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The application of a high-density street-level air temperature observation network (HiSAN): Dynamic variation characteristics of urban heat island in Tainan, Taiwan

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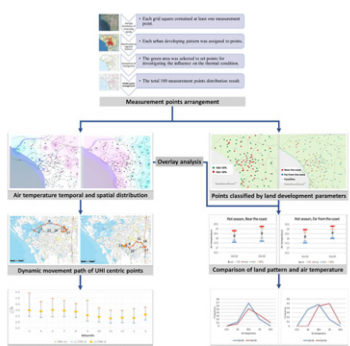
HIGHLIGHTS

- The high-density street-level air temperature observation network can be helpful for evaluating urban heat island.
- The urban heat island intensity can be at least 3 °C every month in Tainan and can reach up to 5 °C in hot season daytime.
- Urban development pattern and geographic feature both affect thermal condition in the areas far from the coast in hot season.
- The centric points of urban heat island will dynamically move from the west to the east in the daytime and opposite at night.
- The impermeable surface area and the distance from the coast are the two most obvious factors on influencing UHI in Tainan.

GRAPHICAL ABSTRACT



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ABSTRACT

The effects of urban heat island (UHI) have recently become a crucial issue. This study utilized a high-density street-level air temperature observation network (HiSAN) to understand the UHI characteristics in Tainan City. A total of 100 measurement points were established throughout the city. The average distance between two neighboring measuring points was 1.9 km in rural areas and 0.8 km in metropolitan areas. The UHI caused a temperature differences of at least 3 °C in each month over the study period, and the UHI's centric point moved from west to east during the day and from east to west at night, mainly because of the physical effects of the different urban environment including location and the impermeable surface area (ISA), total floor area, and sky view factor in urban areas. The results also indicated that factors such as ISA and distance to the coast had the strongest influence on thermal conditions at various times, especially in the areas far from the coast during the hot season. This was mainly because of differences in how heat was retained over the study area. The HiSAN method can be used by urban planners, architects, and policymakers to mitigate the thermal stresses caused by complex urban environments.

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1. Introduction

A small number of meteorological stations are insufficient for representing the atmospheric changes and understanding the microclimate, thermal conditions, and built environment in large complex urban areas (Chen et al., 2016a, 2016b; Honjo et al., 2015; Chang et al., 2010; Merbitz et al., 2012). The urban heat island (UHI) effect indicates that the temperature differences between various environments are affected not only by natural climatic conditions, but also by different built environments (Baker et al., 2002; Kotharkar and Surawar, 2015; Lu et al., 2012). Therefore, a suitable number of meteorological stations is required in urban areas to accurately understand how different land covers, land uses, and other factors such as impermeable surface area (ISA) and total floor area (TFA) affect thermal conditions.

The built environment in cities is complex. Accurately evaluating climatic conditions and understanding the relationship between an urban environment and UHI variations cannot be achieved by relying on the meteorological data provided by a few meteorological stations. A network with numerous intensive measurement points, arranged according to the type of urban typology, is required to accurately understand UHI phenomena.

In this study, 100 instruments were used to obtain comprehensive meteorological information, such as air temperature and humidity, in Tainan. These instruments comprised a high-density street-level air temperature observation network (HiSAN). In the HiSAN, the measurement points were arranged in different development districts to examine the relationship between thermal conditions and urban development patterns. Using the HiSAN in this study yielded the following advantages: we were able to use numerous stations to observe the distribution of climatic conditions in the study area; an accurate representation of the thermal conditions was achieved because enough stations were distributed in the study area; all instruments recorded data at 5-min intervals every day, enabling the temporal and spatial distribution of the UHI to be presented clearly over the study period.

The data of urban development patterns and geographical characteristics were used to explore the thermal environmental conditions in a large urban area to understand the microclimatic changes. Urban planners who do not have meteorological background ca use the results from this study to understand the relationship between urban development and thermal environments.

