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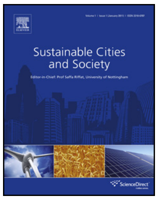

Network optimization for enhanced resilience of urban heat island measurements

Tsuyoshi Honjo[a,*], Hiroaki Yamato[b], Takehiko Mikami[c], C.S.B. Grimmond[d]

[a] Department of Environmental Science and Landscape Architecture, Faculty of Horticulture, Chiba University, Matsudo, Chiba 271-8510, Japan
[b] Chuo University, 1-3-27 Kasuga, Bunkyo-ku, Tokyo 112-8551, Japan
[c] Faculty of Liberal Arts, Teikyo University, Hachioji, Tokyo 192-0395, Japan
[d] Department of Meteorology, University of Reading, Earley Gate, PO Box 243, Reading RG6 6BB, UK

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A B S T R A C T

The urban heat island is a well-known phenomenon that impacts a wide variety of city operations. With greater availability of cheap meteorological sensors, it is possible to measure the spatial patterns of urban atmospheric characteristics with greater resolution. To develop robust and resilient networks, recognizing sensors may malfunction, it is important to know when measurement points are providing additional information and also the minimum number of sensors needed to provide spatial information for particular applications. Here we consider the example of temperature data, and the urban heat island, through analysis of a network of sensors in the Tokyo metropolitan area (Extended METROS). The effect of reducing observation points from an existing meteorological measurement network is considered, using random sampling and sampling with clustering. The results indicated the sampling with hierarchical clustering can yield similar temperature patterns with up to a 30% reduction in measurement sites in Tokyo. The methods presented have broader utility in evaluating the robustness and resilience of existing urban temperature networks and in how networks can be enhanced by new mobile and open data sources.

1. Introduction

The urban heat island is a well-known phenomenon (Stewart, 2011) that impacts a wide variety of city operations (e.g. energy usage, need for snow clearance). With the drive to develop both “Smart Cities” and the “Internet of Things” (Perera, Zaslavsky, Christen, & Georgakopoulos, 2014), and the availability of relatively cheap meteorological sensors, it is now desirable and possible to observe the spatial pattern of atmospheric variables with much more detail than in the past. Many cities now have multiple sensors installed (see the examples in Table 1). Such networks allow the spatial dynamics of air temperature to be considered.

In the design and operation of a meteorological measurement network for spatial characterization of the urban heat island, many questions arise. In the planning stage, key questions include what is the optimal number of measurement points and what is their optimal distribution? Should measurement points be distributed evenly or unevenly? Are there important features which must be measured? Once measurements are initiated, if instruments malfunction or are withdrawn, questions need to be answered as to whether sensors should be substituted at these points or is this unnecessary? How significant are missing data to the overall performance of the network? *A priori* it might be expected that a larger number of measurement points is better, but what is the trade-off with respect to resources, such as labor to service and sustain the network?

In this study, we analyze an existing meteorological measurement network around the Tokyo metropolitan area – Extended METROS (Yamato, Takahashi, & Mikami, 2009) to consider optimal network design for urban heat island measurements to address some of these questions.

2. Material and methods

2.1. Data sets

The measurement points of Extended METROS are shown in Fig. 1. The area is one of the most populated in the world, with more than 30 million people. The area analyzed extends from 35.3° to 36.3° N latitude (about 90.4 km) and from 139.2° to 140.2° E longitude (about 111.3 km) and includes Tokyo Bay (Fig. 1, note 1 station is beyond the specified area). To the east of the study area

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* Corresponding author. Tel.: +81 473088896.
E-mail address: honjo@faculty.chiba-u.jp (T. Honjo).

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Table 1
Examples of air temperature networks that have been installed in cities. Table ordered by year first installed. Note that some cities have had multiple networks installed, these are listed separately.

City	Number of sensors	Spatial extent (km^2)	Period of operation	Project	References
Tokyo, Japan	120	2187	2002–2005	METROS	Mikami, Ando, Morishima, Izumi, & Shioda (2003)
Taipei, Taiwan	60	271.79	2003–present	TWIN	Chang, Wang, Peng, & Hsu (2010)
Washington. DC, USA	16	177	2003–present	DCNet	Hicks, Callahan, Pendergrass, Dobosy, & Novakovskaia (2012)
Helsinki, Finland	102	150	2005–present	Helsinki Testbed	Koskinen et al. (2011)
Cambridge, MA, USA	25	18.47	2006–2010	CitySense	Murty et al. (2008)
Tokyo, Japan	200	7000	2006–present	Extended METROS	Yamato et al. (2009)
Oklahoma City, USA	40	1440	2007–2010	OKCNET	Basara et al. (2010)
Hong Kong	105	1104	2007–present	Co-WIN	Hung & Wo (2012)
London, UK	91	1577	2009–present	OPAL	Davies et al. (2011)
Worldwide	N/A	N/A	2013–present	Weather Signal	Overeem et al. (2013)
Shanghai, China	200	6340.5	N/A–present	SUIMON	Tan et al. (2014)

