Anthropogenic Heat and Moisture Emissions in the Urban Environment

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Abstract

Anthropogenic emission of waste heat is one factor contributing to the development of urban heat islands. These emissions vary significantly both in time and space, and are not readily measured. As a result, detailed models of anthropogenic emissions are not commonly available for most cities. Furthermore, early attempts to quantify anthropogenic emissions focused on anthropogenic sensible heat, largely ignoring anthropogenic moisture emissions and invoking assumptions that limited the accuracy and usefulness of the resulting anthropogenic emission data. This presentation will provide a historical perspective of the development of models of anthropogenic emissions and their inclusion in atmospheric models. It will also highlight some fundamental questions regarding the basic definition of anthropogenic emissions and suggest a roadmap forward for including anthropogenic emissions in modeling of the urban environment.

Key words: anthropogenic emissions; energy use; waste heat

1. INTRODUCTION

This paper focuses on the development and use of methods for including anthropogenic heat emissions in models of the urban atmosphere. It starts by describing the characteristics of the various sources of emissions. It then describes three categories of approaches used to estimate the magnitude, spatial distribution, and diurnal profiles of anthropogenic heating. Examples are given where researchers have developed sophisticated estimation techniques and applied them to specific cities of interest. The paper concludes with a discussion of next steps needed to enable widespread and accurate representation of anthropogenic heating for cities around the world.

2. SOURCES OF ANTHROPOGENIC HEAT

2.1. Metabolism

According to Fanger, 1972 the sleeping metabolic rate for a typical 70 kg man is about 75 W. During the daytime this metabolic rate may increase to 100 or 200W. The magnitude of anthropogenic heating from human metabolism clearly depends upon population density. If city-scale daytime population densities are on the order of 10,000 persons km^{-2} the corresponding metabolic heat flux is on the order of 1.5 W m^{-2}. While many cities around the world have higher population densities in their urban cores it is important to note that at any instant in time much of the urban population is located in buildings. Thus, in representing total anthropogenic heating in an urban area it is important to note that the building sector anthropogenic heat model likely accounts for occupancy loads, and human metabolism should not be treated separately as it will lead to a double-counting of that source.

2.2. Manufacturing and Industry

Industrial energy use is relatively insensitive to variations in weather and has a somewhat uniform diurnal and seasonal distribution. In fact, once the spatial distribution and intensity of industry within a city is determined it is fairly common to simply assume that the energy consumption is uniformly distributed across the year. Depending upon the region or city under study, the monthly or annual energy consumption within the industrial sector can be obtained from power utility and/or governmental energy agency data bases (e.g., EIA, 2004). Land use data can then be used to apportion the industrial sector energy consumption into the corresponding regions within the city. While much of the energy consumption in the industrial sector is converted directly into sensible waste heat, some is removed using evaporative cooling towers or by exchanging heat with a large body of water. As a result, it is difficult to estimate the partitioning of waste heat in the industrial sector between sensible and latent components.

2.3. Buildings

During occupied hours the building's heating, ventilation, and air conditioning (HVAC) controls seek to moderate internal thermal comfort conditions. As the building exchanges heat with the outside environment and experiences internal heat loads from lighting and equipment, the HVAC system must compensate. In winter internal heat is lost to the outside through conduction and both intentional air exchange and unintentional leakage. For example, residential buildings typically have 0.3 to 0.5 air exchanges per hour. That is, within one hour half of the volume of air is replaced by outside air. In summer, in addition to conduction of heat into the building through its envelope, windows (with a short wave transmissivity of 65 to 75%) admit a significant environmental (solar heating) load into buildings that must be removed by the air conditioning system. As a result, the waste heat removed from a building in summer by the air conditioning system may be significantly larger than the thermal load associated with a simple inventory of energy consumption within the building. Furthermore, some air conditioning systems use evaporative cooling to exchange heat with the outside environment. In such systems less than half of the heat is removed as sensible heat with the remainder being removed as latent heat.

As a result of these complexities it is particularly problematic to simply represent waste heat emission from the building sector using an energy use inventory approach. An approach that simply equates energy consumption with sensible waste heat can either over or under estimate sensible emissions depending upon the season and types of buildings under consideration. Furthermore, inventory approaches will generally neglect the latent heat component of anthropogenic emissions which can be quite large.

2.4. Vehicles

As vehicles travel along roadways they release heat and moisture associated with the combustion of gasoline or diesel fuel. A typical heating value for vehicle fuels is 45 MJ/kg. Also, as fuel is burned the chemical reaction leads to generation of water vapor. In fact, for each liter of gasoline or diesel fuel burned about 1.0 kg of water vapor is generated. The challenging aspect of determining anthropogenic emissions from the vehicle sector involves estimating the spatial and temporal distribution of vehicles on major and minor roadways within the city. Further, the actual fuel economy of vehicles varies among vehicle types, and the distribution of vehicle types on roads changes over the course of the day. Fleet fuel economy depends very much on the city and country of analysis, but typically is in the range of 7 to 10 km/l (16 to 24 mpg). Many regional transportation agencies track vehicle use in one form or another. In the US the range is from about 30 to 60 km/person/day (USDoT, 2003).

