Diurnal and Seasonal Characteristics of Surface Urban Heat Island in Taiwan

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***Abstract*[+]— Surface urban heat island (SUHI), a well-known consequence of urbanization, is one major anthropogenic modification on the Earth's surface. In the recent decades, SUHIs have been greatly studied because of its significant impacts on the living environment of the humanity through easy access and continuous spatial coverage of satellite products. Some efforts were made to understand possible underlying mechanisms and factors of SUHI's spatial variability over large regions. The purpose of this work is to analyze the diurnal and seasonal patterns of SUHI intensity (SUHII) over eleven major cities and counties (called cities for simplicity thereafter in the paper) in Taiwan using the latest version 6 Aqua/Terra Moderate Resolution Imaging Spectroradiometer (MODIS) data acquired during the period 2003−2020. The results reveal that the SUHIIs are more intensive in the daytime than nighttime in all seasons and the northern cities exhibit higher SUHIIs than the southern cities (except in spring nighttime and winter nighttime). As for seasonal cycle, the SUHII considerably varies with season, with a higher seasonal variation in the daytime than nighttime for all cities. While the daytime SUHII's spatial pattern is strongly controlled by land-air latent heat exchange (as described by Normalized Difference Latent Heat Index; NDLI) in all seasons, the night SUHII is significantly correlated with NDLI in summer and autumn.**

***Keywords*— land surface temperature (LST), normalized difference latent heat index (NDLI), surface urban heat island intensity (SUHII), diurnal cycle, seasonal cycle**

I. INTRODUCTION

Urbanization, one major anthropogenic alteration over Earth surface, has been leading to a series of pronounced negative environmental consequences in the past decades [1]. Among the consequences, the urban heat island (UHI) is one of the most well-known examples of urbanization-induced impacts [2]. The temporal and spatial pattern of SUHI can be found in the previous researches at global scale [3, 4] or regional scale [5-7], but there are no similar comprehensive researches conducted in Taiwan. In Taiwan, numerous previous UHI researches have mainly focused on air UHI phenomenon, but little attention has been paid to investigate the SUHI effects [8-10]. So far, SUHI studies in Taiwan have been mainly conducted in individual or several major cities and mostly concerned the SUHI magnitude rather than diurnal and seasonal characteristics [11, 12]. Here, we estimate the urban-rural difference in land surface temperature (LST) over eleven selected cities of Taiwan using the latest version 6 of MODIS LST data. The objectives of this work are (1) to investigate the diurnal, seasonal, and spatial patterns of SUHII over the eleven selected cities in Taiwan, and (2) to examine the relationship between NDLI [13, 14] and SUHI intensity across various cities.

II. MATERIALS AND METHODS

This work focused on eleven selected Taiwanese cities (Fig. 1), which were broadly categorized into two regions in consideration of their geographical location as well as their main Land use/ Land cover (LULC) types in rural area: North Taiwan (Taipei (TP), Taoyuan (TY), Taichung (TC), Hsinchu (HC), and Miaoli (ML)) and South Taiwan (Tainan (TN), Kaohsiung (KS), Changhua (CH), Chiayi (CY), Pingtung (PT), and Yunlin (YL)) to examine the SUHII's spatial variability of the eleven cities.

A. Datasets

In this present work, MODIS-derived LSTs were used to characterize the SUHI phenomenon. For each city, the LST data from 2003 to 2020 at four times a day (01:30 am, 10:30 am, 13:30 pm, and 22:30 pm) were retrieved from 8-day composite and 1-km resolution products of MODIS (version 6) [15].

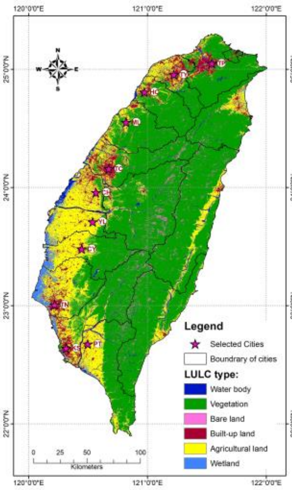

Figure 1. Spatial distribution of the selected eleven cities in Taiwan with the background map presenting the land use land cover of Taiwan

Also, we used NDLI, recently proposed by Liou, et al. [13], as an indicator to characterize the potential latent heat flux of the Earth's surface. The NDLI is calculated from MODIS surface reflectance product (MOD09A1). In addition, Land use/ Land cover (LULC) maps were retrieved from the 30-m Landsat satellite data in 2005, 2010, 2015, and 2020, which were freely downloaded from the website https://earthexplorer.usgs.gov/. From the LULC map, built-up intensity (BI) data, which was used to define the urban and rural regions, was extracted.

B. Calculation of SUHI intensity

The method proposed by Zhou, et al. [16] was applied to delineate urban and rural regions. After mapping of urban and surrounding rural areas, we defined the SUHI intensity (SUHII) as the urban-rural contrast of LST [6] and SUHII is computed using the equation below:

$$SUHII = LST_{urban} - LST_{rural} \quad (1.)$$

where the LST_{urban} and LST_{rural} are the mean remotely sensed LST for the urban pixels and rural pixels, respectively.

