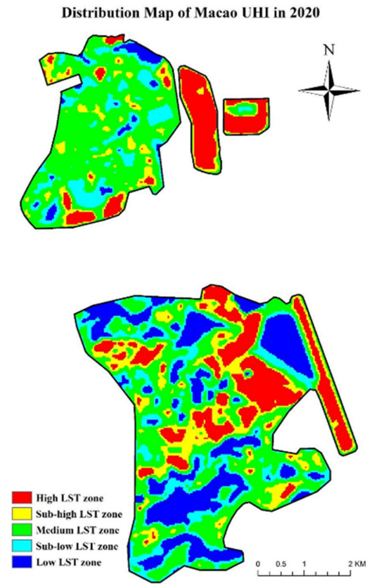

Figure 5. Temporal-spatial distribution map of Macao UHI phenomenon in 2020

4.3 Interrelation between UHI Effect and Land Utilization in Macao

A temporal evolution of Macao's urban land use pattern from 2000 to 2020 (in five-year increments) is predominantly characterized by construction land, woodland, and bodies of water.

Construction land tends to be concentrated in the central and northern sectors of the Macao Peninsula, Taipa Island, and Cotai, whereas woodlands are primarily situated in the southern portion of Coloane Island and bodies of water dispersed across the regions (refer to Figures 6 through 10). In a temporal context, there is negligible alteration in the urban form of the Macao Peninsula from 2000 to 2020. However, noticeable development leaps can be seen in Taipa Island and Coloane Island, with the waters between the two islands gradually being replaced by construction land and grassland.

Cross-referencing the spatial distribution maps of UHI in Macao reveals a conspicuous positive correlation with the distribution of construction land, particularly in areas like the Macao Peninsula and Cotai. These regions are characterized by high construction and population densities, leading to extensive anthropogenic energy consumption and substantial heat release. This aligns with the study by Shi et al. (2018), which underscored the crucial role of urban form and land use in influencing the UHI effect [42]. The dense urban constructions in these areas obstruct air circulation, inhibiting efficient heat dissipation and reducing the city's cooling efficiency. This issue is exacerbated by the prevalent use of materials with low solar reflectivity like masonry, asphalt, cement, and concrete in urban construction. These materials absorb a significant amount of solar radiation energy, aiding in the temperature increase in urban areas [43].

Moreover, the majority of residential, tourist, and commercial buildings in Macao incorporate glass curtain wall structures. This architectural feature results in multiple reflections and absorptions of solar radiation between walls, exacerbating the formation of UHIs. This occurrence has been noted in various global urban centres, and it's been observed that the architectural design of buildings significantly influences the UHI effect [44]. Addressing the UHI effect in Macao necessitates a comprehensive understanding of its relationship with land utilization. Urban planners and policymakers must consider the implications of construction materials, urban design, and land use patterns on the UHI effect. Integrating green spaces and vegetation in urban areas has been identified as a potential strategy to mitigate UHI, as they can enhance the urban heat dissipation capacity and contribute to the overall cooling of the city [45].

In brief, the UHI effect in Macao is intricately linked to land utilization, with construction and population densities, urban design, and material choices all playing pivotal roles. Addressing this issue requires a holistic approach, taking into consideration the various factors that contribute to UHI and implementing strategies to mitigate its impact.

