Subsurface urban heat island and its effects on horizontal ground-source heat pump potential under climate change

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Subsurface urban heat island and its effects on horizontal ground-source heat pump potential under climate change

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Abstract:

Recent urban air temperature increase is attributable to the climate change and heat island effects due to urbanization. This combined effects of urbanization and global warming can penetrate into the underground and elevate the subsurface temperature. In the present study, over-100 years measurements of subsurface temperature at a remote rural site were analysed , and an increasing rate of 0.17^0C per decade at soil depth of 30cm due to climate change was identified in the UK, but the subsurface warming in an urban site showed a much higher rate of 0.85^0C per decade at a 30cm depth and 1.18^0C per decade at 100cm. The subsurface urban heat island (SUHI) intensity obtained at the paired urban-rural stations in London showed an unique 'U-shape', i.e. lowest in summer and highest during winter. The maximum SUHII is 3.5^0C at 6:00 AM in December, and the minimum UHII is 0.2^0C at 18:00PM in July. Finally, the effects of SUHI on the energy efficiency of the horizontal ground source heat pump (GSHP) were determined. Provided the same heat pump used, the installation at an urban site will maintain an overall higher COP compared with that at a rural site in all seasons, but the highest COP improvement can be achieved in winter.

Keywords: subsurface, urban heat island, climate change, ground source heat pump, urbanization

1. Introduction

Urban heat island (UHI) refers to a higher urban temperature in the urban centre compared to the surrounding rural areas, which is mainly the consequence of rapid urbanization by changing permeable forest and agriculture landscapes into sealed and water-proof man-made urban texture. A significant urban warming can lead to: 1) deterioration of the human thermal comfort especially during hot summer nights in temperate climate; 2) increase of the building energy consumption by turning on air-conditioning for summer cooling; and 3) exacerbation of carbon emissions from higher electricity demand and energy expenditure. According to [1], there are basically three types of UHI, i.e., urban air heat island, urban surface heat island, and urban subsurface heat island. The former two types are well investigated with different methodologies; however, the latter subsurface urban heat island (SUHI) is much less addressed. As a matter of fact, the subsurface soil temperature is a crucial variable to control the ecosystem's biological and chemical processes such as soil respiration, thawing of permafrost, microbial decomposition and groundwater flow [2]. It also has a strong impact on the underground infrastructure especially in an urban context.

The subsurface soil temperature is determined by the combined effects of ground heat flux, the heat flow from the Earth's interior, the soil thermal properties, as well as the direct anthropogenic stimulations such as sewage networks and reinjection of thermal waste water, poorly-insulated district heating pipes, especially in built-up areas [3]. A higher subsurface temperature can be expected in urban areas. Subsurface warming has been observed and analysed in several cities at various spatial and temporal scales [4,5]. Taniguchi et al. [4] identified the subsurface warming in Tokyo was 2.8 ^{0}C, the strongest among the four cities studied in Asia. One-year measurement of soil temperature at rural and urban locations was conducted in Nanjing, China. The urban soil was found 1.21 ^{0}C warmer than the rural soil [6]. Müller et al [7] studied soil temperature (<=2 m) at eight locations in the city of Oberhausen, Germany. A maximum SUHI of 9^{0}C was found between the city centre station and the rural station. They also pointed out that a high subsurface soil temperature in the city centre had the potential to jeopardize the quality of drinking water from the pipelines. Savva et al [2] measured the daily average soil temperature at a 10-cm depth at both urban and rural sites and found the average annual soil temperature was higher at the urban site. A soil-temperature model was also developed to evaluate the effects of land use changes on soil temperatures. The effects of urbanization on the soil temperature in Ankara were analysed by Turkoglu [8] by comparing paired urban and rural stations. The SUHI was observed higher during night time and lower in the daytime. Yeşilırmak [9] found a general increase of soil temperature in all seasons in Turkey, which was consistent with the increasing trend of air temperature. The highest trend magnitude was 2.05 ^{0}C per decade. Ferguson and Woodbury [10,11] observed that the urban aquifers in urban centre were several degrees (3-5^{0}C) warmer than those in the surrounding rural area. The SUHI was normally analysed for a short term such as one year, a long term observation is still lacking. Moreover, both climate change and urbanization can affect subsurface temperature, but few studies were able to distinguish them. In the present study, long-term observations (over 100 years) at a remote rural station in the UK were conducted to investigate the effect of climate change on SUHI, furthermore two paired station representing urban and rural characteristics in London were employed to examine the difference of SUHI between urban and rural sites.

The subsurface warming has many potential consequences on such as drinking water quality (1-2m subsurface), groundwater systems at a deeper layer (100m) as well as ground thermal energy potential(both shallow and deep layers). Subsurface soil can act as the heat sink in summer and the heat source in winter when being integrated with ground-source heat pumps (GSHP). GSHP is a low-carbon energy-efficient technology for domestic heating and cooling. The performance of the GSHP system is largely determined by the interactions between the heat exchanger and the subsurface soil environment [12]. Therefore, subsurface soil temperature has a predominant influence on the GSHP efficiency such as Coefficient of Performance (COP) [13,14]. The subsurface warming will decrease the efficiency for supplying coolness in summer, but enhance the heating performance in winter [15]. Florides et al [16,17] studied the geothermal properties of the ground in Cyprus for a better utilization of GSHP. They concluded that for the same GSHP used, the efficiency of GSHP for heating in Cyprus was higher than that in Germany due to a higher subsurface soil temperature in Cyprus.

