The Subtropical Urban Heat Island Effect Revealed in Eight Major Cities of Taiwan

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Abstract: The statistical relationships between ascending rates of urban heat island effect (referred as ARUHI) of eight major cities in Taiwan with their corresponding populations have been examined. On average, the UHI intensity is about 1.83 °C from 1995 to 2004 based on temperature records of eight cities in Taiwan. About 88% of urban-rural pairs (seven out of eight stations) exhibit negative UHI values during the daytime due to the impact of denser urban developments. Only Hualien-HDAIS pair shows the opposite pattern due to its less developed pace in the last decade. Our results shows the urban population has a strong correlation with the ARUHI and clearly suggest that rapid and denser urbanization of large cities play a very important role on the observed negativity of urban heat island effect during the daytime in Taiwan.

Key-words: Urban heat island, Ascending rate of urban heat island (ARUHI) intensity, Population

1. Introduction

Taiwan, a rapidly industrializing society with population density as high as 602 people/km^2 (23 million people within an island of 36,000 km^2) has advanced at an unprecedented pace in urban expansion over the past few decades. This has caused the diurnal temperature range has increased by about 1.1 degrees since 1950, about twice the corresponding values over major continents. The rapid expansion of urban centers and their peripheries has led to a series of complex problems such as loss of agricultural land and natural vegetation, uncontrolled urban sprawl, increased traffic congestion and degradation of air and water quality, especially urban heat island effect. Owing to an extraordinary rapid economic development in the last four decades, Taiwan has experienced an increase in energy consumption up to about 20 times. Thus, Taiwan presents an excellent case for examining and evaluating the relationship between UHI intensity and its population.

The Western Plain of Taiwan, where Taipei, Taitung, Tainan, Chiyi, and Kaohsiung etc. are located, has suffered a regional scale heat-island effect [10] and that is clearly visible through remote sensing [11]. The impact of urbanization was estimated by comparing observations in cities to those in surrounding rural areas, but the results differ significantly depending on how population data or satellite measurements of night light [8] are used to define urban and rural areas. Oke [7] and Torok et al. [15] show that small towns with a population of 1000 people have an urban heating of about 2.2°C compared to the nearby rural countryside. Since the UHI increases with population as about 0.73 in logarithm, a large city with a million people would have a warming up to 4.4°C [7]. The first national census in South Korea began in 1966 and thereafter has been done regularly in a 5-year interval [1]. Chung et al. formulated regression equations for monthly temperature changes between the periods of 1951–1980 and 1971–2000, as a dependent variable, and the logarithm of population changes during the same two periods as an independent variable. Murakami et al. [12] pointed out that Asian mega cities have experienced rapid population growth and will continue to expand.

Urbanization in those areas is proceeding differently from the patterns of city growth in Western countries. Kalnay and Cai [8] suggested that half of the observed decrease in diurnal temperature range is due to urban and other land-use changes. Moreover, their estimate of 0.27 ^{o}C mean surface warming per century due to land-use changes is at least twice as high as previous estimates based on urbanization alone [3, 4]. The well-known UHI effect actually takes place at night, when buildings and streets release the solar heating absorbed during the day. The magnitude of the net change in heat storage is more significant to the energy balance of urban areas than other land covers, bare soil etc. [16, 17]. At the time of the maximum temperature the UHI effect tends to be slight cooling, owing to shading, aerosols [1], and possibly to thermal inertia differences between city and country. Chung et al. also pointed out that the increase in daily minimum temperature may be accounted by local phenomena resulting from rapid urbanization, not by regional warming [1].

Despite the increase on the heat island researches, little studies have sought to directly associate the ascending rate of urban heat island (referring as ARUHI) effect in diurnal cycle from the lowest point to highest) with population. This paper intends to evaluate this question through a relationship between ARUHI and its population for eight large cities in Taiwan. This study was conducted to identify the urbanization components of the apparent change in urban heat island intensity in Taiwan during the past ten years (1995-2004). In this research we concerned: (1) the relation between the ARUHI and the urban populations respect to rural stations; (2) the relation between negative UHI in daytime and corresponding population; and (3) the UHI characteristics of eight urban-rural pairs in Taiwan.

