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RESEARCH ARTICLE

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The effect of urbanization on temperature indices in the Philippines

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Abstract

This paper presents a comprehensive analysis of the effect of urbanization on the surface air temperature (SAT) from 1951 to 2018 in the Philippines. The daily minimum temperature (T_{min}) and daily maximum temperature (T_{max}) records from 34 meteorological stations were used to derive extreme temperature indices. These stations were then classified as urban or rural based on satellite night-lights. The results showed a significant difference in the SAT trends between urban and rural stations, indicative of the effect of urbanization in the country. Larger and more significant warming trends were observed in indices related to T_{min} than those related to T_{max}. In particular, the effects of urbanization were significant in the annual index series of T_{min}, diurnal temperature range, minimum T_{min}, percentage of days when T_{min} was less than the 10th percentile (T_{N10p}), percentage of days when T_{min} was greater than 90th percentile (T_{N90p}), and the number of coldest nights. The effects of urbanization were not as clear on the index series of maximum T_{max} (T_{Xx}), minimum T_{max} (T_{Xn}), percentage of days when T_{max} was less than 10th percentile (T_{X10p}), and the number of hottest days. The effects of urbanization on the annual series of extreme temperature indices were statistically significant at the 95% confidence level, with the exception of T_{max}, T_{Xn}, T_{Xx}, T_{X10p}, and the number of hottest days. Further analysis revealed that the effect of urbanization was the greatest during the DJF (December–January–February) season. These findings serve as a baseline study that focuses on the countrywide effect of urbanization on SAT trends in the Philippines.

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KEYWORDS
extreme temperature indices, satellite night-light, surface air temperature, urbanization

1 | INTRODUCTION

The rapid population growth and urbanization in megacities, especially in developing countries such as the Philippines, have drawn the attention of the scientific community to study their impacts at different spatio-temporal scales (Griffiths *et al.*, 2005; Marcotullio *et al.*, 2014). The combined effects of urbanization and climate change will most likely affect the future trends in surface air temperature (SAT) in urban areas and exacerbate the impacts of health-related hazards (IPCC, 2014, 2018). Therefore, a better understanding of the impacts of urbanization on SAT is necessary for improving adaptation strategies to the future climate.

The Urban Heat Island (UHI) effect or the observed warming in urban areas relative to the surrounding rural areas, is one of the prominent impacts of urbanization and has been associated with land-use changes, increased retention of solar heat by some building materials with low albedo and high heat capacities as well as the increased anthropogenic heat emissions (e.g., transportation, industry, and heating from the usage of air conditioning units). Some studies that analysed the trends in extreme temperatures in urban areas reveal that the frequency and intensity of warm days (cold nights) have generally increased (decreased) (e.g., Hua *et al.*, 2008; Ren and Zhou, 2014; Zhao *et al.*, 2019). These studies have also shown that the observed increasing trends are more apparent in indices related to minimum temperature (T_{min}) than the maximum temperature (T_{max}), indicating the potential impacts of urbanization on the detected trends.

One way of investigating the UHI effect is to directly compare the SATs between the urban and rural (or reference) stations. However, classifying the stations remains a challenge and a consensus for the most accurate method has yet to be reached. Various indices for classifying the stations have been proposed and include the use of population data where the stations are located (Hua *et al.*, 2008; Fujibe, 2011), gross domestic product (GDP; Zhao *et al.*, 2019), distance to the nearest city centre (Ren and Ren, 2011), land-use information (Ren *et al.*, 2008), proportion of built-up area (Zhou and Ren, 2011), and satellite night-lights (Gallo *et al.*, 1996; Paranunzio *et al.*, 2019). While other studies have considered methods such as derivatives of cooling rate in terms of land-use and land cover change to examine individual stations (Chow and Svoma, 2011), some limitations are still conspicuous. For example, in Metropolitan Phoenix, Arizona, Chow and Svoma (2011) was able to provide a classification scheme that reflects historical variations in urban areas, however, they also mentioned that the changes in urban structure that may occur in areas near the station may not be quantified in the absence of relevant data and was assumed that these factors are relatively minor and thus, unlikely to affect the results from their analysis. Other studies have emphasized the advantages of using satellite night-lights in classifying the stations (Hansen *et al.*, 2001; Henderson *et al.*, 2003; Yang *et al.*, 2011) because it is more objective than the other indices (Paranunzio *et al.*, 2019) and insensitive to variations in cultures, traditions, and social development levels of different countries and regions (Ren *et al.*, 2015). Hu and Zhang (2020) have also stated that satellite night lights have become more uniform than before, this provides an opportunity for further utilization of satellite night lights due to their easy access, spatial proximity, and high spatial resolution. Ren and Zhou (2014) developed a method for quantifying the effect of urbanization, based on the difference between the observed SAT trends in urban and rural stations and its contribution, based on the ratio of statistically significant urbanization effects to the trends of selected temperature indices. They demonstrated that urbanization in mainland China led to a significant decreasing trend in diurnal temperature range primarily caused by the more rapid warming trend in T_{min} than those in T_{max}.

Many studies have investigated the impacts of urbanization over the Philippines but focused only on specific urban areas, particularly over Metro Manila. For instance, Tiangco *et al.* (2008) showed that the hot spots with higher UHI intensity in the central business district of Metro Manila using the Advanced Spaceborne Thermal Emission and Reflection Radiometer data. With the aid of numerical model simulations, Dado and Narisma (2019), as well as Oliveros *et al.* (2019), showed that urbanization had contributed to the near-surface atmospheric warming and eventual increase of rainfall in Metro Manila. Such findings were able to demonstrate the impacts of urbanization within the specific metropolitan area of Manila. However, it is unclear at present, whether or to what extent the rapid urbanization in a countrywide context has affected the trends in extreme temperature based on the observational dataset. Hence, this study aims to fill the gap of current scientific understanding by investigating the effect of urbanization and estimating the countrywide urban contribution on the observed trends in extreme temperature over the Philippines.

The rest of the paper is organized as follows: In Section 2, the study area, the data used, including the quality control procedures and homogenization are described. The method used for classifying the stations either urban or rural based on satellite night-lights is presented in Section 3. The urbanization effects and estimated contribution on annual and seasonal trends of selected extreme temperature indices are discussed in Section 4. Then, the important findings and obtained conclusions are summarized in Section 5.

2 | STUDY AREA AND DATASETS

2.1 | Study area

The Philippines is an archipelagic country consisting of three major island groups; Luzon, Visayas, and Mindanao (Figure 1). The country spans a total area of approximately 300,000 km^2, and is located in the western North Pacific between 4°40′N to 21°10′N and 116°40′E to 126°34′E. Based on the 2015 census, the total population of the Philippines is 100,981,437; 51.2% of the population resides in an urban area (PSA, 2018). The World Population Prospects (United Nations, 2018) projected