In the UK, it is estimated that the number of installations of GSHP could increase to 35,000 units by 2015 and 55,000 by 2020 [18]. Approximately 44% of the total housing stocks are in favour of horizontal ground source heat pump systems due to the lower installation cost with the slinky ground loop or double tier pipe arrangement installed at the shallow sub-ground layers (usually 1-2m in depth)[14] . To our best knowledge, no studies regarding the effects of SUHI on the horizontal GSHP in London, UK, have been carried out so far. Therefore, the present paper serves two aims: 1) to investigate the effect of urbanization and climate change on SUHI in London; 2) to estimate how the SUHI will affect the performance and potential of horizontal GSHP.

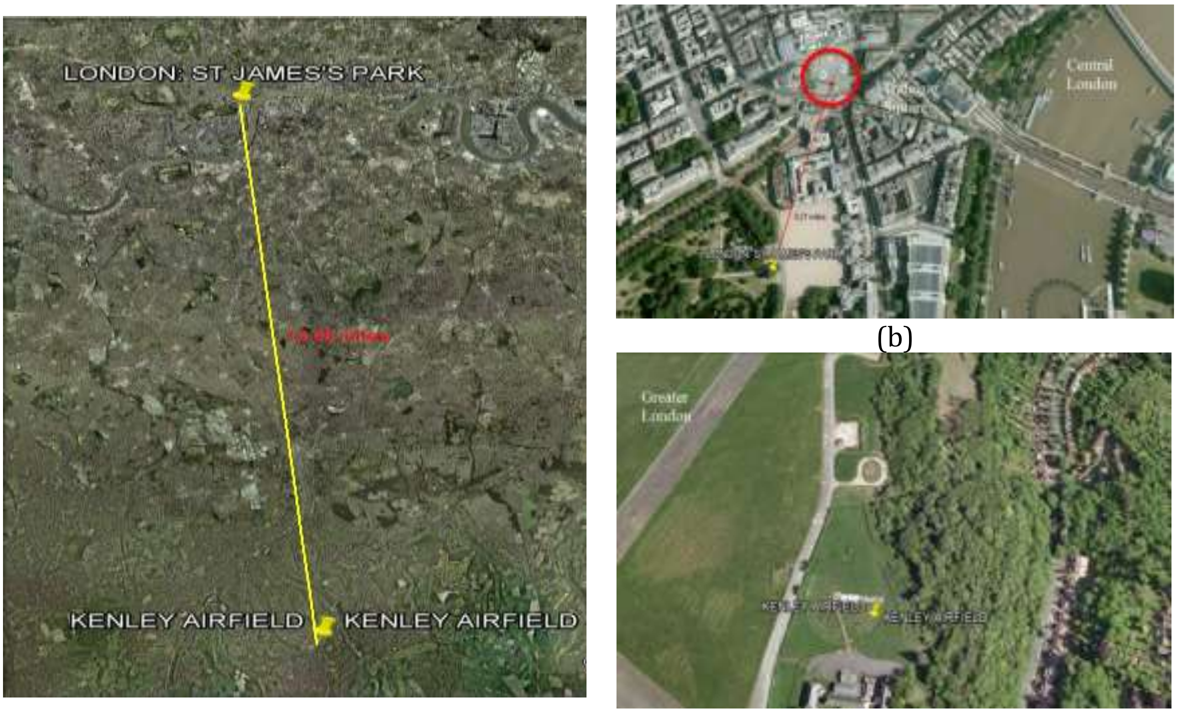
2. Study sites and data collection

In order to investigate the changes of the subsurface soil temperature in the urban and rural environment in London, two stations with long and continuous observation period were chosen. These stations are provided and affiliated with the British Atmosphere Data Centre (BADC). The paired stations representing urban and rural features are located in the Greater London: St James Park (SJP) in central London and Kenley Airfield (KA) in the outskirts of London. As shown in Figure 1, SJP is an urban station (51°30' N, 0°07' W) at an altitude of 5m, which is only 0.27 miles from Trafalgar Square, the most populated area in central London. The SJP station was built in 1903 and started its operation since 01/01/1959 till present. The station of SJP has been used as an urban station for urban air heat island research in many studies although it was located in an urban park [19-21]. Soil temperature at this station was measured once daily at 9:00pm at 30, 50 and 100cm depths from 1980 till present. The hourly soil temperature at 10cm depth was measured since 1999; however, the hourly data were only available from 2000 to 2007. KA station, which is about 20 miles away from SJP, is located in a rural area to the North West of London (51°18' N, 0°05' W), at an altitude of 170m. It commenced on 1st Jan, 1995. Since then, KA station measures hourly soil temperature at 10cm depth and daily soil temperatures at 9:PM at the depths of 10, 30 and 100cm, respectively. To make it comparable, hourly data from 2000-2007 were collected on both stations for analysis.

To investigate the effect of climate change on the subsurface soil temperature, another station, Cockley Park (CP), which is located in the county of Northumberland, UK, was chosen. CP is considered to be free of urban influence as shown in Figure 2. It has an altitude of 95m between N55°12' Latitude and W1°41' Longitude. It was firstly built in

1897, and then operated since 1907. The station recorded daily soil temperatures at different depths at 9:00 PM. But not all depths are recorded every day, only soil temperatures at the depth of 30 cm were recorded continuously from 1907 to 2011. The data collected from 100 cm only cover 1907 to 1959, the other depths such as 10cm, 20cm and 50cm are excluded from current study as more than half of the data were missing. Table 1 lists the characteristics of the three stations.