2 Data, Sites and Method

It is generally difficult to get a long term and high resolution data for UHI study. We took data of hourly temperature data from regular meteorological stations of Central Weather Bureau (CWB) and its Automation Observatory Stations (AOS) for the periods of 1995–2004, in Taiwan. Due to high-relief feature in Taiwan, few ground stations are available. Eventually we choose eight urban-rural pairs from CWB and AOS stations, which include Taipei-Wenshan, Hsishu-Hsinwu, Yilan-Giaosi, Hualien-HDAIS, Taitumg-TARI (referred as Taichung Agriculture Research Institute), Chiayi-Shisi, Tainan-Chiali, and Kaohsiung-Chaocho. Fig. 1 shows the locations of Automatic Weather Observing Stations (AWOS) of eight large cities and its corresponding rural ones selected for the study. Population data for these stations were collected from Ministry of the Interior, Taiwan.

Situated off the east coast of Asia and in the path of warm ocean currents, Taiwan enjoys an oceanic and subtropical monsoon climate that is conspicuously influenced by the local topography. Summers are long with high humidity, while winters are short and usually mild. Urban development has long been recognized to generate significant impacts on the social structure of the cities and their surroundings, in terms of population distribution or land use characteristics. Instead of using UHI intensity, the ARUHI slope was considered to evaluate the correlation between the UHI and its corresponding population. ARUHI is defined as the UHI change from the lowest value to highest one in time lapsed of one event due to a better representation for the correlation of UHI intensity with population. Because more rural stations were built in the past decade, enough data can be collected for this study for city-rural pairs. We noted that a big difference exists in the number of population for various rural stations. For example, the population in Wenshan is about four times higher than that of Giaoshi. The number of population can reflect the degree of development of urban that could influence UHI intensity due to urban climate changing. In Taiwan, the population remains more or less steady in the latest ten years. There was no significant change in meteorological observing conditions during the study period (1995–2004).

Anping station in Tainan is exceptional, because it has been relocated due to considering as historical building. Originally Tainan meteorological station located at Anping then relocated their geographical locations to Yunkan in May 1998, In Nov. 2001, Tainan meteorological station again moved back from Yunkan.

3. Analysis and Result

3.1 Diurnal UHI in eight urban-rural pairs

The recent increase of nocturnal warming within city limits for the past decade in Taiwan may not be the direct effect of global warming in viewing our analytical results presented above. The real cause may be the result of rapid urbanization of big cities, which result in the increase in energy consumption, changes in land use and land cover, removal of vegetation, and so on. These unfavorable changes associated with urbanization contribute to our observed UHI values. This observation is in good agreement with that studied by Chung, et al. [1]. Diurnal cycles of eight city-rural pairs in Taiwan are shown in Fig. 2. Apparently, ARUHI of Taipei-Wenshan is most significant among these eight pairs. Unusual phenomena were observed for most pairs that the temperature in rural site is higher than that of urban station during the daytime of diurnal cycle. The major reason for this unusual phenomenon may be attributed to the heat storage of large cities in the daytime [9, 10, 16, 17].

Only one pair (Hualien-HDAIS) shows the opposite patterns that the temperature of city station is consistent higher than that of rural site. It shows that Hualien is not well-developed compared with other seven large cities. The UHI intensities investigated in Taiwan ranges from 1.36 to 2.33 ^{o}C, with higher values in southern cities and well correlate with populations. It is worth to note that UHI intensity of Taipei-Wenshan has a low rate (1.60^{o}C) in viewing its high population, thus its UHI may be underestimated because the chosen Wenshan (rural station) actually is a relative high population of about 150,000 and because it is located in Taipei county, a biggest one in Taiwan.

3.2 Correlation between negative UHI intensity and city population

The correlations between ARUHI, highest UHI and average of daily maximum UHI with corresponding city populations are shown in Fig. 3. All three important parameters are positively correlated with city populations, suggesting the more the city population the higher the UHI intensity, that observation well matches the study by Oke [7]. In Fig. 3(a), correlation coefficient exhibits a high value (r_a=0.92) between ARUHI and city populations, implying that ARUHI is the most sensitive parameter in expressing the relationship between UHI intensity with population. The reason is the urban area absorbs solar energy in stored heat capacity during daytime and releases the heat after sunset [5, 7-9, 13]. Usually, the bigger the city size, the heat can be released more rapidly; thus resulting the higher slope of the ascending rate of UHI intensity. The highest UHI of diurnal variation also shows good correlation with city population (r_b=0.82), though the value is less than that of ARUHI. Probably the highest UHI reaches with a slow pace within the city.

