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DIURNAL VARIABILITY OF URBAN HEAT ISLAND INTENSITY: A CASE STUDY OF METRO MANILA, PHILIPPINES

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Abstract We present the first analysis of the diurnal variability of the urban heat island (UHI) intensity in the metropolitan Manila (Metro Manila) in the Philippines. We used measurements from two automatic weather stations (AWSs) of the Philippine Atmospheric Geophysical and Astronomical Services Administration of the Department of Science and Technology (PAGASA-DOST) that operated in Metro Manila from 2014 to 2018. The highest averaged UHI intensity (UHI_{max}) was 4.03°C, observed in the city of Manila (Port Area station) at 19:00 local time (LT), whereas, in Quezon City (Science Garden station), UHI_{max} was 3.02°C and was observed at 18:00 LT. The seasonal mean of the daily UHI_{max} (daily maxima) occurred during the hot dry season (March–May), when lower normalized difference vegetation index (NDVI), relative humidity, and wind speed, as well as longer sunshine duration were observed. Results suggest that the influence of local characteristics on the locations of the station such as the building density, wind speed, and green spaces largely determined the UHI intensities in the study region.

Keywords: urban heat island, urban climate, diurnal variability, normalized difference vegetation index, Metro Manila; the Philippines

1. Introduction

One of the most direct impacts of anthropogenic climate modification is the urban heat island (UHI) effect, which has been considered as a major problem in recent decades. The UHI is defined as the difference between air temperature in urban environments and air temperature in the surrounding undeveloped rural areas (Oke *et al*. 2017). Most UHI studies focus on mid-latitude regions around the world, while tropical cities remain relatively under-investigated (Roth 2007; Oke *et al*. 2017; Huang and Lu, 2018; Kim and Brown, 2021). So far, the following two main differences between tropical and mid-latitude cities regarding UHI intensities are known: (1) For cities with similar population size, UHI intensities in the tropics are lower than those in temperate regions (Jauregui 1997; Chow and Roth 2006; Roth 2007); (2) the diurnal UHI maxima occur earlier in the day in the tropics than in the temperate regions, where they occur at midnight or before dawn (Chow and Roth, 2006). While earlier studies on tropical regions have provided these

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*Regional Climate Systems Laboratory, Manila Observatory, Ateneo de Manila University Campus, Quezon City, Philippines fundamental results, several questions remain unanswered; studying the UHI in cities with different backgrounds in the tropics should elucidate the general underlying mechanism.

Urbanization studies using numerical models, such as Dado and Narisma (2019) and Oliveros *et al*. (2019), demonstrated the UHI effect on rainfall, as well as the overall air-temperature increase over Metro Manila, i.e., the most populated city in the Philippines. This air-temperature increase was most likely driven by changes in the biogeophysical characteristics of the land surface, such as albedo, emissivity, and vegetation cover, when croplands or natural vegetation were changed to urban areas. Other studies, such as Tiangco *et al*. (2008) and Landicho and Blanco (2019), used remotely sensed data and showed that the UHI hot and cold spots were mainly confined in the central business districts and green areas in Metro Manila, respectively. Such studies provided fundamental information on how urbanization affects the local atmospheric conditions in Metro Manila; however, they conducted primarily daily scale analyses based on daily maximum and minimum air temperatures, while focusing less on the diurnal cycle based on higher temporal resolution analysis of air temperature. In this study, we focused for the first time on the diurnal variability of the UHI intensity in the two most populated cities in Metro Manila (i.e., the city of Manila and Quezon City) using automatic weather station (AWS) measurements from 2014 to 2018. The remainder of this paper is organized as follows: In section 2, we present a brief description of the climate and demography of Metro Manila; in section 3, we present the observed differences between the three stations used in this study; in section 4, we discuss a comparison of our results with those of earlier studies in the Southeast Asian region; and in section 5, we conclude the paper.

