Anthropogenic Heat Release: Estimation of Global Distribution and Possible Climate Effect

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Abstract

The estimation of the distribution of global anthropogenic heat release (AHR) from 1992 to 2009 was obtained by applying Defense Meteorological Satellite Program (DMSP)/Operational Linescan System (OLS) satellite data. The results indicate that global AHR was geographically concentrated, essentially correlating to economic activities. The anthropogenic heat flux concentrated in the economically developed areas, such as East Asia, Europe, and Eastern North America, reached a level high enough to influence regional climate. In contrast, the anthropogenic heat flux in vast areas, such as Africa, Central and North Asia, and South America, is very small. With the increases in global population and economic development, an increase in AHR was easily found. The model results show that AHR has a significant impact on surface temperature and that it is able to affect global atmospheric circulation, leading to a 1–2 K increase in the high-latitude areas of Eurasia and North America. The results show that AHR is able to affect global climate despite being limited to a region. Although the influence to global warming by AHR is not as large as greenhouse gases, such as carbon dioxide, on a global scale, AHR is an important factor in global climate change that should not be ignored.

Keywords anthropogenic heat release; estimation of the distribution; global climatic effect

1. Introduction

The social production and lifestyle of mankind has dramatically changed since the 1750s’ Industrial Revolution. Vast amounts of fossil fuels were consumed in the industrialization process. Green-
anthropogenic heat greatly influences climate in urban areas (Block et al. 2004; Fan and Sailor 2005; IPCC 2007). Anthropogenic heat release (AHR) can have a significant influence on the dynamics and thermodynamics of urban boundary layers (Ichinose et al. 1999; Block et al. 2004; Fan and Sailor 2005), and it can influence the reaction rates and reaction types of emitted species (Makar et al. 2006). Anthropogenic heat greatly influences urban climate and is one of the primary causes of heat islands (Fan and Sailor 2005; Crutzen 2004; Betts and Best 2004). The average value of anthropogenic heat flux is approximately 0.03 W m$^{-2}$ globally and 0.10 W m$^{-2}$ for global land area (Chen and Shi 2012). In developed and populated regions, such as Tokyo, AHR flux may exceed 400 W m$^{-2}$ (Ichinose et al. 1999), reaching a level high enough to affect regional climate and weather (Fan and Sailor 2005). Compared with other climate change factors, such as greenhouse gases, the anthropogenic heat does not appear to be as “hot” as the other factors. AHR flux is very small on a global scale, compared with global mean radiative forcing by CO$_2$ (+1.66 ± 0.17 W m$^{-2}$) at present (IPCC 2007). However, previous studies indicate that anthropogenic heat is very important for urban regional climate (Block et al. 2004; Oleson et al. 2011; Feng et al. 2012). Global AHR is geographically concentrated, essentially correlating to economic activity (Chen et al. 2012; Chen and Shi 2012). Urbanization is estimated to result in 6 billion people living in cities (McCarthey et al. 2010), which means that the population density in urban areas is increasing. With the further development of society, global energy demand is continuing to rise. AHR will become increasingly serious in the future; hence, the climatic effect of AHR on global climate change should not be ignored. The climatic effect of AHR has attracted significant attention (Washington 1972; Washington and Chervin 1979; Nordell 2003; Block et al. 2004; Flanner 2009; Zhang et al. 2013). Since most previous studies on the climatic effect of AHR have been limited to regional urban areas, research on the global climatic effect of AHR is lacking. In this paper, a new method for estimating the distribution of global AHR is established, which leads to the global perspective compared with the local one in the previous studies. In addition, the outcomes of the global distribution of AHR are applied in a global climate model to discuss the possible global climatic effect of AHR.