The instrument for soil temperature measurement was either Liquid-in-glass thermometer or electrical resistance thermometers suspended at different depths below the ground in a steel tube which was sealed at the surface. The accuracy of the thermometers was below 0.2°C which had been validated from the QA lab in Bracknell.



(a) (b) (c)

Figure 1. urban and rural station in Greater London, (a) pair stations on the map with the distance of 14.08 miles; (b) urban characteristics around SJP station; (c) rural characteristics around KA station

Figure 2: Morpeth: Cockley Park (CP) station which is located in the county of Northumberland, UK, with rural characteristics.

Table 1 Three stations for study

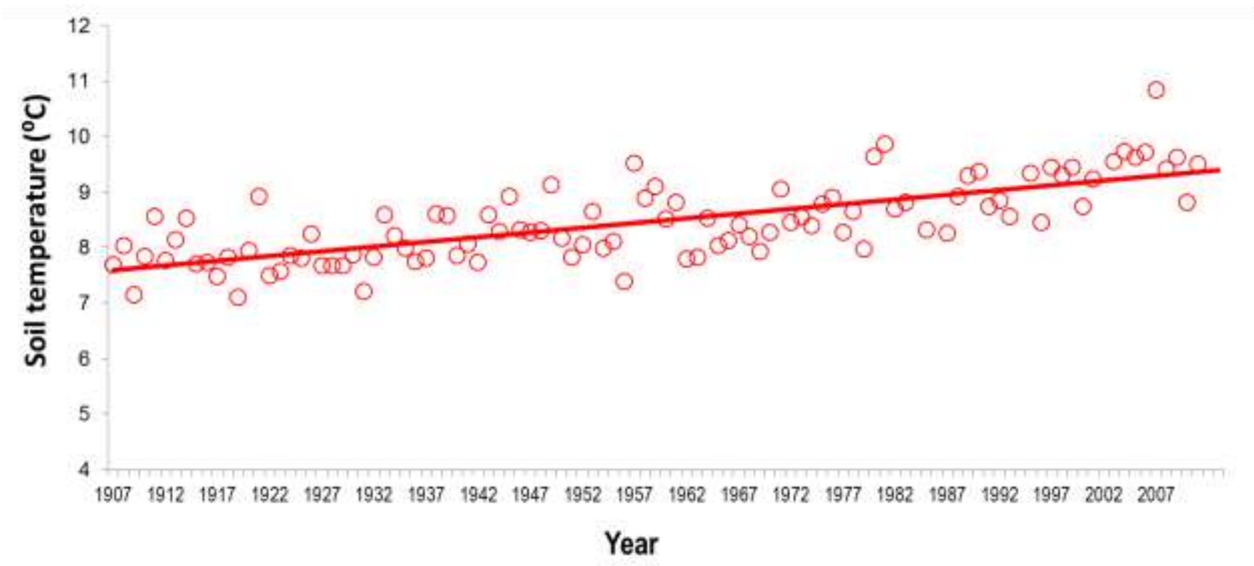
Station	Location	Year		Measurement frequency and depth
		Start	End	
Cockley Park, (CP) Northumberland	Rural	1907	2011	Daily: 9:00PM at 10, 20, 30, 50 and 100 cm; Only 30cm and 100cm are included in current study. Hourly: None
St James Park, (SJP) Central London	Urban	1980	2012	Daily: 9:00PM at 30, 100cm; Hourly: 10cm from 2000-2007
Kenley Airfield, (KA) Greater London	Rural	1995	2012	Daily: 9:00PM at 30, 100cm; Hourly: 10cm from 2000-2007

3. Results and discussions

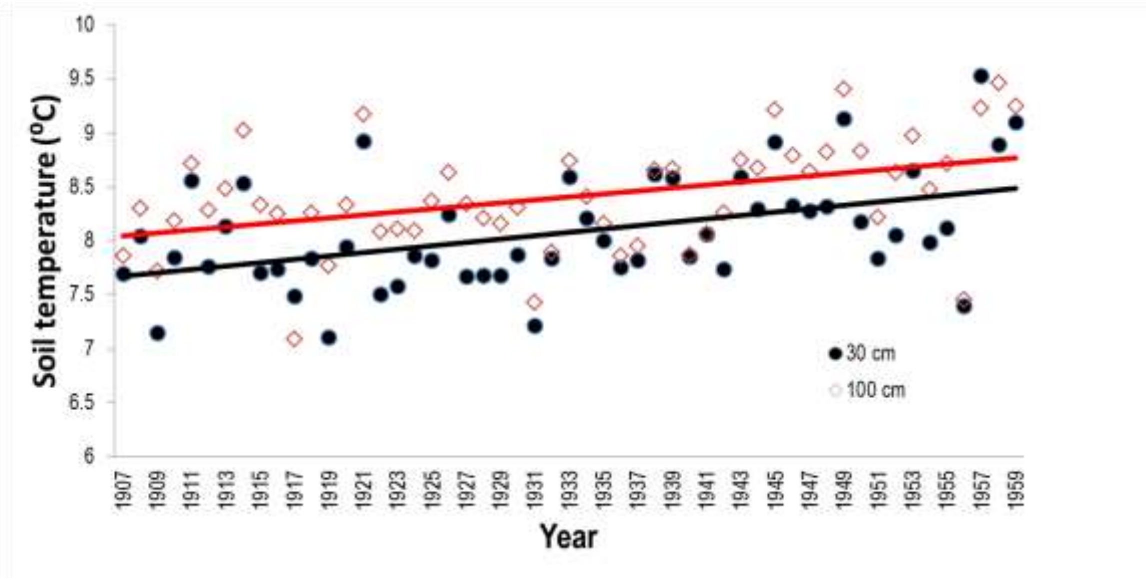
3.1 Long-term (100 years) annual mean soil temperature variations

