Environmental Pollution 208 (2016) 118–124

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Data concurrency is required for estimating urban heat island intensity

Shuqing Zhao [a], [*], Decheng Zhou [a], Shuguang Liu [b]

[a] College of Urban and Environmental Sciences, and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing 100871, China
[b] Geospatial Science Center of Excellence (GSCE), South Dakota State University, Brookings SD 57007, USA

ARTICLE INFO

Article history:
Received 23 April 2015
Received in revised form
21 July 2015
Accepted 23 July 2015
Available online 1 August 2015

Keywords:
Urban heat island (UHI)
Definition of UHI
Urban expansion
Mapping urban extent
Concurrency of data

ABSTRACT

Urban heat island (UHI) can generate profound impacts on socioeconomics, human life, and the environment. Most previous studies have estimated UHI intensity using outdated urban extent maps to define urban and its surrounding areas, and the impacts of urban boundary expansion have never been quantified. Here, we assess the possible biases in UHI intensity estimates induced by outdated urban boundary maps using MODIS Land surface temperature (LST) data from 2009 to 2011 for China's 32 major cities, in combination with the urban boundaries generated from urban extent maps of the years 2000, 2005 and 2010. Our results suggest that it is critical to use concurrent urban extent and LST maps to estimate UHI at the city and national levels. Specific definition of UHI matters for the direction and magnitude of potential biases in estimating UHI intensity using outdated urban extent maps.

1. Introduction

Urbanization, broadly defined as a simultaneous process of demographic shift from rural to urbanized areas and physical urban land expansion, represents the most visible and pervasive human-driven modifications to the Earth System (Seto et al., 2010; Wu, 2014). More than half of humanity now resides in urban areas and more will follow (UN, 2014). Urban land expansion is an indispensable process to accommodate increasing urban population. Urban heat island (UHI), a phenomenon that urban centers experience elevated temperature compared to neighboring suburban or rural areas (Howard, 1833; Manley, 1958; Oke, 1973), is one of the most important manifestations of urbanization-induced impacts. UHI can generate profound impacts on socioeconomics, human life, and the environment such as increased energy consumption for cooling (Kolokotroni et al., 2012), compromised human health and comfort (Patz et al., 2005), and degraded water and air quality (EPA, 2003; Sarrat et al., 2006). Therefore, UHI effects have received significant attention in recent decade, particularly across large geographical areas thanks to the development of thermal remote sensing technology (Imhoff et al., 2010; Schwarz et al., 2011; Peng et al., 2012; Clinton and Gong, 2013; Zhao et al., 2014; Zhou et al., 2014).

UHI is typically presented as the temperature difference between urban and its surrounding areas. It is therefore a necessary first step to accurately define and map urban and its surrounding areas. The land cover map of a city provides an objectively quantifiable and consistent basis to define urban and non-urban areas, and urban development intensity across large areas (Imhoff et al., 2010). However, it is still a challenge to obtain a series of dynamic urban extent maps at regional to global scales (Schneider et al., 2010). As a consequence, most previous studies have characterized UHI intensity based on outdated urban extent maps that might fail to capture the influence of urban boundary expansion. For example, Imhoff et al. (2010) assessed the UHI intensity in 38 of the most populous cities in the continental United States using MODIS land surface temperature (LST) averaged over three annual cycles (2003–2005), but their urban extents were derived from Landsat TM-based NLCD for 2001. Peng et al. (2012) characterized UHI intensity across 419 big cities in the world using MODIS LST data from 2003 to 2008. However, their corresponding land cover, the basis for defining urban extent, was the 2000 MODIS Global Land Cover Map. Zhou et al. (2013) studied the UHI intensity of European cities using MODIS LST daytime data from 2006 to 2011 and the 2006 CORINE land cover map.

---

[*] Corresponding author.
E-mail address: sqzhao@urban.pku.edu.cn (S. Zhao).

http://dx.doi.org/10.1016/j.envpol.2015.07.037
0269-7491/

Given the rapid conversion of land from non-urban to urban and the equally rapid intensification of urban land uses within existing built up areas, the lack of concurrency in LST and urban extent maps might lead to significant biases in estimated UHI intensity, especially for the regions undergoing rapid urban expansion. However, the impacts have never been quantified. In a previous study, we quantified UHI intensity in China's 32 major cities based on urban boundaries defined by dynamic urban extent maps from 2003 to 2011, but did not explicitly explore the possible biases using outdated urban boundary maps (Zhou et al., 2014). In the present study, we attempted to investigate the possible biases in UHI intensity estimation induced by outdated urban boundary maps using MODIS Land surface temperature data from 2009 to 2011 for China's 32 major cities, in combination with the urban boundaries generated from urban extent maps of the years 2000, 2005 and 2010. Our null hypothesis is that the concurrency of urban boundary and land surface temperature maps is not required to estimate UHI intensity.