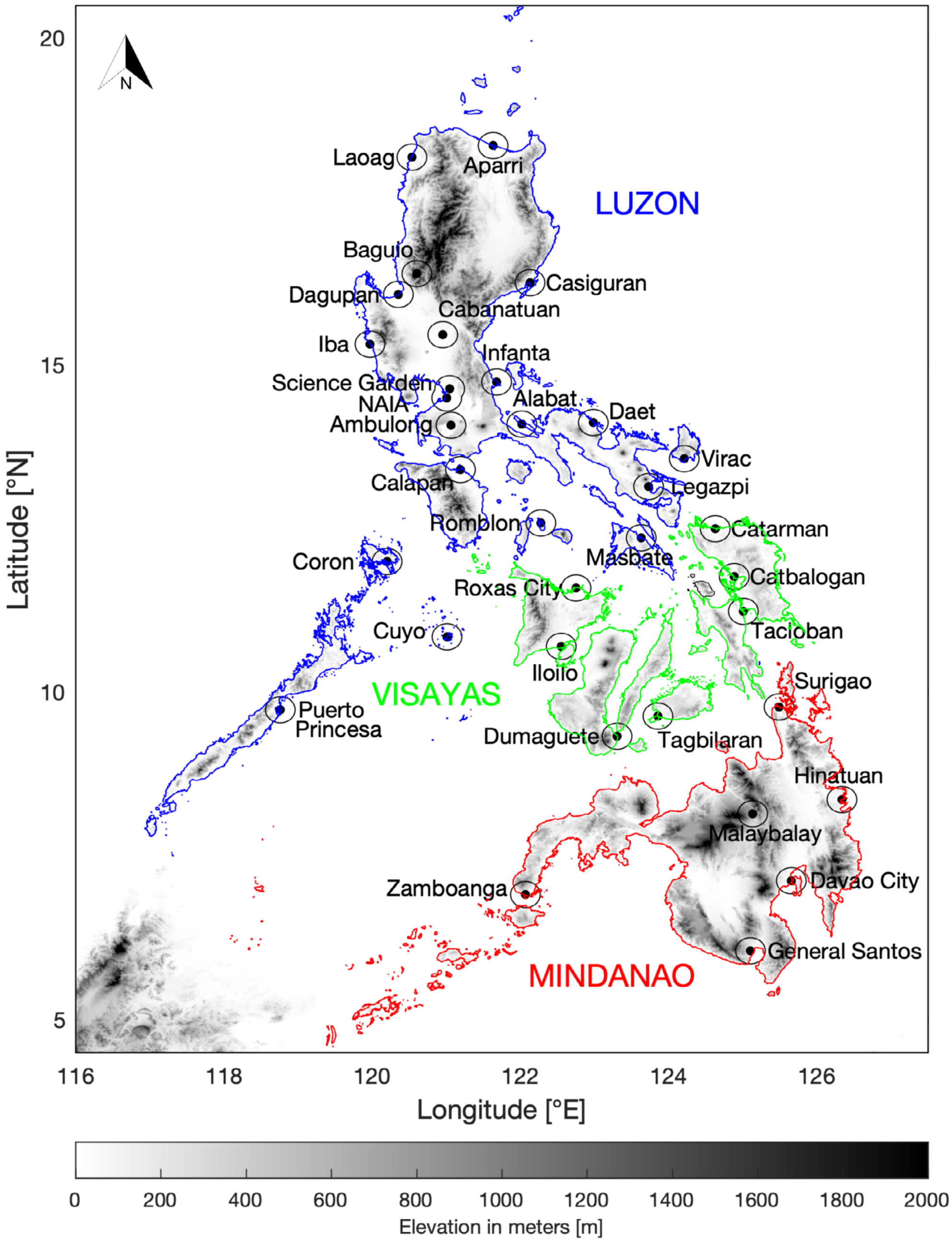

FIGURE 1 Location of the 34 synoptic stations (black encircled points) used in the study and the topography (m) of the Philippines [Colour figure can be viewed at wileyonlinelibrary.com]

that by 2050, the Philippine population will grow to 151 million, with 61.6% living in urban areas.

According to the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA, 2019), the climate of the Philippines is tropical and maritime, with relatively high amounts of annual rainfall varying from 965 to 4,064 mm, as observed at meteorological stations. With the exception of Baguio (with an elevation of 1,500 m), the mean annual temperature of the country is 26.6°C, the coldest month is January (25.5°C), and the warmest month is May (28.3°C). The high temperature together with the surrounding bodies of water around the country contributes to a relatively high monthly relative humidity that varies from 71% in March to 85% in September. The climate may be divided into two major seasons: (1) the wet season, from May to November, and (2) the dry season, from December to April (Matsumoto *et al.*, 2020). The latter season may be categorized into two additional seasons; the cool dry season (December–February) and the hot dry season (March–April). The climate is strongly influenced by mesoscale and synoptic-scale systems, such as tropical cyclones, monsoons, cold surge shearlines, and the El Niño–Southern Oscillation (ENSO) (Chang et al., 2005; Jamandre and Narisma, 2013; Villafuerte *et al.*, 2015; Olaguera and Matsumoto, 2019; Porio *et al.*, 2019; Olaguera *et al.*, 2021).

2.2 | Data and quality control

This study used the T_{min} and T_{max} records spanning from 1951 to 2018 from synoptic stations of PAGASA. These datasets have passed the quality control procedures as discussed by Villafuerte *et al.* (2021). This study also conducted additional quality checks; days with unrealistic temperature values, such as $T_{max} > 45°C$ and $T_{min} < 4°C$, were classified as missing observations. Only the stations with the sufficient number of valid observations were included in the analyses. Stations that were included in the analyses were those with less than 20% missing data during the baseline period (1961–1980), used for evaluating the anomaly values, and for the entire study period (1951–2018) (Figure 1).

2.3 | Data homogenization

Climatic observations may be influenced by several non-climate-related factors such as station relocation, instrument changes, and altered methods of observation (Aguilar *et al.*, 2005; Shen *et al.*, 2018). Some of these artificial shifts (i.e., significant change in the time series, hereafter referred to as "breakpoints"), were documented in the metadata, while others were not. Such factors may cause inhomogeneity in the data, impacting the mean and trends of a time series. As such, methods to detect breakpoints must be used even without metadata support. There are several ways to detect breakpoints in a time series without metadata (Wang, 2008a, 2008b). This study used the penalized maximal *F*-test proposed by Wang (2008a, 2008b) to detect breakpoints in the temperature series. This method has been widely used to test data discontinuities whilst allowing the time series being tested to have zero-trends or linear trends throughout the entire dataset (Wang, 2008a, 2008b; Vincent *et al.*, 2012; Keggenhoff *et al.*, 2015). The open-source software package "RHtestV4" was used to test data homogeneity and identify possible data breakpoints. This software package uses the quantile-matching algorithm to adjust the series so that empirical distributions of the de-trended base series can match each other (Wang *et al.*, 2010; Vincent *et al.*, 2012). We used the available metadata provided by PAGASA for the Tagbilaran station, which was transferred in April 2013. For all stations, only significant breakpoints unrelated to any large atmospheric system such as ENSO and the Mt. Pinatubo eruption in June 1991, were adjusted. Table 1 summarizes the detected breakpoints, where adjustments were made in the original temperature series.

3 | METHODS

3.1 | Classification of stations

The classification of stations is one of the most important aspects in studying the effects of urbanization on climatic data such as the SAT. It is recognized that such a process is necessary to accurately detect climatic trends in a data series (Zhang *et al.*, 2014). In this study, we adopted the station classification methodology suggested by Ren and Zhou (2014) and Zhao *et al.* (2019) based on satellite night-lights retrieved from the National Aeronautics and Space Administration (NASA) Earth Observatory in 2012 (https://earthobservatory.nasa.gov/images/79765/night-lights-2012-map; 750-m resolution). A four-step procedure was executed: (a) all grids within a 12 km radius centred at station locations were extracted; (b) the number of (urban) grids exceeding the 25.5 Digital Number (DN; unit for satellite night-lights) were counted; (c) the percentage of urban grids relative to the total number of grids ($\left[\frac{\text{number of Urban Grids}}{\text{number of Total Grids}}\right] \times 100$) was calculated; and (d) stations with <33% of urban grids were considered as reference rural stations (Figure 2), following the threshold used in Ren and Zhou (2014).

TABLE 1 List of breakpoints identified in this study

Stations	T_{max}	T_{min}
Alabat	1970	1971,1987
Ambulong	1993	1973
Aparri	2010	—
Baguio	1995	2009
Cabanatuan	—	1962
Calapan	2005	1964,1966,1994,1990
Casiguran	1988	1962,1969,1991,1994, 2010, 2011
Catarman	1995	1996
Catbalogan	—	2002, 2008, 2009
Coron	—	1973,1974,1977,1982,1989
Cuyo	—	1979,1993
Daet	1981	1996, 2012
Dagupan	—	1967,1971,1974, 2001
Davao City	1973,1992	1978, 2014
Dumaguete	1976	1978
General Santos	—	1960,1963, 2003
Hinatuan	1981,1994	1995, 2007
Iba	1968,1973,1991	1968,1974,1991,1995
Iloilo	1972	1973,1977,1991, 2007, 2009
Infanta	1996,2013	2017
Laoag	2013	—
Legazpi	—	1978
Malaybalay	1985	2009, 2014
Masbate	—	1979
NAIA	—	—
Puerto Princesa	—	1993
Romblon	2011	2011
Roxas city	1971	1971
Science garden	—	—
Surigao	1992	—
Tacloban	1991	1993
Tagbilaran	1970, 2013[a]	2013[a]
Virac Synop	1965,1969,1992	1967,1987,1993
Zamboanga	1965	2009, 2010, 2011

[a]Supported by metadata.