2. Study Area, Data, and Methods

Metro Manila

The study area is Metro Manila, which is officially known as the National Capital Region (Figs. 1b and c) and is the capital and the most populated region in the Philippines, with approximately 630 km^2 total land area and 12.9 million total population based on the 2015 census of the Philippine Statistics Authority (https://psa.gov.ph/content/urban-population-philippines-results-2015-census-population). Based on the climatic classification in the Philippines, as employed by Kintanar (1984), Metro Manila is categorized as climate type 1, with two main seasons, i.e., the wet season from June to November and the dry season from December to May. The dry season can be further divided into (a) cool dry season from December to February and (b) hot dry season from March to May. Figure 1a shows the climatological monthly variability of air temperature and precipitation in Metro Manila, where the lowest and highest daily mean air temperatures were 26.1°C and 29.8°C and were observed in January and May, respectively. Maximum and minimum precipitation were 451.7 and 11.0 mm and were observed in August and February, respectively, with 2,148.6 mm annual average precipitation from 1981 to 2010.

Data and methods

The location and aerial photographs of the stations used in this study are shown in Figs. 1b–c and 2a–d, respectively. To analyze the diurnal UHI, instead of synoptic stations, which typically have lower temporal resolution, we utilized two Automatic Weather Stations (AWS) from the Philippine Atmospheric Geophysical and Astronomical Services Administration of the Department of Science and Technology (PAGASA-DOST). The Indang station (Fig. 2a), located outside the urban area of Metro Manila (Fig. 2d), was used as the reference for estimating the UHI intensity. The Port Area station is very close to the shore (~3 km from the shoreline) and is surrounded by buildings and concrete objects most commonly present in an urban setting (Fig. 2b). Quezon City, where Science Garden station is located, has the largest population among the municipalities in the Philippines; however, the Port Area station is surrounded by a larger population density, which is an important factor regarding UHI intensity (Table 1). The northern part of the Science Garden station is surrounded by residential areas, while the southern part is surrounded by greenery, as shown in Fig. 2c. Detailed differences between the stations are summarized in Table 1. The classification of stations (i.e., urban or rural) was based on remotely sensed Moderate Resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index (NDVI; 2014–2018) and land-use (2018) data (Friedl *et al*., 2010; Didan, 2015), and showed that the Indang station, which is located outside the urban extent of Metro Manila (Fig. 2d), has higher NDVI value (~0.77) compared to those of the Science Garden (~0.30) and Port Area (~0.26) stations.

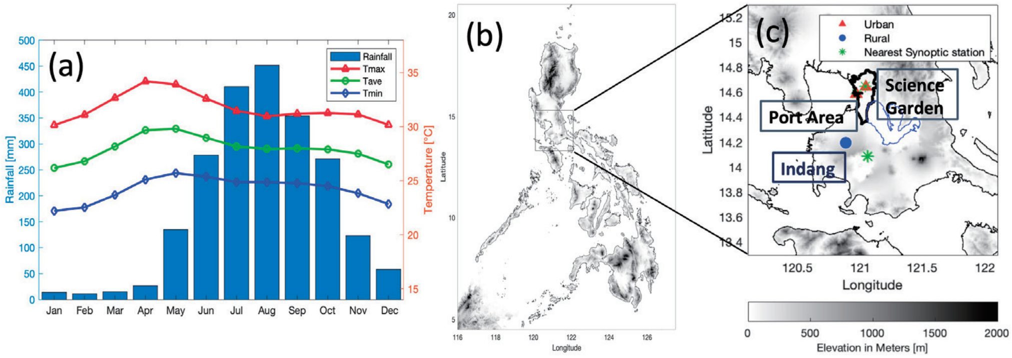

Fig. 1 (a) Climatological monthly variability of the daily mean (T_{ave}; green), maximum (T_{max}; red), and minimum (T_{min}; blue) air temperature (lines; °C); and rainfall (bars; mm) in Metro Manila from 1981 to 2010. Topography over (b) the Philippines and (c) Metro Manila, including the locations of stations.

Measurements were conducted every 10 min by the two urban stations, while a combination of hourly (i.e., between December 2014 and July 2016), 15-min (i.e., between August 2016 and July 2017), and 10-min measurements (i.e., between August 2017 and December 2018) were conducted by the Indang station. In this study, we used all available data from the three AWSs between 2014 and 2018. We used also additional data, such as daily sunshine duration, wind speed, and relative humidity, from PAGASA-DOST and NDVI from MODIS for the entire study period. The quality of the data was checked according to Villafuerte *et al*. (2021).