2. Data and methods

2.1. Study cities

This study covered China's 32 major cities including municipalities, provincial/autonomous regional capitals, and the city of Shenzhen. Shenzhen, the first Special Economic Zone established in 1978 by the Chinese government, was included because it is now considered one of the fastest growing cities in the world (Fig. 1).

2.2. Data

Cloud-free Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM) remote sensing imageries with a resolution of 30 m × 30 m, were used to obtain the information on urban land cover and extent maps of those 32 cities for the years 2000, 2005 and 2010. The urban land was defined as all non-vegetative areas dominated by human-made surfaces (e.g., roads, parking lots and buildings), including residential, commercial, industrial, and transportation space. The detailed procedures on how to derive the extent of urban area can be found in our previous work (Zhao et al., 2015).

Remotely sensed land surface temperature (i.e., LST) data were used to characterize the temperature difference between urban and its surrounding areas. The LST data for each city from 2009 to 2011 were obtained from Aqua MODIS 8-days composite products (version 5) with a spatial resolution of 1 km × 1 km (MYD11A2). The LST products include daytime (13:30 h) and nighttime (1:30 h) temperature observations.

2.3. Analysis

In this study, we defined the UHI intensity as the LST difference between urban and its surrounding suburban areas. Following the commonly adopted convention (Schneider et al., 2009), all areas dominated by built-up land (>50%) was defined as urban areas. Specifically, an impervious surface area (i.e., ISA) map indicating urban development intensity was first generated from urban

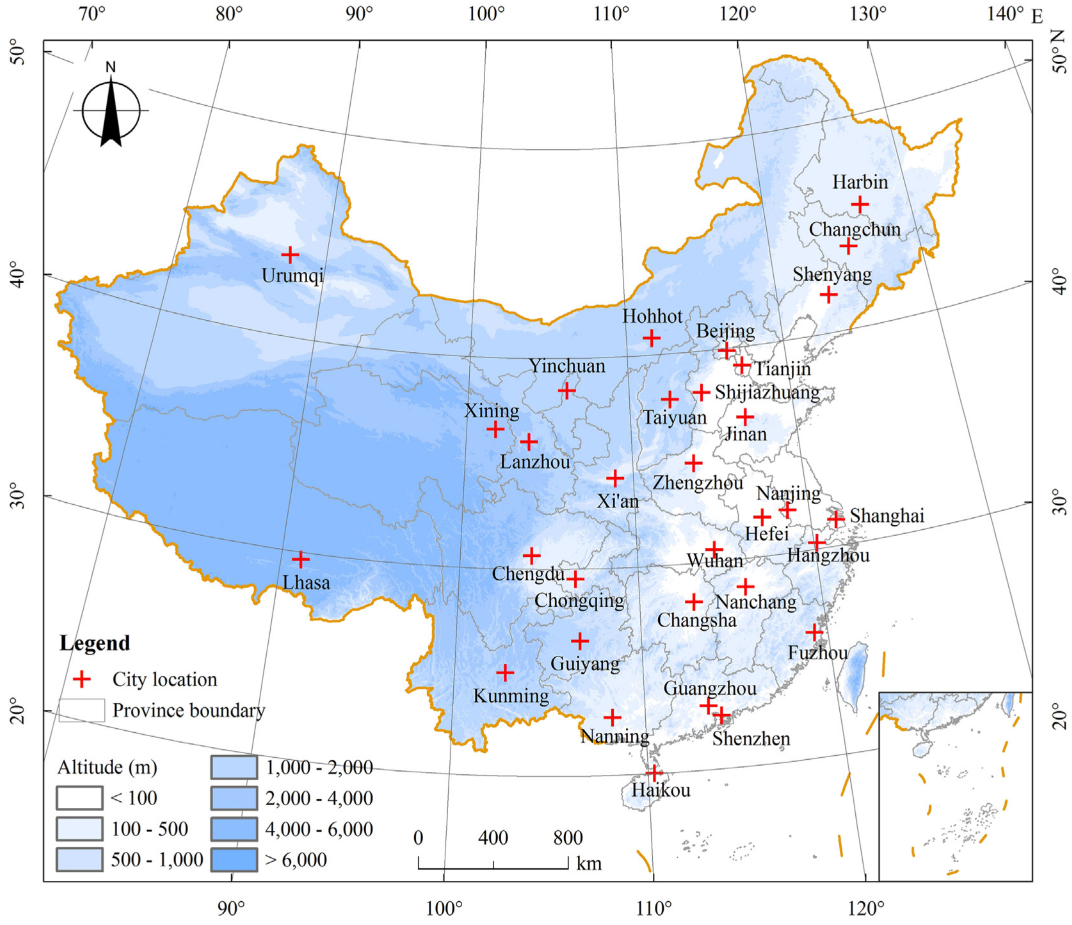

Fig. 1. The locations of 32 major cities in China. All of them are municipalities or provincial/autonomous regional capitals except Shenzhen, which is China's first special economic zone established in 1978 and is now considered one of the fastest growing cities in the world. The background map shows the topography of China.