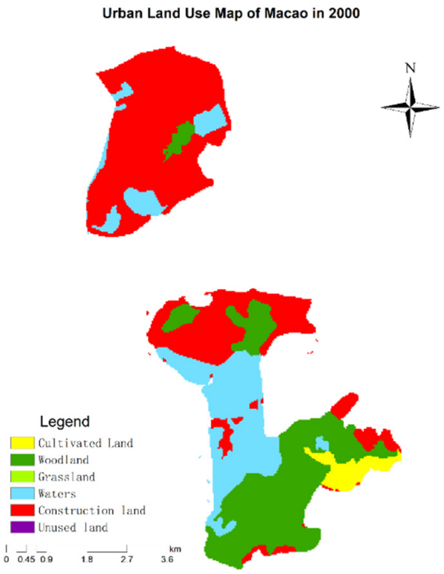

Figure 6. Macao urban land use distribution map in 2000

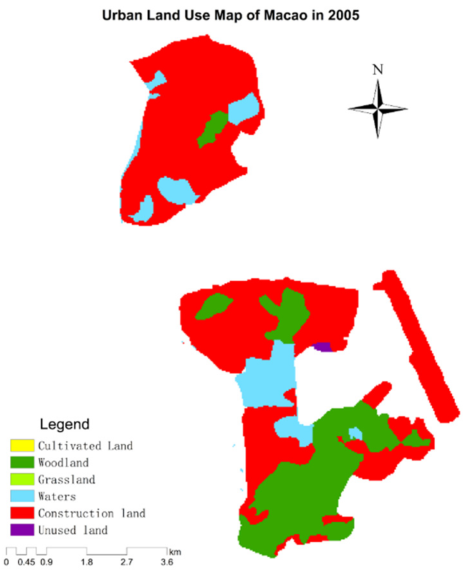

Figure 7. Macao urban land use distribution map in 2005

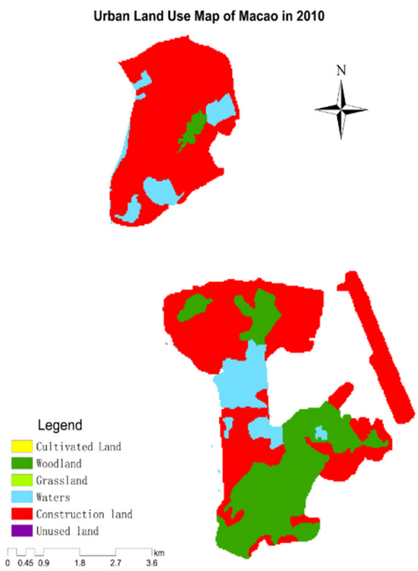

Figure 8. Macao urban land use distribution map in 2010

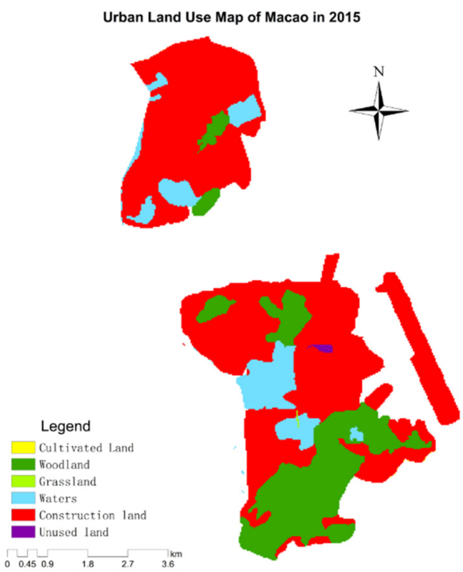

Figure 9. Macao urban land use distribution map in 2015

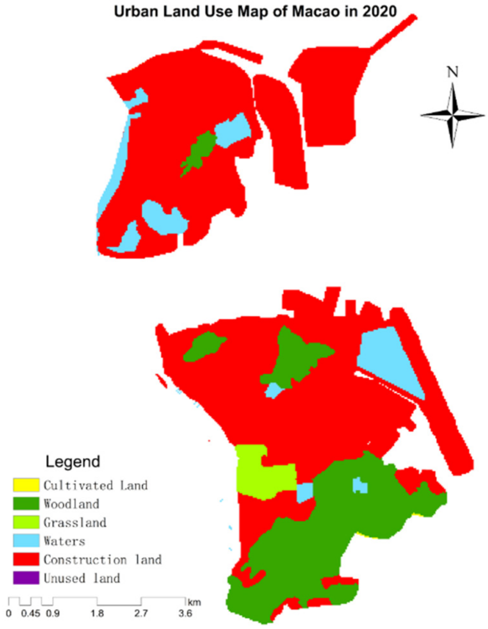

Figure 10. Macao urban land use distribution map in 2020

4.4 Interrelation between UHI Effect and Population Density in Macao

The evolution of Macao's population density from 2000 to 2020 (in five-year intervals) illustrates a concentration of inhabitants primarily on the Macao Peninsula and Taipa Island (refer to Figures 11 through 15). A more pronounced population density is observed in the parishes of Nossa Senhora de Fátima, Santo António, and Nossa Senhora do Carmo, specifically in Tamagnini Barbosa, Areia Preta e Iao Hon, NATAP, Fai Chi Kei, Horta e Costa e Ouvidor Arriaga, Barca, and Baixa da Taipa. Temporally, the year 2000 witnessed significant population concentration on the entire island of the Macao Peninsula, notably in the northern and central districts of Areia Preta e Iao Hon, NATAP, Horta e Costa e Ouvidor Arriaga, and Barca. Post-2005, while the population further densified in already high-density areas, expansion also began into outlying islands, leading to higher concentrations of inhabitants. By 2020, the major population concentrations were segmented into three key areas: the northern region inclusive of Tamagnini Barbosa, Areia Preta e Iao Hon, and NATAP, the central region encompassing Fai Chi Kei, Horta e Costa e Ouvidor Arriaga, and Barca, and the southern region of Baixa da Taipa.