3.2 | Definition of extreme temperature indices

Extreme temperature indices such as those recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI) of the Commission for Climatology of the World Meteorological Organization (WMO) are often used to investigate trends and detect changes in the climate. Fourteen temperature indices were used in this study; nine from the ETCCDI (http://etccdi.pacificclimate.org/list_27_indices.shtml), T_{min}, T_{max}, and daily average temperature (T_{ave}), and two indices adopted and revised from Cinco *et al.* (2014), these are all summarized in Table 2. The hottest day was defined as the percentage of days when T_{max} exceeded the 99th percentile of the data series. The coldest night was defined as the percentage of days when T_{min} was below the first percentile of the data series. These 14 indices were used to analyse the years and seasons that had less than 20% missing data (i.e., < 72 days and < 18 days of missing data, respectively).

3.3 | Analysis method

The annual and seasonal trends in the temperature indices were computed from T_{min} and T_{max}. The seasons used were December–January–February (DJF), March–April–May (MAM), June–July–August (JJA), and September–October–November (SON). As climatic data from each station in the country may be influenced by various topographical and geographical factors (e.g., elevation, latitudinal, and longitudinal differences, distance to the coast, and other local and mesoscale atmospheric processes), we re-expressed the indices into anomaly values. To consider warming in recent decades, the long-term mean values from 1961 to 1980 were used as the baseline period to obtain anomalies. Linear trend analysis was also used, as it has been frequently utilized to investigate long-term changes in temperature indices (Hua *et al.*, 2008; Fujibe, 2009; Cinco *et al.*, 2014; Ren and Zhou, 2014; Matsumoto *et al.*, 2017). The Mann–Kendall trend test was applied to determine the significance of all trends in the data series (Oliveros *et al.*, 2019; Zhao *et al.*, 2019).

The effect of urbanization refers to the impact of urbanization on the temperature indices, which was similarly defined as those used by Bian *et al.* (2015) and Zhao *et al.* (2019). The effect of urbanization in this study was defined as the trends in the temperature indices attributed to the intensification of the UHI effect and other local anthropogenic factors surrounding the stations, expressed as:

$$\Delta T_{urban-rural} = T_{urban} - T_{rural}, \quad (1)$$

where T_{urban} is the linear trend of temperature indices in urban stations, and T_{rural} is the linear trend of temperature indices in rural stations. If the effect of urbanization

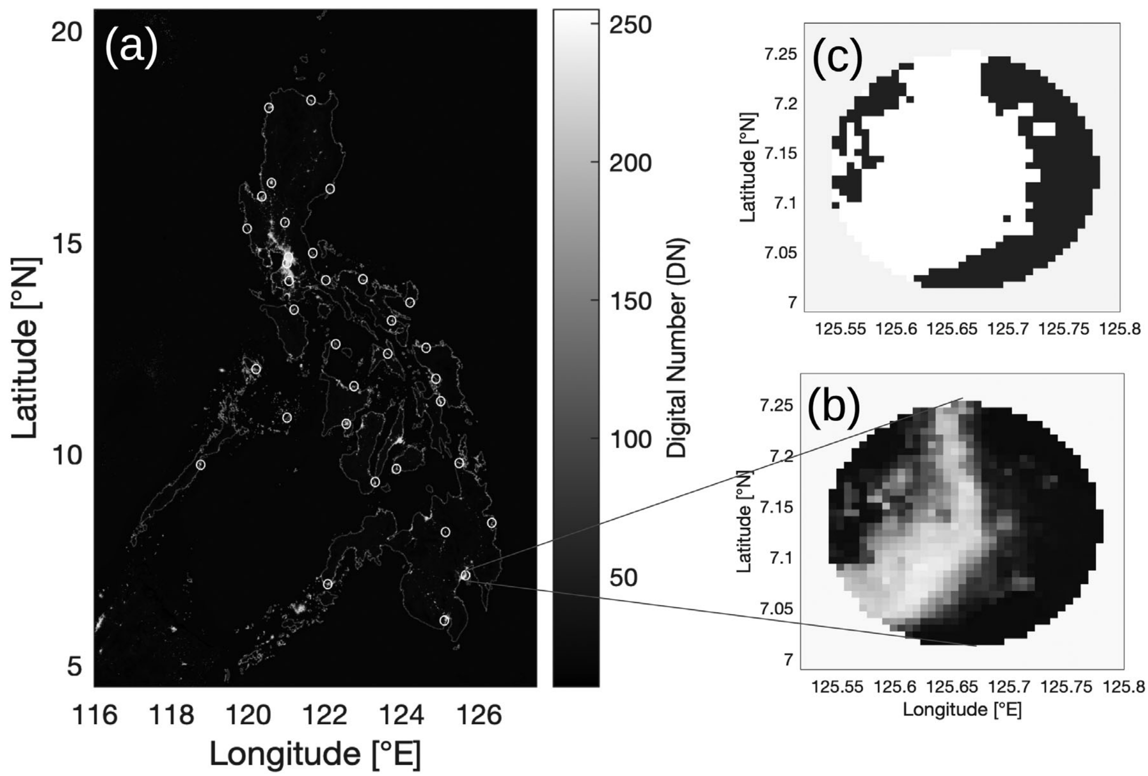

FIGURE 2 Satellite night-lights over the Philippines captured in 2012. Counter-clockwise from left showing: (a) the entire country and location of meteorological stations used in the study; and magnified grids of the sample station (b) before and (c) after applying the threshold value of 25.5 DN. The white hollow circles in (a) indicate the 12 km radius from the centre of the 34 stations, and the white grids in (b) and (c) represent the DN value and urban grids, respectively, within the 12 km radius from the station center

is positive (i.e., $\Delta T_{\text{urban-rural}} > 0$), it indicates that there has been a relative increase in the trend due to urbanization. In contrast, if the effect of urbanization is negative (i.e., $\Delta T_{\text{urban-rural}} < 0$), it indicates that there has been a relative decrease in the trend due to urbanization (Ren and Zhou, 2014).

The urbanization contribution *(C_u)*, as defined by Bian *et al.* (2015) and Yang *et al.* (2017), is the proportion of the statistically significant effect of urbanization accounting for the overall trend in the temperature indices of urban stations, expressed as:

$$C_u = \left| \frac{\Delta T_{\text{urban-rural}}}{T_{\text{urban}}} \right| \times 100\%, \quad (2)$$

where $C_u = 100\%$ indicates that trends observed at the urban stations is mainly a result of urbanization. If C_u exceeds 100%, this implies that the trend may involve contributions from known local anthropogenic factors, unknown local anthropogenic factors, or the errors in the data; as such, the upper threshold for C_u was set to 100%. The lowest value for the statistically significant C_u was set to 1%, and if the urbanization effect was not statistically significant, C_u was not calculated.