2.5. Relative Importance of Each Sector

It is important to recognize that energy use partitioning among the sectors varies from one country to another and from one city to another within any country. Nevertheless, for illustrative purposes, consider the annual energy consumption statistics for the US. According to EIA, 2005 about 40% of all end-use energy consumption in the US occurs in the building sector, about 30% is in transportation, and about 30% is in industry/manufacturing. So, clearly, any accounting of waste heat emissions must include each sector. It must be noted, however, that each sector is not uniformly distributed among all cities. For example, Houston TX is a city with an incredibly large petrochemical and manufacturing industry, located within the city. In fact, a number of these large facilities have on-site electric generation power plants. Many other cities are dominated by the other sectors with relatively small industry and manufacturing components. So, making any blanket statements regarding the relative size of the various components of anthropogenic heating is dangerous. That said, cities with a large industrial base such as Houston may have on the order of half their energy consumption in the industrial sector with the remainder somewhat evenly split between buildings and vehicles. In cities with a relatively small industrial base the building and vehicle sectors may comprise 80% or more of the total energy consumption.

3. REPRESENTATION OF ANTHROPOGENIC HEATING FOR URBAN MODELING APPLICATIONS

Various approaches have been used to estimate anthropogenic heat emissions in the urban environment. These include inventory approaches, micrometeorologically-based energy budget closure methods, and building energy modeling approaches. Each approach has its advantages and limitations as described below.

3.1. Inventory approaches

An inventory approach is one in which energy consumption data are gathered, typically at coarse resolution in time and space. These approaches may rely on utility scale energy consumption data, or data resulting from energy consumption surveys. The vast majority of inventory applications make the assumption that consumption is equal to sensible waste heat emissions, with no time lag and no partitioning into sensible and latent components. Further, they generally must use some mechanism to map annual or monthly consumption onto diurnal profiles. They must also map city-wide or regional estimates onto a finer scale grid to represent spatial variability within the city. One of the earliest inventory studies was that of Torrance and Shum, 1975 who related annual statistical data on energy consumption to population density to arrive at annual estimates of 83.7 W m^{-2} for a densely populated city. Despite its limitations, this study was perhaps the first to estimate anthropogenic heat emissions (up to 135 W m^{-2} for a summer day in an unspecified dense city) and estimate the impact on urban air temperatures (up to a 4 ^{o}C warming in summer). Subsequent studies improved both on the spatial and temporal disaggregation of inventoried energy consumption data. Kimura and Takahashi, 1991, for example, used detailed land use data in combination with energy consumption data to estimate anthropogenic heating and its impact on urban air temperatures in Tokyo. While they used a fairly simple approach to estimate the diurnal profile, they were able to take advantage of detailed gridded land use data to create a somewhat realistic spatial map of waste heat emissions. In feeding these emissions into a hydrostatic three-dimensional numerical model they estimated that most of the nocturnal summertime heat island in Tokyo (2-3 ^{o}C) is due to anthropogenic heating. Klysik, 1996 used an inventory approach to estimate anthropogenic heat emissions in Lodz, Poland. In his work the annual heating energy consumption data were mapped to monthly profiles using variability in monthly air temperatures. Population density was used as a parameter for discerning electricity use. Klysik's analysis suggests monthly averaged anthropogenic heat flux in Lodz ranging from 12 W m^{-2} in summer to 54 W m^{-2} in winter. Ichinose et al., 1999 linked energy statistics for various building types and end uses in Tokyo (obtained from Ichinose et al., 1994) with detailed digital geographic land use data to estimate hourly anthropogenic heating at a 25 m by 25 m grid resolution. They found that hourly energy consumption at this scale (assumed equal to anthropogenic sensible heating) could be as large as 1590 W m^{-2} in the winter and was more than 400 W m^{-2}

during summer daytime hours. Their analysis also integrated anthropogenic heat into a numerical simulation. They found that anthropogenic heating resulted in summer air temperature elevations of less than 1 ^{o}C during the day, but as much as 1.5 ^{o}C at night. In winter, when the magnitude of anthropogenic heating was much higher they found that the nocturnal warming reached 2 to 3 ^{o}C. Fan and Sailor, 2005 implemented the inventory-based approach of Sailor and Lu, 2004 in a study of anthropogenic heating in Philadelphia, Pennsylvania. That study found peak city-scale anthropogenic heating to be 60 W m^{-2} in summer and approximately 90 W m^{-2} in winter. The impacts of this anthropogenic heating on urban air temperatures ranged from 1 ^{o}C in summer to 3 ^{o}C in winter. One of the unique characteristics of the method presented in Sailor and Lu, 2004 is that it emphasized use of data that are widely available for most large US cities. The modeling approach was inventory based and diurnally distributed based on widely applicable profile functions. As with most inventory-based approaches, the work of Sailor and Lu implemented the assumptions that energy consumption equals anthropogenic heat and that all of this heating is sensible. Another limitation of this work was that it provided no mechanism for mapping city-wide anthropogenic heating data onto finer spatial scales. Nevertheless, its wide applicability led to its application in Sailor and Hart, 2006 to 50 US cities.