Comparison with the Nearest Synoptic Station

Strong positive correlations (not shown) were found between the AWS measurements and those from the nearest synoptic stations; the correlation coefficients where in ascending order 0.68, 0.84, and 0.89 for the Indang, Port Area, and Science Garden stations, respectively. Such comparisons revealed good agreement between the two observation platforms; differences may be due to several factors such as differences in elevation, demography, distance between the AWSs and the respective synoptic stations, and other factors that affect the local weather in the study area.

Table 1 Metadata of the stations. The NDVI, wind speed, and relative humidity represents the mean over the study period

Station	Indang	Science Garden	Port Area
Region	Calabarzon	Metro Manila	Metro Manila
City/Municipality	Cavite	Quezon	Manila
Rural/Urban	Rural	Urban	Urban
Latitude (°N)	14.20	14.65	14.59
Longitude (°E)	120.88	121.04	120.97
Population (2015)	65,699	2,936,116	1,780,148
Population Density (per km^2)	880	17,099	71,263
Distance from shore (km)	19.3	12.6	3.0
Distance between AWS and the nearest synoptic station (km)	23	< 1	< 1
NDVI (MODIS 2014-2018)	0.77	0.30	0.26
Wind speed (m s^{-1})	1.65	2.48	1.06
Relative Humidity (%)	79.87	77.94	74.40
Elevation (m)	315	48	3
Data period of AWS	2015–2018	2016–2018	2014–2017

3. Results

Diurnal variability

The results of this study are based on all available hourly averaged air-temperature measurements conducted under all meteorological conditions by each station. The mean diurnal variations of temperature at Port Area and Indang station were shown in Fig. 2e: At the Port Area station, the maximum air temperature (i.e., 30.97°C) was observed at 14:00 LT, whereas, at the Science Garden station, the maximum air temperature (i.e., 31.26°C) was observed 1 h earlier (i.e., 13:00 LT). The different magnitudes of the continuous heat accumulation during noon might have been due to the combined influences of the local wind patterns and environment around the stations (Table 1). The Port Area and Indang stations were classified as urban and rural stations, respectively: In the morning, the Indang station recorded faster warming than the one recorded the Port Area station (Fig. 2f); in the late afternoon, the rural station recorded faster cooling than the one recorded at the urban station, thereby contributing to the UHI intensity increase.

Maximum UHI intensities at the Port Area in Metro Manila were observed during nighttime (Fig. 3a), which is consistent with earlier studies (Chow and Roth 2006). However, the case of the Science Garden station was different: The maximum UHI intensity at this station was observed at around 18:00 LT, but the minimum UHI intensity was observed at approximately 5:00 LT. Science Garden station has smaller UHI intensity variation than Port Area station (Fig. 3a), indicating a potential cool island effect, which might be related to the greenery surrounding this station. We note that the presence of greenery near the Science Garden station (with 0.30 NDVI, i.e., 0.04 higher than that at the Port Area station) can constitute an important factor affecting the local air-temperature measurements as pointed out by Chow and Roth (2006). Influences of other factors, such as the density of buildings and local weather patterns, cannot be ruled out. Figures 2b and c show the locations of the two urban stations, while clearly depicting the differences in greenery and density of buildings within ~100-meter from the stations.