The correlation between average of daily maximum UHI with city population is very low (r_c=0.16), however, it is a good correlation ($r_{c'}$=0.78) if we do not consider Taipei-Wenshan pair. This can be explained as above mentioned that (UHI intensity only 0.16 ^{o}C) is not very accurate. The reason may be due to the limited weather stations to be selected as candidates for the rural sites, as well as to the neighboring Taipei area almost being a same type of urban [9]. Also, we compared the UHI intensity in eight urban-rural pairs in Taiwan with Torok et al. [15] who found that the urban-rural temperature difference has a relationship with increasing population via the equation delta T (u-r(max)) =1.42 log(population)-2.09. Our result in eight pairs average to estimate UHI intensity is overestimate of 4.19 ^{o}C when used their equation. Nevertheless we thought that Taiwan case (subtropical country) is similar to that Australian towns (tropical country) and cities are likely to have smaller maximum UHI effects than those observed on Europe and North America with the same population [15].

3.3 Correlation between ARUHI intensity and city population

Chung et al. [1] pointed out that explicit scheme may potentially be used to account for the population effect on local temperature. Fig. 4 illustrates the correlations between the city population with average of negative UHI and lowest diurnal UHI of our eight city-rural pairs, respectively. There is a correlation coefficient of $r_a = -0.58$ between negative UHI values and corresponding populations. The lowest diurnal averages of negative UHI also express a correlation coefficient of $r_b = -0.63$ with populations. These observations imply that the bigger the size of city, the more the average negative UHI value would be. For example, population of Taipei-Wenshan pair is the largest, consequently it produces more negative UHI values among all eight urban-rural pairs.

3.4 Correlation UHI intensity in daytime with urbanization in eight urban-rural pairs

The daily diurnal cycles of average UHI intensity from 1995~2004 for eight city-rural pairs are shown in Fig. 5. The populations for the eight big cities are illustrated in the upper-right small box for reference. Once again, it clearly demonstrates that the bigger the city size, the more negative UHI would be observed. The curves of urban-rural pairs start from Hualien-HDAIS (the lowest negative value) followed sequentially by Hsinchu-Hsinwu, Yilan-Giaosi, Tainan-Chiali, Chiayi-Shisi, Taipei-Wenshan, Taichung-TARI, Kaohsiung-Chaocho. Among these eight pairs, two of them (Taipei-Wenshan and Chiayi-Shisi) show their negative UHI values are not matching with their populations. This discrepancy again may be related to the selection of rural sites.

Interesting finding is during 9:00AM ~17:00 PM that Hualien-HDAIS pair emerges the highest UHI value, followed as Hsishu-Hsinwu, Yilan-Giaoshi, Tainan-Shanhua, Chiayi-Shishi, Taipei-Wenshan, Taichung-TARI, and Kaohsiung-Chiaotou. These pairs in sequence are corresponded with the size of urban in Taiwan, only Taipei-Wenshan is underestimated due to Taipei is the biggest city in Taiwan. We also notice that summer temperature shows minor decreasing trend in rural areas of Taiwan but not universal. For example, the UHI intensity (1.60 ^{o}C) in Taipei, the biggest city in Taiwan, is not consistent with its degree of urbanization and is lower than other cities such as Taichng, Chiayi, Tainan, Kaohsiung (Fig. 2). The major reason is that Taipei and its surrounding area have already been overdeveloped hence there is no actual rural area to be chosen [9]. However, the correlations between UHI parameters still present clear trends with city populations (Fig. 3-5).

4. Conclusion

The statistical relationships between ascending rates of urban heat island effect (ARUHI) of eight major cities in Taiwan with their corresponding populations have been examined in this study. The mean UHI intensity in Taiwan is estimated to be about 1.83 ^{o}C from 1995 to 2004 from temperature records of these eight cities. About 88% of urban-rural pairs exhibit negative UHI values during the daytime due to the impact of denser urban developments. Only Hualien-HDAIS pair shows the opposite pattern due to its less developed pace in the last decade. The UHI intensity and ARUHI value of each site express strong correlations with corresponding city populations. In the case of Taiwan, the 1.2 ^{o}C rising in the past century is a factor of 2 compared with 0.6 ^{o}C increase of global average temperature with the same period. The higher value of temperature increase in Taiwan can be partly attributed the urbanization in addition to global warming.