To minimize the errors due to outdated urban maps, urban and reference rural zones were delineated for the years of 2005, 2010, 2015, and 2020. The seasonal and annual SUHI intensities in daytime and nighttime were then calculated for the period 2003-2020 for each city separately [17]. At the same time, the urban-rural contrast of Normalized Difference Latent Heat Index (i.e. ΔNDLI) was also computed using the same way as in (1). Pearson's correlation analysis was performed to explore the relationship of the spatial variabilities of SUHII with ΔNDLI factor across cities.

III. RESULTS AND DISCUSSION

A. Diurnal variations of SUHII

The annual SUHII in the daytime is significantly greater than that at night for the Northern Taiwan, with mean SUHII values ranging from 1.09 °C at 01:30 a.m. to 4.99 °C at 13:30 p.m. (Fig. 2). As for the Southern Taiwan, the diurnal pattern is the same, but with a smaller difference (from 1.05 °C at 01:30 a.m. to 3.38 °C at 13:30 p.m.) (Fig. 2).

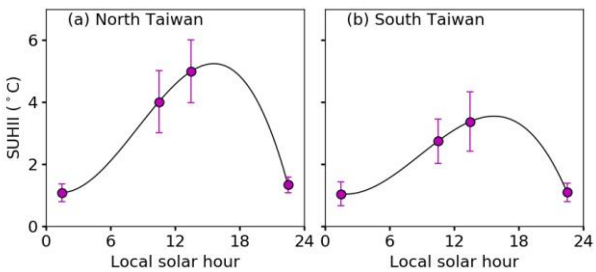

Figure 2. The diurnal variation of SUHII in the two regions of Taiwan, (a) North Taiwan and (b) South Taiwan (mean ± standard deviation).

These patterns are consistent with the findings of Imhoff, et al. [6] for the continental United States, but they slightly differ from the results of some previous studies who reported that the mean annual SUHI intensity was smaller in the daytime compared to that in the nighttime in the Northern part of China, but the reverse patterns occurred over the Southeast part of China [5, 17].

B. Seasonal variations of SUHII

Large seasonal variations were observed in the daytime SUHIIs of 11 Taiwanese cities. Generally, the strongest SUHIIs in the daytime are found in summer season and the lowest in winter, primarily due to the greatest and smallest cooling effects generated by activities of vegetation in rural areas in summer and winter, respectively [3-6, 17]. In addition, the daytime SUHIIs averaged in the Northern Taiwan are greater than those in the Southern Taiwan in all four seasons and annual circumstance (Fig. 3).

However, the SUHIIs during the night are more stable with less fluctuation by season, as suggested by the significantly less variances as compared to daytime SUHIIs for both regions of Taiwan (Fig. 3). In contrast, the nighttime seasonal patterns are more complex. More specifically, the spring and winter SUHIIs averaged in the Southern Taiwan (1.16 °C and 0.88 °C) are greater than those in the Northern Taiwan (0.99 °C and 0.47 °C), but the Northern cities experience more intense summer and autumn nighttime SUHIIs (1.57 °C and 1.17 °C) than those in the Southern Taiwan (1.05 °C and 1.11 °C) (Fig. 3).

C. Relationship between NDLI and SUHII

In this work, NDLI was used as a surrogate to evapotranspiration demands of vegetation [13]. The transpiration process from vegetation and evaporation from the water bodies can create a cooling effect on land surface temperature (LST) in the rural region so that they can mitigate the effects of SUHI [4, 18]. The results from the Table 1 support the above mechanism with the strong negative correlation between daytime SUHII and ΔNDLI in all seasons, more in the daytime than in the nighttime.

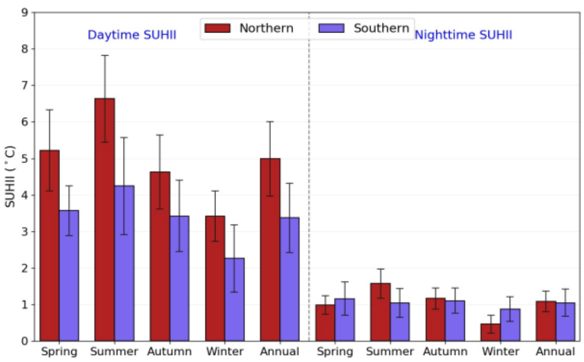

Figure 3. The daytime SUHIIs (at 13:30) and nighttime SUHIIs (at 1:30) in two regions of Taiwan (mean ± standard deviation).

TABLE 1. Coefficients of Pearson's correlation between the SUHI intensity and ΔNDLI

Diurnal	Spring	Summer	Autumn	Winter	Annual
Day	-0.86**	-0.93**	-0.92**	-0.95**	-0.93**
Night	0.10	-0.85**	-0.79**	0.00	-0.63

** $p < 0.01$, p: significance level (p-value)
 * $0.01 < p < 0.1$

IV. CONCLUSIONS

Based on the results of this work, three main findings are described as follow. Firstly, overall, the SUHIIs are more pronounced during daytime than at night regardless of season and northern cities exhibit higher average SUHII than that of their southern counterpart in daytime/nighttime in all seasons, except in spring nighttime and winter nighttime. Secondly, the SUHII varies considerably with season, with a higher seasonal variation in the daytime than nighttime, maximum in summer and minimum in winter across most cities (except in spring night). Finally, the daytime SUHIIs have negative and significant correlation with ΔNDLI, which control the latent heat flux, regardless of seasonality. This work is the first attempt to consider the NDLI as a surrogate to evapotranspiration demands of the vegetation into a SUHI study.

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