The non-parametric Mann-Kendall test was employed to search for trends in soil temperature and Sen's Slope estimator was used to predict the magnitudes of the trends. The similar approaches have been adopted to assess the trend in other time-series analysis in climatological and hydrologic studies as suggestd by the World Meteorological Organization (WHO) [8,9,26,27]. When a trend exists, the null hypothesis (H0) is rejected (H0=the slope of the regression is zero). The Mann-Kendall tests were performed using XLSTAT 2015. Mann-Kendall test statistics for soil temperature at different depths at different sites are present in Table1. All sites except for KA show a significant warming trend (at 5% confidence as shown in bold in Table1) at all depths. No significant trend is observed at KA station is partly due to the relatively small number of data available. Annual mean soil temperature data at the depth of 30cm at the remote rural station of CP from 1907 to 2011 were plotted in Fig.3 (a). Over one hundred years, the increasing rate of soil temperature is 0.17ºC per decade in CP. Other studies also reported similar results. Changnon [22] observed an increase of 0.67 K in soil temperature at a depth of 91.5 cm in Urbana, Illinois, USA, during the period of 1903-1947. Yeşilırmak [9] analysed the soil temperature at different depths in Turkey from 1970 to 2006, and found a general positive increasing rate for all seasons and the signal was stronger at upper soil layers. The trend magnitudes were within the spectrum of -0.91 to 2.05ºC decade^{-1}. Carcia-Garcia-Suarez and Bulter [23] reported a soil warming trend within a range of magnituides of 0.04 to 0.25ºC decade^{-1}at three stations in Northern Ireland from 1904 to 2002. The annual trends for both 30cm and 100cm depths were 0.13K/decade. This is one of very few studies with the similar length of observation duration as ours. Compared with other studies available, our analysis result falls in among them. This trend on soil temperature is also comparable to the annual air temperature trends (0.12-0.14ºC decade^{-1}) from 1931 to 2006 at several stations in and around London [24].

As the soil temperature at 100cm was only available from 1907 to 1959, a comparison between 30cm and 100cm can only be made during this period and depicted in Fig.3 (b). Generally, the soil temperature at a deeper depth of 100 cm is higher than that at 30 cm, but exhibiting a similar increasing rate of 0.15°C decade^{-1}. A slightly smaller warming rate of 0.15 °C decade^{-1} was obtained for soil temperature at 30cm at the early half of the 20th century, indicating the climate change became intenser after 1960s. As CP station is located in the rural area which is free of urban influence, the increase of subsurface temperature can be regarded as the sole impact of climate change. The present study showed that the rise in subsurface temperature parallels atmospheric air temperature in the framework of global warming.



(a) At the depth of 30cm from 1907-2011.



(b) At the depths of 30cm and 100cm from 1907 to1959

Figure 3. Annual soil temperature in CP station at 9:00 PM

Table 1 Mann-Kendall test statistics for soil temperature at different depths at different sites

Variables	Z	Slope (^{o}C/decade)
30 cm at CP station (1907-2011)	**8.3**	0.17
100cm at CP station (1907-1959)	**3.28**	0.15
30cm at CP station (1907-1959)	**3.41**	0.15
30 cm at SJP station (1980-2012)	**4.32**	0.85
100 cm at SJP station (1980-2012)	**4.62**	1.18
30 cm at KA station (1994-2012)	0.56	0.26
100 cm at KA station (1994-2012)	1.85	0.75

Z, Mann–Kendall test statistics; slope, Sen's Slope Estimator. Significant trends at 5% level are shown in bold

3.2 Urban vs. rural observations

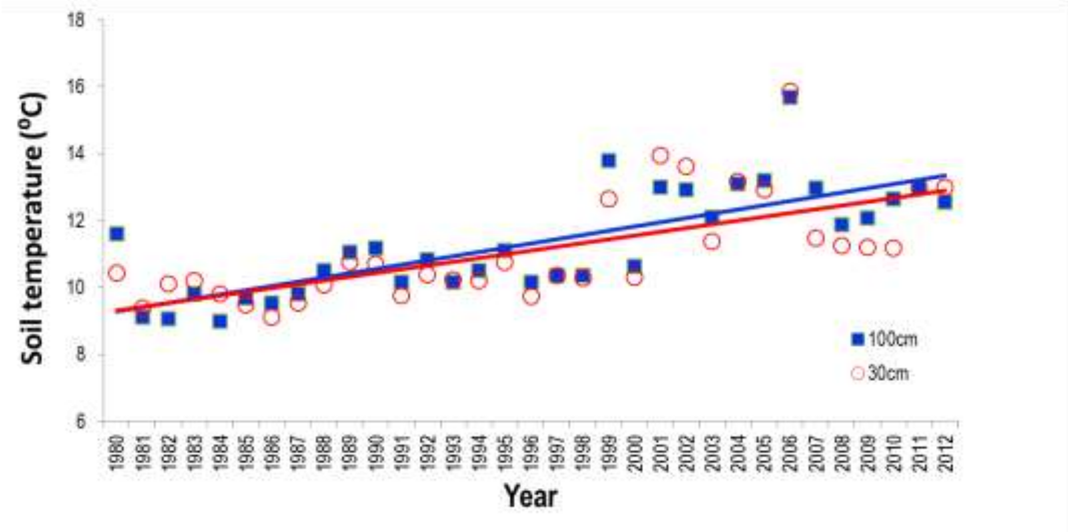
In order to investigate the urbanization effect, the soil temperature at two depths of 30cm and 100cm collected from urban and rural stations in London were futher analysed and shown in Fig.4. A much more profound warming trend (1.18^{o}C decade^{-1} at 100cm and 0.85^{o}C decade^{-1} at 30cm) is observed in SJP at all depths compared with that at the rural station of KA. The temperature time profile at KA is rather flat and there is no trend observed at 5% significance level as shown in Table1. The temperature difference between 30 cm and 100 cm is not significant at both sites. This rising rate of temperature in urban station is a result of combined effect of urbanization and climate change. By subtracting the temperature increase of 0.17^{o}C decade^{-1} due to climate change from the value due to combined effects, the warming rate attributable to urbanization alone can be roughly estimated as 0.7^{o}C per decade at 30-cm depth. Therefore, the signal of urbanization preserved in the subsurface soil accounts for almost 5 times of that due to climate change alone previously reported at CP station.