4 | RESULTS AND DISCUSSION

4.1 | Classification of reference stations

Figure 3a presents the classified stations, as discussed in Section 3.1. Of the 34 stations, 10 were classified as urban and 24 were identified as rural. Previous studies have shown that urbanization has a greater impact on $T_{\min}$ than on $T_{\max}$ (e.g., Ren and Zhou, 2014; Zhao *et al.*, 2019). As such, the analysis has shown that the stations with higher satellite night light indices are associated with higher trends of $T_{\min}$, with correlation coefficient $r = 0.5$, statistically significant at the 99% confidence level (Figure 3b). This means that the classification demonstrates that the percentage of urban grids is directly proportional to trends in $T_{\min}$; this is important to adequately represent urban stations. Further verification using both satellite night lights and population density (https://neo.sci.gsfc.nasa.gov/view.php?datasetId=SEDAC_POP; CIESIN, 2018) was also conducted and have shown that the 12 km radius threshold is more associated with the trends of $T_{\min}$ for all stations, with higher correlation coefficient ($r = 0.45$) as compared to 5 km (Zhao *et al.*, 2019; $r = 0.40$) and 2 km (Ren and Zhou, 2014;

TABLE 2 Definition of extreme temperature indices used in this study

Index	Definition	Unit
T_{ave}	Annual and seasonal mean value of daily average temperature	°C
T_{min}	Annual and seasonal mean value of daily minimum temperature	°C
T_{max}	Annual and seasonal mean value of daily minimum temperature	°C
DTR	Annual and seasonal mean difference between maximum and minimum temperatures	°C
T_{Xx}	Annual and seasonal maximum value of T_{max}	°C
T_{Xn}	Annual and seasonal minimum value of T_{max}	°C
T_{Nx}	Annual and seasonal maximum value of T_{min}	°C
T_{Nn}	Annual and seasonal minimum value of T_{min}	°C
T_{X10p}	Annual and seasonal percentage of days when T_{max} <10th percentile	%
T_{X90p}	Annual and seasonal percentage of days when T_{max} >90th percentile	%
T_{N10p}	Annual and seasonal percentage of days when T_{min} <10th percentile	%
T_{N90p}	Annual and seasonal percentage of days when T_{min} >90th percentile	%
Hottest days	Percentage of days when T_{max} >99th percentile	%
Coldest nights	Percentage of days when T_{min} <first percentile	%

$r = 0.23$) radius. The urban stations were distributed in the three main islands of the Philippines (with at least one urban station). This means that the classification was able to represent the entire country. Nevertheless, there were a greater number of urban stations in the western part of Luzon.

4.2 | Trends in the extreme temperature indices

Table 3 shows the annual and seasonal trends of temperature indices in the Philippines from 1951 to 2018. All obtained trends were statistically significant, exceeding the 95% confidence level, with the exception of seasonal trends in the diurnal temperature range (DTR) during the DJF, MAM, and SON seasons. In terms of the hottest days and coldest nights, the results were consistent with the findings of Cinco *et al.* (2014), despite the use of an extended dataset to 2018, different criteria for station selection, and a different data homogenization method. In particular, the trend in coldest nights was larger than that of the hottest days. Extreme temperature indices were also included, demonstrating that generally, indices relating to T_{min} such as T_{Nn}, T_{Nx}, T_{N10p}, and T_{N90p} with trends equivalent to 0.20, 0.19 (°C/decade), −1.98, and 2.46 (%/decade), respectively, had higher and more significant trends compared to the T_{max} indices such as T_{Xn}, T_{Xx}, T_{X10p}, and T_{X90p} with trends of 0.16, 0.14 (°C/decade), −0.94, and 1.58 (%/decade), respectively. The observed higher trends in the T_{min}-related indices compared to T_{max}-related indices have been reported in several regions (Manton *et al.*, 2001; Vose

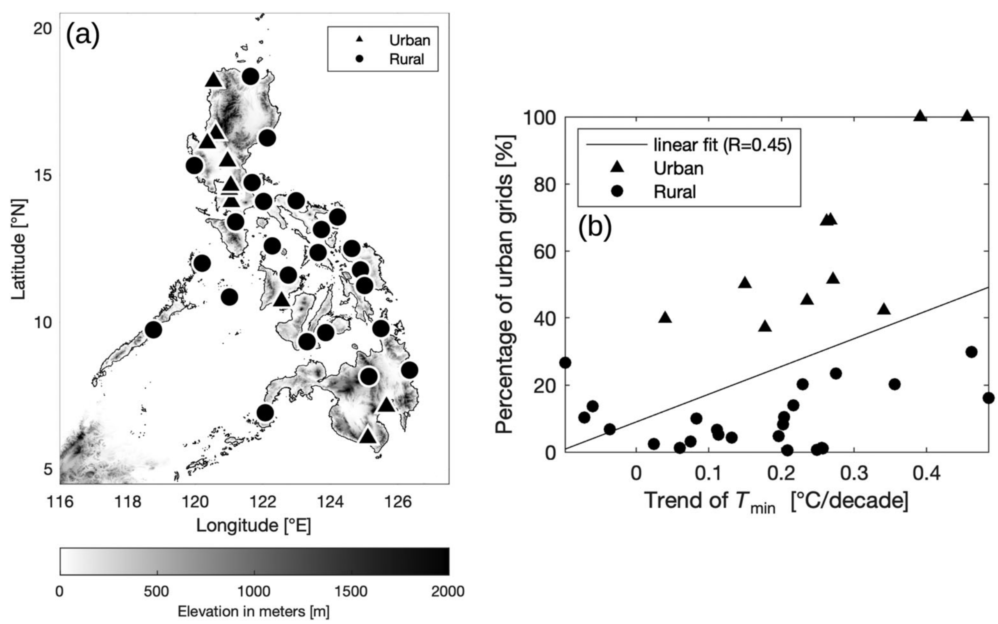

FIGURE 3 (a) Distribution of classified urban (triangles) and rural (circles) stations in the country; and (b) scatter plot and slope line of the T_{min} trend and the satellite night-light index

TABLE 3 Annual and seasonal trends of the temperature indices in the Philippines from 1951 to 2018

	Annual	DJF	MAM	JJA	SON
T_{ave}	0.17***	0.17***	0.17***	0.16***	0.17***
T_{min}	0.19***	0.18***	0.19***	0.18***	0.18***
T_{max}	0.15***	0.15***	0.15*	0.14**	0.16***
DTR	*−0.04**	*−0.04*	*−0.04*	*−0.04**	*−0.02*
T_{Nn}	0.20***	0.23***	0.24***	0.16***	0.22***
T_{Nx}	0.19***	0.17***	0.16*	0.14***	0.12***
T_{Xn}	0.16***	0.19***	0.13***	0.16***	0.20***
T_{Xx}	0.14***	0.15***	0.15***	0.16***	0.16***
T_{N10p}	*−1.98****	*−3.58****	*−1.58****	*−0.95****	*−1.49****
T_{N90p}	2.46***	0.75***	3.29***	3.40***	1.98***
T_{X10p}	*−0.94****	*−1.98****	*−0.26**	*−0.66****	*−0.91****
T_{X90p}	1.58***	0.42***	2.63***	2.07***	1.22***
Hottest days	0.20***	—	—	—	—
Coldest nights	*−0.21****	—	—	—	—

Notes: *Significant at α = 0.05; **significant at α = 0.01; ***significant at α = 0.001; Italicized: decreasing trend.

et al., 2005; Whan *et al.*, 2014; Keggenhoff *et al.*, 2015; Cheong *et al.*, 2018; Bagtasa, 2019; Qian *et al.*, 2019). They were observed in the global context and in the Southeast Asian region from 1950 to 1993 and 1961 to 1993, respectively (Easterling, 1997). These findings at a national level show consistency with previous studies conducted at the regional to global scales. The results highlight that local and countrywide climatic observations and analysis are important based on the contribution to climatic changes at a sub-continental to global scale.

The analysis of countrywide seasonal trends indicated that most of the indices exhibited higher trends during the DJF and MAM (dry) seasons, specifically the T_{min}, T_{Nn}, T_{Nx}, T_{N10p}, T_{X10p}, and T_{X90p}. This may be related to the lower boundary layer height during the cool and dry DJF season, which promotes mixing in the lower atmosphere during the day which is sustained throughout the night, resulting in a warmer urban boundary layer (Oke *et al.*, 2017). The reduced presence of clouds during the dry season (Flores and Balagot, 1969) helps release surface heating more efficiently (Oke *et al.*, 2017), and its potential contribution should thus not be disregarded. The highest seasonal trend was observed in T_{N10p} during the DJF season with a trend equivalent to −3.58%/decade, indicating that the number of cool nights has decreased. This is in part related to the UHI effect introduced by urbanization in cities (e.g., Ren *et al.*, 2007; Oke *et al.*, 2017). Lower trends of SAT were observed during the JJA and SON seasons, similar to that observed by Easterling (1997) in a global context.