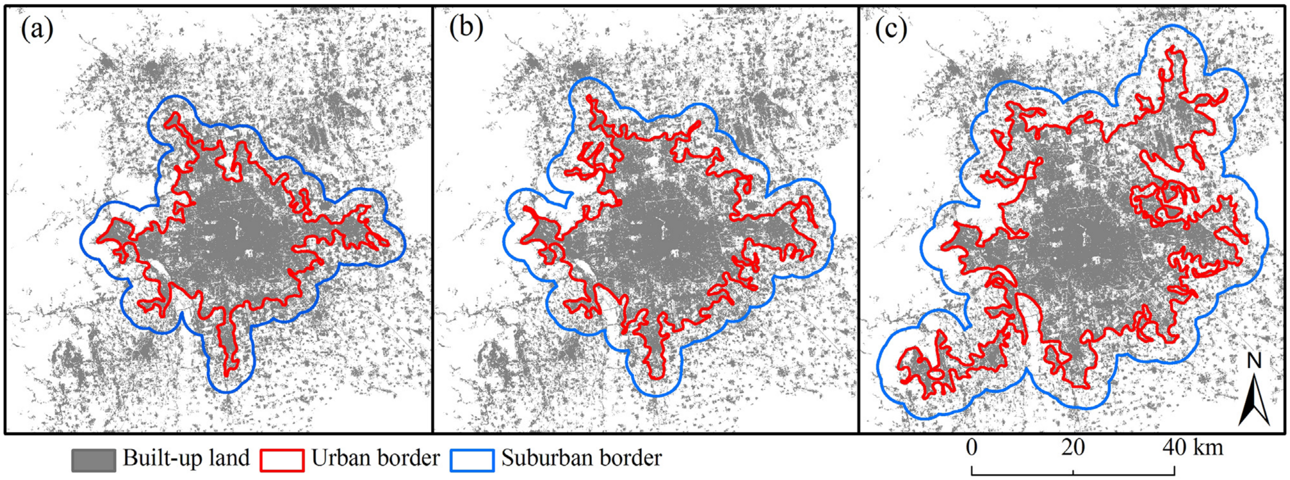

Fig. 2. The delineation of urban and suburban areas, using Beijing as an example. Urban and suburban areas were delineated based on urban extent maps of the years 2000, 2005 and 2010, respectively. The urban extent map of 2010 (grey area) is the base urban land cover map. The red line stands for the border of urban area, the land within the border was considered as the urban area, and that outside the red line but within the blue line represents the suburban area that covers the same amount of land as the urban area.

extent map using a 1 km × 1 km moving window, which matches the pixel size of MODIS LST data. The areas with an ISA of more than 50% were then aggregated to delineate the urban border using an aggregation distance of 2 km, which is equivalent to two MODIS LST pixels and sufficient to include the scattered and most adjacent high-intensity built-up patches into the urban area. The land within the urban border (excluding water pixels) was considered as the urban area of a city. A buffer zone around the urban area (excluding water pixels), having exactly the same size as the urban area, was defined as the suburban area (Zhou et al., 2014). The urban and suburban areas for each city were generated based on urban extent maps of the years 2000, 2005 and 2010, respectively (Fig. 2).

UHI intensity was calculated as the MODIS LST difference between the urban and suburban areas (Peng et al., 2012; Zhou et al., 2014). The LST averaged from 2009 to 2011 using urban extent map of 2010 was used as the base LST map to investigate the possible biases in UHI intensity estimation induced by using outdated urban boundary. Annual and seasonal UHI intensities in the day and at night were then separately calculated using urban extent maps from 2000, 2005, and 2010. Summer and winter were defined as the periods from June to August, and from December to February, respectively. Any differences in the estimated UHI intensity between the outdated maps and that of 2010 would be considered as the impacts of lacking concurrency in the urban extent maps.

Two methods were used to investigate the impacts of lacking concurrency in the two data layers. First, UHI intensity comparison between using concurrent and outdated urban extent maps across 32 cities was performed using total least square (TLS) regression or orthogonal regression analysis (Van Huffel and Vanderwalle, 1991). The reason that TLS regression rather than the ordinary least square regression was used was both UHI intensities estimated from using the concurrent and outdated extent maps contained errors and they were independent. Second, impacts of lacking concurrency might vary across cities. To examine the overall impacts across all cities, we generated and examined the probability density functions (PDF) of the bootstrapped mean differences of UHI intensity. All statistical analyses in this study were performed using the R packages (R Development Core Team, 2013).

