Subtropical Urban Heat Island Development and Estimation Around Taipei City, Taiwan

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Abstract: This study presents the heat island phenomena by using hourly temperature data from 1994~2003 of two stations (one urban and one rural) in Taipei, Taiwan. The results show that the nocturnal heat island was quickly cooling in a divergent pattern between the urban and the rural environment and produce a more sharp increase in intensity within 2 hours after sunset. The monthly average maximum heat island intensity is 1.6°C and the average monthly change in urban/rural thermal contrast is 2.2 °C in summer (July to September) and 0.8 °C in winter (December to February), respectively. Multivariable regression analyses indicate that the UHI (urban heat island) intensity patterns have an increasing tendency for the past ten years, and the most significant parameter is EEU (electrical energy use) in the study area.

Key-Words: Urban heat island effect, Multivariable regression, Subtropical urban, Electrical energy use, Taipei city.

1. Introduction
The presence of warmer air over cities has been documented first in mid-latitude urban areas and later in the tropical environment. The nocturnal heat island results from diverging rates of cooling between the urban and the rural environments which in temperate climate cities produce a sharp increase in intensity soon after sunset to a maximum of about 4 hours later [5]. The thermal performance of an inner city is usually affected by land area, massing and surrounding buildings [2]. Taipei is a rapidly expanding capital of Taiwan with approximately 2280,000 inhabitants; its climate is hot and low relative humidity in summer, cool and high relative humidity in winter. The impact of the urban climate in the subtropical Taipei city is alarming. Well known of its dense population, the city itself is compact and dominated by high-rise building blocks across all sectors spanning from public, industrial, commercial, to domestic. The above geographical factors and recent changes make it ideal for studying heat island climatology in Taipei. The temperature records from an urban and a rural station were analyzed for the period 1994-2003 in order to explain possible seasonal change.

The present urban influence was investigated with urban climate station built by Central Weather Bureau (CWB) (urban area) and a rural weather station managed by Council of Agriculture, Executive Yuan, Taiwan (rural area). This study is firstly concerned with the phenomena of urban high-density development that have already expanded to surrounding areas thus it is difficult to define a rural section, secondly...
characterize the maximum UHI intensity in Taipei from 1994 to 2003 using multivariable regression method.

2. Site and Methodology

2.1 Study area and methodology
Taipei is the largest city and political, economic, educational, cultural, transportation, information and technology hub of Taiwan. In addition it is a basin surrounding by mountains and located on the northern Taiwan (25.1° N, 156.5°W) (Fig.1) as well as an administration district of 271.8 sq. Km. Firstly, it has to be mentioned that there is not enough meteorological stations adjacent to this city to serve as a rural area when we examined the surrounding rural stations of Taipei city from their geographic conditions and justified whether there were long term data records. Moreover, due to high density development almost expanding everywhere in Taipei area, it is difficult to find a rural section in Taipei basin, thus we included neighboring mountains area as candidates. In practice, almost every definitions of the UHI suffer from certain degrees of ambiguities or uncertainties. Here, we adopted a definition of the maximum UHI at any time that is the difference between the average maximum near surface air temperature within a city over its surrounding rural (or non-urban) stations [6].

2.2 The phenomena of urban development and the assessment of rural area
To decide the rural station, we took seven rural synoptic stations surrounding Taipei with long-term records into consideration. They are Wenshan, Tucheng, Shinjuang, Sindian, Tamshui, Panchiao and Wanli (Fig.1). Wenshan agricultural weather station (WAWS) is mainly 8.8 ha of tea research and one extension station located in Shihding village in Taipei county with an altitude about 410 meter above sea level. Besides WAWS all other six ones have been developed rapidly, thus their temperature differences compared with Taipei station are less significant. In particular, TamShui and WanLi are coastal stations where are influenced easily by sea/land breezes, therefore they are not fit to be chosen.

Meteorological data of six synoptic stations were compared with Taipei station by monthly averages temperature. In the end we chose WAWS as the rural station (actual on mountain area) in our study not only because its location most adjacent Taipei city but it is a synoptic weather station supervised by CWB. Although it locates on mountain site we include it as a virtual rural one in our study. The altitude difference between WAWS (mountain area) and ground level (about 410m) has to be corrected from original temperature data to account for the altitude effect. We deduced the mean hypsometric temperature by a gradient of -0.61 degree/100m derived from radiosonde station located at Panchiao in Taipei country (Fig. 2).