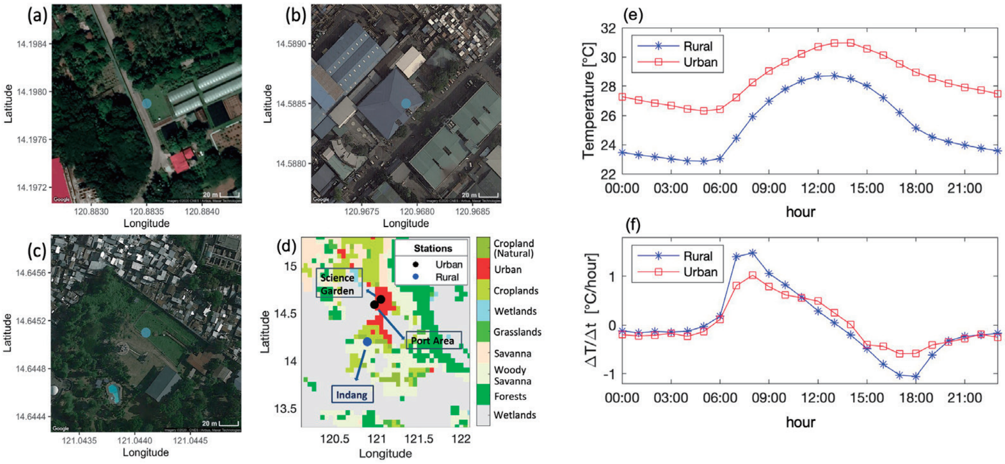

Fig. 2 Aerial photographs of the stations (~100-meter). (a) Indang station: reference rural station; (b) Port Area station: located in Manila seaport; (c) Science Garden station: highly urbanized with greenery surrounding the station; and (d) extent of the built-up area in Metro Manila based on the 2018 MODIS land-use data; (e) diurnal variation of air temperature (°C); and (f) warming/cooling rates (°C/hour) for urban (red; Port Area) and rural (blue; Indang) stations.

The observed lower UHI intensity in the Science Garden was concurrent with higher daily mean relative humidity compared to the respective values at the Port Area station (Table 1). Regarding the distance from the nearest seashore, even though the Port Area station is closer to the sea (~3 km distance) than the Science Garden station (~12.6 km distance), higher UHI intensity was observed at the Port Area station. This indicates that the UHI in the study area might have persisted despite the sea breeze occurrence, which was also observed and discussed by Yoshikado (1994).

Seasonal comparison

Seasonal analysis was conducted based on the three main seasons in Metro Manila (see section 2) for all weather conditions. The analysis revealed that the highest nocturnal UHI intensity was observed during the hot dry season, as shown in Fig. 3b, which is consistent with earlier studies (e.g., Chow and Roth 2006; Jongtanom *et al.* 2011). Such findings were to some extent corroborated by sunshine duration, rainfall, and wind speed observations at the synoptic stations in the urban area (Table 2). The sunshine duration analysis revealed that during the hot dry season, the duration reaches up to ~7.4 hours per day indicating more frequent clear sky conditions (i.e., ~2 h longer than other seasons). This was partially supported by the rainfall data, where the lowest number of days with >5 mm rainfall (28 out of 460 days; 6.1 %)) was observed during this season.

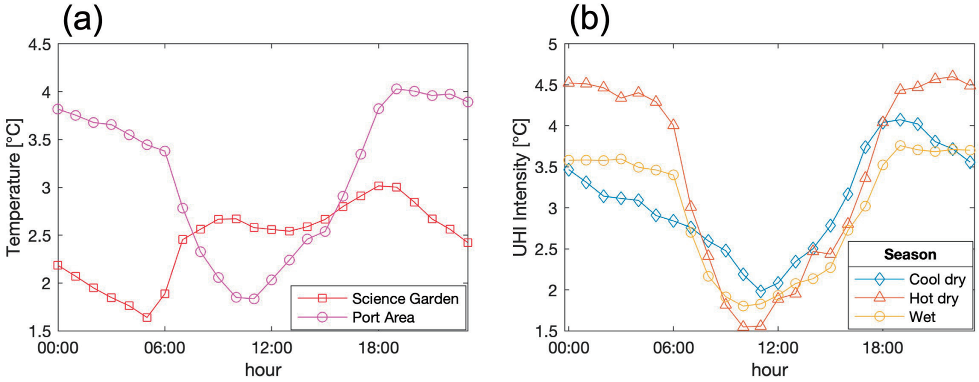

Fig. 3 (a) UHI intensities (°C) defined as the air-temperature differences between urban (Science Garden [red] and Port Area [pink]) and rural (Indang) station; (b) diurnal variation of the UHI intensity (°C) at the Port Area station for cool dry (blue; December–February), hot dry (March–May), and wet (June–November) seasons.

