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Application of Low-Cost Sensors for Urban Heat Island Assessment: A Case Study in Taiwan

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Abstract: In the urban environment, the urban heat island effect, the phenomenon of high temperature in the city relative to the suburbs, has become significant due to a large amount of artificial heat dissipation, rare green spaces, high building density, and a large surface material heat capacity. The study of the urban heat island effect has been carried out for many years. Even though many studies have evolved from the measurement and analysis stage to the improvement of the urban heat island effect, the measurement method is still the most important issue of the studies in this field. Basically, the measurement method of the urban heat island effect intensity has three types: remote sensing, mobile transect observation, and fixed station. In order to achieve the dual purpose of reducing research funding requirements and maintaining the accuracy of research results, this study proposes a way to combine mobile transect observation and fixed station. This study exploits the advantages of mobile transect observation and fixed station, and uses low-cost sensors to achieve the basic purpose of urban heat island effect research. First, in this study, low-cost sensors were mounted on mobile vehicles for more than ten mobile transect observations to identify relatively high temperature and low temperature regions in the city; meanwhile, the low-cost sensors were also placed in a simple fixed station to obtain long-term instantaneous urban temperature data. Furthermore, it is possible to analyze the 24-hour full-time variation of the urban heat island effect. Therefore, the results of this study can not only provide a reference for relevant researchers, but can also serve as an important criterion for government departments to establish an "urban heat island effect monitoring system" to achieve the goal of efficient use of the public budget.

Keywords: low-cost sensor networks; real-time data; environmental monitoring; mobile transect; fixed station

1. Introduction

Due to the scarcity of green space in the city, dense construction, increased artificial heat, and impeded wind mobility, the phenomenon of high temperature in the city relative to the suburbs is called the urban heat island effect (UHI). In general, UHI can be classified into two categories (air and surface) based on the ways and heights that they are formed; air UHI refers to UHI effects in the canopy (CLHI) or boundary (BLHI) layer, and in contrast, the surface UHI (SUHI) represents the radiative temperature difference between urban and non-urban surfaces by remote sensing data [1]. The study of the urban heat island effect has been carried out for many years. In particular, one research results published in 1982 put forward many basic concepts and scientific data on the heat island effect, and has become an important reference in this field [2]. In order to understand the phenomenon and causes of the urban heat island effect, many scholars and scientists have invested in research. Some investigators have observed the relation between urban land cover and urban temperature patterns. In addition, some research has indicated that the urban landscape thermal behavior should assist in explaining the urban heat island phenomenon [3].

Moreover, some studies have begun to observe not only the urban heat island effect phenomenon, but also methods to effectively mitigate the urban heat island effect. One paper reviewed some of the characteristics, such as the impacts of surface albedo, evapotranspiration, and anthropogenic heating of urban climates and the effects of urban heat islands; furthermore, it also applied the numerical simulations and field measurements to indicate that increasing albedo and vegetation cover can reduce the surface and air temperatures near the ground [4]. Another research article concluded that the heat re-radiated by the urban structures plays the most important role in causing the urban heat island, and also concluded that the future research should be focused on design and planning parameters for mitigating the effects of the urban heat island [5]. In addition, one paper provided some urban design strategies, such as rearranging buildings or adding green spaces, to mitigate the urban heat island, and applied the strategies in the design to two existing Dutch neighborhoods [6].

Even though many studies have evolved from the measurement and analysis stage to the improvement of the urban heat island effect, the measurement method is still the most important issue of the studies in this field. Basically, the measurement method of urban heat island effect intensity has three types: remote sensing, mobile transect observation, and fixed station.

The research using remote sensing as the main measurement tool is used to calculate the surface temperature using images taken by satellite or aircraft, and then to obtain the basic data of the urban heat island effect analysis. In a study for evaluating the urban heat island effect, the satellite remote sensing data of Tainan City, Taiwan, obtained from a satellite were used to estimate surface heat balance, and the result implied that density of vegetation has a significant influence in decreasing temperatures [7]. In order to investigate the influences of the city scale, usage, topography, and climate on the surface heat balance, a study compared the surface heat balance for three urban areas in Taiwan that were estimated using satellite data, and its results imply that the terrain around a given city as well as the scale of urban activity significantly affect the heat balance in the cities [8]. In a study, satellite images from 1990 to 2000 were selected to retrieve the brightness temperatures, which were estimated from the surface radiance observed by the satellite sensor assuming the surface as a blackbody, and land use/cover types. The results indicated that the urban heat island effect has become more prominent in areas of rapid urbanization in the study area; besides, they showed the correlations between temperature and several indices, which related to vegetation, water, bareness land, and building intensities [9].