The monthly mean soil temperature at 10cm at both stations and the resultant urban heat island intensity (UHII) (difference between urban and rural soil temperature) are shown in Fig.5. Four typical hours per day, i.e., 6:00, 12:00, 18:00 and 24:00 are chosen. Generally, urban soil temperautres are higher than their rural counterparts in all months. The maximum temperature occurred in July or August and minimum soil temperautre was observed in Janary or December at both sites. This shows the similar pattern as monthly air temperature. During warm months, the ground surface temperature is higher than the deep soil temperature due to the strong solar radiation, the heat is conducted from the ground surface to the deeper layers. While in cold winter, the heat condiction direction reverses especially at nighttime or when there is a snow cover.

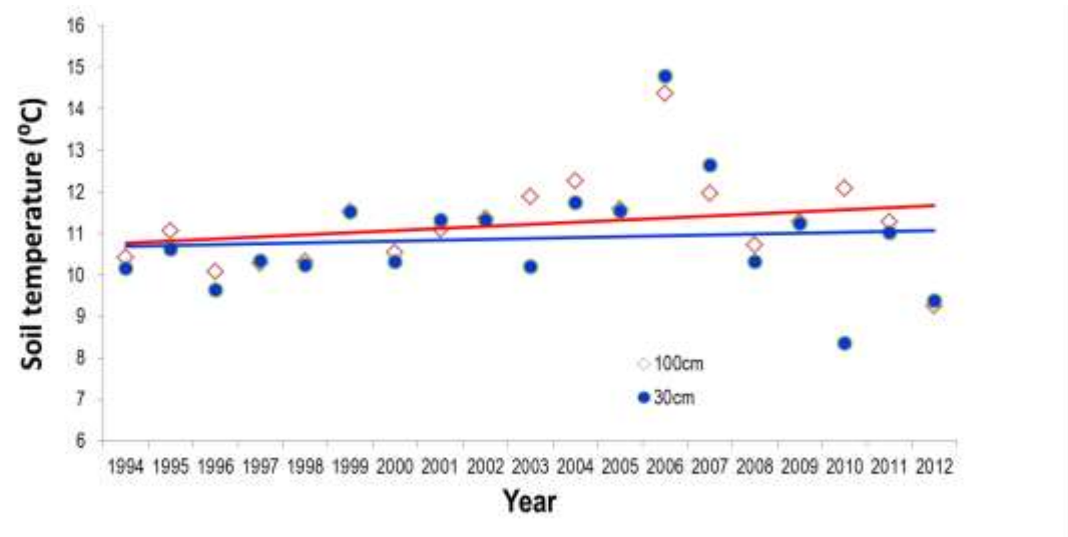
On the contrary, the SUHII exhibits a typical U-shape, by peaking in cold winter months and valleying in warm summer months. The maximum UHII is 3.5^{0}C at 6:00 AM in December, and the minimum UHII is 0.2^{0}C at 18:00PM in July. This pattern is totally different from the observation in Ankara,Turkey [8] and Nanjing, China [6]. A higher

UHII was confirmed in warm seasons compared to cool seasons in Ankara, Turkey (see Fig.2 in [8]), while a 'W-shape' UHII curve was found in Nanjing (see Fig.6 in [6]). This may be due to the different climates and anthropogenic heat patterns in these cities. Both Ankara and Nanjing have a hot summer and cool winter, where cooling in summer predominates building energy consumption compared to winter. Significant anthropogenic heat was released into urban areas in summer periods, which contributes a significant part to the higher urban heat island intensity. In Nanjing, there is few central-controlled heating systems in winter, but the local heating such as air-source heat pump and household gas boiler emerged in recent years. This may explain why there is a slightly higher UHII in winter than the transition periods of spring and autumn in Nanjing. While London in the UK enjoys cool summer and cold winter. Most of building energy is used for space heating in winter, a large contribution of anthropogentic heat released in the urban areas was from heating in winter [25], which may enhance the urban heat island intensity both above and below the ground surface. This echoes a similar monthly UHI pattern of air temperature observed in London.