2. Estimation of global distribution of AHR

Estimating the distribution of global AHR is essential for studying its climatic effect in climate models. Most previous studies focused on the anthropogenic heat flux in a single area or in only urban areas (Ichinose 1999; Sailor and Lu 2004; Lee et al. 2009; Hamilton et al., 2009), thereby limiting the study of AHR climatic effects to regional areas (Tong et al. 2004; Block et al., 2004). In recent years, AHR has been applied to global climate models (Flanner 2009; Zhang et al. 2013), but the parameterization for AHR used in those models does not suit a wider application. The results obtained using grid points for global AHR distribution in previous studies seemed a little rough. Hence, it is critical to obtain a credible distribution of global AHR for the research on the climatic effect of AHR using climate models.

2.1 Data and method

In this paper, the distribution of global AHR from 1992 to 2009 is estimated using data from the National Oceanic and Atmospheric Administration’s (NOAA’s) Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS), which provides a useful parameterization for climate models. DMSP/OLS has the unique capability to detect low levels of visible and near-infrared radiance at night. It is able to detect lights from cities and towns, gas flares, and short-duration events, such as fires and lightning (Elvidge et al. 1997a, b). DMSP/OLS data were widely applied in various studies, including estimations of economic activity (Tilottama et al. 2009), energy consumption (Elvidge et al. 1997a, b; Husi et al. 2010), human settlement and urban extent (Small et al. 2005), population (Amaral et al. 2006), and greenhouse gas emissions (Oda and Maksyutov 2011; Doll et al. 2000). Recent studies have shown that DMSP/OLS data are closely correlated with the
area’s level of economic development and energy consumption, and the use of these levels proved to be a good method of estimating the energy consumption and economic development level of an area (Tilottama et al. 2009; Husi et al. 2010; Oda and Maksyutov 2011). The areas in which DMSP/OLS data are larger typically have developed economies and huge energy consumption, resulting in more anthropogenic heat emissions.

The statistical data of U.S. Energy Information Administration (EIA, http://www.eia.gov/), International Energy Agency (IEA, http://www.iea.org/), and the National Bureau of Statistics of China (http://www.stats.gov.cn/tjsj/ndsj/) were used in this study. The method applied in this paper is based on the fact that DMSP/OLS data are closely correlated with the local economy, population, and energy consumption. Assuming that all energy consumed by human activities is converted into heat and eventually released into the atmosphere, the anthropogenic heat flux density \( Q_a \) of a specific area and over a specified time could be approximated by

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Q_a = \frac{\text{Anthropogenic Heat Release}[J]}{\text{time[s]} \cdot \text{area[m}^2]} \tag{1}
\]

Chen et al. (2012) and Chen and Shi (2012) showed that a strong linear relationship \( R^2 > 0.99 \) exists between DMSP/OLS data and \( Q_a \). In addition, the results of applying DMSP/OLS data to AHR estimation seem credible. Thus, DMSP/OLS data are suitable for estimating the distribution of global AHR. Based on an error analysis of the estimation process, the results are consistent with the statistical data, and the estimated trend is consistent with the energy consumption data (Chen et al. 2012; Chen and Shi 2012).

The results of estimating the distribution of global AHR from 1992 to 2009 are as illustrated in the following Figs. 1, 2, and 3.

From Figs. 1, 2, and 3, the distribution of the global AHR is geographically concentrated, essentially correlating to the development level of the local economy. In developed and populated areas (e.g., Tokyo), AHR is large enough to affect local climate (Ichinose et al. 1999); in less populated areas, however, AHR is very small, most likely zero. Europe, North America, East Asia, and South Asia are regions in which the anthropogenic heat is concentrated, including global coastal populated regions. AHR is generally much greater than the global