The influence of ocean-atmospheric processes such as the ENSO, known to affect the climate in the Philippines on the interannual time-scale (Lyon *et al.*, 2006; Hilario *et al.*, 2009; Villafuerte *et al.*, 2015) was also observed and showed an influence on country-wide annual average temperatures, specifically in 1987,1998, 2010, and 2016 (Figure 4). In addition, a decreasing trend was detected for the annual countrywide T_{ave} during 1992–1995; this may be related to the Mt. Pinatubo eruption in 1991 in central Luzon, which affected global annual temperatures in the following years. This was particularly evident in the tropical and subtropical regions where annual temperature changes are not as large as those at higher latitudes (Easterling, 1997; Cinco *et al.*, 2014).

The observed relatively higher trends in T_{min} compared to those in T_{max} contributed to a decreasing trend in the annual DTR series of approximately −0.04°C/decade; this was particularly evident following the early 1990s (Figure 4d). To determine the commencement year for the annual DTR trend, we used the sequential Mann–Kendall test proposed by Bisai *et al.* (2014) to detect changes in the sign of the trend in the SAT time series. The results show that the DTR had a significant trend change (from increasing to decreasing) around 1992, with a continuous decrease until recent decades. A significant change in the early 1990s was also observed when the sequential Mann–Kendall test was applied to the annual DTR series for urban and rural stations. The significant increase in rural stations was observed one year earlier (1991) than that in urban stations (1992). This may reflect the indirect effect of the Mt. Pinatubo eruption in 1991 or the lag time effect of warming as a result of urbanization. Significant changes in the annual DTR trend were also observed in several studies in other parts of the world

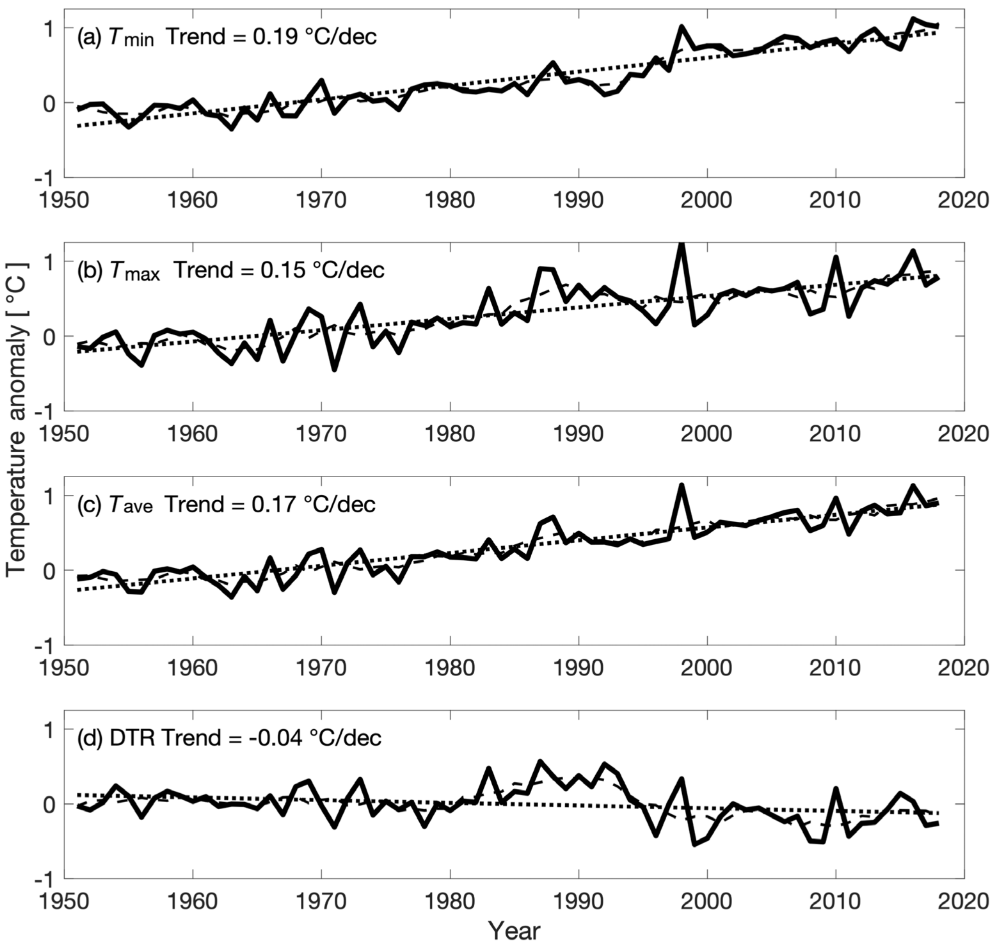

FIGURE 4 Time series of the country-averaged annual mean anomaly of (a) T_{min}; (b) T_{max}; (c) T_{ave}; and (d) DTR from 1951 to 2018. Anomaly values were taken relative to the baseline period of 1961–1980. Heavy lines indicate the annual values, dashed lines denote the 5-year running mean, and dotted lines represent the trend line. All were statistically significant at the 95% confidence level

using different study periods (e.g., Makowski *et al.*, 1950; Easterling, 1997; Vose *et al.*, 2005; Shahid *et al.*, 2012). A reversal (from decrease to increase) in the annual DTR trend was observed in the 1970s in Western Europe and during the 1980s in Eastern Europe (Makowski *et al.*, 1950). However, Shahid *et al.* (2012) observed different results, finding that the difference between T_{min} and T_{max} was not sufficiently large to prompt a significant shift in the DTR in Bangladesh from 1961 to 2008. In the global context, the T_{min} and T_{max} have increased across most parts of the globe from 1950 to 2004, while a widespread decrease in the DTR was only evident from 1950 to 1980 (Easterling, 1997; Vose *et al.*, 2005). This implies that observations and regional analysis of the changes in DTR which is affected by both surface shortwave and longwave radiation as stated in the study of Makowski *et al.* (1950), are essential for a better understanding of the changes in the DTR in relation to global climate change. Moreover, another possible reason for the observed decrease in DTR in terms of geophysical indicators as explained by Varquez and Kanda (2018), are both direct and indirect effects of the increase in heat capacity and enhancement of heat transport by turbulence, respectively. They also stated that the DTR is strongly linked with the UHI effect, such that dry tropical climates tend to have a lower DTR and thus, lower UHI effect as compared to those in temperate regions (Varquez and Kanda, 2018). The observed changes in the DTR are also related to a more localized urbanization process and long-term changes in clouds, aerosols, rainfall, soil moisture, and changes in terrestrial vegetation (Dai *et al.*, 1999; Ren and Zhou, 2014).