3.2. Estimates based on energy budget closure

From the micrometeorological standpoint, if one can track net radiation, advection, and ground heat flux/storage, it would be possible to estimate anthropogenic heating as the residual term in an energy balance. That is, measure all terms in the energy balance except for anthropogenic heating and assume that any imbalance in the equation is entirely due to anthropogenic heating. This sort of approach has been applied by a small number of investigators. Offerle et al., 2005 applied this concept to data gathered in a downtown region of Lodz, Poland. The challenge with using an energy balance residual approach is that any errors within the measurement system are simply incorporated into the estimate of the residual. Further, due to significant challenges in using eddy flux methods in a non-homogeneous urban system, the magnitude of the errors in estimating sensible and latent fluxes may be large. As a result, it is not surprising that the results of Offerle et al., include unrealistically negative numbers for anthropogenic heating in summer months. Their estimates for wintertime anthropogenic heating had magnitudes around 50 W m^{-2}. In a contrasting approach, Kato and Yamaguchi, 2005 employed an energy budget residual approach in which remote sensed satellite data were used in conjunction with surface meteorological data to estimate anthropogenic heating in Nagoya Japan. Due to the nature of their measurements (surface radiation) Kato and Yamaguchi's results do not allow estimation of anthropogenic heat directly, but rather, the increase in surface sensible heat flux resulting from anthropogenic heating and the associated warming of the near-surface air.

Pigeon et al., 2007 conducted an analysis of anthropogenic heat release for Toulouse France as part of the CAPITOUL experiment. Their study included both an inventory-based approach with similarities to Sailor and Lu, 2004 and an energy budget approach similar to Offerle et al., 2005. The particularly useful aspect of their study was that it enabled direct comparison of the two approaches. They found the two approaches to be in general agreement with wintertime anthropogenic heating as high as 70 W m^{-2} and summertime values about 15 W m^{-2}.

3.3. Estimates based on building energy models

Anthropogenic heating from the building sector is particularly complicated and has been the subject of a number of focused studies. These studies generally involve explicit modeling of energy consumption within buildings and careful evaluation of heat rejection. Kikegawa et al., 2003 presented one of the first studies that integrated building energy simulation results with an urban canopy meteorological model. Their building energy submodel explicitly accounted for building occupants, radiative transfer through windows, type of air conditioning heat exchanger (air-cooled vs. evaporatively cooled) and coefficient of performance (COP) of air conditioning systems (typically an air conditioning system requires one unit of energy to remove about 3 units of heat from a building; COP~3). They were able to partition waste heat between latent and sensible components and provide a more realistic estimate of anthropogenic emissions. Subsequent studies by Kondo and Kikegawa, 2003 and Kikegawa et al., 2006 explored various implementations of this model.

In another series of studies researchers have successfully integrated detailed building energy simulations of prototypical buildings with geographical information system data bases containing characteristics of building types, sizes, and locations. Such studies allow researchers to model a representative building stock and then for each land use parcel within a domain associate a floor-space scaled waste heat emission from the corresponding building prototype. Hsieh et al., 2007 conducted such a study for Taipei Taiwan using 10 building prototypes. Heiple and Sailor, 2008 conducted a very similar study in which they used a total of 30 building prototypes to represent the building stock in Houston Texas. This approach was later implemented in a study that extracted building sector waste heat and moisture and linked these data to an inventory-based transportation sector model (Sailor et al., 2007). This study found that, due to significant environmental loads, heat rejection from buildings can be 50 to 100% greater than the energy consumption of the building. It also found that of the heat rejected from buildings in a city such as Houston (with many large buildings with evaporative cooling towers), 50 to 80% of the heat is rejected as latent heat.

4. DISCUSSION AND CONCLUSIONS

The three approaches to estimating anthropogenic heating in urban environments each have their strengths and limitations. The ultimate goal of estimating anthropogenic heating is to develop information that can readily be incorporated into an urban atmospheric model. As a result there is a need for a balance between accuracy and simplicity. It is particularly important that any modeling approach adopted be readily integrated into an atmospheric modeling code and that the necessary data can be obtained with a modest amount of effort for a large number of cities. This author suggests then that the necessary characteristics of any anthropogenic heating modeling approach are as follows: (1) it should accurately account for all major sources of heating including buildings, industry, and vehicles; (2) it should account for both moisture and sensible heat emissions; (3) it should be easily applied to many cities by relying on readily available data bases of energy consumption, land use, and building characteristics. The oral presentation of this paper will expand upon these themes and make recommendations regarding how the community might move forward to make representation of anthropogenic heating in atmospheric models more accurate and widely available.

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