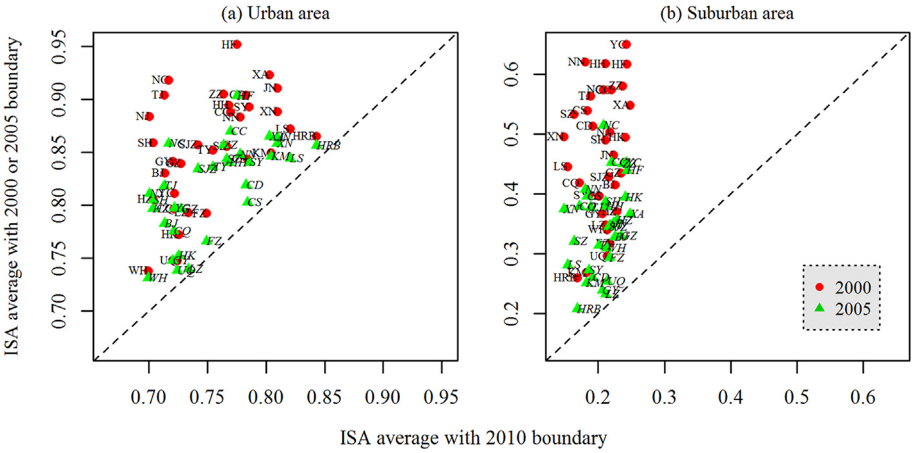

Fig. 3. Comparison of ISA averages in 2010 for the urban and suburban areas of 32 cities defined by outdated boundary of 2000 or 2005, and concurrent boundary of 2010. City acronyms are shown in plain and italic fonts for 2000 and 2005, respectively. BJ: Beijing; CC: Changchun; CS: Changsha; CD: Chengdu; CQ: Chongqing; FZ: Fuzhou; GZ: Guangzhou; GY: Guiyang; HK: Haikou; HZ: Hangzhou; HRB: Harbin; HF: Hefei; HH: Hohhot; JN: Jinan; KM: Kunming; LZ: Lanzhou; LS: Lhasa; NC: Nanchang; NJ: Nanjing; NN: Nanning; SH: Shanghai; SY: Shenyang; SZ: Shenzhen; SJZ: Shijiazhuang; TY: Taiyuan; TJ: Tianjin; UQ: Urumqi; WH: Wuhan; XA: Xi'an; XN: Xining; YC: Yinchuan; ZZ: Zhengzhou.

3. Results

3.1. ISA averages calculated from different urban boundaries

Fig. 3 compares the 2010 ISA averages calculated from urban boundaries derived from 2000, 2005, and 2010 maps across all 32 cities. ISA values calculated using earlier urban boundaries were all higher than those based on the 2010 boundary for both the urban and suburban areas in the 32 cities. The differences between using 2010 and 2000 boundaries were larger than those between using 2010 and 2005 boundaries. In addition, the differences in the suburban areas were higher than their counterparts in the urban areas.

3.2. UHI intensity averages calculated from different urban boundaries

The 2010 UHI intensity averages calculated using urban boundaries derived from different time periods were highly correlated with the Pearson correlation coefficients ranging from 0.78 in summer day to 0.96 during winter night ($p < 0.0001$). It can be seen from Fig. 4 that the 2010 UHI intensity can be either over- or under-estimated at the city level using any of the boundaries. However, there was a strong tendency of underestimation for daytime UHI intensity as most of the data points in Fig. 4 were below the 1:1 line.

The probability density functions (PDF) of the estimated bootstrapped means of the UHI intensity differences between the concurrent and outdated urban boundaries for the 32 cities showed the significance of the biases on average across the 32 cities in China (Fig. 5). Overall, the daytime UHI intensities tended to be strongly underestimated when using dated (non-concurrent) urban boundaries, and the larger the non-concurrent gap, the higher the bias in the estimate. Specifically, the mean UHI intensity of the 32 cities during the daytime, regardless of the time period considered (summer, winter or the entire year), would be all negatively biased if the boundary used was from 2000, and two out of three would be all negatively biased if the boundary layer was from 2005. Although the biases of UHI during summer daytime were heavily and negatively biased, small positive biases were possible. In addition, the modes of the PDF indicated that the modes of the relative biases during daytime were all higher than 50%. Although the absolute mean biases were only a fraction of a degree, they were very significant for UHI estimation. These results suggested the null hypothesis that the concurrency of LST and urban extent maps is not required for estimating UHI intensity should be rejected during the day.

The concurrency of boundary and temperature layers is not required for estimating the mean UHI during nighttime across the 32 cities except for the summer night UHI estimated using 2000 boundary (Fig. 5). The main reason for not requiring the concurrency was probably related to the low responses of the nighttime UHI to the mismatch of boundary and temperature fields in China on average. None of the 6000 bootstrapped mean UHI differences for the 32 cities for nighttime was higher than 0.3 °C.