In general, the surface temperature data obtained by remote sensing images must be derived from other diffraction algorithms (or using geographic information system data [10]) to calculate the air temperature data in order to obtain the basic data for analyzing the urban heat island effect. Therefore, the limitation of image data and the error of the algorithm are the biggest disadvantages of using remote sensing as the study of urban heat island effect [11]. A study systematically reviewed the main satellite/sensors, methods, key findings, and challenges of the surface urban heat island (SUHI) research, and confirmed that the applications of SUHI research are largely impeded by a series of data and methodological limitations; meanwhile, the study proposed key potential directions and opportunities for future efforts [1].

Measuring the urban heat island effect with mobile transect observation is one of the most traditional methods. The temperature sensor can be installed on a car or a mobile platform, and the mobile measurement can be carried out according to the pre-planned route and location to obtain instant data of the urban temperature. Therefore, as long as the measurement route planning is appropriate, and the measurement time or time correction of the data is controlled, the urban temperature data obtained by the mobile transect observation method is very efficient for the urban heat island effect analysis.

In a pioneering study, mobile transect observation was used to gather time-series air temperature data of cities on selected nights; meanwhile, the result shows that heat island grew most rapidly following sunset because of much stronger rural cooling and the maximum heat island occurred 3–5 h after sunset [12]. In an analysis study of the winter magnitude of the heat island in Phoenix (Arizona State, USA) using automobile transects, fixed stations, and remote sensing techniques, the result indicated the highest urban temperature difference between the downtown and rural area, heat island intensity (UHIs), observed was more than 8.0 °C, and they determined that thermally induced nighttime cool drainage winds could account for the inflation of the urban heat island magnitude in winter [13]. The overall result of a comparison study of fixed stations and mobile transects for investigating urban and rural temperatures post-sundown in the metropolitan area of Phoenix highlights the important role of surface vegetation and moisture in reducing temperatures in this urban desert [14].

In addition, a study tries to determine the types and structures of small green spaces for effectively reducing air temperature in urban spaces by using mobile loggers on clear summer days, and the results are very useful to planners and designers to determine the types and structures of urban green spaces to optimize the cooling effect [15]. In another study estimating the impact of street characteristics on the thermal environment in an urban street canyon in a hot and humid region, transect data were used to analyze the relation between factors (urban green ratio, building ratio, and height-to-width ratio) and air temperature with the data collected by transects in two streets; meanwhile, the analysis results demonstrate that increasing the green ratio and decreasing the building density are important strategies to mitigate the urban heat island effect and to create a comfortable thermal environment [16]. Besides, one research performed nighttime mobile air temperature measurements and examined the differences between and within the local climate zones for urban temperature study [17]. Moreover, there is a study that uses both remote sensing data and mobile transect observation to analyze the relationship between urban greening and thermal environment [18].

In the above several research cases, the biggest advantage of mobile transect observation is that it can directly obtain urban temperature data. However, its disadvantage is that it takes a lot of manpower to measure each time, and the data obtained must go through a "time correction" procedure, so it is easy to derive errors. Therefore, the study using the mobile transect observation method will also use the existing weather station data as a reference for calibration [19–23].

In addition, since the existing weather station data is an easily accessible and accurate data, many urban heat island effect studies are analyzed using fixed stations. Through the time-based data of fixed stations, it is possible to clearly analyze the temperature of the urban and rural areas, and easy to calculate the temperature difference between urban and rural areas.

In a research study in Lisbon (Portugal) that used fixed station data for studying the existence of a nocturnal urban heat island, the stepwise multiple regression and a Geographic Information System were used to model the relation between air temperature and parameters related to land use and topography [24]. However, if there are not enough fixed weather stations, the accuracy of the research results will be reduced due to insufficient data. In a special study, a network of micrometeorological observational stations was set up across the city. Site selection for 30 stations was based on dominant land use–land cover classification; therefore, the urban heat island intensities could be classified into high, medium, and low categories, which overall correlated well with the land use–land cover in the study area [11]. Another research used meteorological data, including a time series of daily maximum and minimum temperatures, for three stations between 1984 and 2007 to create a better understanding of heat island and related weather modifications [25].

In addition, a paper explores the climate variability of temperatures in two stations located in a city, and its results confirmed the prevalence of UHIs for industrialized areas; meanwhile, the presence of industrial structures, even in rural areas, showed a clear increase in summer maximum temperatures [26]. Besides, there are some studies applied the fixed station method for doing research about the relationship between urban air temperature and greenery [27,28], or using weather station data for study day to day temperature variation of cities [29]. However, such a large number of plans to set up a fixed weather station will inevitably require high installation and maintenance costs.

