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Development of a national anthropogenic heating database with an extrapolation for international cities

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HIGHLIGHTS

- City-specific anthropogenic heating profiles are needed for urban climate modeling.
- Diurnal and seasonal profiles of anthropogenic heating are developed for 61 US cities.
- An extrapolation method for calculating international city profiles is introduced.

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ABSTRACT

Given increasing utility of numerical models to examine urban impacts on meteorology and climate, there exists an urgent need for accurate representation of seasonally and diurnally varying anthropogenic heating data, an important component of the urban energy budget for cities across the world. Incorporation of anthropogenic heating data as inputs to existing climate modeling systems has direct societal implications ranging from improved prediction of energy demand to health assessment, but such data are lacking for most cities. To address this deficiency we have applied a standardized procedure to develop a national database of seasonally and diurnally varying anthropogenic heating profiles for 61 of the largest cities in the United Stated (U.S.). Recognizing the importance of spatial scale, the anthropogenic heating database developed includes the city scale and the accompanying greater metropolitan area. Our analysis reveals that a single profile function can adequately represent anthropogenic heating during summer but two profile functions are required in winter, one for warm climate cities and another for cold climate cities. On average, although anthropogenic heating is 40% larger in winter than summer, the electricity sector contribution peaks during summer and is smallest in winter. Because such data are similarly required for international cities where urban climate assessments are also ongoing, we have made a simple adjustment accounting for different international energy consumption rates relative to the U.S. to generate seasonally and diurnally varying anthropogenic heating profiles for a range of global cities. The methodological approach presented here is flexible and straightforwardly applicable to cities not modeled because of presently unavailable data. Because of the anticipated increase in global urban populations for many decades to come, characterizing this fundamental aspect of the urban environment – anthropogenic heating – is an essential element toward continued progress in urban climate assessment.

1. Background and motivation

Energy consumption in cities leads to emissions of waste heat into the urban air shed. These emissions arise from the functioning of cars, electricity use in buildings (e.g., from building heating, ventilation and air conditioning (HVAC) systems), industry, and individuals (referred to as human metabolism). The magnitude of this anthropogenic heat flux (Q_f) correlates well with population

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density. At the continental scale anthropogenic heat emissions are small, averaging less than 0.4 W/m^2 in the United States, less than 0.7 W/m^2 in western Europe, and 0.2 W/m^2 in China (Flanner, 2009). The greater population density at the metropolitan or city scales results in substantially larger magnitudes of Q_f. For example, using energy consumption inventories at the city scale researchers have estimated anthropogenic heat emissions on the order of 10–100 W/m^2 for cities as diverse as Lodz, Poland (Klysik, 1996) and Philadelphia PA, USA (Fan and Sailor, 2005). Sailor and Lu (2004) present detailed summer and winter profiles for 6 cities in the United States (Atlanta, Chicago, Los Angeles, Salt Lake City, San Francisco, and Philadelphia). Their results illustrate the important role of both local climate and population density in affecting the magnitude of Q_f. For example, while San Francisco has a population density of roughly 0.00599 persons/m^2, the winter magnitude of Q_f in Chicago (with a population density of 0.00492 persons/m^2) is roughly 7 W/m^2 greater than that of San Francisco. Conversely, despite the relatively harsh winter conditions in Salt Lake City, its low population density results in a much lower winter Q_f (~12 W/m^2) than that of Los Angeles (~30 W/m^2).

The notion of scale must be considered when estimating urban-induced Q_f and subsequent impacts on urban meteorology and climate. At the scale of a city block, the magnitude of anthropogenic heating from the building sector increases proportionally with the height (number of floors) of buildings. Thus, in central Tokyo, Ichinose et al. (1999) found that Q_f exceeded 400 W/m^2 during the daytime and reached values up to 1590 W/m^2 in winter. Therefore, the magnitude of anthropogenic heating varies substantially both as a function of underlying climate, but also in direct proportion to the population density of the region under study. Furthermore, within any single city, the magnitude of anthropogenic heating varies as a function of the spatial extent of the area of analysis, necessarily incorporating diverse types of urban form and function (Stewart and Oke, 2012) with contributions depending on localized energy consumption, traffic patterns, and microclimate. Hence, Q_f is typically largest at the neighborhood scale in downtown areas, is lower in magnitude when averaged over the city, and lower still when averaged over the greater metropolitan region.

