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Response to Comment on "Surface Urban Heat Island Across 419 Global Big Cities"

In her comment on our paper "Surface Urban Heat Island Across 419 Global Big Cities",[1] N. Schwarz raised several questions on our analyses relating surface urban heat island intensity (SUHII) to city division, city size and population intensity. We welcome this opportunity to clarify and reiterate a few important points made in our paper[1] concerning SUHII and urban social-economical status at *global* scale.

First, N. Schwarz questioned our rationale of dividing the world cities by belonging to developed and developing countries, and conjectured that the significantly higher annual daytime SUHII in developed countries than in developing countries found in our paper[1] is due to the latitudinal differences of the SUHII. The reason of comparing SUHII in developed versus developing countries is apparent: The division represents significant difference in urbanization as well as in social-economy and environment, and the comparative results are likely to provide compelling evidence on how different natural and social-economic factors impact the SUHII. The reason that developed countries tend to have a higher daytime SUHII, however, is not the latitudinal effect conjectured by N. Schwarz. The explanation power of latitude on the spatial variation of annual daytime SUHII is less than 1%. Similarly, the explanation power of mean annual temperature on the spatial variation of annual daytime SUHII is also limited (3%, Figure S2F in the Supporting Information[1]). On the other hand, if N. Schwarz's hypothesis was correct, then the higher annual daytime SUHII of developed over developing countries might become less evident in a narrower latitudinal range such as in the northern temperate regions (35°N-50°N). However, we found that in this latitudinal range, annual daytime SUHII over developed countries (2.30 ± 1.20, $N = 62$) is still much significantly higher ($P < 0.001$) than that over developing countries (1.20 ± 0.79, $N = 62$). Similar results can also be found within a narrower climate gradient (delimited by mean annual temperature). Indeed, the higher SUHII over developed countries could be inferred from the significant negative correlation between SUHII and the difference of vegetation cover fraction between urban and suburban areas (δVCF, Figure 4 in our paper,[1] $R^2 = 0.51$, $P < 0.001$). Over all the 419 big cities, the average δVCF of cities in developed countries (-0.12 ± 0.10, $N = 116$) is significantly lower ($P < 0.001$) than that for cities in developing countries (-0.06 ± 0.07, $N = 303$). This is also true when we limit the analysis only within the northern temperate regions.

Second, N. Schwarz suggested that the insignificant impact of city size on SUHII found in our paper[1] could be due to our choice to include only big cities (> 1 million people). We made this choice purposely for a specific comparison of big cities around the world, given that the data we used are satellite observations with a spatial resolution of 1 km. Further investigation using higher resolution images could incorporate smaller cities, but is beyond the scope of our study. Yet, the range of urban areas included in our analysis[1] goes from ~5 km^2 to more than 1000 km^2 and thus represents a large range of city sizes. In a similar study but limited to the United States, Imhoff et al.[2] selected 45 cities ranging from 1 km^2 to more than 1000 km^2 and found a strong explanation power (71%) of city size on the variation of SUHII (their Figure 9 in ref 2). Unlike suggested by N. Schwarz, the different results between Imhoff et al.[2] and our study are not likely due to our incomplete sampling of the range of city size. The analysis using 42 cities whose sizes are equal or larger than 5 km^2 from Figure 9 in Imhoff et al.[2] shows a similar high explanation power (61%) of city size on the variation of SUHII for the North-Eastern United States. On the other hand, the regression slopes of SUHII against city size are different over different countries or regions such as North America, China and Europe. Thus, in our global rather than a regional analysis, other factors such as differences in surface properties (e.g., albedo, emissivity, vegetation cover/amount, surface roughness, thermal properties etc.), climates and economic development could play a more important role and mask the possible regionally important impacts of city size on SUHII, and lead to its limited explanation power on the spatial variation of annual daytime SUHII found in our paper.[1] In addition, the city size in our work depends on the classification of urban pixels in MODIS land cover map and the algorithm to define the urban area, which has uncertainties as discussed.[1]

Third, N. Schwarz argued that population density is merely used as a proxy for anthropogenic heat fluxes, including the total energy consumption for transportation, buildings and industry and human metabolism.[3] However, this is based on the assumption of equal or similar energy consumption per capita across different cities, countries or regions. This assumption might hold true within a country or across countries with similar economic development. However, it is apparently not correct at global scale. For example, in 2003, energy consumption per capita in China and the United States are 48 GJ and 327 GJ, respectively.[4] Thus, to avoid such a confusion, in our paper[1] we only used the population density to calculate the metabolic heating,[3] which is more constant across the global scale. The heat release from human metabolism is much smaller than energy consumed by transportation, buildings and industry,[3] which could explain why this flux contributed little to explain spatial gradient of SUHII. Due to the limited data availability for other anthropogenic sources, we used the night light as a proxy index of the anthropogenic heat fluxes in our paper.[1] However, how to quantify the anthropogenic heat emissions for different cities needs more efforts in future studies.

In summary, N. Schwarz raised important questions on possible explanation for SUHII differences among big cities. Unfortunately, each argument raised by N. Schwarz is based on a postulation, which is not supported by independent evidence or new data. Our analysis of SUHII was based on observations

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and these data, although arguably imperfect, are available for contradictory analysis. The observational evidence that we collected and analyzed do not support any of the three hypotheses of N. Schwarz, except for the fact that city size may be regionally important in controlling SUHII, although it was not found significant at global scale. The results of our global analysis indicate consistently that spatial variations of annual daytime SUHII are mostly explained by the difference of vegetation cover fraction between urban and suburban areas, but not by the latitude or climate variables. In addition, we are well aware that a linear contribution analysis has some limitations, that we made our best to identify the most important factors, but that nonlinear interactions may be poorly captured by our analysis. On the global scale, the effects of city size on SUHII, which may be important at some regional scales, could be masked by differences in climate and other social-economic factors. Because of the large variation in per capita energy consumption across the globe, population density is not suitable to be used as a proxy of anthropogenic heat fluxes for global studies, especially when countries with different economic development levels are pooled altogether. Further studies are still needed to investigate the natural and anthropogenic contributions to urban heat islands.

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Notes

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