Because the measurement methods of the above three urban heat island effects have their limitations, in order to achieve the dual purpose of reducing research funding requirements and maintaining the accuracy of research results, this study proposes a way to combine mobile transect observation and fixed station. This study combines the advantages of mobile transect observation and fixed station, and uses low-cost sensors to achieve the basic purpose of urban heat island effect research.

First, in this study, low-cost sensors were mounted on mobile vehicles for more than ten mobile transect observations (in 2006–2007) to identify relatively high temperature and low temperature regions in Tainan City, Taiwan; meanwhile, the low-cost sensors are also placed in a simple fixed station (in 2007) to obtain long-term instantaneous urban temperature data. Furthermore, it is possible to analyze the 24-hour full-time variation of the urban heat island effect. Therefore, the results of this study can not only provide a reference for relevant researchers, but it can also serve as an important criterion for government departments to establish an "urban heat island effect monitoring system" to achieve the goal of efficient use of the public budget.

2. Methods and Materials

The study of urban heat island effects usually uses remote sensing, fixed weather stations, or mobile transect observation to collect air temperature data. The remote sensing can only obtain the surface temperature data. Therefore, some papers focused on the estimation of air temperature from surface temperature [30–33]. Fixed weather stations are usually small in number and are not located in the highest or lowest temperature areas of the city; therefore, the limited data obtained cannot be the basis for calculating the heat island effect. Although mobile transect observation can get a lot of data at the same time, it takes a lot of manpower to complete. Therefore, in order to conduct urban heat island research with high efficiency and low cost, a comprehensive measurement method must be developed.

This study is based on the Tainan metropolitan area (Figure 1). The Tainan Metropolitan Area has a population of 800,000 people, with a longitude of 120'12 degrees and a latitude of 23'00 degrees. It is located in the south of the Tropic of Cancer and belongs to the subtropical climate. It is mild and rainless and has sufficient sunshine throughout the year. The annual average temperature is 24.1 °C.

Figure 1. The map and location of the Tainan metropolitan area.

Since the temperature distribution in Tainan city will vary with the urban structure, the study of the urban heat island must obtain the urban relative high and the low temperature zone through the mobile transect observation, and it must adjust the position of the fixed observation station when necessary. Therefore, in this study, the relatively higher temperature and lower temperature regions of the city are obtained through a low-cost sensor device installed in a motor vehicle. In addition, this study selects appropriate campus green spaces to set up a simple temperature and humidity measurement station in the relatively high temperature and ground temperature areas of the city. Finally, the urban heat island effect intensity is calculated from the temperature data obtained by the measurement station.

In the mobile observations of this study, the TR-72U recorders (Figure 2) were installed on motor vehicles (Figure 3), and the four observers followed the pre-planned route to measure the temperature and humidity of the Tainan metropolitan area. The low-cost sensor used in this study was TR-72U recorder (380 USD), which is data logger capable of measuring, displaying, and recording temperature and humidity data. TR-72U has one temperature and one humidity channel, and it was designed with low energy consumption for longer battery life (Table 1). In this study, 12 mobile transect observations (including 9 times at night and 3 times during the day) were carried out (at each measurement point staying at least 15 seconds), and the urban temperature isotherm diagram and the high temperature and low temperature regions were obtained based on the data (Figure 4).

Figure 2. The low-cost sensor used in the research, TR-72U.