Anthropogenic heating can be an important component of the urban energy budget. For example, Fan and Sailor (2005) found that inclusion of anthropogenic heating in mesoscale modeling of Philadelphia resulted in air temperature elevations as large as 2–3 °C in winter. Salamanca et al. (2014) have similarly shown, via utility of mesoscale modeling with the Weather Research and Forecasting (WRF) model dynamically coupled to a building energy parameterization, that usage of air conditioning (AC) systems increased summertime nighttime air temperatures by more than 1 °C for the Phoenix metropolitan area. Notably, in addition to highlighting this non-negligible warming effect, the authors demonstrate that explicit representation of waste heat from AC systems improved 2m-air temperature correspondence to observations, thereby confirming the critical role of this aspect of the urban energy balance for improved predictability.

Inclusion of Q_f clearly has significant implications for urban climate, air quality, and energy demand. Thus, modeling efforts aimed at investigating the urban environment must appropriately characterize this aspect of the urban energy balance. At the present time, users have two choices. First, usage of the WRF system (which is easily coupled to a single layer urban canopy parameterization by means of a namelist setting the user may turn on), or other similar modeling systems, provides a default anthropogenic heating profile scaled by a magnitude parameter (in WRF, these default values are 90, 50, and 20 W/m^2 respectively for commercial, high-density residential, and low-density residential urban land categories). While these profiles (Fig. 1) are user-editable, the lack of available

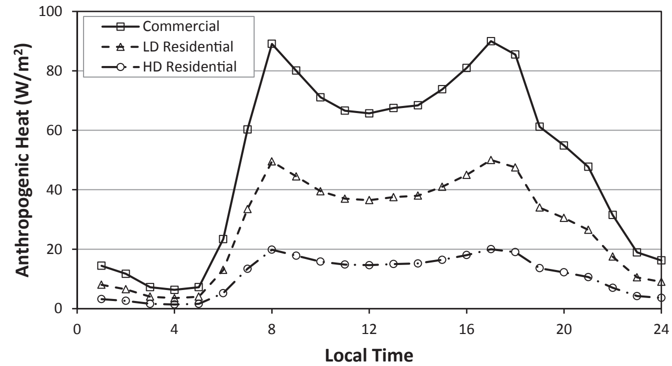

Fig. 1. Representative diurnal profiles of anthropogenic heating available in WRF.

anthropogenic heating data for many cities increases the likelihood that users simply use the profiles unchanged. In some cases, lack of data leads urban modelers to either set anthropogenic heating magnitudes off (e.g., Holt and Pullen, 2007), or to use custom profiles that neglect some key emissions component such as the vehicle sector (e.g., Lin et al., 2008). Maximum values occur at 8am and 5pm local time, regardless of city or season. A second option within WRF is to use the BEP + BEM (building effect parameterization with integrated building energy model) option. However, as noted by Salamanca (Salamanca et al., 2012) this approach may lead to underestimation of the anthropogenic heat effect as it completely ignores emissions from transportation. Alternatively, researchers can develop their own city-specific diurnal profile of Q_f for their region of interest. Development of detailed representations for select regions (Chow et al., 2014) has begun, but coordinated local agency (e.g., for provision of readily accessible and appropriate data) and institutional efforts (e.g., for comprehensive multi-scale modeling of the urban air shed coupled to the overlying atmosphere) are required for the representation of spatially explicit, time-varying profiles of Q_f. Such coordination remains costly and therefore elusive for many cities, but the need for the creation of a national (and by extension international) anthropogenic heating database is as essential as ever given the current, and projected, hydroclimatic significance of urban areas (Georgescu et al., 2014), and is therefore in high demand for individual researchers, as well as local, state, and national planning agencies addressing urban sustainability concerns.

To address the growing need for a national database of anthropogenic heating profiles, we have applied a published top-down methodology (Sailor and Lu, 2004) to develop representative month-specific Q_f profiles for 61 of the largest U.S. cities. The method is "top-down" in that it uses suitably downscaled coarse spatial and temporal resolution data to estimate diurnal profiles for cities. These data have been obtained from the Bureau of Transportation Statistics (U.S. Department of Transportation), the Energy Information Administration (U.S. Department of Energy), the National Climatic Data Center (U.S. Department of Commerce), and the Urban Transportation Planning Package (U.S. Census). For each urban area we have calculated diurnal profiles for two spatial scales: city scale, and the accompanying greater metropolitan area. For presentation purposes, however, we will summarize only the city-scale (i.e., municipal definition of the spatial extent) results here, but have made these and metropolitan area results available online at geoplan.asu.edu/research-and-outreach/projects/AHdata.

2. Methodology

There are two basic approaches to estimating diurnal profiles of Q_f. Starting at the neighborhood scale, one approach is to monitor