Figure 5 illustrates the trends in the annual temperature anomaly of T_{min} and T_{max} for the 34 stations from 1951 to 2018. Higher trends in T_{min} were observed for urban stations than for rural stations. Relatively higher trends in urban cities have also been observed and discussed in several studies focusing on the UHI effect (e.g., Chow and Roth, 2006; Tiangco *et al.*, 2008; Jongtanom *et al.*, 2011; Oliveros *et al.*, 2019). Figure 6 depicts further differences in the trend between the rural and urban stations. The trends in T_{max} and T_{ave}, averaged among the urban stations, corresponded to 0.15 and 0.20°C/decade, respectively. For rural stations, the trends in T_{max} and T_{ave} were 0.15 and 0.16°C/decade, respectively (Figure 6b). This apparent difference in the T_{ave} trends between rural and urban stations was due to the more rapid warming trend in the T_{min} for urban stations (0.25°C/decade). A 0.09°C/decade difference in the annual

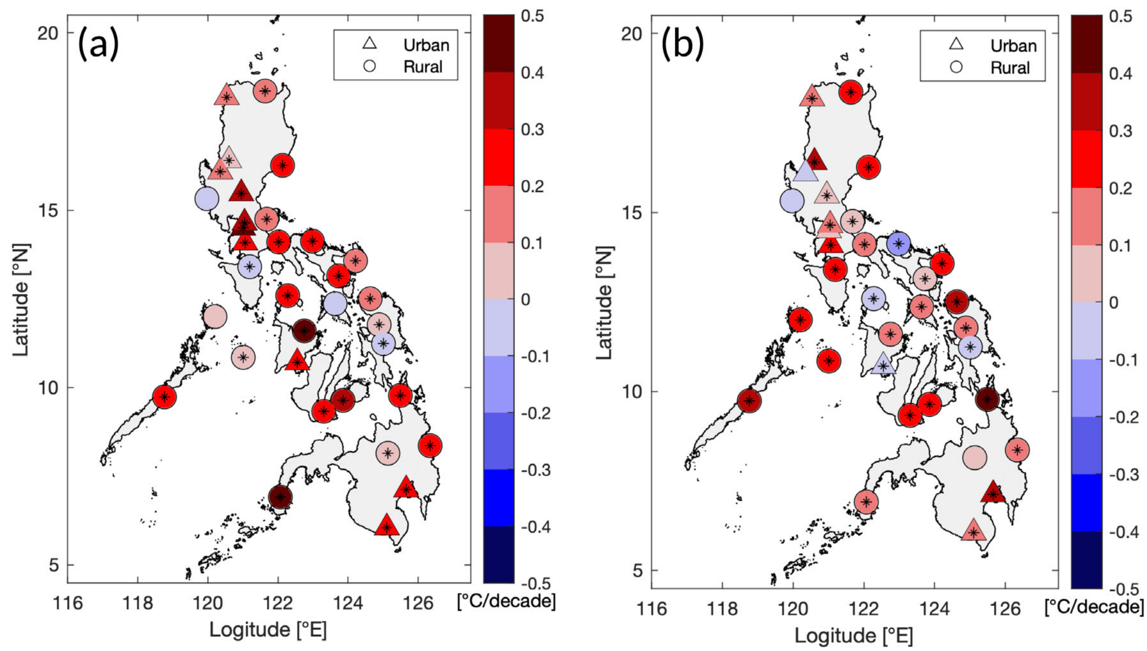

FIGURE 5 Long-term trends of the annual (a) minimum (T_{min}) and (b) maximum temperature (T_{max}) for the 34 stations in the Philippines from 1951 to 2018. The white star symbol at the centre of the circles denotes that the trends were statistically significant at the 95% confidence level. The shading corresponds to the trends of the urban (triangles) and rural (circles) stations [Colour figure can be viewed at wileyonlinelibrary.com]

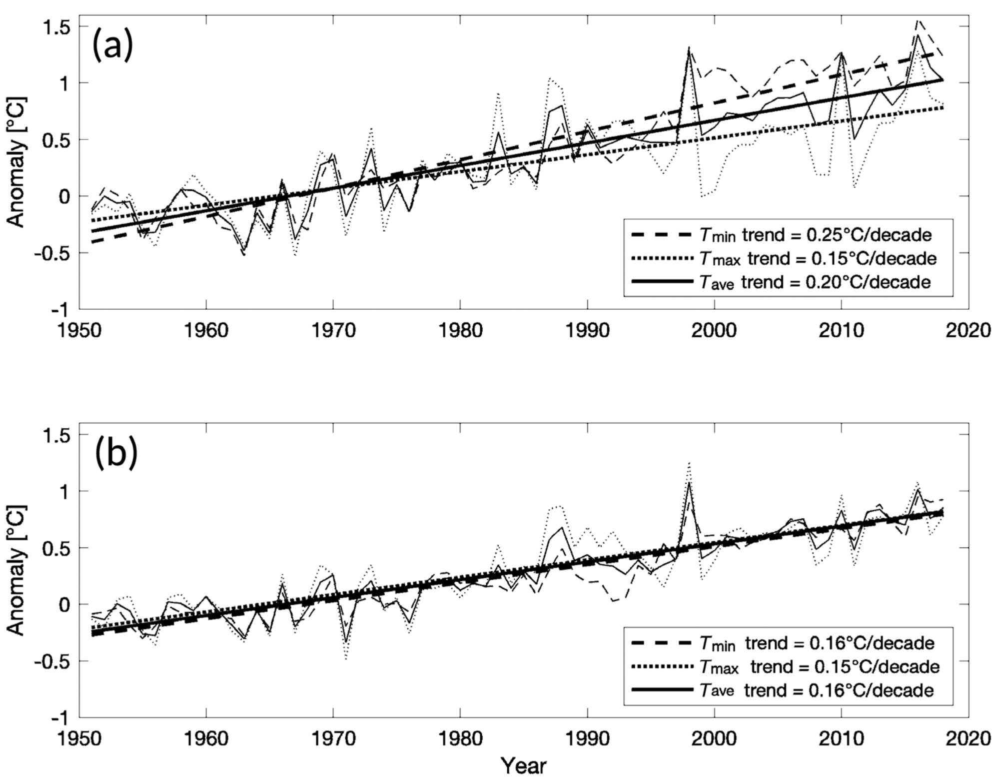

FIGURE 6 Time series of the annual T_{min}, T_{max}, and T_{ave} anomaly for (a) urban and (b) rural stations from 1951 to 2018. The dashed, dotted, and solid lines represent the time series of T_{min}, T_{max}, and T_{ave}, respectively. The thin and thick lines correspond to the annual values and linear trend-line, respectively. All obtained trends were statistically significant at the 95% confidence level

T_{min} was observed between urban and rural stations, indicating that the classification of the stations is able to illustrate the effects of urbanization in the long-term temperature trends in the Philippines. The results also show that the T_{min} and T_{max} trends for rural stations were both 0.16°C/decade, while T_{min} showed a larger increase compared to T_{max} for urban stations, with a difference equivalent to 0.05°C/decade. This implies that urbanization impacts night-time temperatures more than daytime temperatures, furthermore, the trend in rural stations which is almost twice of the global land temperature warming, with approximately 0.15°C/decade difference using 1974–2004 data (Vose *et al*., 2005), may have also been influenced by local anthropogenic activities such as biomass burning, transportation, buildings, pollution, and deforestation, to name a few, an important factor that must be considered to interpret how global warming has affected the climate in the Philippines. The observed significant night-time heating may be an atmospheric response to a less turbulent nocturnal boundary layer (Walters *et al*., 2007; Oke *et al*., 2017), and an increase in anthropogenic aerosols that act as an absorber of long-wave radiation from the ground (Rosenfeld *et al*., 2014; Bagtasa, 2019).

4.3 | Urbanization effect and contribution

Table 4 shows the annual and seasonal effect of urbanization on the extreme temperature indices for urban stations in the Philippines from 1951 to 2018. The time series of the annual urbanization effect, shown in Figures 7 and 8, were the anomaly differences of indices between urban and rural stations in the Philippines from 1951 to 2018.