Our results clearly suggest that rapid urbanization of big cities play very important role on the observed negativity of urban heat island effect during the daytime in Taiwan. It is recommended that ARUHI approach can be extended to other countries to examine if the same mechanism of urbanization can be observed with their local UHI effects. Further study is certainly needed to explore the complicated relationship between local UHI with global warming. The observation in this study is also useful in forming an effective mitigation strategy for UHI effects for big cities in Taiwan as well as other metropolitan areas.

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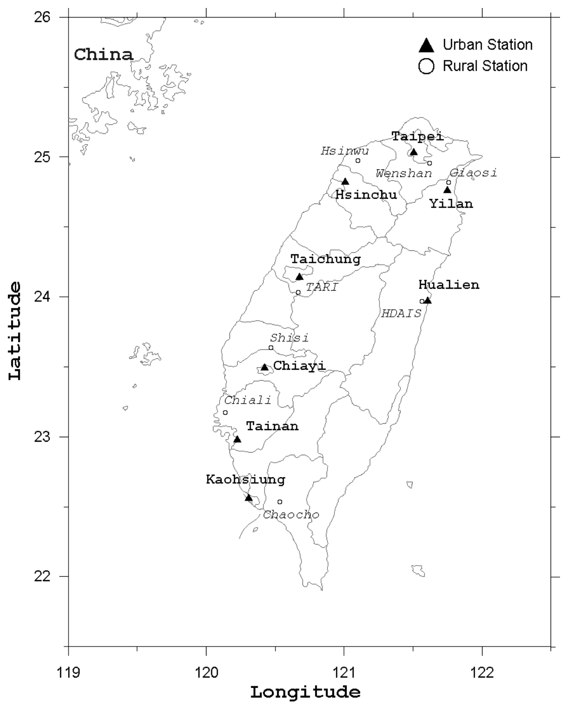

Fig. 1 Locations of meteorological stations (urban-rural pair) selected for this study. The distances between pair station are: Taipei-Wenshan, 14.8 km; Hsishu-Hsinwu, 12.8km; Yilan-Giaoshi, 6.1 km; Hualien-HDAIS, 3.9 km; Taichung-TARI, 12.8km; Chiayi-Shishi, 16.1km; Tainan-Shanhua, 22.9km; Kaohsiung-Chiaotou 23.3km.