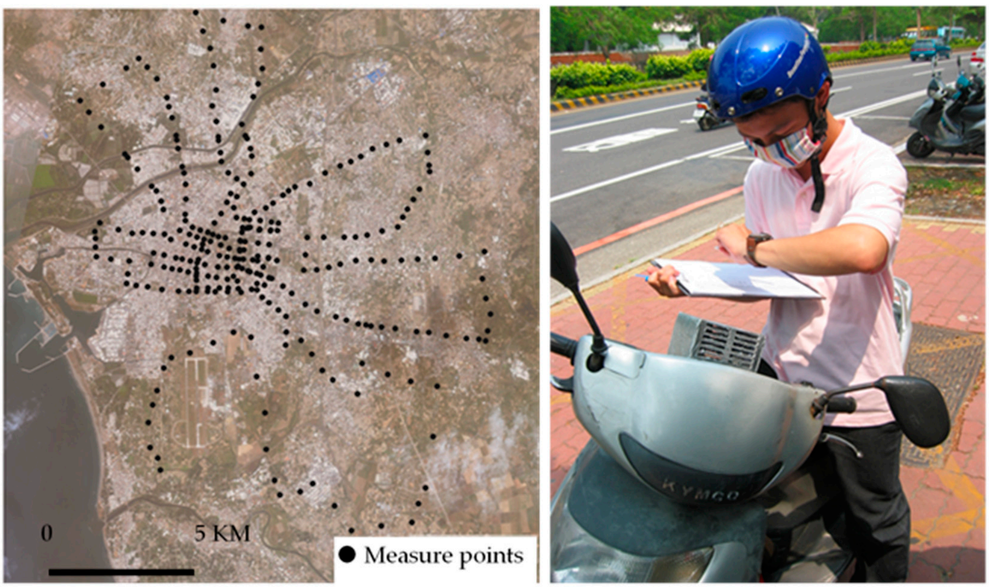

Figure 3. Measured loops and measured points of the Tainan metropolitan area (left) and photos of surveyors (right).

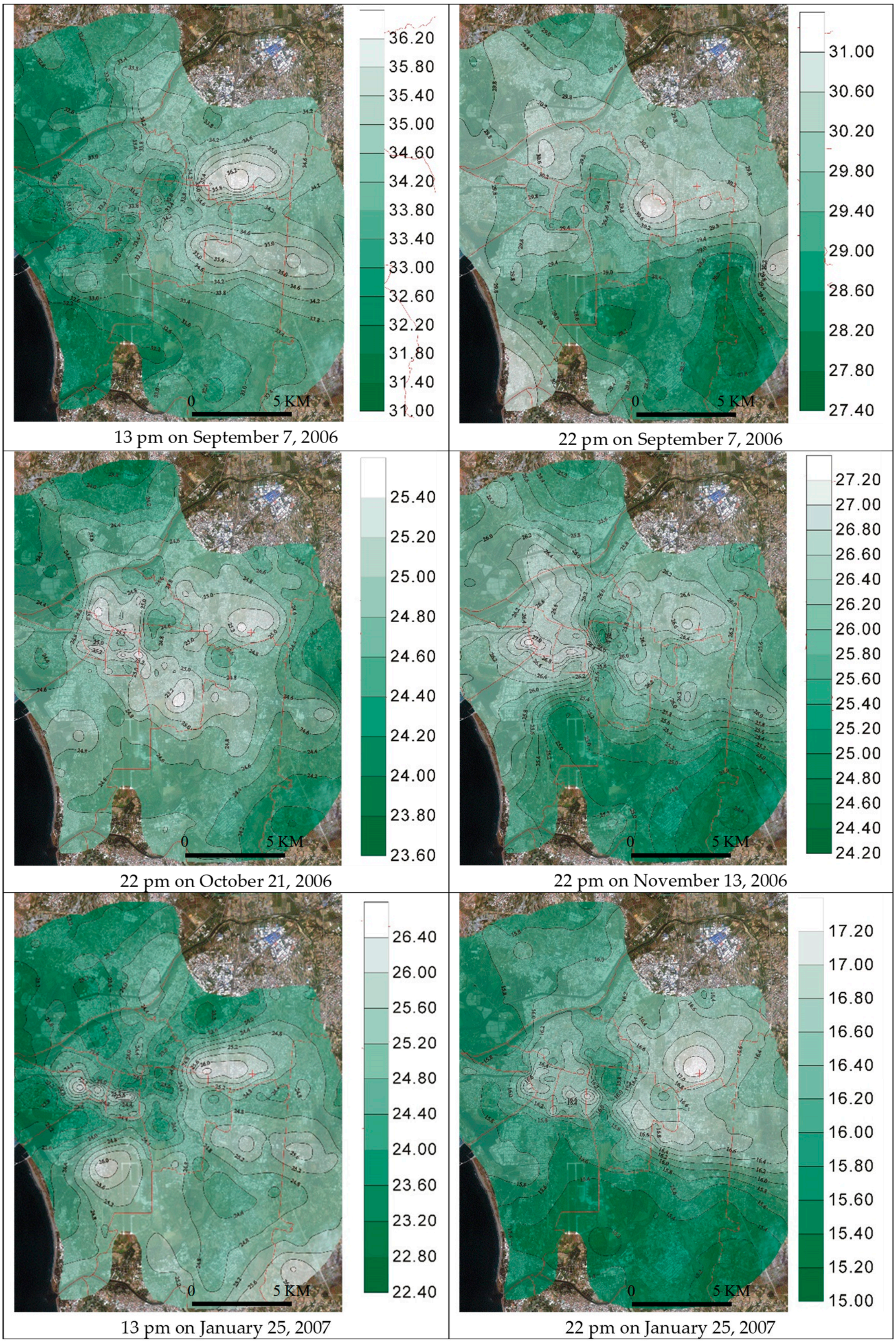

Figure 4. The temperature contours of the Tainan metropolitan area based on the mobile transect observation data.

