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Global anthropogenic heat flux database with high spatial resolution

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HIGHLIGHTS

- A global database of anthropogenic heat emission (AHE) with high spatial resolution was constructed using a top-down approach.
- Annual average AHE was estimated from four heating components, based on different sectors of energy consumption.
- A population-adjustment using nighttime light was created to improve estimating AHE spatial variability in urban areas.
- A sensitivity function of AHE relative to temperature was derived to provide a way to evaluate AHE monthly variability globally.

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ABSTRACT

This study developed a top-down method for estimating global anthropogenic heat emission (AHE), with a high spatial resolution of 30 arc-seconds and temporal resolution of 1 h. Annual average AHE was derived from human metabolic heating and primary energy consumption, which was further divided into three components based on consumer sector. The first and second components were heat loss and heat emissions from industrial sectors equally distributed throughout the country and populated areas, respectively. The third component comprised the sum of emissions from commercial, residential, and transportation sectors (CRT). Bulk AHE from the CRT was proportionally distributed using a global population dataset, with a radiance-calibrated nighttime lights adjustment. An empirical function to estimate monthly fluctuations of AHE based on gridded monthly temperatures was derived from various Japanese and American city measurements. Finally, an AHE database with a global coverage was constructed for the year 2013. Comparisons between our proposed AHE and other existing datasets revealed that the problem of overestimation of AHE intensity in previous top-down models was mitigated by the separation of energy consumption sectors; furthermore, the problem of AHE underestimation at central urban areas was solved by the nighttime lights adjustment. A strong agreement in the monthly profiles of AHE between our database and other bottom-up datasets further proved the validity of the current methodology. Investigations of AHE for the 29 largest urban agglomerations globally highlighted that the share of heat emissions from CRT sectors to the total AHE at the city level was 40–95%; whereas that of metabolic heating varied with the city's level of development by a range of 2–60%. A negative correlation between gross domestic product (GDP) and the share of metabolic heating to a city's total AHE was found. Globally, peak AHE values were found to occur between December and February, while the lowest values were found around June to August. The northern mid-latitudes contributed most to the global AHE.

1. Introduction

Surface air temperatures have risen at a rate of 0.13 °C per decade over the last 50 years, which is approximately twice that of the last 100 years (IPCC, 2007). In cities, rising temperatures can be influenced by two factors: the background change in climate and the specific local conditions of the city. Local differences in thermodynamic and aerodynamic properties, such as albedo, moisture, roughness, and thermal storage between the city and its surrounding rural environment often results in the occurrence of an urban heat island (UHI), a phenomenon whereby urban environments experience higher air temperatures than surrounding suburban areas. A further factor that influences the UHI is the heat released due to urban activities (Ichinose et al., 1999). Such excess

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heat arising from the direct human consumption of energy is commonly referred to as anthropogenic heat emission (AHE). Temperature increases and AHE have a two-way interaction. Rising temperatures, resulting from AHE, could potentially trigger increasing energy demands for cooling, which in turn, leads to more AHE (Crutzen, 2004). In studies to develop mitigation and adaptation strategies against climate change, priority is being given to measure the impact of climate change on cities, mainly due to the increased vulnerability of populations brought about by rural to urban migration (IPCC, 2013).

Because of its important role in urban atmospheric studies, AHE has been used as a representative urban forcing in weather models to reproduce and understand the factors influencing the UHI of a target city. In a case study series of simulations for Philadelphia (Fan and Sailor, 2005), AHE was incorporated as a source term in the near-surface energy balance within a mesoscale atmospheric model. The results suggested that AHE contributes 2–3 °C to the nighttime heat island in winter and also has impacts on the stability of a nocturnal planetary boundary layer during the morning transition. Kusaka and Kimura (2004) also found that the impact of anthropogenic heating on the nighttime heat island is the largest of all of the factors in Tokyo. In addition, annual mean temperature and planetary boundary layer height are estimated to increase, particularly in the region over which anthropogenic heating flux exceeds a 3 W m^{-2} threshold (Flanner, 2009). The inclusion of detailed anthropogenic heating data in atmospheric simulations of the urban environment will elucidate how UHI effects develop spatially and temporally, and their impact on air quality and other features of urban climates (Sailor and Lu, 2004). Furthermore, changes in AHE quantity and distribution will be a necessary parameter for future climate studies. Without further measures to mitigate the UHI, the increase in temperatures and energy demand will continue (Allen et al., 2011). Therefore, a quantitative and qualitative analysis of the impact of anthropogenic heating on urban environments is required for both urban climatology and climate change studies.