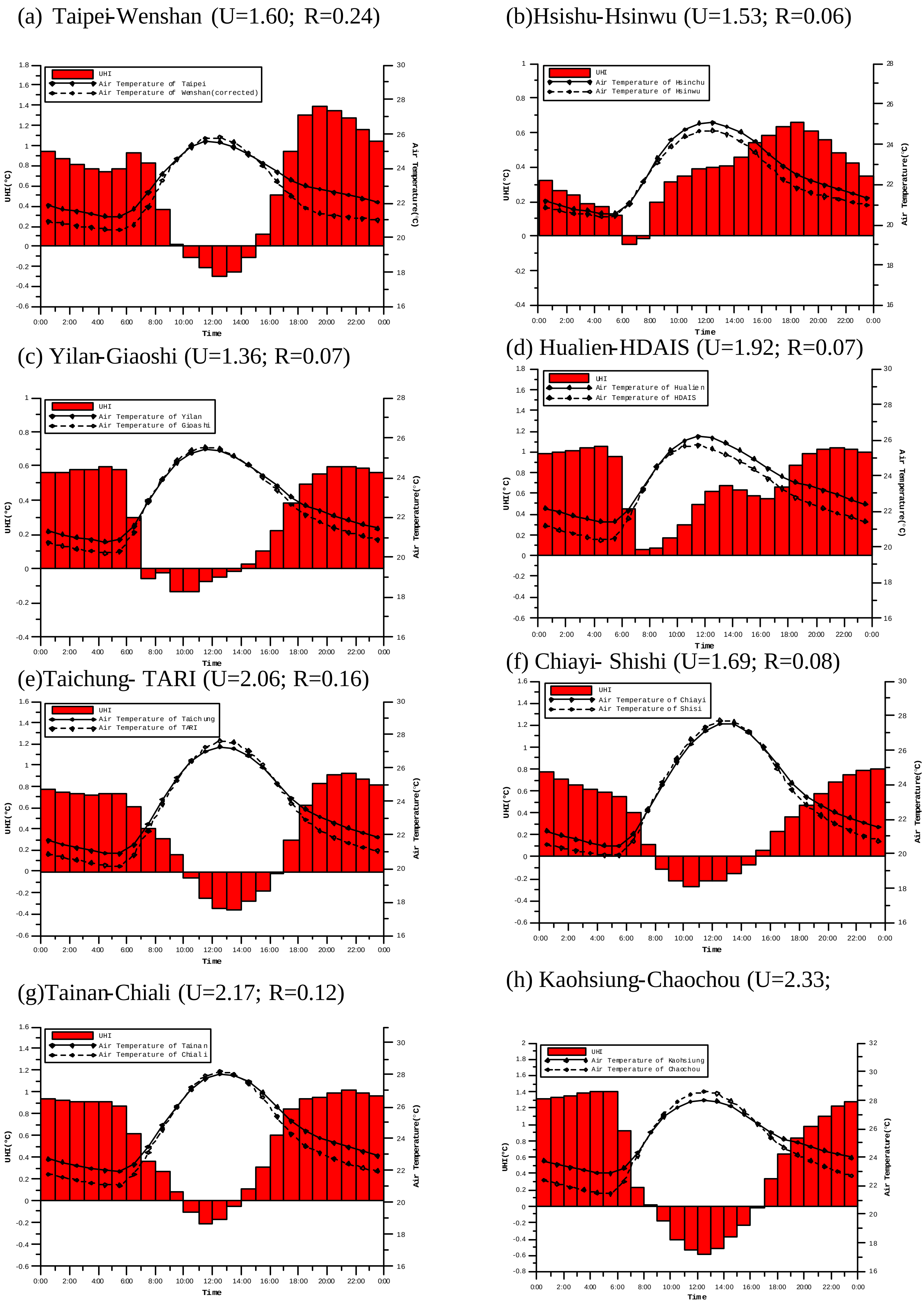

Fig. 2 Diurnal cycle of eight urban-rural pairs from 1995~2004 in the study; U: UHI and R: ARUHI. Seven out of eight stations exhibit negative UHI values during the daytime.

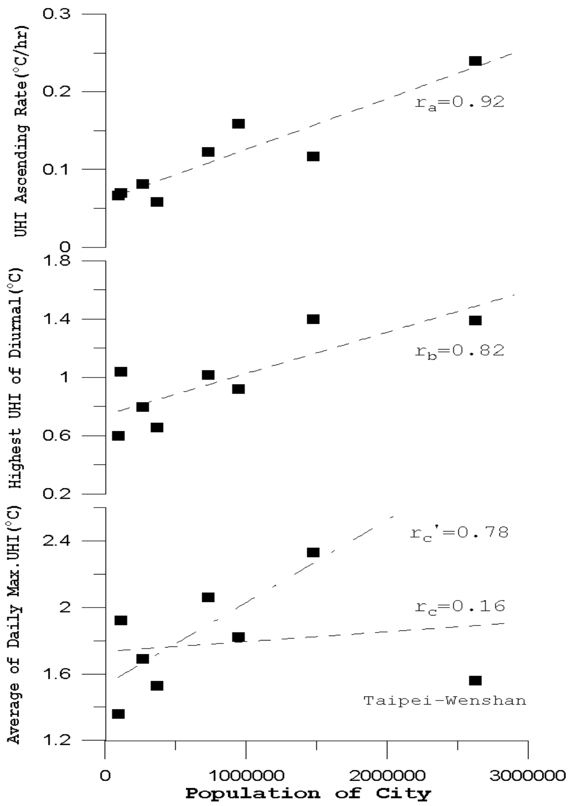

Fig. 3 Correlation between city population with (a) ARUHI, r_a=0.92; with (b) average highest daily heat island effect, r_b=0.82 ; and with (c) average daily maximum heat island effect effects, r_c=0.16. If excluding Taipei-Wenshan station, this correlation will raise to $r_{c'}$ =0.78.