Table 1. Basic performance data of the TR-72U instrument [34].

Basic Performance	Sensor: TR-72U	
Measurement Item	Temperature	Humidity
Internal Temperature Sensor	−10 to 60 °C	
External Sensor	0 to 50 °C	10 to 95% RH
Optional Sensors	−40 to 110 °C	
Measurement Resolution Display	0.1 °C	1% RH
Sensor	Thermistor	Macromolecular Humidity Sensor
Battery & Battery Life	AA Alkaline Battery (LR6)/About 1 year	
Recording Intervals	1, 2, 5, 10, 15, 20, 30 s/1, 2, 5, 10, 15, 20, 30, 60 min/Total of 15 choices	
USB Communication Time	When downloading 1 unit at full logging capacity: About 8 s.	
Dimensions	H55 mm × W78 mm × D18 mm	
Weight	About 62 g (Including AA alkaline batteries)	
Operating Environment	Temperature: −10 to 60 °/Humidity: under 90% RH (without condensation)	

According to the isotherm diagram obtained through mobile transect observation, several areas in the Tainan metropolitan area between daytime and nighttime are relatively high temperature and low temperature areas. In this study, there are about three high-temperature locations in the core area of the Tainan metropolitan area based on the isotherm diagram, and it is confirmed that the three regions can be representative of the high temperature zones during the day and night. Besides, it also shows that the objective data of the heat island effect can be obtained with a low-cost sensor through multiple mobile transect observations.

After analysis of the urban high-temperature and low-temperature regions, this study selected 6 suitable sites to set up 6 simple fixed stations (Figure 5), and used the TR-72U sensors to collect the urban temperature and humidity data. The temperature data collected by the 6 stations is used as the basis for calculating the intensity of the urban heat island. The biggest advantage of using the mobile transect method with the fix station method to measure the urban heat island effect is that it can adapt to the changing temperature distribution in the city at any time, and it can flexibly adjust the setting location of the fix stations so that the calculation of the maximum heat island effect intensity becomes more accurate.

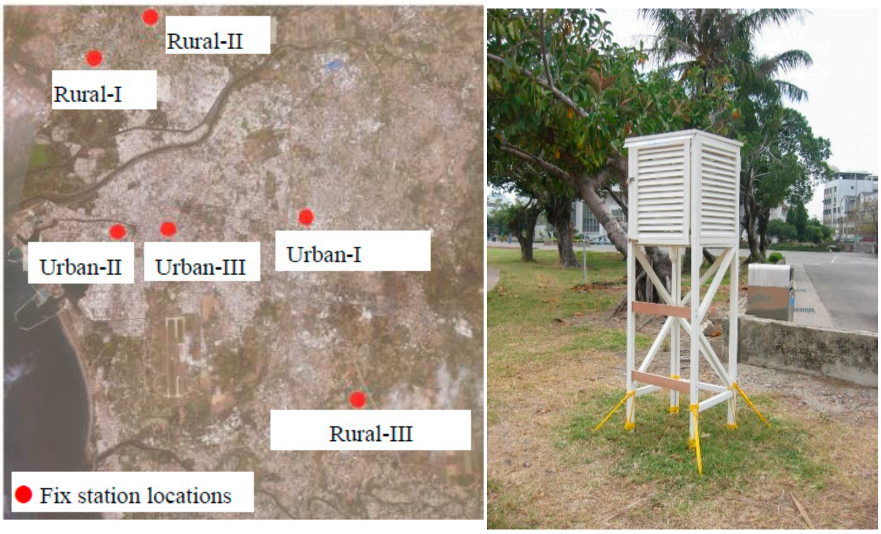

Figure 5. Fix stations setting locations (left) and photos (right).

3. Results and Discussions

3.1. The Typical Day With Low Heat Island Effect Intensity

Due to the island-type climate in Taiwan, windless and cloudless weather conditions are rare, and the most typical climatic conditions are "partial cloud coverage and moderate average wind speed". Therefore, the urban temperature distribution shown in Figure 6 is the most typical example of the urban heat island effect in Tainan Metropolitan. In the measured day on July 4th, 2007, due to the amount of partial cloud coverage blocking the absorption of solar radiant heat by the urban surface materials during the day, and the wind continuously taking away the heat in the city, the average UHIs, the difference between the average temperature of urban and rural stations, is only about −1.0–1.0 °C all day.