4. Discussion

The responses of UHI to varying dated boundaries were not as consistent as those of ISA across cities. At city level, ISA values were consistently overestimated if the urban boundaries were not concurrent, particularly in the suburban areas (Fig. 3). This overestimation signifies the intensification of urbanization (i.e., the increase of urban built-up fraction) that has occurred in China along with the fast urban expansion in China. In contrast, the UHI responses at city level was more complex than ISA responses, showing the existence of both negative and positive responses across the 32 cities, owing to a variety of driving factors and processes for UHI (Oke, 1982; Arnfield, 2003).

Our results suggest that it is critical to use concurrent urban extent and LST maps to estimate UHI at the city and national levels. We found that the underestimation of daytime UHI intensity using

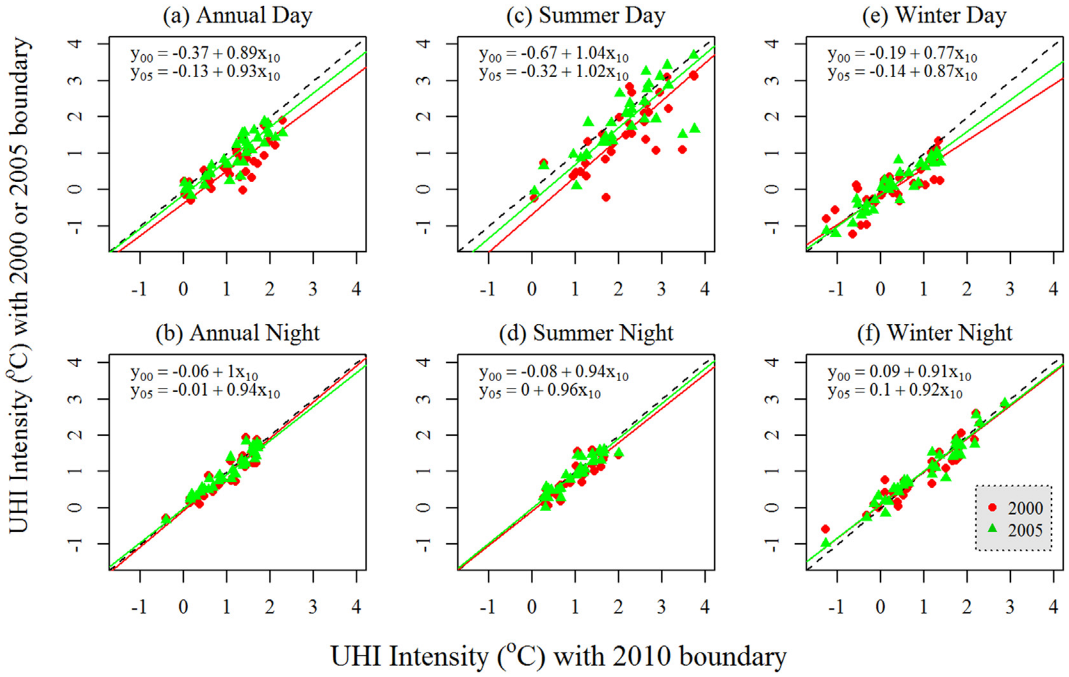

Fig. 4. Comparison of UHI intensity averages from 2009 to 2011 for 32 cities based on urban and suburban areas defined by outdated boundary of 2000 or 2005, and concurrent boundary of 2010. Points above the 1:1 line (dashed) would indicate overestimation of UHI intensity relative to that using the 2010 urban boundary, and points below indicate underestimation.