2. Method

2.1. Study area

The metropolitan area of Tainan (22° 59′ N, 120° 11′ E), a high-density city in southern Taiwan (Fig. 1a), and its surrounding areas were selected as the study area. Compared with other cities in Taiwan, Tainan is rapidly expanding, which makes it more crucial to regulate urban planning in accordance with the meteorological information provided in this study.

The total study area was 175.6 km^2, comprising various natural and built environments. In 2010, Tainan City was upgraded to a special municipality, which subsequently led to a rise in the population and urban development. Therefore, microclimatic research is needed to influence local government urban development policies in Tainan.

Tainan City has a tropical savanna climate with a mean annual temperature of 24.6 °C. The hottest month is July (mean temperature is 30.4 °C) and the coolest month is January (mean temperature of 17.6 °C). The annual mean relative humidity (RH) is 74.4%. The average wind direction in the summer is from the west at approximately 270°.

Most urban development is concentrated in the central part of the city, with the density gradually decreasing outward (Fig. 1b). Most vegetation (comprising farms, parks, and lawns in urban areas) is located on the east and south sides of Tainan (Fig. 1c).

2.2. HiSAN

2.2.1. Measurement instruments

One hundred automatic recording instruments (LOGPRO TR-32, Tecpel Co., Ltd.) were distributed in the study area to collect meteorological data. The LOGPRO (Fig. 2a) was selected for the study because it is lightweight, energy efficient, and can store a large amount of data. The sensors in the LOGPROs were checked before installation to confirm accuracy. Air temperature (Ta) and RH were recorded at 5-min intervals in the study area with an accuracy of ±0.5 °C and ±5% and a measurement resolution of 0.1 °C and 1%, respectively.

Radiation covers were used to protect the LOGPROs from the elements (rain, sun, and wind) and ensure that all data collected were accurate (Fig. 2b). The LOGPROs were installed on the utility poles of street lamps at a height of 2.5 m (Fig. 2c). At this height, the LOGPROs were adequately ventilated and posed no safety concerns for pedestrians or motorists. (Fig. 2d).

Data were collected from the LOGPROs monthly to ensure that the batteries remained charged. At each inspection, the LOGPROs were synchronized with a standard LOGPRO that Tecpel Co. Ltd. calibrated monthly. This ensured that the field LOGPROs were accurate during the study period.

2.2.2. Measurement points

The measurement locations were selected according to the following three principles (Fig. 3a): First, to achieve an average distribution of measurement points, the study area was equally divided into 58 sections, each comprising a 3 km × 3 km grid (Fig. 3b). The measurement points were scattered in each grid (each grid contained at least one measurement point). Second, the sections were then classified according to regional features, including land use, land cover, building density (such as TFA), and normalized difference vegetation index (NDVI). Doing this prevented the selection of sections with the same or similar urban patterns (Fig. 3c). Third, the comparison of homogeneity, the green areas were intentionally selected to investigate the influence of green spaces on thermal conditions in the study area (Fig. 3d). The final measurement points were selected because they represented the most significant attributes of Tainan's urban morphology (Fig. 3e).

Overall, the selected measurement points accurately recorded the characteristics of UHI, including temporal temperature distribution and movement of the UHI over the study period, which revealed the impacts of urban development on the thermal conditions in the study area.

2.2.3. Data processing

The statistical analysis software R language was used to batch process and consolidate the large volume of data collected during the study period. Ta data were calculated hourly. Using meteorological information provided by the Tainan Meteorological Station, various climatic conditions could be chosen and the corresponding data could be intercepted to reveal the corresponding thermal conditions.

For example, the average Ta was calculated for selected periods when the proportion of solar radiation was >75%. The inverse distance weighting interpolation method was applied to calculate the Ta distribution in the study area with a 30 m resolution. The Ta distribution and variations were generated to visualize the thermal conditions at different periods.

To prevent the collection of extreme data due to measurement errors or unpredictable events such as heavy rain or a typhoon, this study compared the differences between the maximum and minimum Ta but used the 2nd and 5th percentile values instead of the minimum Ta and the 95th and 98th percentile values instead of the maximum Ta. This was done to ensure that the normal climatic conditions were accurately depicted.