Applied Geography 76 (2016) 62–74

Contents lists available at ScienceDirect

Applied Geography

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

Predicting air temperature simultaneously for multiple locations in an urban environment: A bottom up approach

Shai Kaplan*, Aviva Peeters, Evyatar Erell

Desert Architecture and Urban Planning Unit, Swiss Institute for Dryland Environmental and Energy Research, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Israel

ARTICLE INFO

Article history:
Received 5 March 2016
Received in revised form
10 September 2016
Accepted 11 September 2016
Available online 19 September 2016

Keywords:
Computer modelling
Urban heat island
Urban planning
Spatial variability
GIS

ABSTRACT

Cities are characterized by high heterogeneity that results in varied microclimate effects. The current study introduces a new bottom–up approach linking the urban Canyon Air Temperature (CAT) model with spatially distributed inputs extracted from a GIS data-base and remote sensing products to predict intra-urban temperature variability simultaneously for multiple locations in an urban environment. To provide proof of concept, the model was applied for the city of Bat-Yam, Israel. Simulation shows a maximum nighttime urban heat island (UHI) intensity of 2–2.25 °C, relative to a rural reference point, during both summer and winter, with significant spatial variability related to the height-to-width ratio of urban street canyons and to the surface land cover. The CAT simulation also highlighted the important influence of the local wind regime on the development and persistence of the nocturnal UHI. We conclude that linking CAT to a GIS data-base supports simulations at the city scale that reflect the local intra-urban variability. The model can be used to investigate both macro and micro scale spatio-temporal characteristics of the UHI in various urban development scenarios, which may be applied to generate appropriate geographically-explicit mitigation and adaptation measures.

1. Introduction

The link between cities and climate and its impact on human comfort and building energy consumption is often evaluated using sophisticated model simulations. These models may rely on weather data obtained from the nearest station outside the city or at the nearest airport. However, the data represent historical climate rather than current or future conditions urban dwellers and infrastructure will be exposed to. Furthermore, cities are characterized by high heterogeneity that results in substantial intra-urban variations of the microclimate. In other words, the weather at any given location within the urban area may differ in a meaningful way from that of the reference weather station.

The rapid urbanization of the past 50 years has changed the physical urban environment, creating a more heterogeneous landscape. Cities are known to be warmer than their rural surroundings due to different thermal, radiative, moisture and aerodynamics characteristics of the built environment (Howard, 1820; Oke, 1973, 1987), a phenomenon referred to as the urban heat island (UHI). However, many studies show that the UHI is not uniform in time or space: It is typically greatest on clear, windless nights (Oke, 1981), and land cover heterogeneity has a significant spatial effect on air temperature (Erell & Williamson, 2007; Georgescu, Moustaoui, Mahalov, & Dudhia, 2012; Lookingbill, 2003; Loridan & Grimmond, 2012; Oke, 1981, 1982; Pielke, 2001; Weaver & Avissar, 2001). A comprehensive review of UHI research can be found in Arnfield (2003). The UHI does not only impact the physical environment but further exacerbates thermal stress through changing the energy balance both between the surface and the atmosphere and between the human body and the atmosphere.

Thermal stress has been associated with heat related vulnerability (illnesses and death) (Guo et al., 2014) and epidemiological studies have described a substantial increase in morbidity and mortality in conjunction with heat episodes (Basu & Samet, 2002), of which the 2003 heat wave in Europe is a well-known example (Robine et al., 2008). Rosenthal, Kinney, and Metzger (2014) demonstrated that, crucially, excess mortality was strongly related to the physical properties of neighborhoods, so mitigating the effects of future heat events requires a means of assessing which neighborhoods are most likely to suffer from overheating.

---

* Corresponding author.
E-mail address: kaplans@bgu.ac.il (S. Kaplan).

http://dx.doi.org/10.1016/j.apgeog.2016.09.015

Although air temperature is but one factor contributing to thermal stress, the evidence from numerous epidemiological studies indicates that it is of sufficient importance for detailed study even in the absence of contemporaneous data on other factors such as the radiant exchange and humidity.

Numerous studies (Merbitz, Buttstädt, Michael, Dott, & Schneider, 2012; Rotem-Mindali, Michael, Helman, & Lensky, 2015; Saaroni, Ben-Dor, Bitan, & Potchter, 2000) have indicated the importance of urban characteristics, such as land-use, building density, vegetation or materials on the spatial pattern and complexity of the UHI. For example, Saaroni et al. (2000) found both positive and negative pockets of UHI within Tel-Aviv city center. Chow and Roth (2006) found intra-urban UHI differences >1 °C in Singapore and attributed it to enhanced anthropogenic heat, green spaces and distance to the water front. Similar findings were reported for Hong-Kong by Giridharan, Ganesan, and Lau (2004; 2005). Hart and Sailor (2009) reported UHI intensity differences of up to 10 °C within Portland between areas with high canopy coverage and surrounding urban regions. Furthermore, they found freeways and major roads experience UHI of up to 5 °C while both the downtown and suburban areas experience temperature anomalies of up to 2 °C.