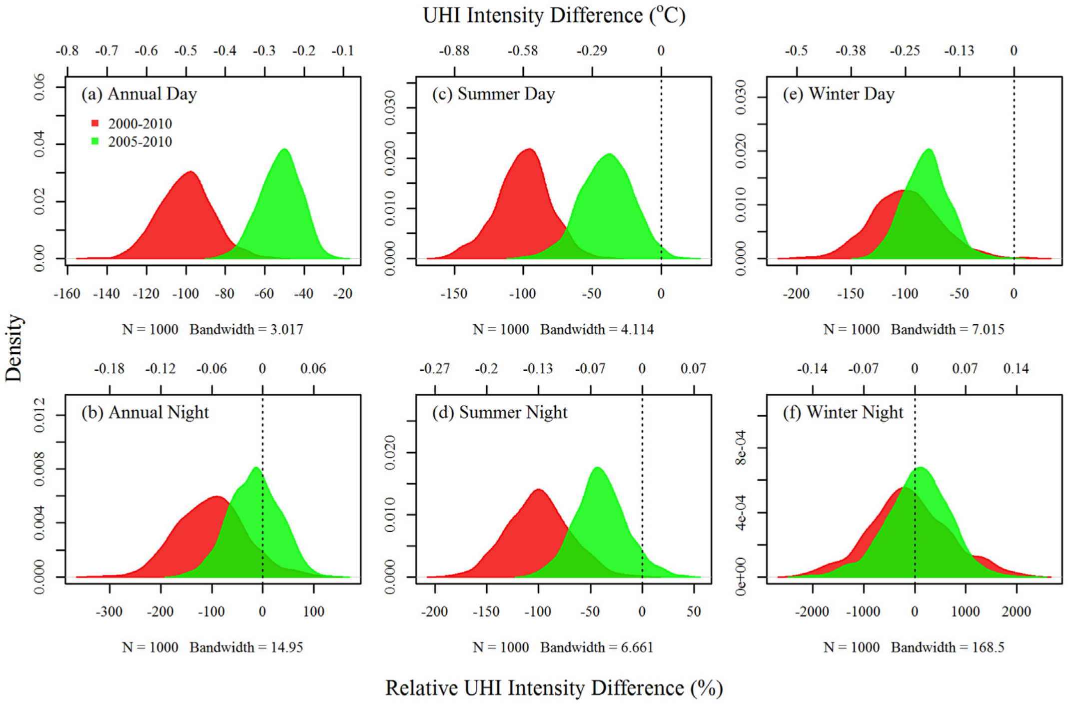

Fig. 5. The probability density functions (PDF) of the bootstrapped means of the UHI intensity differences between the outdated (2000 or 2005) and concurrent (2010) urban boundaries for the 32 cities when defining the UHI as the urban–suburban difference. The reference line of zero difference (dashed vertical line) is drawn to show if any of the distributions is significantly different from zero.

outdated urban extent maps can be higher than 50% of the actual UHI intensity. These findings have two implications. First, it might imply that previous studies using outdated urban extent maps might have vastly misestimated UHI estimates. Therefore there is an urgent need to reevaluate the magnitude of UHI intensity using concurrent land cover maps. Second, the need for concurrent urban extent maps for UHI studies in essence calls for accurate land cover maps in urban environment because inaccurate land cover maps can lead to large biases in UHI intensity estimates. This echoes the observation that explicitly mapping the extent and dynamic characteristics of urban areas accurately and timely is essential for understanding the impact of humans on the environment (Ramalho and Hobbs, 2012).

It is worthwhile to explore and understand why data concurrency is needed for daytime UHI but not for nighttime UHI intensity. The formation of UHI during daytime is largely driven by solar radiation and distinct radiative and thermal properties of urban land surfaces. Particularly, evapotranspiration cooling effect is greatly subdued in the urban areas compared with surroundings and more energy is partitioned into sensible heat or trapped in the environment (Grimmond and Oke, 1991). Because the driving forces of daytime UHI are highly related to urban development intensity, it is therefore critical to map land surface conditions accurately and timely which demands the concurrency of land cover maps. On the other hand, the major driving forces for UHI at night when there is no solar radiation and minimal evapotranspiration are quite different from those during the day. The major drivers for nighttime UHI are mainly the release of solar energy trapped during the day and anthropogenic heating sources (Oke, 1981; Voogt and Oke, 2003). The change of dominance in driving forces between day and night produce two distinct patterns of heat domes: one characterized by the urban–rural temperature “cliff” (Oke, 1982) during the day and the other by gradual urban–rural temperature decline during the night (Zhou et al., 2015). Therefore, estimating UHI intensity during the day would require a closer match of land cover map and land surface temperature map (i.e., data concurrency) than at night because the land surface temperature gradient is larger during the day than that at night.

In this study, we defined the UHI using the urban–suburban difference. Many previous studies defined the UHI as the urban–rural difference (e.g., Oke, 1982; Runnalls and Oke, 2000; Stewart, 2011). Difference in UHI definition does matter for quantifying the magnitude and pattern of UHI effect (Schwarz et al., 2011; Zhou et al., 2015). To examine the generality of our results, we also investigated the potential biases in estimating UHI intensity defined by the urban–rural difference (rural area is defined as ISA $\leq 5\%$). Results still suggest the importance of data concurrency for UHI assessment (Fig. 6). However, a strong tendency of overestimation for UHI intensity using outdated urban extent maps was observed when defining the UHI as the urban–rural difference. Because of the intensification of urbanization and urban expansion over time, the ISA in urban, suburban and rural areas will be overestimated using outdated urban extent maps, resulting in an overestimation of surface temperature in those areas. Therefore, the direction and magnitude of potential biases in estimating UHI intensity associated with using outdated land cover maps will depend on the overestimation difference in ISA between urban and its surrounding areas. The overestimation of ISA in urban area is more likely to be less than that in suburban area whereas that tends to be higher relative to rural area. As a consequence, the UHI tends to be underestimated and overestimated using outdated urban boundary maps to define the UHI as the urban–suburban and the urban–rural difference, respectively (Figs. 5 and 6). It is understood that UHI intensity depends on UHI definition (i.e., which background temperature (rural or suburban) is used to compare with the urban temperature). Our study further showed that the definition difference can even alter the direction and magnitude of potential biases in estimating UHI intensity using outdated urban extent maps.