This investigation revealed that the UHI effect in Macao is strongly influenced by population density, with severe impacts in densely populated and built-up areas such as the Macao Peninsula and Cotai. The high anthropogenic energy consumption in these regions, due to residential, commercial, and industrial activities, generates significant heat, contributing to the UHI effect [46]. The populated urban formations in these areas obstruct air circulation, preventing efficient heat dissipation and reducing the city's cooling capacity [47]. The construction materials commonly used in Macao, such as masonry, asphalt, cement, and concrete, possess low solar reflectivity, thus absorbing more solar radiation energy [48]. This situation is further amplified by the prevalent use of glass curtain wall structures in residential, tourist, and commercial buildings, causing multiple reflections and absorptions between walls, thereby amplifying the UHI effect [49]. The spatial layout of UHIs in Macao exhibits a positive correlation with the distribution of construction land, underscoring the significant role of land use in the UHI effect [50]. The quick-paced urbanization and land development in Macao have led to the emergence of high-rise, high-density structures, contributing to the centralization of migration and population growth in these areas [51]. This architectural evolution and population concentration have led to increased energy usage, thereby escalating the UHI effect [52]. The UHI effect's intensity acts as a quantitative marker of the thermal modification imposed by the city on its territory, reflecting its relative warming compared to the surrounding rural environment, especially during the night [53].

In summary, the intricate relationship between the UHI effect and population density in Macao is driven by a multitude of factors including land use, construction materials, urban formation, and energy consumption. Tackling this issue necessitates a holistic strategy, incorporating sustainable urban planning, expansion of green spaces, and innovative architectural designs to mitigate the UHI effect and boost the city's resilience to urban heat.