Table 2 Seasonal mean sunshine duration, NDVI, winds speed (Ws), relative humidity, total rainy days (Rd; days with >5 mm rainfall in a day), and percentage of Rd in Metro Manila from 2014 to 2018

Variable/ Season	**Cool dry**	**Hot dry**	**Wet**	**Unit**
Sunshine duration	5.0492	7.4365	4.9138	hour
NDVI	0.2209	0.2516	0.3016	-
Ws (Whole day)	2.1740	2.5967	2.6017	m/s
Ws (Daytime)	2.1101	2.6853	2.4827	m/s
Ws (Nighttime)	2.2504	2.5017	2.7226	m/s
Relative Humidity	71.82	66.91	78.86	%
Rd (total number of days)	36 (451)	28 (460)	324 (915)	day
Percentage of Rd	8.0	6.1	35.4	%

Relative humidity, wind speed, and NDVI were based on all observations and under all weather conditions.
Daytime: 06:00–18:00 LT; Nighttime: 18:00–06:00 LT.
All datasets are based on Port Area synoptic station except for sunshine duration and relative humidity, which are based on the Science Garden synoptic station because the description here focuses on differences among the seasons, and the similar seasonal changes can be assumed in the same urban area.

4. Discussions

Factors affecting UHI Intensity

The observed high UHI at nighttime and low UHI at daytime, specifically over the Port Area station, is consistent with other UHI studies (Chow and Roth 2006; Jongtanom *et al*. 2011). Earlier studies suggested that the timing of the UHI peak is influenced by the different warming and cooling rates of the building materials (Kim and Baik 2005), as well as their heat-retention capacities (Rizwan *et al*. 2008), at the locations of the stations. The density of buildings around urban stations affects the heat-release efficiency, as heat is trapped and transmitted from one building to another; conversely, at rural stations, heat is released to the surroundings more efficiently (Rizwan *et al*. 2008). Oke *et al*. (2017) suggested that the surface geometry and thermal properties of building materials common in urban areas can also affect the UHI timing and intensity. Incoming solar radiation is strongly absorbed by building materials during daytime and released as longwave radiation during nighttime, resulting in increased UHI intensity during nighttime. In this study, we found that the UHI intensity is also affected by the greenery surrounding a station, e.g., at the Science Garden station, where lower UHI intensity was observed, which was also observed and discussed by Oke *et al*. (2017). The high UHI values at the Port Area station are comparable to those presented by Chow and Roth (2006), whose stations were located near the coast in Singapore (~1.5–3.0 km away from the nearest coastline). We note that the differences regarding the strength of interaction between UHI intensity and sea breeze are controlled by several factors such as (1) the size and width of the urban area, (2) distance from the sea, and (3) magnitude of the UHI intensity (Yoshikado 1994).

The seasonal UHI analysis revealed that the maximum UHI occurs during the March–May (MAM) season, which corresponds to the dry season in Metro Manila. Jongtanom *et al*. (2011) found a decrease in UHI intensity during rainy season, indicating that rainfall variability affects the UHI intensity. Other studies have also demonstrated the impact of local weather conditions on the seasonal UHI pattern (Kim and Baik 2002; Matsumoto *et al*. 2020). Kim and Baik (2002) noted that the seasonal UHI variability in Seoul, South Korea, was driven by the seasonal wind-speed changes. They found that the maximum UHI intensity in Seoul was high (low) during winter (summer). In this study, we found the difference, i.e., we observed a high UHI intensity during the MAM season rather than during the December–February (DJF) season. The cold and dry air supplied by the northeasterlies during the DJF season in the Philippines might contribute to the observed UHI intensity variation during this season. In addition, we note that the study areas of some of those earlier studies were located in temperate regions with higher UHI intensities, and thus, seasonal comparison might not be the best way to discuss such mechanism. Nevertheless, our study contributes to urban climate research by highlighting the importance and influence of the local meteorology (e.g., wind speed, sunshine duration, rainfall) and characteristics of the surrounding areas on the diurnal UHI patterns in the study area.