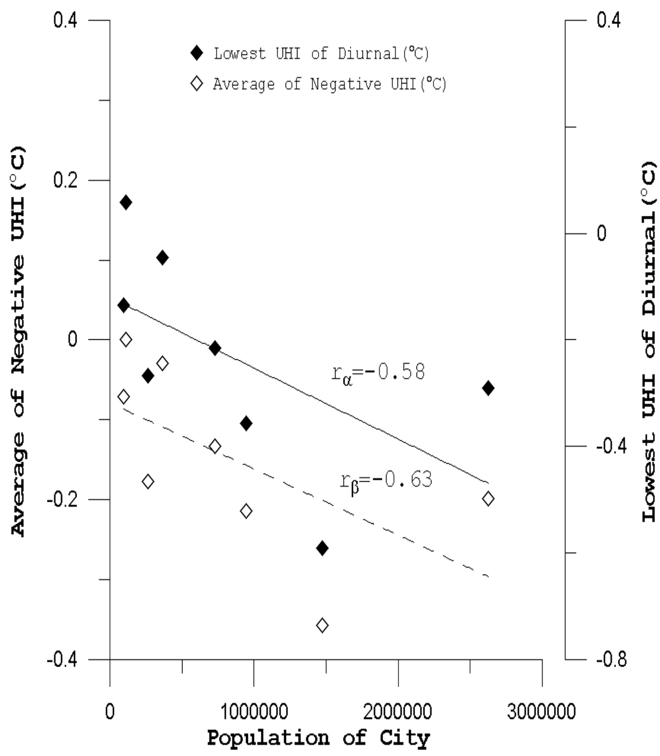

Fig. 4 Correlation between population of city with (a) the lowest UHI, r_α= -0.58; with (b) average negative UHI, r_β= -0.63. These observations imply that the bigger the size of city, the more the average negative UHI value would be. For example, population of Taipei-Wenshan pair is the largest, it produces highest negative UHI values among eight pairs

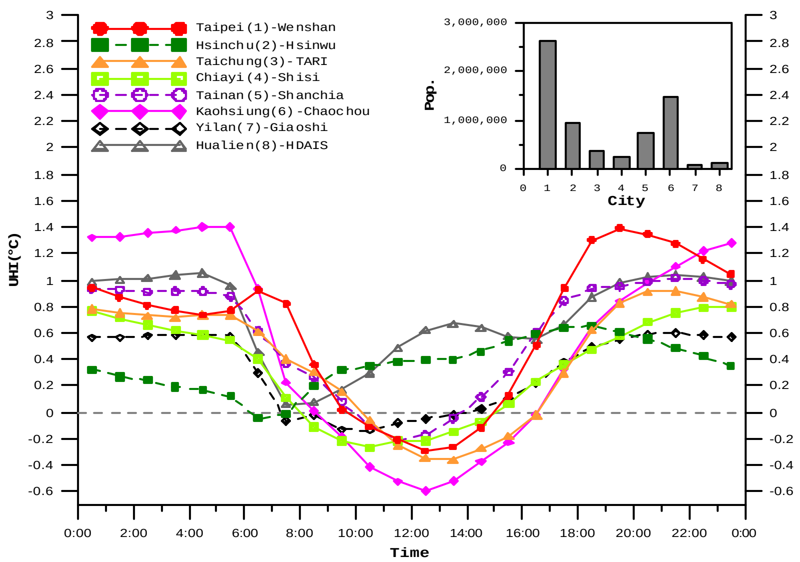

Fig. 5 Comparison of diurnal cycle of the eight urban-rural pairs from1995~2004. During 9:00AM ~17:00 PM Hualien-HDAIS pair emerges the highest UHI value due to its less developed pace in the last decade, followed as Hsishu-Hsinwu, Yilan-Giaoshi, Tainan-Shanhua, Chiayi-Shishi, Taipei-Wenshan, Taichung-TARI, and Kaohsiung-Chiaotou. These pairs in sequence is well corresponded with the size of urban in Taiwan, except there is an underestimation found in Taipei-Wenshan pair.