Larger and significant values were found in the annual series of T_{min}, DTR, T_{Nn}, T_{Nx}, T_{X90p}, T_{N10p}, T_{N90p}, and coldest nights with absolute values of 0.10, 0.11, 0.13, 0.09°C/decade, 0.52, 0.84, 1.19, and 0.10%/decade, respectively. In contrast, lower and insignificant effects of urbanization were observed for T_{Xn}, T_{Xx}, T_{X10p}, and hottest days. The highest annual effect of urbanization was observed for T_{N90p}, corresponding to 1.19°C/decade. This means that urbanization has a greater effect on temperature indices related to T_{min}, while weaker effects were observed for temperature indices related to T_{max}. This may be related to the cooling effect as a result of the presence of pollutants near urban stations (MacKenzie, 1997; DENR, 2012). Besides pollution, another possible reasons for such differences in the daytime and night-time temperature are: (a) the changes in the solar radiation (e.g., solar dimming and brightening) (Shen *et al*., 2014). For example, Shen *et al*. (2020) have found that in Northeast China, a significant urbanization effect was observed

TABLE 4 Annual and seasonal urbanization effect (UE) and urbanization contribution (UC) on the extreme temperature indices in the Philippines from 1951 to 2018

		T_{ave}	T_{min}	T_{max}	DTR	T_{Nn}	T_{Nx}	T_{Xn}	T_{Xx}
Annual	UE (°C/dec)	0.04	0.10	−0.02	−0.11	0.13	0.09	0.00	−0.05
	UC (%)	20	37	—	92	43	36	—	—
DJF	UE (°C/dec)	−0.04	0.11	−0.18	−0.29	0.29	−0.32	−0.50	−0.22
	UC (%)	2	6	—	100	2	1	—	—
MAM	UE (°C/dec)	−0.05	0.03	−0.13	−0.16	−0.47	0.06	−0.28	−0.10
	UC (%)	8	9	—	8	3	1	—	—
JJA	UE (°C/dec)	0.06	−0.04	0.17	0.21	0.12	−0.18	−0.09	0.12
	UC (%)	50	15	—	26	1	1	—	—
SON	UE (°C/dec)	0.00	0.02	−0.02	−0.04	−0.09	−0.06	−0.08	0.29
	UC (%)	1	6	2	8	1	1	—	—

		T_{X10p}	T_{X90p}	T_{N10p}	T_{N90p}	Hottest days	Coldest nights
Annual	UE (°C/dec)	0.09	−0.52	−0.84	1.19	0.00	−0.10
	UC (%)	—	43	33	36	—	35
DJF	UE (°C/dec)	7.10	−0.49	−2.69	−0.09		
	UC (%)	27	100	8	—		
MAM	UE (°C/dec)	0.47	−1.44	0.39	1.16		
	UC (%)	—	—	—	27		
JJA	UE (°C/dec)	−2.81	−0.56	0.12	−2.54		
	UC (%)	—	29	—	64		
SON	UE (°C/dec)	−0.41	0.05	−1.27	−0.19		
	UC (%)	—	17	—	15		

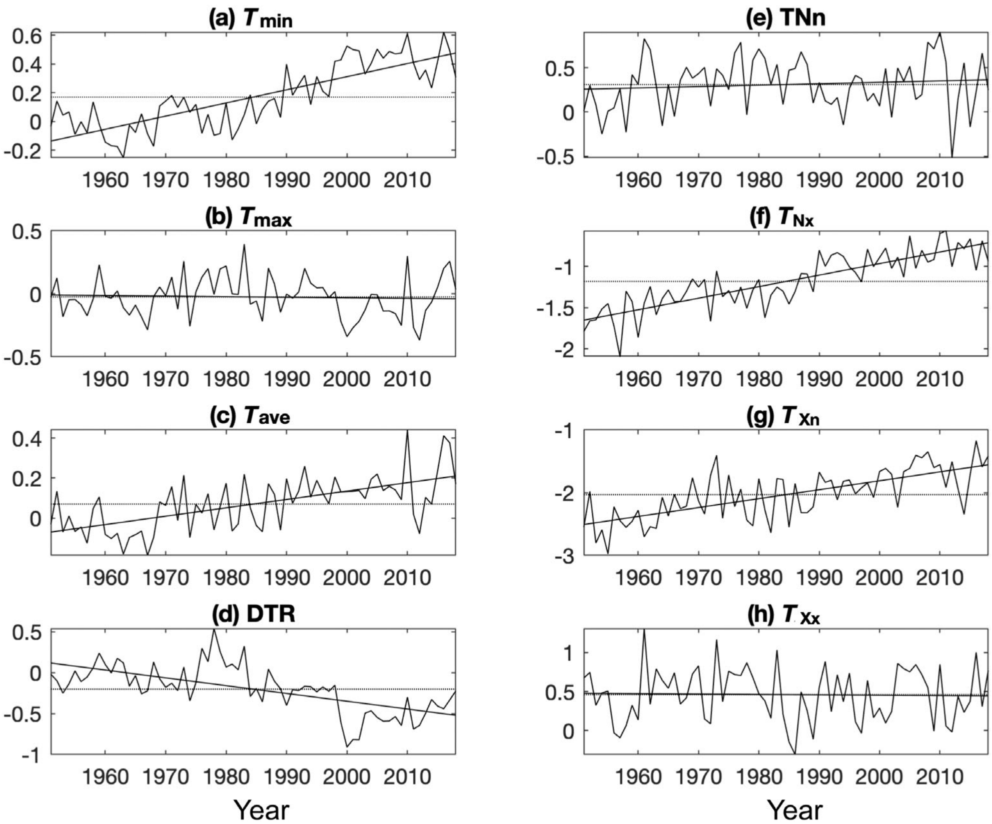

FIGURE 7 Time series of the effect of urbanization on the temperature indices (a) T_{min}; (b) T_{max}; (c) T_{ave}; (d) DTR; (e) T_{Nn}; (f) T_{Nx}; (g) T_{Xn}; and (h) T_{Xx} from 1951 to 2018 in the Philippines. Statistically significant trends at the 95% confidence level were observed for the T_{ave}, T_{min}, DTR, T_{Nx}, and T_{Nn} indices. The horizontal line corresponds to the mean (light colour) and linear trend lines (dark colour)

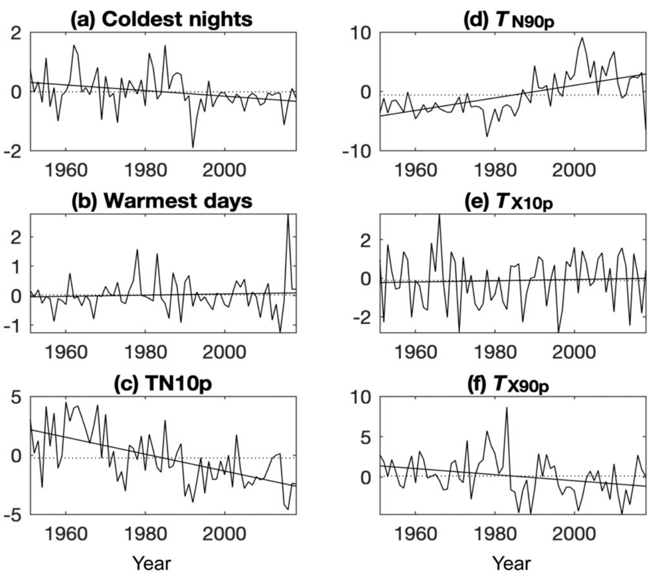

FIGURE 8 Continuation of Figure 7 for (a) coldest nights; (b) hottest days; (c) T_{N10p}, (d) T_{N90p}; (e) T_{X10p}; and (f) T_{X90p} from 1951 to 2018 in the Philippines. Statistically significant trends were observed in the T_{N10p}, T_{N90p}, and coldest nights indices

in T_{min} during night-time, whereas, a different effect was observed on T_{max} during day time under the different changes of solar radiation; and (b) the vertical temperature profiles in the lower atmosphere (Jacobson, 1999; Fujibe, 2012). During night-time, the formation of UHI is influenced by a strong surface inversion that originates in the sub-urban region but is destroyed over the urban surface (Oke and East, 1971). This was also observed in the study of Godowitch *et al.* (1985) and Lu *et al.* (1997). This states that the larger effects of urbanization during night-time are confined to a shallow layer, whereas during day-time, the UHI spreads over the mixing layer resulting to a lower urban-rural temperature difference. These findings are consistent with those reported by Zhou and Ren (2011) for mainland China from 1961 to 2008. They observed that lower and insignificant trends and effects of urbanization were apparent for indices related to T_{max} than for indices related to T_{min}.