Previous studies have tried to estimate the intensity of AHE at both the regional and global scale. The diurnal cycle of the urban anthropogenic heat flux averaged globally ranges from 0.7 to 3.6 W m^{-2} (Allen et al., 2011). The AHE in cities has also been estimated spatially or in bulk. The annual mean value for Greater London has been estimated to be 10.9 W m^{-2} (Iamarino et al., 2011), while for Seoul it has been estimated to be 55 W m^{-2} (Lee et al., 2008). As a consequence of local land use, some extremely high values over specific time periods have also been reported in selected regions, such as Tokyo (Ichinose et al., 1999), Philadelphia (Fan and Sailor, 2005), and Singapore (Quah and Roth, 2012).

Inventory-based methods to estimate AHE are generally classified into either bottom-up or top-down approaches. The bottom-up approach relies on detailed datasets of local land use and hourly varying energy consumption statistics, providing high-resolution AHE profiles at the regional scale. On the other hand, the aim of the top-down approach is to provide a wider area coverage for global or regional applications, by incorporating global datasets. Country-level annual total bulk energy consumption is distributed both spatially and temporally to obtain high-resolution AHE profiles.

Through the bottom-up approach, Ichinose et al. (1999) estimated the anthropogenic heat flux in central Tokyo by applying detailed digital geographic land use datasets, including building height information, at a resolution of 25 m. Klysik (1996) divided local land use into four patterns and investigated energy consumption by neighborhood type for Lodz, Poland. However, due to the limited availability of input data, this approach cannot be used in a global model.

Existing global AHE datasets created via the top-down approach include the works of Flanner (2009) and the large scale urban consumption of energy model (LUCY) developed by Allen et al. (2011). One of the common features of these datasets is that the AHE is spatially gridded and temporally distributed based on several components, such as heat released from vehicles, buildings, and human metabolism. The spatial distribution of AHE can vary substantially based on the assumed population density. The global anthropogenic heat flux modelled by Flanner (2009) was derived from the country-level total consumption of non-renewable energy based on population density at a spatial resolution of 0.5° × 0.5°. Another global AHE model, LUCY (Allen et al., 2011) has been used to calculate the anthropogenic heat flux from numerous global datasets, among which a dataset of 30 arc-seconds population density acquired from the Global Rural-Urban Mapping Project (GRUMPv1) (Lindberg et al., 2013) was used in the spatial decomposition. The main challenge of the population-based top-down approach is the representation of the working population, which if neglected may lead to a significant overestimation in very dense residential areas, but an underestimation in central business districts. Although GRUMP data use adjustments by nightlights, the representativeness of the working population in certain areas is still uncertain (further discussed in Sec. 3.2). On the other hand, Sailor and Lu (2004) developed a measure of the hourly population density by merging non-working resident populations and working populations in urban area. This can effectively reflect how an urban population varies during the day; however, this method is not feasible for global implementation because of the lack of working population data for most cities.

In addition, various methods have been used to estimate temporal variation. In Flanner's modeling of global AHE (2009), annual-mean AHE was scaled with weighting functions that were dependent on the time of day and time of year. The LUCY model relies on a temperature scaling factor, which is a function of an individual country's income. The approach is promising, but still requires further verification. To further investigate monthly changes in AHE according to the local temperature, a more sophisticated estimation of monthly variation at the global scale is required.

Given the abovementioned uncertainties in existing AHE datasets, this study aimed to: construct a highly detailed 30 arc-seconds AHE database, with global coverage, through the use of high-resolution population density data adjusted by nighttime lights; improve accuracy in terms of representing the spatial and monthly variation of AHE in urban areas using a sophisticated function relating energy consumption to temperature variation; and evaluate and verify our proposed database by comparing it with other existing regional-scale and global-scale AHE datasets.

2. Method to estimate global AHE

Annual average AHE ($Q_{f\text{-}y}$) was derived from human metabolic heating and primary energy consumption, which was further divided into three components based on consumer sector. Temporal partitioning of $Q_{f\text{-}y}$ into monthly AHE ($Q_{f\text{-}m}$) and hourly AHE ($Q_{f\text{-}h}$) was done after spatial assignment, using corresponding weighting factors.

A schematic diagram of the methodology is shown in Fig. 1. All data used as inputs are listed in Table 1. The basic assumption of the top-down inventory-based approach is that all energy consumed by human activities in a specified region is directly converted to anthropogenic heat in that region. It should be noted that the waste-heat emissions from the buildings is assumed to be equivalent to the building's energy consumption. In other words, the quantifiable energy consumption of buildings is assumed to refer to the waste-heat coming from the buildings. Any unique features of