Fig. 1. Estimation of the distribution of global AHR using DMSP/OLS data in 1992 (resolution: 0.1° × 0.1°; unit: W m\(^{-2}\)).
average level in developed areas, while AHR flux in developing regions, such as North and West Asia, South America, and Africa, is small. The highest values of AHR flux appear in developed regions, such as the northeastern United States, Central Europe, the United Kingdom, Japan, India, and East China. Moreover, the increase of AHR global distribution is obvious from the estimation results by comparing Figs. 1, 2, and 3. From 1992 to 2009, the global AHR has become important: its range is expanding, and its impact on climate is considered to be increasing. The annual mean AHR flux in concentrated regions reached 20 W m$^{-2}$ in 2009. In vast developing areas, including South America, Central and North China, India, East Europe, and the Middle East, AHR has significantly increased. With the development of the global economy and population, even more energy will be consumed; as a result, the global AHR will become more important. Furthermore, due to the boom of urban agglomeration that is expected in the near future, urban areas will become more populated and crowded. With the development of global urbanization, global AHR will be concentrated in urban areas. Therefore, the climatic effect of anthropogenic heat on urban climate will be greater in the future. The climatic effect of AHR is very important in the research on climate change.

3. The modeling results of the global climatic effect of AHR

3.1 Introduction to GAMIL model

The global distribution of AHR from 1992 to 2009 estimated using DMSP/OLS data was applied to the Grid-point Atmospheric Model of IAP LASG (GAMIL) to study the global climatic effect of AHR. GAMIL is based on a finite difference dynamical core and was developed by the States Key Laboratory for Numerical Modeling of Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS). The GAMIL model has three versions of different horizontal resolutions: high-resolution ($1^\circ \times 1^\circ$), mid-resolution ($2.8^\circ \times 2.8^\circ$), and low-resolution ($5^\circ \times 4.5^\circ$). The resolution applied in this paper is $2.8^\circ \times 2.8^\circ$. The GAMIL model includes 26-$\sigma$ vertical levels. The physical processes in GAMIL mainly originate from the Community Atmospheric Model (Collins et al. 2003), with some
altered parameters and convective schemes (Li et al. 2013). GAMIL model has taken part in various international model intercomparison projects, including the Atmospheric Model Intercomparison Project (AMIP), Seasonal prediction Model Intercomparison Project (SMIP), Climate Prediction and its Application to Society (CliPas) project, and Climate of the 20th Century (C20C). GAMIL is widely used to study the paleoclimate, climate change (e.g., IPCC AR4 experiments) and seasonal forecast, such as the Madden–Julian Oscillation (MJO), ENSO, and Asian–Australian monsoon (Li et al. 2013).

3.2 Modeling results for the climatic effect of AHR on global surface temperature

The annual data of global distribution of AHR during the 1992–2009 period were applied to the GAMIL model, and the grid data were suitable for the model requirements. AHR is integrated in the model by adding excessive vertical flux convergence in the boundary layer. The anthropogenic heating can be in the form of either sensible heat flux or long-wave radiation (Zhang et al. 2013). We assume that AHR is absorbed in the lower atmosphere, which will turn into up long-wave radiation. Based on the physical process analysis, AHR is considered long-wave radiation in the GAMIL model. The running time for the GAMIL model is from 1992 to 2009. Two experiments were simultaneously conducted; one incorporated AHR into the surface energy balance within the model (experiment AHR), whereas the other, which was used as the control experiment, did not. The climatic effect of AHR on global surface temperature is shown in Fig. 4.

From Fig. 4, the climatic effect of AHR could result in an increase in the global annual mean surface temperature of approximately 0.06 K. The surface temperature in the mid and high latitudes of North America and Eurasia increased by 0–1 K. The heating centers are located in the areas of 40°N–60°N of Eurasia and 50°N–70°N of North America. The increase in surface temperature in North America and Eurasia increased by 0–2.5 K and 0–1 K, respectively. These regions correspond well to the area with large differences in surface temperature trends between observations and simulations (Knutson et al. 2006). In the mid and high latitudes of northeastern Eurasia and in the southern and northeastern parts of North America, the surface temperature decreases by approximately 1–2 K. The climatic effect of AHR
has a significant influence on surface temperature. The results indicate that AHR has the ability to affect global climate—not just regional climate.