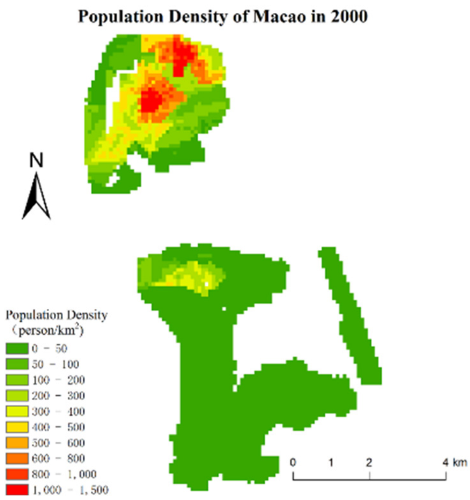

Figure 11. Temporal-spatial distribution map of Macao population density in 2000

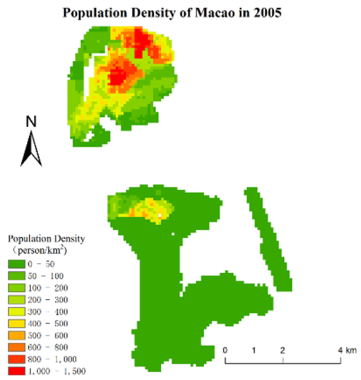

Figure 12. Temporal-spatial distribution map of Macao population density in 2005

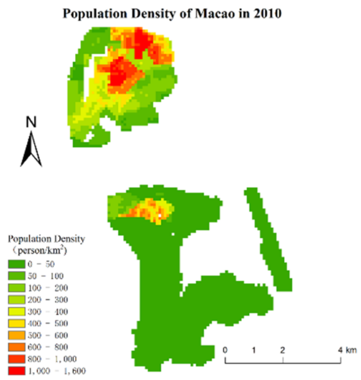

Figure 13. Temporal-spatial distribution map of Macao population density in 2010

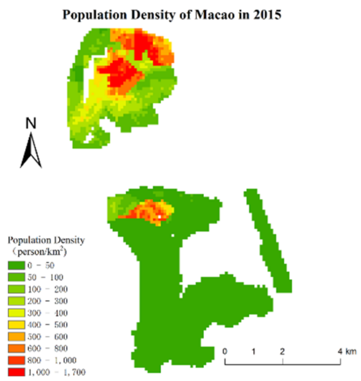

Figure 14. Temporal-spatial distribution map of Macao population density in 2015

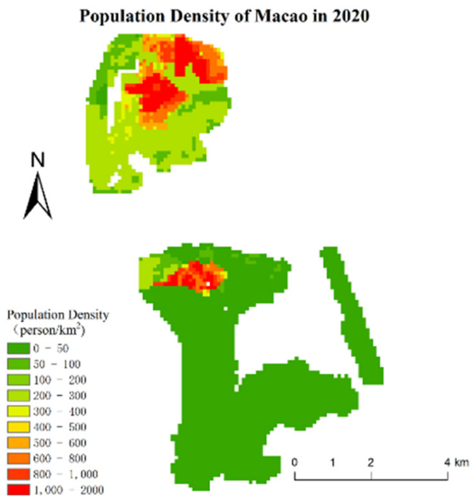

Figure 15. Temporal-spatial distribution map of Macao population density in 2020

5 Exploration into the Origins of Urban Heat Island Effect in Macao

Since Macao's handover in 1999, a strategic emphasis was placed on gaming tourism and the service industry, leading to a surge in development and an unprecedented expansion of the gaming sector. This metamorphosis sparked an increase in land demand which outweighed the availability on the Macao Peninsula. Consequently, the Venetian Group and other enterprises embarked on large-scale resort developments in the Cotai area, utilizing reclaimed land [54].

Over a span of twenty years, the count of casinos in Macao expanded from 11 to 42, and the number of gaming tables escalated from 424 to 6,080. In 2002, the gross gaming revenue was MOP22.1 billion, which soared to MOP292.4 billion by 2019, reflecting an astounding 13.2 times augmentation. Similarly, the inbound tourist traffic increased from 11.53 million in 2002 to 39.4 million in 2019, and the GDP saw an ascent from MOP 59.2 billion in 2002 to MOP 434.7 billion in 2019 [55].

Such developments were double-edged; while they triggered growth in sectors directly and indirectly linked to gaming and tourism, they also led to urbanization. This urban expansion, along with increased population densities in the central regions of the Macao Peninsula and Cotai, disrupted the natural heat dispersion patterns. Natural vegetation was replaced by heat-absorbing concrete pavements and buildings constructed from materials with high heat storage capacities, exacerbating the UHI effect. Furthermore, a rise in energy consumption across multiple sectors contributed to greenhouse gas emissions, leading to the emergence of varied LST zones across Macao.

Therefore, the UHI effect in Macao can be linked to the swift urbanization incited by the flourishing gaming industry and the resultant surge in land and energy requirements.

6 Derivative Impact of the Urban Heat Island Effect in Macao

The UHI effect in Macao, catalyzed by swift urban expansion over the past twenty years, has induced severe environmental transformations impacting climate, hydrological patterns, air purity, vegetation, and waste management, thus posing a threat to the city's sustainability.