Recent studies adopt a more nuanced approach, so that the rural-urban dichotomy is replaced by a continuum of Local Climate Zones (LCZs), classified according to built form, materials and land cover (Stewart & Oke, 2012). Nevertheless, most mesoscale climate models cannot account fully for this heterogeneity, resulting in a contrast between the micro-scale, where the land cover and 3D characteristics impact climate at street level, and the spatial scale at which these models operate, which is typically a grid resolution of 500 m or more.

To obtain detailed microscale air temperature maps, researchers have used high density direct point measurements, remote sensing, or numerical modelling. Direct measurements are labor intensive, require expensive instrumentation and high spatial density, as well as a substantial logistical outlay to provide data over extended periods. Regression and geo-statistical models produced from direct measurements are used to provide interpolated data for locations where no physical measurements were recorded, but these are often site-specific and still require a fairly dense measurement network (Ivajnšič, Kaligarič, & Žiberna, 2014). Remote sensing does not measure canopy layer air temperature directly, but rather 'skin' (surface) temperature. Several studies have demonstrated good correlation between the radiant temperature and canopy level air temperature (Kloog, Chudnovsky, Koutrakis, & Schwartz, 2012, 2014; Pelta, Chudnovsky, & Schwartz, 2016), and the technique has been applied in research on the effect of heat waves on mortality (Laaidi et al., 2012). However, the linkage between surface- and air temperature is extremely complex and the models may not always predict air temperature from remotely sensed skin temperature accurately. Moreover, the temporal resolution of satellites may not be sufficient to produce the hourly or daily time series needed to monitor and model the nocturnal UHI (Yang, Endreny, & Nowak, 2013). Numerical models based on fluid dynamics such as ENVI-met (Bruse & Fleer, 1998) have also been applied in numerous studies, but they are best suited to scenario testing in short timescales and limited spatial extent. They require very detailed input and substantial computational resources, so they are still limited to research rather than planning applications.

Land surface models (LSM) such as the Noah LSM embedded within the Weather Research and Forecasting model (WRF) and the Town Energy Balance model (TEB) (Hamdi & Masson, 2008; Masson, 2000) overcome some of the limitations mentioned above, and have been applied in many major metropolitan regions in different climate zones (Georgescu et al., 2012; Grimmond, 2007; Oleson, Bonan, Feddema, Vertenstein, & Grimmond, 2008). LSMs use thermo-dynamics to estimate the land surface energy fluxes and their partitioning to latent and sensible heat. However, these models are computationally intensive and represent the urban surface in a parameterized fashion, including the urban canopy state variables such as albedo and thermal properties of the built environment and its 3D representation; i.e. they do not represent buildings explicitly or their complex interactions such as long- and short-wave radiation interactions and urban canyon wind channeling effects. Moreover, because spatially distributed boundary and initial conditions are not available for most urban areas (e.g. radiation components), LSMs use mesoscale climate models' output as input and apply a top-down approach in which heat flux is determined by the difference between the model's vertical layers. These requirements limit the model grid size (>500 m), impairing their ability to capture the high heterogeneity of land cover and 3D parameters over small distances that characterizes some built environments.

One such model, PASATH, (Spatial Air Temperature and Humidity) is a physically based analytical model that can provide spatially and temporally detailed microclimate maps (Yang et al., 2013). Similar to WRF, PASATH does not provide a full spectrum of height-to-width ratio, but rather a parameterization scheme for 4 urban canyon types: open space, low-, medium-, and high-intensity development. While this simplification allows the model to be less data-driven and less computationally intensive, it limits its capability to represent the high heterogeneity of some urban areas. Furthermore, the PASATH model uses additional sub-models that require expert knowledge as well as elevation data, and does not include an atmospheric stability correction. This limits its accuracy in calculating aerodynamic resistance.

Over the last decade, GIS technology and 3D digital data have become more widely accessible. These databases may be used to produce temperature maps, usually grid-based maps in varying resolutions, which represent the spatial variation in temperature across the city (Jusuf & Hien, 2009). Ren, Ng, and Katzschner (2011) provided a review of urban climate map studies and demonstrated the need to incorporate climatic aspects into the urban planning, development and decision making processes. They pointed out the advantages of using a GIS-based platform for analyzing and visualizing the urban thermal environments, and concluded that future research should focus on spatial analysis and creating a simplified method to provide spatially explicit climate information for urban outdoor areas. Recently, Kastendeuch and Najjar (2015) developed the LASER/F urban canopy model designed to work with high resolution 3D city geometry from a GIS database. However, the model requires much processing power and time and cannot be used at a city scale. Furthermore, the simulation uses a top-down approach in which the boundary conditions are imposed at the top of each urban canopy box.

The current study introduces a new bottom–up approach in which the point-based urban Canyon Air Temperature (CAT) model developed by Erell and Williamson (2006) is adapted to modelling at a larger spatial scale by linking drawing inputs from a GIS database and remote sensing products to predict air temperature simultaneously for multiple locations in an urban environment. The number of urban locations that can be modeled is not limited and therefore a detailed and more accurate representation of the spatial variations of the urban micro-climate can be generated. CAT offers a mechanism for capturing micro-climate variations resulting from local surface characteristics and canyon geometry. Utilizing GIS to create a detailed spatial urban canyon morphology database allows us to run detailed high resolution CAT simulations that take into account the 3D characteristics and heterogeneity of the urban landscape, and evaluate the spatio-temporal variability of micro-