Subsurface thermal anomalies derived from paired urban and rural observations are directly attributable to two types of controlling parameters including the external meteorological forces acting on the soil-atmosphere interface (solar radiation, air temperature, wind speed etc), and soil thermal properties (heat capacity, thermal conductivity, and moisture content etc). Urbanization alters these parameters by changing the landscape, landuse, surface cover and anthropogenic heat. The replacement of natural landscape with man-made impervous materials in urban area makes it possible to store more heat in the subsurface soil. The extra heat discharge from subsurface infrastructure and heat loss from basement can further elevate the underground soil temperature. No information about the soil thermal properties of current urban and rural sites is available to allow a further interpretation of the data, but previous study in Nanjing showed a relatively drier soil was observed in urban site, contributing to the higher urban soil temperature[6].

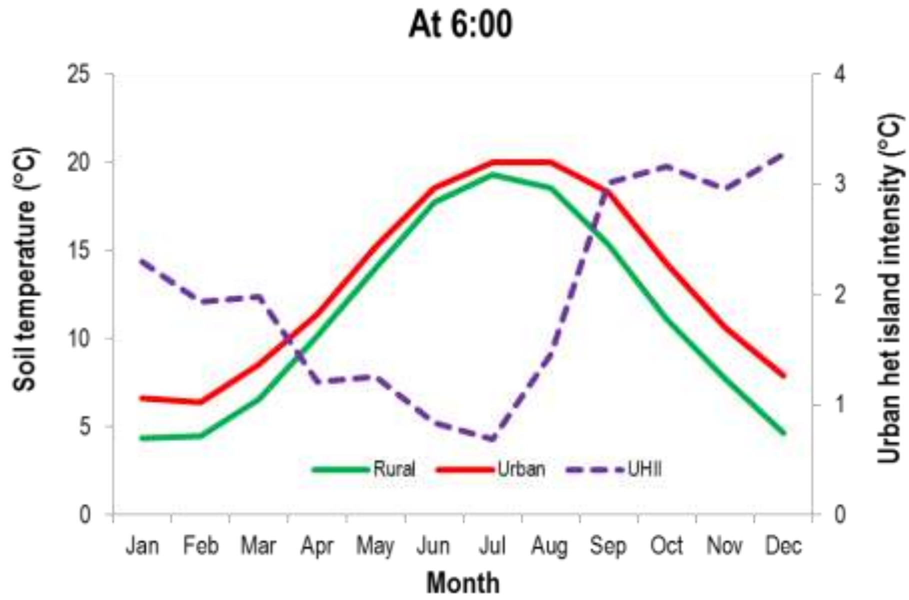


(a) Urban station: SJP

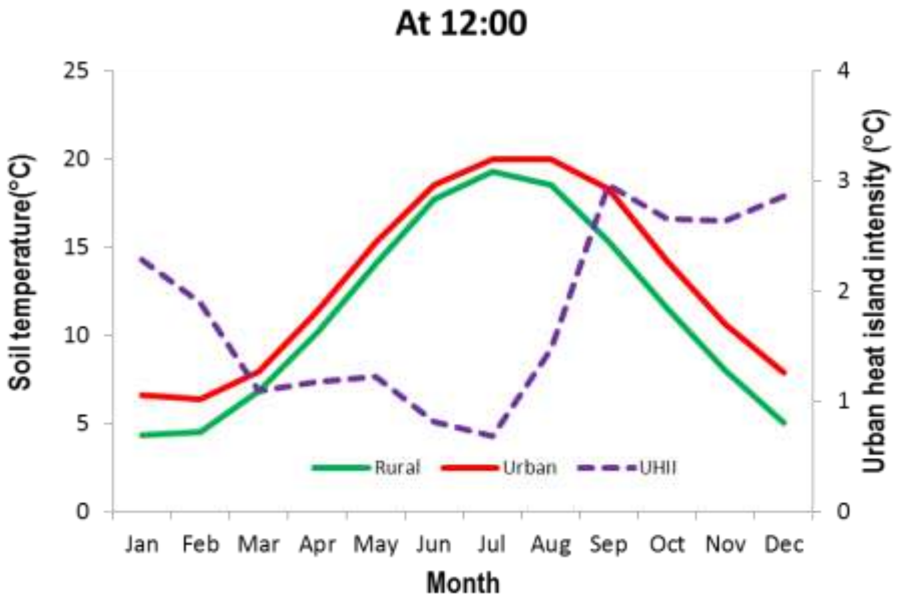


(b) Rural station: KA

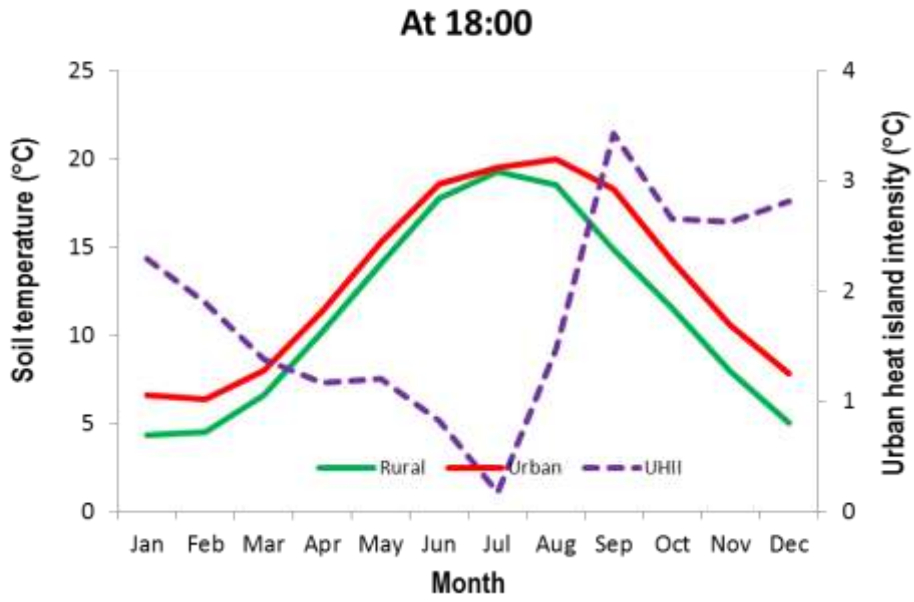
Figure 4. Comparation of yearly soil temperature at depths of 30 and 100 cm at 9:00 PM between urban and rural stations