Our study revealed the importance of concurrency using

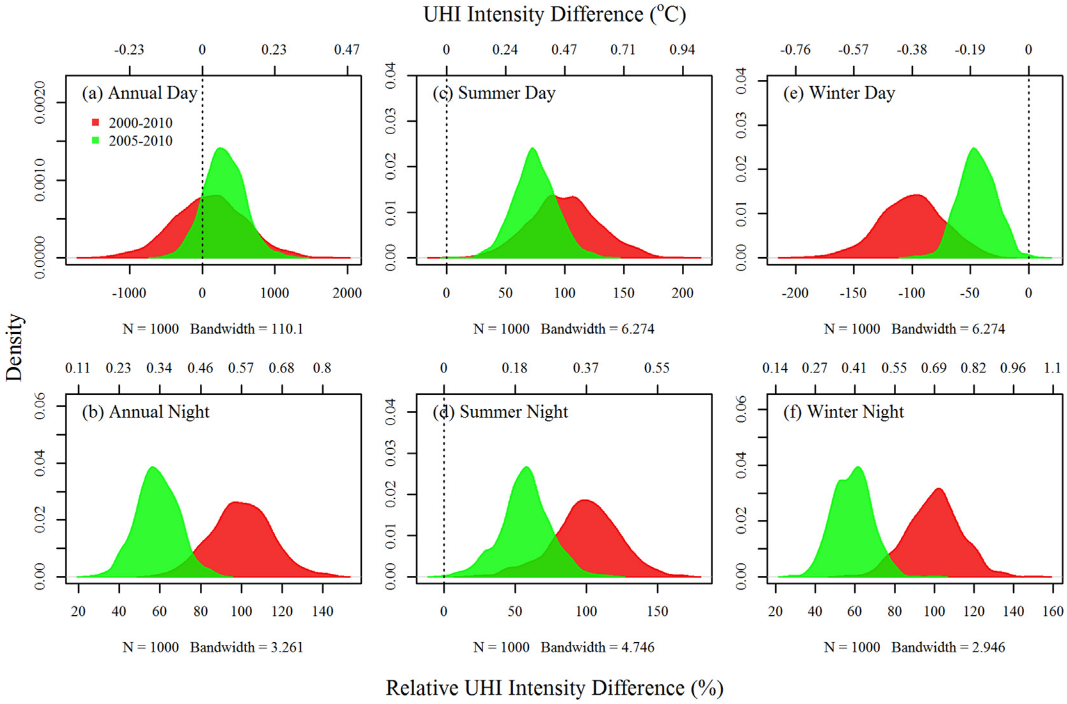

Fig. 6. The probability density functions (PDF) of the bootstrapped means of the UHI intensity differences between the outdated (2000 or 2005) and concurrent (2010) urban boundaries for the 32 cities when defining the UHI as the urban–rural difference. The reference line of zero difference (dashed vertical line) is drawn to show if any of the distributions is significantly different from zero.

observations from China where urban expansion rates were higher than most cities in other regions (Seto et al., 2012; Zhao et al., 2015). It is worthwhile to note that the issue of potential biases in estimating UHI intensity associated with using outdated land cover maps by 5–10 years may not be a big problem for the cities of Europe and North America where urban extent and intensity level of urban development remain relatively stable over time. Nevertheless, given the rapid urbanization that we continue to expect in Asia, Africa and South America, it is prudent and advisable to use concurrent land cover and urban extent maps to quantify UHI intensity, and hence to be able to accurately predict the ecological, social, and economic consequences of UHI for human comfort, health and well-being.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (#31321061 and #41071050), and the 111 Project (B14001).

References

Arnfield, A.J., 2003. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. Int. J. Climatol. 23, 1–26.

Clinton, N., Gong, P., 2013. MODIS detected surface urban heat islands and sinks: global locations and controls. Remote Sens. Environ. 134, 294–304.

EPA, 2003. Beating the heat: mitigating thermal impacts. Nonpoint Source News Notes 72, 23–26.

Grimmond, C.S.B., Oke, T.R., 1991. An evapotranspiration-interception model for urban areas. Water Resour. Res. 27 (7), 1739–1755. http://dx.doi.org/10.1029/91WR00557.

Howard, L., 1833. The Climate of London, Vols. I–Ill. London.

Imhoff, M.L., Zhang, P., Wolfe, R.E., Bounoua, L., 2010. Remote sensing of the urban heat island effect across biomes in the continental USA. Remote Sens. Environ. 114, 504–513.