3.3 Modeling results for the climatic effect of AHR on global annual mean zonal wind

Using the above process, AHR was incorporated into a GAMIL model, with the running time lasting from 1992 to 2009. The effect of AHR on global annual mean zonal wind is shown in Fig. 5.

From Fig. 5, the annual mean zonal wind increased near the surface in the high latitudes of the Northern and Southern Hemispheres, while it decreased in the mid latitudes, i.e., between 20°N–45°N and 20°S–30°S. The results show that the primary effect of AHR is weakening global atmospheric circulation. Comparing the effect of AHR in the areas between 30°–40° of the Northern and Southern Hemispheres, where most of the global population and urban regions are concentrated, the decrease in annual mean zonal wind is more evident in the Northern Hemisphere than it is in the Southern Hemisphere. These results indicate that AHR is able to affect the global atmospheric circulation.

4. Concluding remarks

The climatic effect of AHR was mostly limited to regional urban climate in previous studies. In this paper, the global climatic effect of AHR is investigated. To integrate AHR into the global climate model, DMSP/OLS data were applied to estimate the global distribution of AHR. The increasing effect of the global distribution of AHR could be obtained from the results, and the estimated results appear credible (Chen et al. 2012; Chen and Shi 2012). The theory is based on the fact that DMSP/OLS data are closely correlated with local economy, which is based on local energy consumption. Energy consumption will turn into anthropogenic heat that is eventually poured into the lower atmosphere. Therefore, DMSP/OLS data are fit for use in estimating global AHR. Although a strong linear relationship was found between DMSP/OLS and AHR (Chen et al. 2012; Chen and Shi 2012), the problem of the uneven development of different countries and regions may result in errors in the estimation process. Based on error analysis using statistical data, the estimated results are credible. The estimated results indicate that global
anthropogenic heat was geographically concentrated and expanded and that the anthropogenic heat flux density is large enough to affect local climate change in the concentrated regions. With the development of global economy and population, the climatic effect of AHR will become more serious. Furthermore, with the boom of urban agglomerations, more energy will be consumed in urban areas and the climatic effect of AHR will be enhanced. Three regions in which AHR is concentrated, including East Asia, Europe, and North America, will emerge as heating centers for the lower atmosphere. The estimated results show that the climatic effect of AHR should not be limited to a regional scale. DMSP/OLS data provide a useful method to integrate AHR into global climate models.

Considering the global climatic effect of AHR, the heating centers of AHR are not consistent with the distribution of AHR. The heating centers of AHR are in the mid and high latitudes of the Northern Hemisphere; in these regions, however, the anthropogenic heat is not as serious as that in more populated and developed regions. Moreover, AHR is able to influence global zonal wind and atmospheric circulation. Based on the research by Zhang et al. (2013), there is a robust change in atmospheric circulation in response to AHR. These results indicate that AHR may affect global atmospheric circulation by impacting global climate change further. The climate impact of AHR on global surface temperature shows that AHR will increase the surface temperature by 1–2 K in the mid and high latitudes of Eurasia and North America. Because the global distribution of AHR has increased credibility, the climatic effect of AHR on global surface temperature may seem higher compared with the results of Zhang et al. (2013). In this paper, AHR is considered as long-wave radiation in climate model, while it was taken as sensible heat in Zhang’s study (Zhang et al. 2013). A little difference exists between long-wave radiation and sensible heat in climate model: long-wave radiation could be absorbed throughout the atmosphere layer, while the impact of sensible heat is generally confined within the lower atmosphere.

In short, AHR is able to affect global atmospheric circulation, and the climatic effect of AHR should not be ignored in global climate change. AHR is a very important aspect of the climatic effect of human activities, and it is an important factor in climate change. The research on AHR is very important for understanding global climate change and the climatic effect.
of human activities, which is further useful for future research on extreme weather and climate.

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