3. Data, Parameters and Analysis Method
Because Taipei city is over-crowed population, the increasing emission concentrations of air pollution etc. have generated heavy impact on human health of Taipei residents and the consumption of electric energy use elevates energy demand in summer peak. In our study the parameters and their data resource selected to analyze urban heat island are:
Electrical energy use from residents and commercial activity (EEU): Taiwan Power company; (2) total floor area from building construction (TFA): Public Works Department of Taipei city government; (3) relative humidity (RH): CWB, Taiwan, and (4) particle matter 10 (PM10): Environmental Protection Administration (EPA), Executive Yuan, Taiwan. The selection of these factors is based on small scale climate variations and thermal performance of buildings[2, 6], and TFA parameter is remodeled from built-up area and building height in small scale climate variations [7] when considering a more dense developed city, Taipei.

Among above mentioned parameters, EEU and TFA are the most critical factors because they are related with the urban surface energy balance. Correlation coefficients of EEU and TFA are 0.65 and 0.36, respectively, when only considered single factor. We tried to analyze physical processes in generating the temperature-increasing of UHI such as diurnal cycle, monthly average of UHI, anomaly of monthly average UHI etc. For the understanding of what factors would influence UHI we also performed statistical modeling which may provide useful quantitative information about the framework and the spatial and temporal features of the maximum UHI intensity by employing different urban surface parameters as well as its air quality[1, 7]. The study seeks to find variables influencing urban heat effect of Taipei for energy use, air quality and microclimate condition.

4. Results and Discussion

4.1 Observed monthly average maximum UHI intensity

The average monthly means of air temperature from 1994-2003 in the Taipei city are about 1.6 °C higher than those of WAWS. The bioclimatic conditions in the Taipei city are affected by the basin character. As shown in Fig. 3, the monthly average UHI intensity in Taipei city occurs more frequently in the nighttime than that of daytime and is more prominent with clear skies. The observation is similar to many other cities [6]. The diurnal cycle of UHI in night from 18:00 to 24:00 is very significant with UHI peak happened at 19:00 PM, i.e. 2 hours after sunset. The timing is earlier comparing with 3-5 hours in other cities [5]. That means the degree of urbanization in Taipei city is more high-density developing. Furthermore, the UHI of WAWS (rural area) is higher than Taipei (urban) during 9:30AM~13:00PM. Both phenomena are consistent with the balance of daytime radiant energy which is dissipated to air through turbulent transfer in daytime and later released in the night [6]. Fig. 4. shows that the monthly average maximum UHI intensity is weakest in winter (0.8°C) and strongest in summer (2.2°C). This is because Taipei has been rapidly urbanized at very sections inside Taipei and a regional climate change [4] makes warming phenomenal starting in earlier summer in Taipei. Winter is influenced by northeast monsoon thus it is not significant in temperature difference between rural and urban sites.

4.2 Multivariable regression analyses

In this study we also estimated the mean UHI intensity in Taipei with the aid of urban environmental variables in ten-year periods. The normalized multivariable regression coefficients for four urban environmental variables EEU, TFA, PM10 and RH are 0.726, -0.039, 0.236, -0.307,
respectively, in Taipei city. Among all variables the EEU and PM10 are positively correlated with the monthly average maximum UHI intensity. Regression coefficient of EEU, 0.726, is the highest and its correlation coefficient is 0.65 when considering this variable only. The high coefficient value indicates that as soon as the temperature increased, the electrical energy use also grew spontaneously. In short, monthly UHI intensity tends to be greatly dominated by the EEU in the study period. Similarly PM10 has higher monthly average maximum UHI intensity as well (Fig. 5). The time series of monthly average maximum daily difference of UHI intensity, from 1994~2003, between Taipei city station (urban area) and WAWS (rural area) as shown in. Fig. 6. Solid line represents running average in 13 months and dash line is linear fitting. The UHI intensity revealed an increasing trend with 0.011 °C in monthly average from 1994~2003. The statistic Student test shows that the trend has a value of t=4.45 which is significantly higher than that of the control group (t=1.98) at 95% confidence level.