Kolokotroni, M., Ren, X., Davies, M., Mavrogianni, A., 2012. London's urban heat island: impact on current and future energy consumption in office buildings. Energ. Build. 47, 302–311.

Manley, G., 1958. On the frequency of snowfall in metropolitan England. Q. J. R. Meteorol. Soc. 84, 70–72.

Oke, T.R., 1973. City size and the urban heat island. Atmos. Environ. 7, 769–779.

Oke, T.R., 1981. Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observations. J. Climatol. 1, 237–254. http://dx.doi.org/10.1002/joc.3370010304.

Oke, T.R., 1982. The energetic basis of the urban heat island. Q. J. R. Meteorol. Soc. 108 (455), 1–24. http://dx.doi.org/10.1002/qj.49710845502.

Patz, J.A., Campbell-Lendrum, D., Holloway, T., Foley, J.A., 2005. Impact of regional climate change on human health. Nature 438, 310–317.

Peng, S., Piao, S., Ciais, P., Friedlingstein, P., Ottle, C., Bréon, F.M., Nan, H.J., Zhou, L.M., Myneni, R.B., 2012. Surface urban heat island across 419 global big cities. Environ. Sci. Technol. 46, 696–703.

R Development Core Team, 2013. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria, ISBN 3-900051-07-0.

Ramalho, C.E., Hobbs, R.J., 2012. Time for a change: dynamic urban ecology. Trends Ecol. Evol. 27, 179–188.

Runnalls, K.E., Oke, T.R., 2000. Dynamics and controls of the near-surface heat island of Vancouver, British Columbia. Phys. Geogr. 21 (4), 283–304.

Sarrat, C., Lemonsu, A., Masson, V., Guedalia, D., 2006. Impact of urban heat island on regional atmospheric pollution. Atmos. Environ. 40, 1743–1758.

Schneider, A., Friedl, M.A., Potere, D., 2009. A new map of global urban extent from MODIS satellite data. Environ. Res. Lett. 4 (4), 044003. http://dx.doi.org/10.1088/1748-9326/4/4/044003.

Schneider, A., Friedl, M.A., Potere, D., 2010. Mapping global urban areas using MODIS 500-m data: new methods and datasets based on 'urban ecoregions'. Remote Sens. Environ. 114 (8), 1733–1746.

Schwarz, N., Lautenbach, S., Seppelt, R., 2011. Exploring indicators for quantifying surface urban heat islands of European cities with MODIS land surface temperatures. Remote Sens. Environ. 115, 3175–3186.

Seto, K.C., Güneralp, B., Hutyra, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc. Natl. Acad. Sci.U.S.A 109, 16083–16088.

Seto, K.C., Sánchez-Rodrígue, R., Fragkia, M., 2010. The new geography of contemporary urbanization and the environment. Annu. Rev. Environ. Resour. 35, 167–194.

Stewart, I.D., 2011. A systematic review and scientific critique of methodology in modern urban heat island literature. Int. J. Climatol. 31 (2), 200–217.

United Nations (UN) Department of Economic and Social Affairs, Population Division, 2014. World Urbanization Prospects: the 2014 Revision. United Nations, New York, USA.

Van Huffel, S., Vanderwalle, J., 1991. The Total Least Squares Problem: Computational Aspects and Analysis. SIAM, Philadelphia, PA.

Voogt, J.A., Oke, T.R., 2003. Thermal remote sensing of urban areas. Remote Sens. Environ. 86, 370–384.
Wu, J.G., 2014. Urban ecology and sustainability: the state-of-the-science and future directions. Landsc. Urban Plan. 125, 209–221.
Zhao, L., Lee, X., Smith, R.B., Oleson, K., 2014. Strong contributions of local background climate to urban heat islands. Nature 511, 216–219.
Zhao, S.Q., Zhou, D.C., Zhu, C., Qu, W.Y., Zhao, J.J., Sun, Y., Huang, D., Wu, W.W., Liu, S., 2015. Rates and patterns of urban expansion in China's 32 major cities over the past three decades. Landsc. Ecol. http://dx.doi.org/10.1007/s10980-015-0211-7.
Zhou, D.C., Zhao, S.Q., Zhang, L., Sun, G., Liu, Y., 2015. The footprint of urban heat island effect in China. Sci. Rep. 5, 11160. http://dx.doi.org/10.1038/srep11160.
Zhou, B., Rybski, D., Kropp, J.P., 2013. On the statistics of urban heat island intensity. Geophys. Res. Lett. 40, 5486–5491. http://dx.doi.org/10.1002/2013GL057320.
Zhou, D.C., Zhao, S.Q., Liu, S., Zhang, L., Zhu, C., 2014. Surface urban heat island in China's 32 major cities: spatial patterns and drivers. Remote Sens. Environ. 152, 51–61.