(1) Typhoon Disasters

With global warming instigating a rise in the occurrences of potent typhoons worldwide, Emanuel (2005) observed a significant increment in the potential destructive power of typhoons in the North Atlantic and Northwest Pacific during the past 30 years [56]. Macao, located on the western coast of the Pearl River Delta, is susceptible to typhoon disasters, as the area accounts for 36% of global typhoons [57]. A prime example of this is Typhoon Hato in 2017, which led to extreme flooding and resulted in substantial human and economic losses, underscoring the likelihood of similar future catastrophes.

(2) Waterlogged Disasters

Macao's location and serious sedimentation make it susceptible to coastal and lowland flooding during strong typhoons and storm surges. Typhoon Hato, for instance, resulted in severe storm surges due to lower atmospheric pressure at the typhoon's centre and strong winds pushing seawater towards the shore. Compounding the issue is the extensive land reclamation in Macao and Zhuhai City, restricting the original Pearl River estuary flood discharge outlet and raising the coastal water level.

(3) Air Pollution

Despite an improvement in air quality during the COVID-19 pandemic slowdown, the Environmental Protection Bureau (2023) highlighted an increased proportion of days with poor air quality in High Density Residential Area (Macao), Taipa, Coloane, and Ka Ho due to elevated O3 concentrations. Power plants and vehicle emissions are significant contributors to PM2.5 emissions [58]. While 90% of Macao's electricity is sourced from mainland China, heavy oil-based power generation in Macao and vehicular emissions remain significant pollution sources.

(4) Light Pollution

Macao's rapid economic development and the proliferation of large resorts have led to extensive usage of lighting equipment, resulting in light pollution. This overuse of lighting affects residents' health, wastes energy, jeopardizes road safety, and disrupts the natural life cycles of plants and animals, thereby disturbing the ecological balance.

(5) Scarcity of Green Space

The rapid urban development and population growth in Macao have led to an uneven distribution of green space, particularly on the Macao Peninsula. According to the Environmental Protection Bureau (2023), despite a slight increase in green space in 2022, the per capita urban green space remains disproportionately low, especially in densely populated areas [58]. This situation affects residents' interaction with nature and contradicts the World Health Organization's recommended per capita urban green space.

(6) Waste Disposal

Macao's growing population, increased tourist influx, and GDP growth have led to a significant increase in municipal solid waste disposal. As per the Environmental Protection Bureau (2023), the city's municipal solid waste disposal volume in 2022 was at a high compared to neighbouring cities [58]. Organic materials, plastics, and paper constituted 84.9% of the total municipal solid waste, while the waste resource recovery rate remained low. The landfills are nearly saturated, indicating an urgent need for waste management strategies.

7 Strategies for Mitigating the Urban Heat Island Effect in Macao: Towards a Sustainable, Healthy Urban Environment

In the context of the profoundly urbanized microcosm of Macao, this exploration underlines the fundamental necessity of strategies to counteract UHI effect resulting from its high-density, high-intensity modus operandi. To curb environmental imbalances arising from urbanization, this research recommends interventions spanning ecosystem adjustments, urban infrastructure, transportation, and industrial development, aspiring to foster a sustainable, healthy urban habitat.

(1) Enhancing Urban Ecosystems' Self-Regulating Capacity

Macao's UHI problem emerges from a profusion of heat sources caused by construction and human activities, combined with dense architectural compositions inhibiting air circulation. Hence, it's vital to harness the potential of wind dynamics in UHI mitigation. A gradual implementation of ecological ventilation corridors, informed by factors such as prevailing wind direction, local circulation, existing urban morphology, and future plans, is recommended. These corridors leverage the city's ecological conditions to facilitate air movement and atmospheric cyclicality, thereby improving air quality and climate environment.

(2) Mitigating Urbanization Impact via Green Space and Waters Construction

Plants play a critical role in heat absorption, carbon sequestration, and oxygen production through evapotranspiration and photosynthesis, resulting in a cooling effect. In Macao, it is crucial to enhance green space within its confines, conserve ecological areas, curtail urban sprawl, and fortify countryside as a carbon sink base. Furthermore, the construction of urban parks should be planned optimally to increase the city's carbon sequestration capacity, and green vegetation should be maximized in public spaces, forming a multi-tiered green space system. In addition to green spaces, increasing water bodies can also mitigate UHIs given their superior heat capacity compared to terrestrial surfaces, enabling them to absorb and store substantial heat energy.