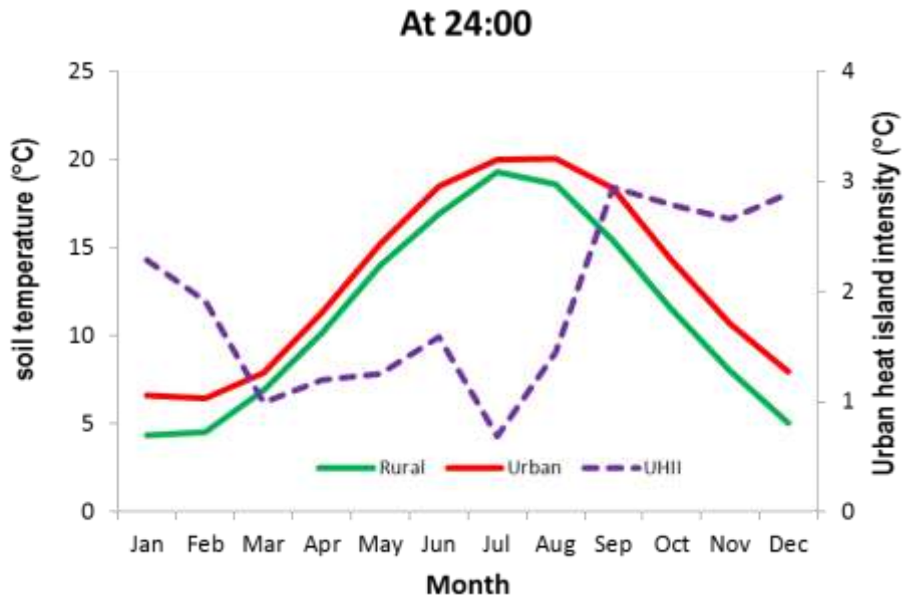
(a) At 6:00



(b) At 12:00



(c) at 18:00



(d) At 24:00

Figure 5 monthly soil temperautre and UHI intensity at 10 cm at urban and rural stations

3.3 Effects on ground source heat pump effiency

The coefficient of performance (COP) of the horizontal GSHP is directly affected by the subsurface soil temperature. Wu et al [14] monitored and measured the performance of a horizontal slinky GSHP for two months in UK. They found the average COP was 2.5 and it decreased with running time as heat was continuously extracted from the soil thermal reservoir. The thermal contrast between urban and rural subsurface will also give rise to the different system performance of horizontal GSHP. The elevated urban soil temperature in winter can improve the COP when GSHP is installed in urban areas.

The seasonal variation of SUHI at both urban and rural sites was calculated and shown in Fig.6. SUHI is higher in autumn and winter when the heating is needed. Therefore, the corresponding GSHP COP with respect to the subsurface soil temperature in both urban and rural areas in heating periods can be determined and shown in Fig.7. The relationship curve (black line) was reproduced from Fig.4 in [16]. The orange-filled circles represented the GSHP installed in urban site while the blue-filled circles were the ones in rural site. It shows clearly that in autumn the GSHP COP in urban site is around 3.3 while that in rural site is about 3.05. In winter, both the GSHP efficiencies are low, but the COP in urban site is still about 0.2 higher than that in rural site. This confirms that, provided the same heat pumps are used, the installation in an urban site will ensure a higher COP for heating than that in a rural site. There are many concerns of the imbalanced heat discharge and storage during the annual operation of GSHP. In warm climate where cooling load is larger than heating load, the heat injected into the ground will be higher than the heat extracted during heating period which gives rise to the decreased working efficiency. This will be exacerbated in urban sites by elevated SUHI. However, for the climate in the UK, where the heating load in winter is predominantly larger than cooling load in summer, SUHI on urban sites will alleviate such imbalance.