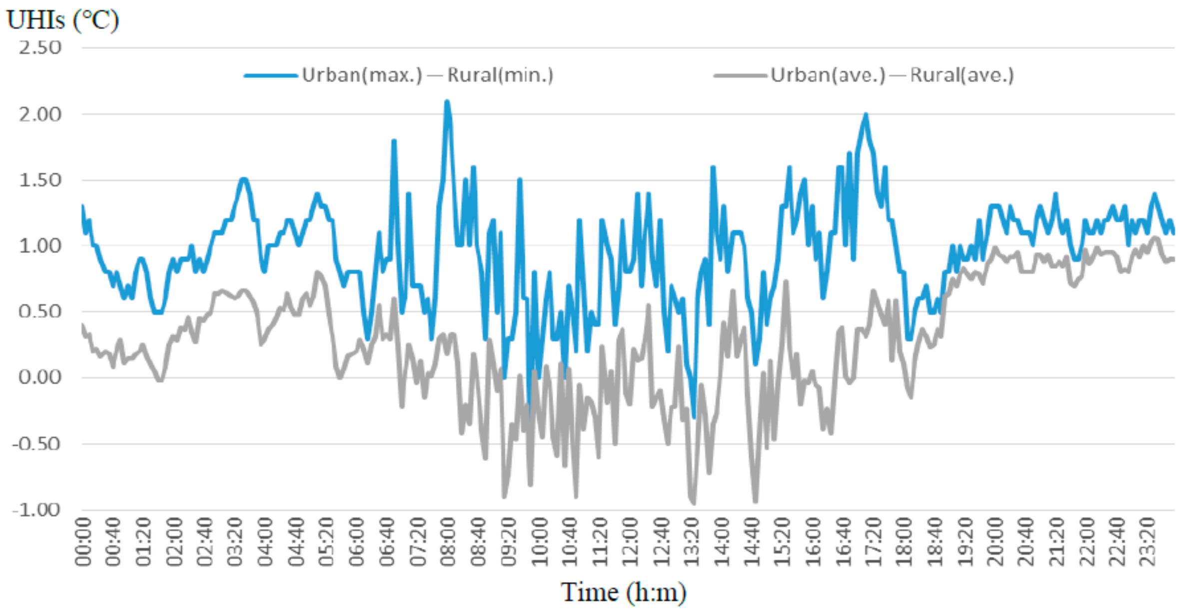

Figure 6. Temperature data of the typical day (4 July 2007) with low heat island effect intensity.

After sunset, due to the continuous release of heat from buildings and roads in the urban area, the urban cooling rate is slower than that of the suburbs. Therefore, the maximum UHIs gradually become much more stable after dusk. However, due to the influence of cloud coverage and wind speed, the city's heat storage during the day is limited, therefore, the intensity of highest UHIs can only reach about 2.0 °C.

3.2. *The Atypical Day with High Heat Island Effect Intensity*

Under the weather conditions of low, cloudless wind speed throughout the day, regenerators such as buildings and roads in the city can fully absorb the radiant heat of the sun during the day and gradually release the heat source into the atmosphere after sunset. Compared with the rapid cooling of the suburbs after the loss of solar radiant heat after sunset, the temperature in the urban area of the city center is significantly higher than that in the suburbs; therefore, the intensity of urban heat islands gradually increases.

Taking Figure 7 as an example, the UHIs of the Tainan metropolitan area immediately increased from 1–2.5 °C to 2–3.5 °C before sunrise and after the sunset of 31 March 2007, and remained until midnight. The difference between the highest temperature of the urban stations and the lowest temperature of the rural stations, the maximum UHIs, all for the day is above 1.5 °C; meanwhile, the difference between the average temperature of the urban and rural stations throughout the day is also about 1.5 °C or more. Therefore, in this atypical day when the heat island effect is significant, the difference between the maximum UHIs can reach above 3.5 °C.