(3) Construction of Environmentally Friendly Buildings and Communities

With Macao's urban expansion, the extensive use of concrete in construction impedes the soil's interaction with rainwater. It is advisable to reduce city hard surfaces by utilizing permeable materials like permeable bricks and concrete pavements, facilitating evaporation and reducing air temperature. Green roof installation on community buildings can decrease the environmental heat via plant evapotranspiration, augment occupant comfort, and minimize the need for energy-intensive air conditioning.

(4) Strategic Planning of City Structural Layout

The Transit Oriented Development (TOD) model recommends that public transport stations form the city core, with all essential facilities reachable within a 10-minute walk. A compact urban layout can enhance energy efficiency. Macao could adopt a mixed spatial layout via master planning, integrating residential, commercial, and transport land resources to create balanced community occupations and housing. By developing pedestrian-friendly networks, a safe slow-moving environment can be cultivated, reducing carbon emissions by limiting motorized travel.

(5) Advocating for Efficient, Low-Carbon Green Travel Modes

For a high-density city like Macao, a diversified public transport system with easy accessibility is paramount. A comprehensive public transport network can be established through the strategic use of light rail, buses, taxis, and bicycles. By constructing efficient transit systems, including footbridges, underpasses, and pedestrian corridors, the convenience of transfers between modes can be enhanced, reducing private vehicle dependency and associated carbon emissions.

(6) Advancement of Green Industries and Implementation of Environmental Protection Incentives

In an increasingly competitive international market, low-carbon industrial structures are becoming more prevalent. It's pivotal for businesses to adopt eco-friendly production methods and set carbon emission targets. The Macao government can help facilitate the growth of low-emission industries through policy guidance and regulation. Providing subsidies to green label product sellers and implementing environmental tax policies or incentives for high consumption, polluting industries can spur societal shift towards a low-carbon economy.

8 Conclusion

This research scrutinized the dispersion of the UHI effect in Macao and its related impacts, by using surface temperature data spanning from 2000 to 2020. The results disclose a bifurcated north-south pattern in the severity of the UHI effect in Macao. This investigation illuminates the firm correlation between land use patterns, population concentration, and the UHI effect in Macao, underscoring the significant role of human-induced heat sources, roadways, urban substrates, and built structures in amplifying the heat island effect. On the contrary, green spaces and water bodies within the city exhibit tangible significance in tempering the UHI phenomenon. Considering the complex origins of the UHI effect, the government of the Macao SAR could institute actions to refine the ecological milieu. These initiatives could encompass enhancing the self-regulating abilities of urban ecosystems, mitigating urbanization impacts through the establishment of green spaces and water bodies, erecting eco-friendly buildings and neighborhoods, implementing a prudent urban structure layout, endorsing efficient and low-carbon transit modes, encouraging the evolution of green industries, and enforcing preferential policies for environmental safeguarding. These strategies aim to mitigate the UHI effect and foster a congenial living environment in Macao.

While the study offers valuable insights into the UHI effect in Macao, it is not devoid of certain constraints. The research's dependence on surface temperature data at five-year intervals may overlook the short-term variations or nuanced changes in the UHI effect, which could be crucial for comprehending its dynamics. Moreover, the singular focus on surface temperature leaves out the potential influences of atmospheric conditions or vertical temperature distributions, which could provide a more holistic view of the UHI phenomenon.

Future research endeavors could delve deeper by utilizing datasets with superior temporal resolutions, potentially on an annual or even monthly scale, to elucidate the intricate dynamics of the UHI effect. Including data on atmospheric conditions and vertical temperature differentials would enhance the comprehension of the phenomenon's breadth and scope. Additionally, an investigation into the socio-economic repercussions of the UHI effect on Macao's inhabitants, such as its influence on energy usage patterns, public health, and overall quality of life, would be a rewarding avenue to explore.

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