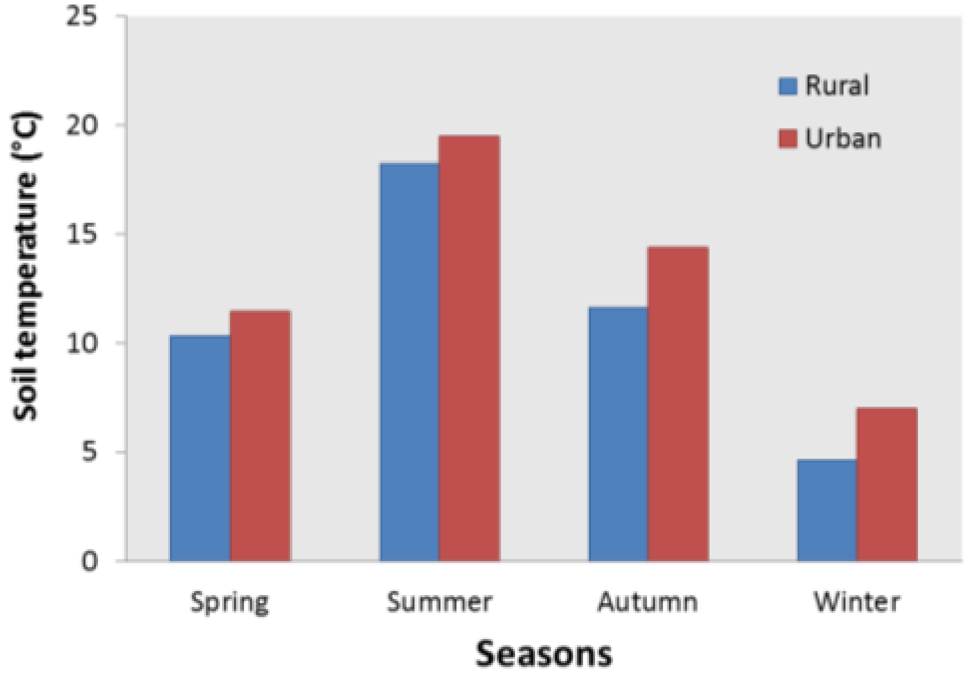


Figure 6. Seasonal variation of soil temperature in urban and rural sites

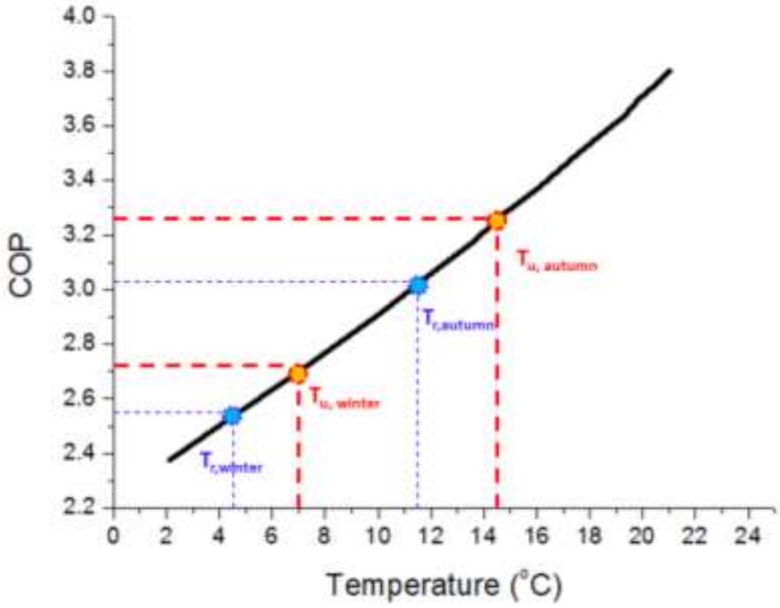


Figure 7. GSHP efficiency with respect to subsurface soil temperature (reproduced from [16]).

4. Limitations and future works

Although our paper presents the first study of subsurface urban heat island on horizontal GSHP, it should be noted that it is subject to some limitations and uncertainties：1）There may be other influential factors contributing to the elevated subsurface soil temperature observed in the urban site, such as permanent local heat sources (heating pipes, heat sources from building basement etc), different soil physical properties；2) Horizontal ground-source heat pump will be influenced by direct solar gains, which is not considered in the present work and deserves future study. 3）Only COP of GSHP is considered in present paper as as it is the most important indicator of the efficiency of GSHP, however, the influence of subsurface urban heat island on the total energy demand can be studied by employing a whole-building energy modelling approach such as Trnsys which we aim to study in the future.

5. Conclusions

Many studies on urban heat island are devoted to the analysis of the surface and air temperatures, few address the subsurface soil warming. This study analysed the long-term data of subsurface soil temperature observations in three weather stations in the UK. One station located in a remote rural site and free of urban influence contains a long-term measurements over 100 years. Paired urban-rural stations in London were chosen as the hourly soil temperature data were continuously recorded from 2000 to 2007. The characteristics of subsurface warming due to urbanization and climate change were identified. The further effects on the performance of the horizontal ground source heap pump were also evaluated. The following conclusions can be drawn from present study:

- An increasing rate of 0.17^{o}C per decade due to climate change was identified in the UK, but the subsurface warming in an urban site in London shows a much higher rate of 1.18^{o}C /decade at the soil depth of 100cm.
- A positive warming trend of 0.7^{o}C /decade at 30-cm depth was regarded to be attributable to urbanization alone, indicating an undeniable global warming effect due to the subsurface urban heat island.
- SUHII in London exhibits an unique 'U-shape', showing lowest in summer and highest during winter. The maximum SUHII is 3.5^{0}C at 6:00 AM in December, and the minimum UHII is 0.2^{0}C at 18:00PM in July.
- Provided the same heat pump used, the COP is consistently higher in urban sites than that installed in rural sites. The improvement of COP can be as high as ~0.2 in winter.
- In the climate of UK where the heating load in winter is predominantly larger than cooling load in summer, a larger SUHII during winter time will help to alleviate such imbalance of heat storage and discharge annually by GSHP when the GSHP is installed on urban sites.

Acknowledgments

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