is the Pacific Ocean. Elevation varies from mean sea level to 300 m. The density of the stations is approximately 1 station per 50 km^2 or a mean separation of 7 km. However, given no measurement points are located in 30% of the area (Tokyo Bay: 9%, mountain area and unpopulated areas 20%), the mean separation of sensors is actually about 6 km.

Thermometers (T&D, TR5106 thermistor sensor with RTR-52a data logger) are housed in unaspirated Stevenson screens at 1.5 m above ground level sited in elementary schools. The individual network, which is operated/coordinated by METROS Research Project, was set up by 12 independent groups. No individual has been to every site, as will be the case for many large networks that are being established (formally or *ad hoc* networks of opportunity). The temperature measurements, collected since 2006, consist of samples taken every 10 min from approximately 200 sites. The actual number at any given time varies because of instrument related issues (malfunctions, etc.).

For the analysis presented here, examples from the hottest and coldest periods are selected to consider the implications of network distribution and density. The data were sampled at 4:00, 10:00, 16:00, 22:00 (local time, note Japan does not use summer time) on 15 and 16 August 2007 (eight summer cases) and 13 and 14 February 2008 (eight winter cases) as explained in Table 2. The mean and standard deviation of the temperature and locations of the heat island of the cases are also reported. The numbers of measurement points were 183 in the summer cases and 200 in the winter cases. Histograms of the original data are shown in Fig. 2.

2.2. *Random sampling and analysis of mean temperature*

Random sampling was undertaken to analyze the effect of reducing the number of measurement points. Each station (183 in summer; 200 in winter) was numbered and for each case a

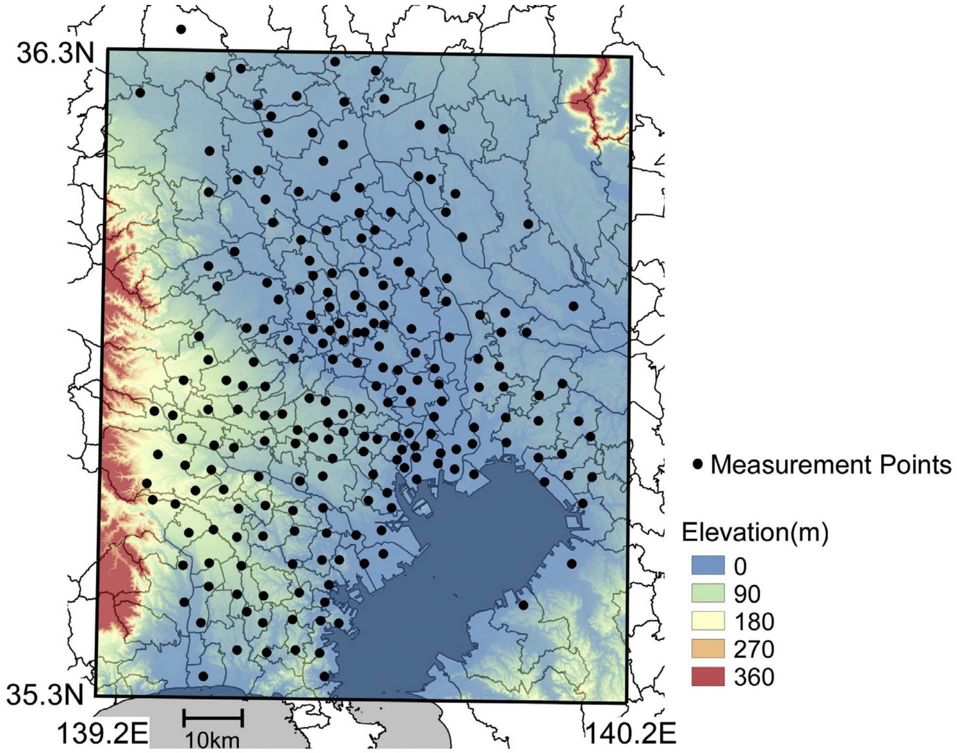

Fig. 1. The location of measuring points of the Extended METROS network in the Tokyo metropolitan area. Lines within the land indicates borders of local governments, i.e., ward, city, town.

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