Comparison with other studies

The maximum UHI intensity at Port Area station (4.03°C) was observed at a time similar to that of the maximum UHI intensity in a commercial area (3.8°C) in Singapore (Chow and Roth 2006). We observed some similarities between the diurnal changes at Port Area and the commercial area, with lower UHI throughout the daytime and higher and roughly constant UHI during nighttime. This suggests that the influence of the materials and other factors (e.g., waste heat) found in the commercial area might have had a similar effect to a station located in a seaport. For example, the commercial area in Singapore is located in an area with very high anthropogenic activity which usually continues until 22:00 LT, as compared to central business district which usually continues until 19:00 LT. This could also illustrate the observed higher UHI at commercial area in Singapore and Port Area station in the Philippines, as compared to other urban sites (Chow and Roth, 2006). We also note that they are both located near the coast, hence, the interaction between the sea breeze and the strength of UHI must be considered. With the aid of a two-dimensional numerical model, Yoshikado (1994) found that for some heavily urbanized regions, this interaction becomes significant, hence, influencing the local climate.

In general, the maximum UHI intensity in Metro Manila would occur at 19:00 LT, i.e., earlier than when the maximum UHI intensity would occur in Singapore (Chow and Roth 2006). The results also showed that, on average, intensities were lower in Thailand (Jongtanom *et al*. 2011) as compared to those in the Philippines. This might have been due to several factors, such as different local weather conditions, topography, and city morphology and size, but further studies are needed on this matter. A characteristic factor in Metro Manila that must be considered for comparison is the possible direct or indirect influence of Laguna lake, a factor that makes the study region (likely weaker influence on Port Area station) complex and different from the previous studies in Southeast Asian region.

Table 3 Comparison of UHI intensities observed in Singapore and Thailand with those in this study

Country	Station/Location	Time of Maxima	UHI Maxima	Mean UHI Maxima
Philippines	Science Garden (Quezon City)	18:00 LT	3.02°C	3.53°C
	Port Area (City of Manila)	19:00 LT	4.03°C	
Thailand (Jongtanom *et al*., 2011)	Bangkok	16:00 LT	2.24°C	2.47 °C
	Chiang Mai	19:00 LT	2.73°C	
	Songkhla	22:00 LT	2.42°C	
Singapore (Chow and Roth, 2006)	Commercial Area	21:00 LT	3.8°C	3.30 °C
	High Rise Residential Flats	00:00 LT	2.8°C	

5. Conclusions

The diurnal variability of the UHI intensity in the two most populated cities in Metro Manila was analyzed for the first time using AWS measurements by the PAGASA-DOST from 2014 to 2018. The following conclusions were drawn from the results of this study:

- The highest averaged UHI intensity observed in the city of Manila (i.e., Port Area station) was 4.03°C at 19:00 LT, while in Quezon City (i.e., Science Garden station), it was 3.02°C at 18:00 LT, based on the respective diurnal variations (Fig. 3a).
- The observed higher UHI intensity in the Port Area was found to be associated more with local factors such as population density, building density, and greenery, than elevation and wind speed.
- Seasonal UHI analysis (Fig. 3b) showed that the maximum UHI intensity occurred during the March–May season, coinciding with the hot dry season in the Philippines.
- Higher UHI intensity was observed at the Science Garden station mainly during daytime; this result is different from what was observed at urban stations of earlier studies, implying that ambient conditions with more greenery and less density of buildings causes the different diurnal variation of UHI intensity at the Science Garden compared with Port Area.

- Earlier studies conducted in Southeast Asia showed that, on average, the Philippines (~3.53°C) had the highest UHI intensity, followed by Singapore (~3.30°C) and Thailand (~2.47°C). UHI intensity occurred earlier in the Philippines than in most stations in Singapore (approximately 1–4 h) and Thailand (approximately 1–2 hours).

In this study, we showed the possible influence of vegetation (i.e., roughly represented by NDVI), local wind speed, rainfall days (days with > 5 mm rainfall), elevation, relative humidity, and distance of the stations from the coast on the diurnal UHI cycle. We note that there are other issues that require further investigation: For example, we did not examine the impact of surface geometry on the UHI intensity, which Oke *et al*. (2017) suggested to be an important factor affecting UHI. In addition, the influence of Laguna Lake and how the local land and sea breezes contribute to the UHI intensity should be examined by future studies. Finally, further analysis with higher spatial and temporal resolution, and numerical simulations using high-resolution regional climate models such as the Weather Research and Forecasting (WRF) model, are necessary for explaining the mechanisms involved in the diurnal UHI cycle and will be the focus of future studies.

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