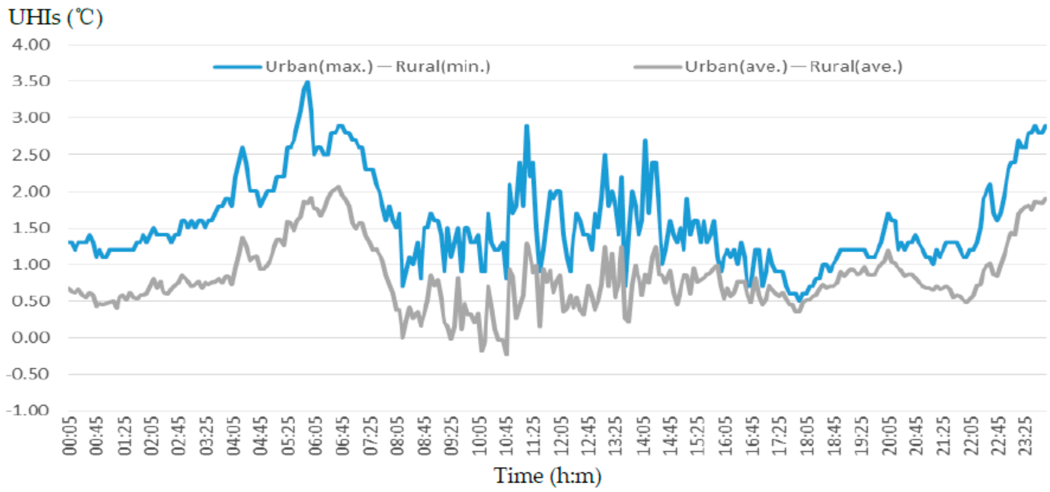

Figure 7. Temperature data of the atypical day (31 March 2007) with strong heat island effect intensity.

3.3. Real Time Heat Island Intensity

In this study, all measured daily data on 30 March to 12 July 2007, were analyzed and calculated, and the average temperature and UHIs in the Tainan metropolitan area (Figures 8 and 9) were obtained. The spring and summer urban heat island effect in Tainan City is more pronounced at night, and is most significant during the period from sunset to sunrise, about 0.5–1.0 °C; the daytime urban heat island effect intensity is small and fluctuating, between 0.5 and 1.5 °C (Figure 8).

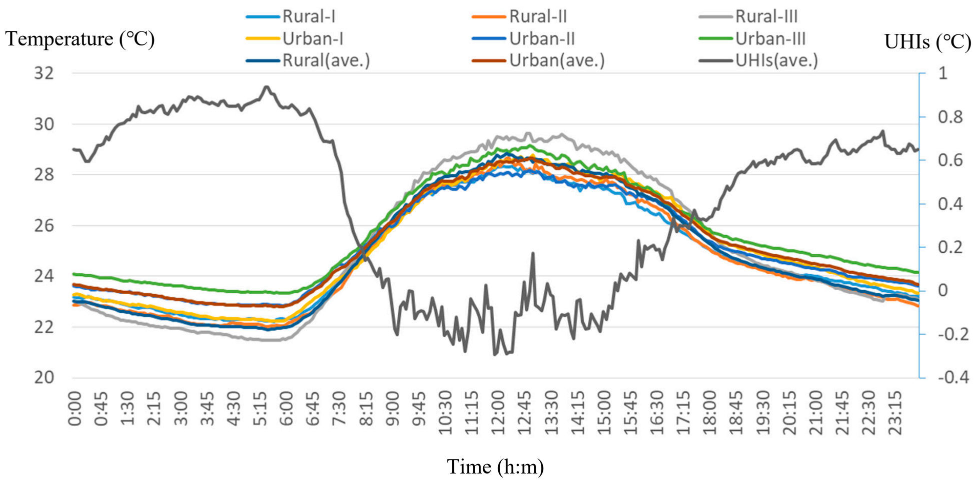

Figure 8. Average temperature of stations and maximum UHIs during 30 March to 12 July 2007.

Figure 9 is a graph showing the average temperature difference between urban stations and rural stations, average UHIs, in the Tainan Metropolitan area. The results of this study show that during the study period (the calculation interval is every 5 min), the maximum UHIs of the Tainan metropolitan area in spring and summer is 5.7 °C, and the minimum UHIs is −4.0 °C (some time periods appear to have the cold island effect), and the average heat island intensity throughout the day is 1.0 °C. In the study area, the station "Rural-III" has the lowest temperature at night, because the surrounding environment is mostly farmland, close to the mountainous area, and the temperature can be very low at night, which becomes the benchmark for calculating the nighttime UHIs.

According to the results of this study, the urban heat island effect in the Tainan metropolitan area during the study period generally occurred from 17:00 pm to 7:30 am the next day (Figure 8). The maximum UHIs of most of the time was about 1 °C, seriously affecting the comfort of the urban thermal environment, and increasing the energy consumption requirements of air conditioning systems.

As urban residents still have a high degree of dependence on air conditioning systems after work, and there are also a large number of nighttime commercial activities in the city, the urban heat island effect has a greater impact on the energy consumption of commercial and residential buildings.