In the latest two years (2001~2003), the UHI anomaly shows most significantly increasing in positive mode. However, the actual impact of the heat island effect during this period may not be so intensive because it is partly a universal phenomenon that spans much of Asia’s low latitude monsoon belt in this specific period, as suggested by Hsu and Chen [8]. Meanwhile, entire Taiwan including Taipei city has been suffering a severe drought period that occurred after the wake of Typhoon Nari in September 2001 and persisted to the end of 2003.

The regression coefficients of TFA and RH are negatively correlated with the monthly maximum UHI intensity. TFA coefficient is very small compared with others and thus it is negligible among the four variables, although TFA normally represents city development condition. The regression equation can explain a total variance of 57.8%, suggesting other related variables such as meteorological condition, urban scale thermal performance etc. needed to be included in future analyses (Fig. 7).

Fig. 8. shows the time series of annually monthly average maximum UHI intensity together with linearly fitted regression lines in Taipei city. The correlation coefficient is 0.76. Again the increasing trend is very significant due to quick urbanization process. On the basis of our statistical analysis we have demonstrated a strong linear relationship between the mean maximum UHI intensity and the selected urban variables (EEU, TFA, PM10, and RH). The UHI intensity patterns exhibits an increasing tendency from 1994~2003.

5. Conclusion

Our results show that the nocturnal heat island was quickly cooling in a divergent pattern between the urban and the rural environment and produce a more sharp increase in intensity within 2 hours after sunset. The monthly average maximum heat island intensity is 1.6°C and the average monthly change in urban/rural thermal contrast is 2.2 °C in summer (July to September) and 0.8 °C in winter (December to February), respectively. It should be noted that the data length covers only ten years. Taipei was already an over-developed city in 1994, the beginning year of the data used in this study. Although Taipei has continued developing for the past ten years, such a sharp trend is still worth to be alarmed to the local government. Multivariable regression analyses indicate that the UHI intensity patterns have an
increasing tendency for the past ten years, and the most significant parameter is EEU in the study area. The model building procedure for the UHI intensity influencing factors in this study may be applicable for other cities with densely buildings and a basin surrounding, but for the purpose of validation it is necessary to have complete databases of the measured UHI intensities. The statistical estimation serves a reliable basis for the model development to adopt the mitigation measures of urban heat island effect with the assistance from additional vegetation and evaporation etc. parameters, and advance toward electrical energy efficient sustainable environment study.

The UHI intensity of 1.6°C in the monthly average during 1994~2003 in Taipei city is an acceptable value and it is in good agreement with 1.2~2.0°C analyzed from other three big cities in Taiwan [3]. In addition, compared with other nations it is lower value when we considered the Taipei city has seriously extended to adjacent mountain area. A regional climate change would be closely correlated with the vast western plain in Taiwan [4] or with global change by the large influencing etc. Extension of this study including climatic variables could be a promising topic for further research deciphering these uncertain environmental factors.

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References:
Fig. 1. The location of seven weather stations considered in this study. Taipei station (urban area) and WAWS (rural area) were chosen in this study, and the distance between these two sites is 14.8 km. Data of PM 10 collected from Chungshan station was obtained from EPA. Dot line represents the boundary of Taipei city.

Fig. 2. The mean hypsometric temperature data from Panchaio radiosonde station. The average temperature gradient is -0.61°C/100m.

Fig. 3. Diurnal cycle of mean UHI from 1994–2003. Peak of UHI intensity occurred at 2 hour after sunset.

Fig. 4. Monthly average of maximum daily UHI intensity from 1994–2003. The error bar indicates the standard deviation of UHI.

Fig. 5. Normalized regression coefficients of the four meteorological variables (EEU, TFA, PM10, and RH) for the multivariable regression.
Fig. 6. The anomaly and linear trend of monthly mean daily maximum UHI between Taipei station (urban) and WAWS (rural) from 1994~2003, the latest two years shows significantly positive increasing trend.

Fig. 7. Correlation of normalized UHI intensity for estimated and observed values from 1994~2003. \( r^2 = 0.58 \).

Fig. 8. Time series of estimated and observed UHI intensity values from 1994~2003. The correlation coefficient is 0.76 and EEU is most important influencing variable. Linear trend is derived from observed values.