In terms of seasonal analysis, almost all extreme temperature indices were found to have a higher effect of urbanization during the DJF season, with the exception of T_{ave}, T_{Nn}, T_{Xx}, T_{X90p}, and T_{N90p}. This might be related to a possibly lower and more stable urban boundary layer (UBL) due to lower temperature measurements observed during DJF as compared to other seasons (Villafuerte *et al.*, 2020). Lower surface temperature reduces turbulence (e.g., eddies, mixtures) near the surface or within the canopy layer resulting to a possibly lower UBL, hence, reduces urban to rural air exchange (Hua *et al.*, 2008) that may sequentially increase surface heating, particularly in urban stations. Another possible reason for the observed significant trends during DJF season is the canopy layer heat island where microscale circulations can exist (Oke *et al.*, 1991). This layer is influenced by factors such as thermal admittance (Oke, 1981; Oke *et al.*, 1991) that might be enhanced during DJF season. In the simulations conducted by Oke *et al.* (1991) during calm and cloudless conditions at night, they found that the thermal admittance between urban and rural alone can produce a heat (or cool) island effect, such that the absolute magnitude of the rural admittance can produce seasonal variation in the heat island. Furthermore, as mentioned by Oke *et al.* (2017), the magnitudes of urbanization effect critically depend on the moisture content and the nature of the rural surface due to its greater seasonal variation. In terms of moisture content, based on JRA-55 atlas, the total column moisture is smaller in DJF compared with other season (https://jra.kishou.go.jp/JRA-55/atlas/jp/column.html), although at the surface, relative humidity is less in MAM (Flores and Balagot, 1969). Nevertheless, it is noted that the statements by Oke *et al.* (2017) are previously and mostly observed in temperate regions (e.g., China, Canada), thus, further analysis on the nature of rural surface and UBL must be conducted.

The analysis of annual and seasonal mean urbanization contributions for all indices within the 68-year range shows low and insignificant urbanization contributions on T_{max}, T_{Xn}, T_{Xx}, T_{X10p}, and hottest days. In contrast, higher contributions from urbanization were observed for T_{min}, DTR, T_{Nn}, T_{nx}, T_{X90p}, T_{N90p}, and coldest nights. The annual analysis shows that the contribution of urbanization across all indices ranged from 20 to 92%, while this range was 1–100% for the seasonal analysis. The T_{ave}, T_{min}, DTR, T_{Nn}, and T_{nx} exhibited a significant influence from urbanization across all seasons. Such differences in the observed trends may have been driven by the two general mechanisms for UHI formation as stated by Varquez and Kanda (2018): the (a) increase in sensible heat in urban areas and the (b) increase in thermal inertia of urban surfaces.

The increased effect of urbanization shown in Figures 7 and 8 is easy to comprehend as the urban population in the country has been increasing since the middle of the 20th century, mainly due to internal migration (Quisumbing and McNiven, 2005; Bohra-Mishra *et al.*, 2017), which specifically includes migration of people from rural areas to Metro Manila (Basa *et al.*, 2009). It is considered that the effect of the decrease in population in provinces (rural areas) due to internal migration is minimal as compared to a denser population in urban areas and thus, unlikely to affect the results of this study. The effect of urbanization on the time series of the coldest nights and hottest days indicates the potential influence of the variability in the ocean-atmospheric system on urban and rural stations. The negative effect of urbanization observed in the coldest nights from 1992 to 1995 may be related to Mt. Pinatubo eruption. In contrast, for the hottest days, the highest effect of urbanization was observed in 2016, relating to a strong El Niño event that caused significant drought in Mindanao Island, where some cities were in a state of calamity (Jocson and Magallon, 2018).

It is worth noting that the estimated urbanization effect and contribution on the temperature indices series may have also been influenced by the classification scheme of the stations applied in the study. This means that the satellite night-lights alone could not fully represent the characteristics of an urban station. For example, fewer stations were classified as urban and more stations as rural, this might lead to potential underestimation or overestimation of urbanization effect in the study region. Further investigations on the effect of urbanization using different methodologies of station classification, such as those using remotely sensed land-use data (Tysa *et al.*, 2019), integrated procedures (Ren *et al.*, 2015), and machine learning (Zhang *et al.*, 2021), are needed to improve the classification of reference stations in the study area (Hua *et al.*, 2008; Zhao *et al.*, 2019). Moreover, other studies (e.g., Ching *et al.*, 2018) have implied the surrounding natural landscape into local climate zone types (Stewart and Oke, 2012) and have used maps (e.g., land cover/land use maps and satellite images) to provide finer information to present all urban elements that may exist for some urban areas. Such procedures are important to provide a more localized climate analysis and better representation of the urbanization effect which might be the next topic of this research and also noting that UHI is fundamentally a local scale phenomenon driven by urban morphology (Oke *et al.*, 2017). Nevertheless, this analysis may serve as a baseline study in the Philippines that focuses on the countrywide effect of urbanization on climatic data, particularly on long-term trends of extreme temperature indices.

5 | CONCLUSIONS

The Philippines experiences several climatic hazards and environmental challenges as a result of climate change and urbanization. As such, it is essential to obtain an in-depth understanding of extreme climate change and the potential impact of urbanization on observed climatic change. Cinco *et al.* (2014) analysed temperature trends in the Philippines, suggesting that days and nights were becoming warmer. However, their findings were influenced by several factors, such as urbanization, which plays an important role in observed temperature trends.

This study offers an in-depth analysis of the effect of urbanization on long-term trends of extreme temperature indices in the Philippines from 1951 to 2018. The results of this study were used to draw the following conclusions:

- The classification of stations using satellite night-lights highlighted a positive correlation for trends in T_{min}, with a correlation coefficient of approximately 0.5, statistically significant at the 99% confidence level. A total of 10 urban stations and 24 rural stations were classified using this method.
- The observed annual and seasonal trends of extreme temperature indices were all statistically significant at the 95% confidence level, with the exception of seasonal DTR (during DJF, MAM, and SON seasons). This may have been due to the observed shift in the DTR trend (from increasing to decreasing) in the 1990s.
- A higher trend in T_{min} of approximately 0.25°C/decade was observed in urban stations, while this was approximately 0.16°C/decade in rural stations. This indicates a clear influence of the enhanced UHI effect on night-time temperatures detected at urban stations.
- Larger and more significant effects of urbanization were observed on indices related to T_{min}, such as T_{Nn}, T_{Nx}, T_{N10p}, T_{N90p}, and coldest nights, compared to indices related to T_{max}. Seasonal analysis has shown that the greatest effect of urbanization is observed during the DJF season.
- The annual effect of urbanization was more significant for T_{min}, DTR, T_{Nn}, T_{Nx}, T_{X90p}, T_{N10p}, T_{N90p}, and coldest nights, with trends equivalent to 0.09, −0.10, 0.14, 0.14°C/decade, −0.38, −0.72, 1.06, and 0.09%/decade, respectively. This effect was low for the T_{Xx}, T_{Xn}, T_{X10p}, and hottest days indices, with trends of −0.01, 0.02°C/decade, 0.03, and 0.02%/decade, respectively. All trends were statistically significant at the 95% confidence level, with the exception of T_{max}, T_{Xx}, T_{X10p}, and hottest days.

The study contributes to the growing urban climate studies in Southeast Asia by showing a clear urbanization effect on the temperature indices using satellite night-lights data. This may also contribute to heat-related risk and stress in energy sector in terms of urban planning and management. Nonetheless, we recognize that there are other issues left unaddressed in this study. For example, there are other methods available for classifying the stations into urban and rural stations that should be tested in future studies. How the urbanization affects the trends of temperature in terms of the changes in the atmospheric conditions should also be examined using high resolution numerical models.

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AUTHOR CONTRIBUTIONS

John Manalo: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing-original draft. **Jun Matsumoto:** Conceptualization; investigation; resources; supervision; validation. **Hiroshi Takahashi:** Investigation; resources; supervision; validation. **Marcelino II Villafuerte:** Conceptualization; investigation; validation. **Lyndon Mark Olaguera:** Investigation; validation. **Guoyu Ren:** Methodology; validation. **Thelma Cinco:** Data curation.

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