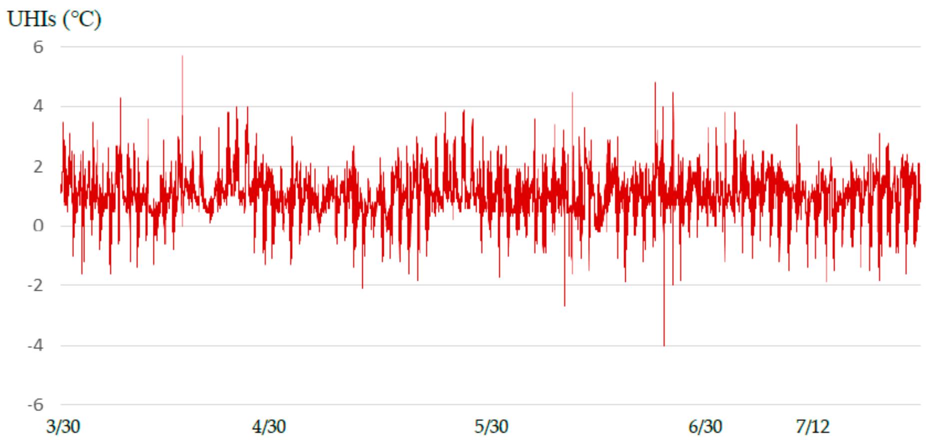

Figure 9. Maximum UHIs during 30 March to 12 July 2007.

In addition, although the UHIs in the Tainan metropolitan area is strong at night and small during the day, the average UHIs in the day is about −0.2–0.2 °C, which is not enough to see the impact of urban heat island effect on energy consumption. Therefore, through the control of the urban heat island effect, the city's energy saving effect can be achieved at night.

4. Conclusions

The urban heat island effect not only affects the public's thermal comfort, but also increases the air conditioning energy consumption in the city, violating the city's sustainable development goals. Therefore, there is much research literature on the status of heat island effects and improvement guidelines in major cities around the world.

The common urban heat island effect measurement methods include remote sensing, mobile transect, and fixed station. Remote sensing can measure the surface temperature of buildings on the roof, ground, or plants in the city at the same time. It is a way to obtain large amounts of data simultaneously. Moreover, with the sharp reduction in the price of remote sensing data, remote sensing has been widely used in urban heat island effect research in recent years. However, the error derived from the process of estimating the temperature of the air from the surface temperature has always been an important issue in the study of urban heat island effect by remote sensing.

Mobile transect observation is another measurement method commonly used in urban heat island effects. By installing sensors on a car or a movable platform and moving through the urban space, instant urban temperature data can be obtained, which greatly reduces the problem of research technology threshold and data processing. However, urban temperature data can only be obtained when performing measurement, and each measurement requires a lot of manpower. Therefore, this method lacks the advantage of automated measurement.

In addition, due to the high cost of setup and maintenance of fixed weather stations, the number of stations that can be set is severely limited by budget. Some studies have directly used urban fixed weather station data from all government or research institutions to conduct urban heat island effect studies. However, due to the limitation that the location of existing weather stations is not located in relatively high temperature areas or low temperature areas of the city, some studies usually cannot analyze the areas with the most severe urban heat island effect.

This study combines the advantages of mobile transect observation and fixed station, and uses low-cost sensor (about 380 USD) to achieve the basic purpose of urban heat island effect research. First, in this study, low-cost sensors were installed on mobile vehicles for more than ten mobile transect observations to identify relatively high temperature and low temperature regions in the Tainan metropolitan area. Second, low-cost sensors are placed in several simple fixed stations to obtain long-term instantaneous urban and rural temperature data. Furthermore, it is possible to analyze the 24-hour full-time variation of the UHIs.

Due to the influence of urban development and government infrastructure investment, relatively high-temperature areas and low-temperature areas in cities will also change, and areas with severe heat island effects will also be transferred. The hybrid method proposed by this study is very suitable for obtaining the key areas of urban heat island effect study through mobile transect observations, re-adjusting the location of simple fixed stations, and collecting effective data with low-cost sensors. Therefore, the results of this study can not only provide reference to relevant researchers, but can also serve as an important criterion for government departments to establish an "urban heat island effect monitoring system" to achieve the goal of efficient use of the public budget.

However, the composite measurement method proposed in this study still has the problem that the mobile observation method requires a lot of manpower, and the cost of the simple weather station is low but has the problem of durability. Therefore, it is recommended that sensors be installed on buses or taxis in the future to reduce the labor cost of obtaining temperature data in the metropolitan area, and to consider making a simple weather station with materials that are both economical and durable.

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